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DOE Hydrogen Program

Coatings for Centrifugal Compression

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Argonne National Laboratory

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PDP_25_Fenske

U.S. Department of Energy

UChicago Argonne LLC

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Overview

Timeline

- Start: Oct 2006
- Completion: Sept 2012
- Completion (%): 30 %

Budget

- Total project funding
  - DOE share ($725K)
- Funding for FY08 ($275K)
- Funding for FY09 ($0K-CR)

Partners

- MITI – Mohawk Innovative Technologies Incorporated
  - Oil-free, high-speed centrifugal compressor (bearings)
- John Crane - seals

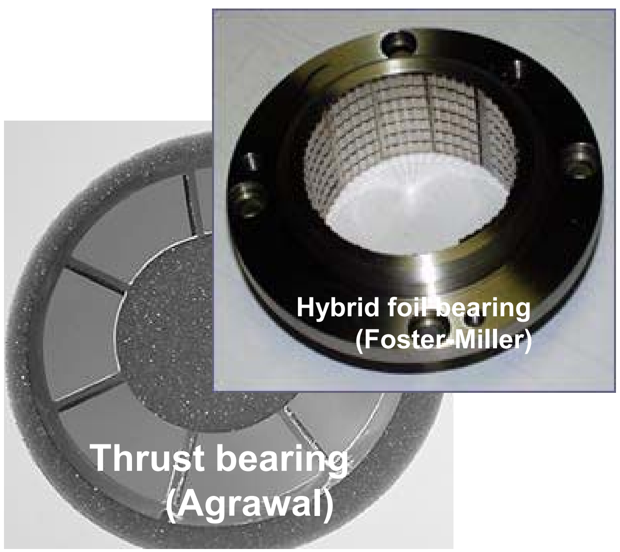
Barriers

- Barriers addressed
  - Delivery Barrier B – 'Reliability and Costs of Hydrogen Compression'
- Targets – Pipeline and Forecourt Compressors

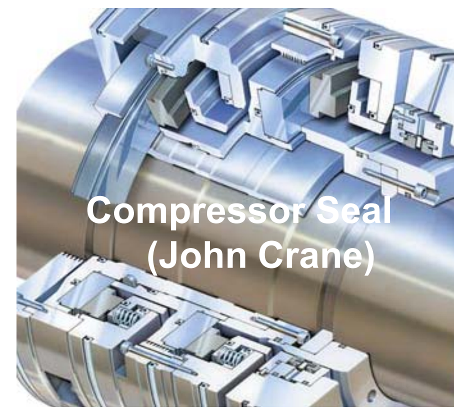
Target	Status	FY 2010	FY 2012	FY 2015	FY 2017
Reliability					
- Pipeline	Low		Improved		High
- ForeCourt	Low	Improved		High	
Capital Cost					
- Pipeline (200K kg/day)	$15M		$12M		$9M
- ForeCourt (1500 kg/day)	$4.6K	$4.0K		$3.0K	
Contamination	Varies by design			none	none
Forecourt Fill Pressure	5ksi – 6+ksi	5 ksi – 6+ksi		10ksi – 12ksi	

Relevance & Objectives

- **The primary objective of this project is to identify, and develop as required, advanced materials and coatings that can achieve the friction, wear, and reliability requirements for dynamically loaded components (seal and bearings) in high-temperature, high-pressure hydrogen environments prototypical of pipeline and forecourt compressor systems.**



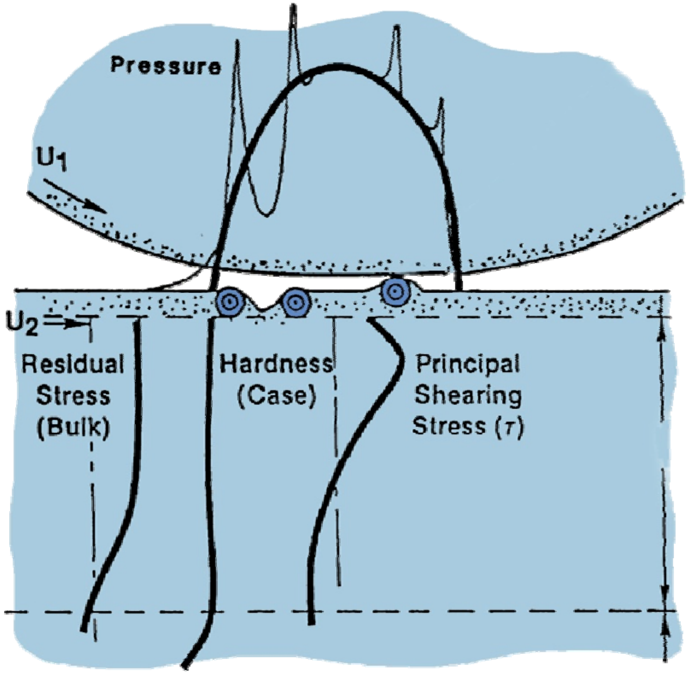
- **The reliability and efficiency of hydrogen compressors will depend on the tribological performance of critical bearings and seals**
- **Knowledge of the tribological performance of materials and coatings in hydrogen environments is insufficient to design reliable, efficient hydrogen compressors**



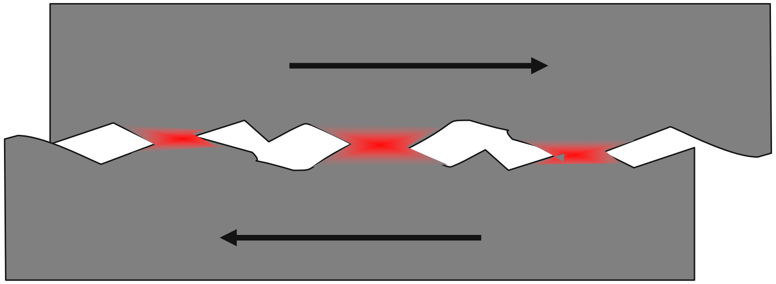
-High reliability,
-Low capital cost

Issues Addressed in Research

- The tribological (friction, wear, reliability, fatigue and hydrogen embrittlement) properties of dynamically loaded components in compressors are strongly affected by tribochemical reactions at the interface.
- The formation (or lack of formation) of protective tribofilms at the interface of surfaces sliding against one another will depend strongly on the local environment.



- Local heating and shear/wear of near surface regions & asperities will expose fresh material with different properties.
- Important spatial and temporal parameters that must be considered include: bulk and local temperatures, loads/stresses, speed, frictional heating, microstructure, and environment (air, O_2, inert gases, H_2, CH_4, impurities, ….)



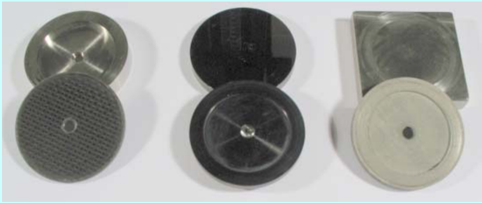
Approach

- Identify critical dynamically loaded compressor components, materials/alloys/surfaces, and operating environments.
- Evaluate tribological performance of candidate materials and advanced solutions under well-defined tribological conditions.
  - Temperature, H_2 pressure
  - Speed, load/stress
  - Air/inert/inert-H_2/CH_4/H_2/impurities
  - Lubrication (?)
- Characterize/identify critical phenomena/mechanisms that control tribological performance
  - Fatigue, wear, surface chemistry
- Develop/select solution(s) to optimize reliability, durability, efficiency, and cost.
- Target: durable friction coefficient < 0.1
- Engineer and validate solution(s) into compressor design
  - Component and compressor tests

Bearings, seals, valve surfaces, couplings…, Pipeline and forecourt compressors …., alloys, coatings …

Atm. H2,
High Speed,
Low Stress,
RT

Atm. H2,
High Speed,
Low Stress,
High Temp



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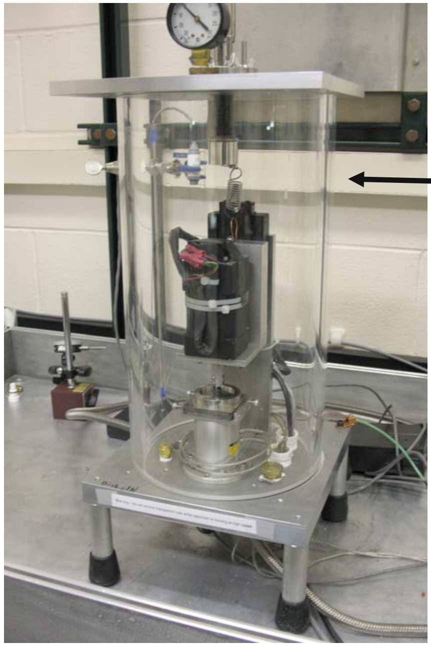
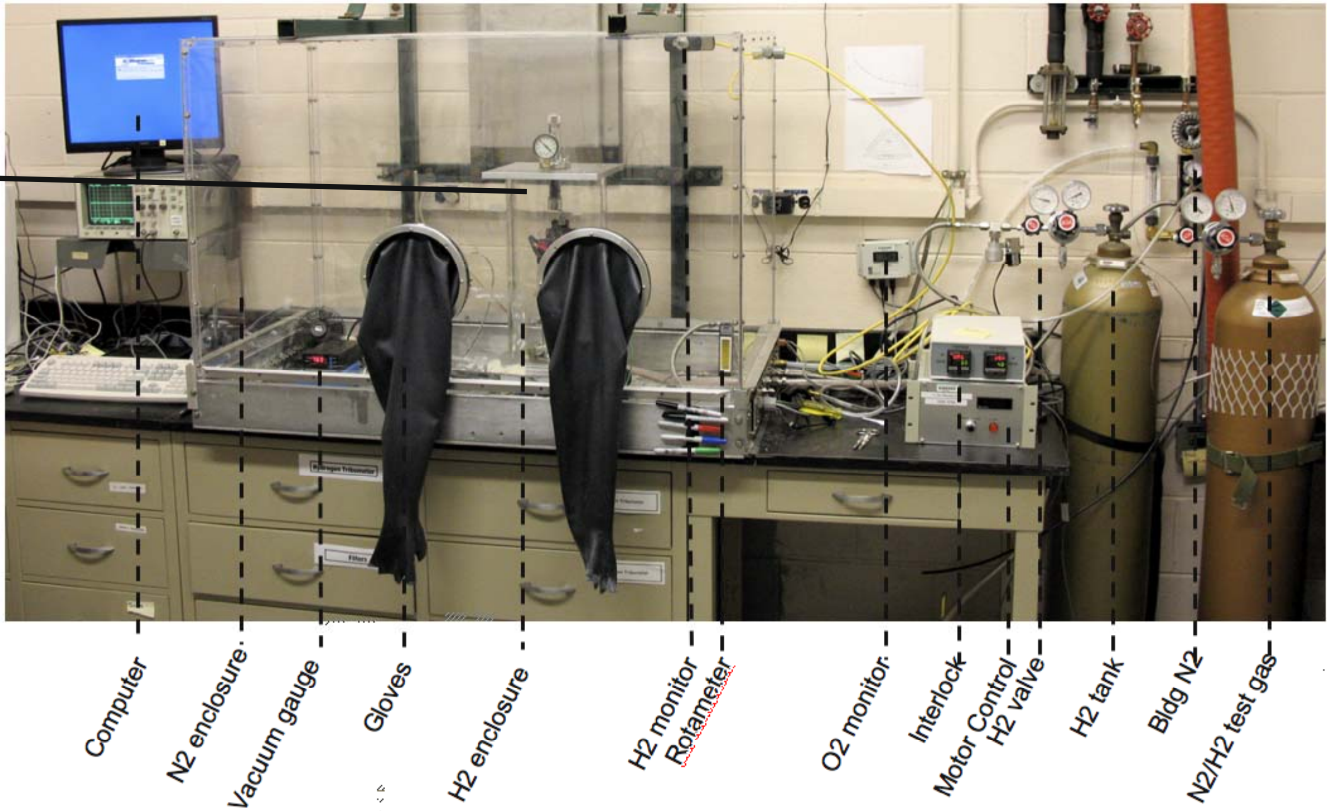
Approach/Milestones

- COMPLETED Initiate low-temperature tests to evaluate tribological properties of materials and coatings in hydrogen (and baseline gases – air, inert, CH_4). — March 2008
  - Low-speed, high stress
  - Medium speed, low stress
- COMPLETED Develop design specs and initiate procurement of a high speed, high temperature hydrogen tribometer. — July 2008
- Rank promising materials and coatings — September 2009
- Site preparation for high temperature hydrogen tribometer. — August 2009
- Operation of hydrogen tribometer and high temperature tests — February 2010

Technical Accomplishments 2009

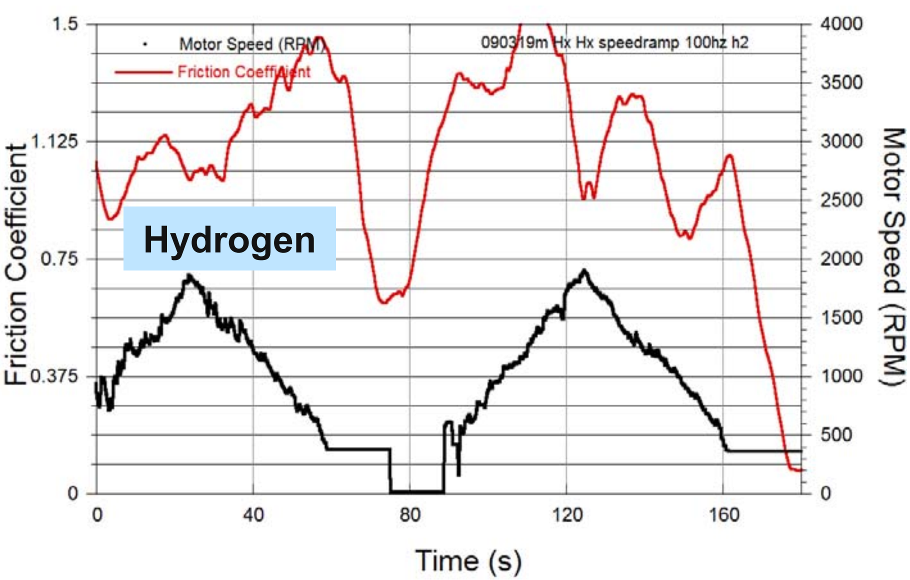
- **Tribometer developed and made operational with capability to test candidate materials and coatings in hydrogen <u>and methane</u> at high speeds**

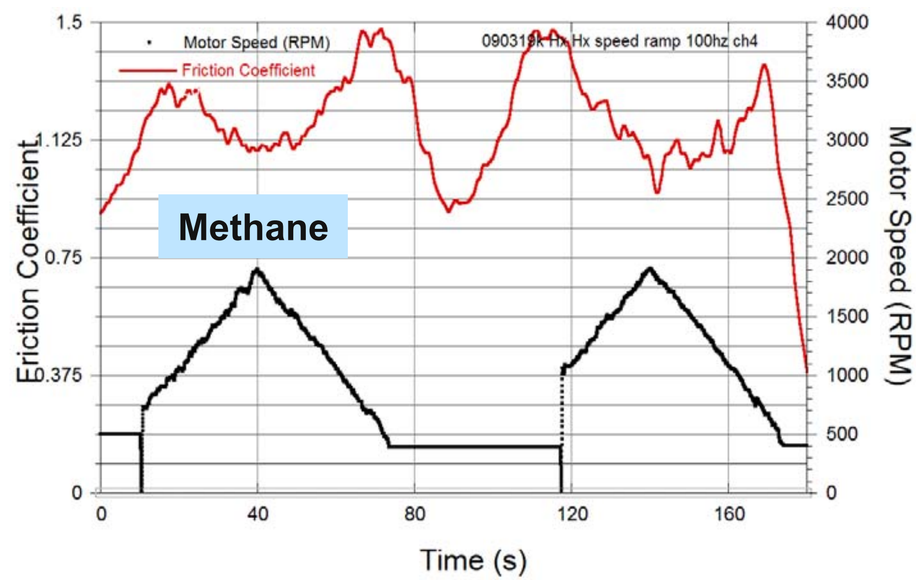




Technical Accomplishments 2009

- **Started friction tests of baseline materials in pure methane (natural gas) in addition to hydrogen**
  - **Ability to test in methane added to test matrix to determine if alloys currently used in natural gas pipeline compressors behave differently in hydrogen - side-by-side comparison of alloys and coatings in both hydrogen and methane**
  - **Data below demonstrate that Hastelloy® shows no apparent difference in frictional behavior at room temperature due to test environment (H_2 vs. CH_4)**



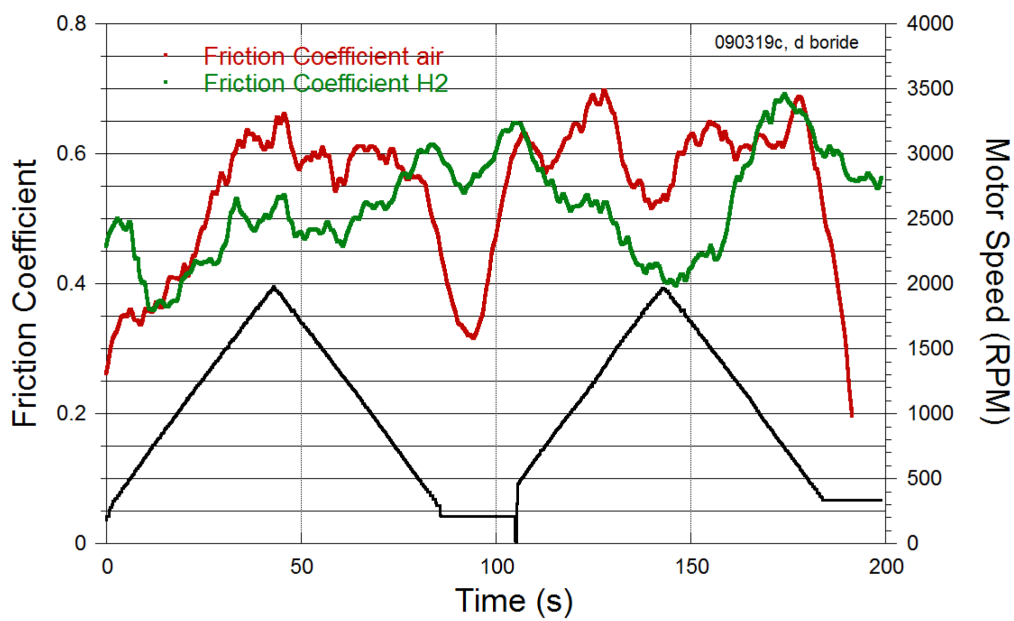


Technical Accomplishments 2009

- **Started tests on <u>new</u>, inexpensive chemical-conversion coating (Fe/Ni/B) in pure hydrogen and air which gives little wear against 316 ss in either hydrogen or air but friction is unacceptably high**

Fe/Ni/B

Lower counterface coupons show negligible wear in air or hydrogen



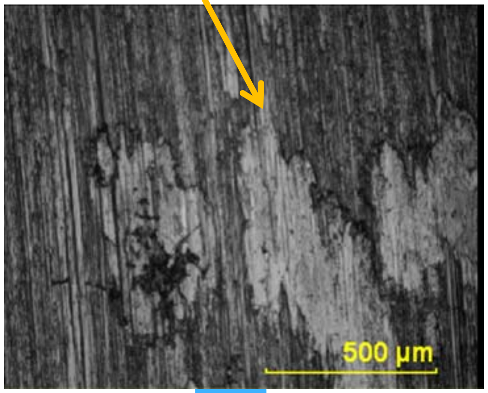
316 ss counterface in air

316 ss counterface in H_2

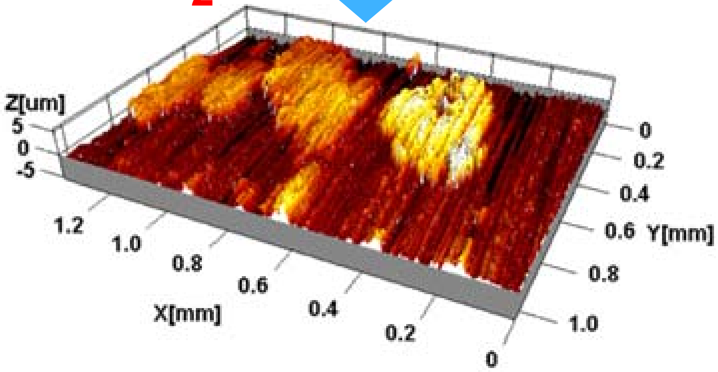
Technical Accomplishments 2009

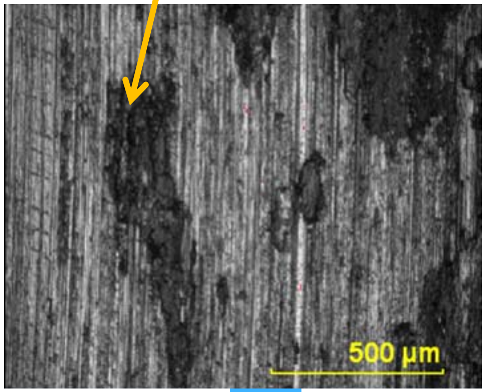
- **For boride conversion coating, wear of counterpart is different in hydrogen than air suggesting oxidative wear in air, metallic transfer film in H_2**
  - **–Light metallic galling marks on counterface after testing in hydrogen (metallic transfer film)**
  - **–Dark metallic galling marks on counterface after testing in air (oxide film)**

Fe/Ni/B

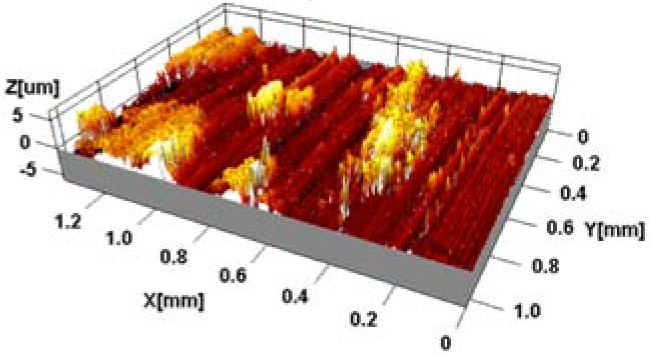


H_2





Air



Both light and dark marks are raised above the surface

Technical Accomplishments 2009

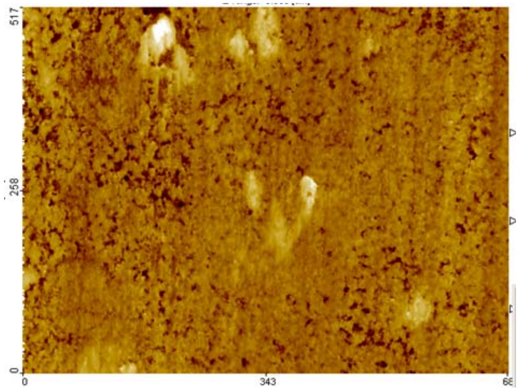
- **For boride conversion coating, no significant difference in wear appearance**

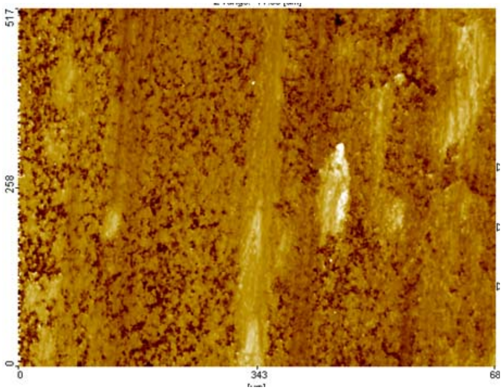
The worn borided disk surface is essentially the same regardless of test gas

H_2

Fe/Ni/B

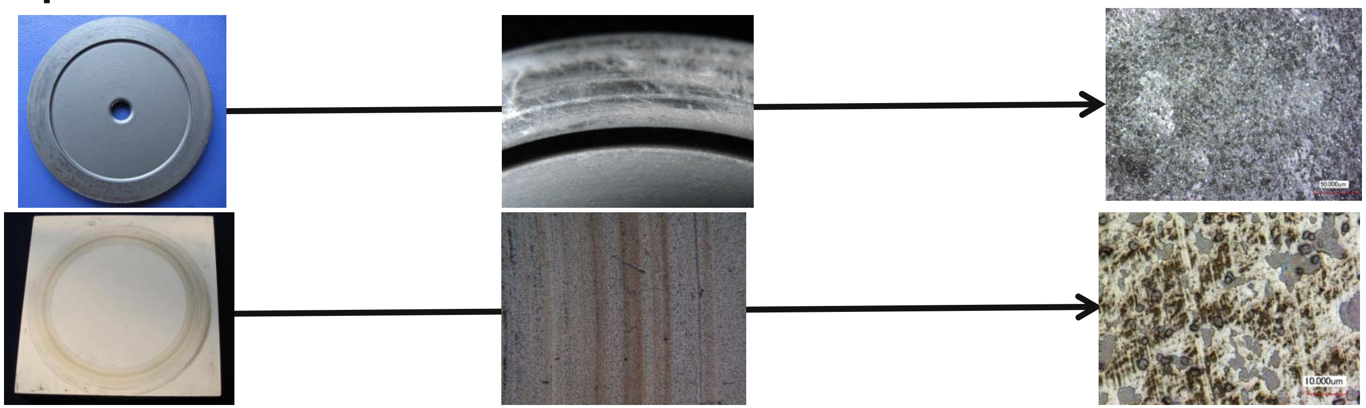
Air

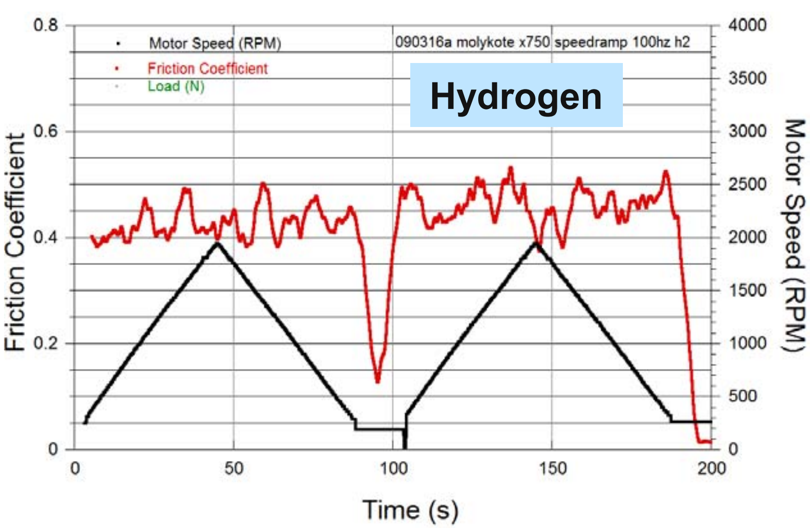


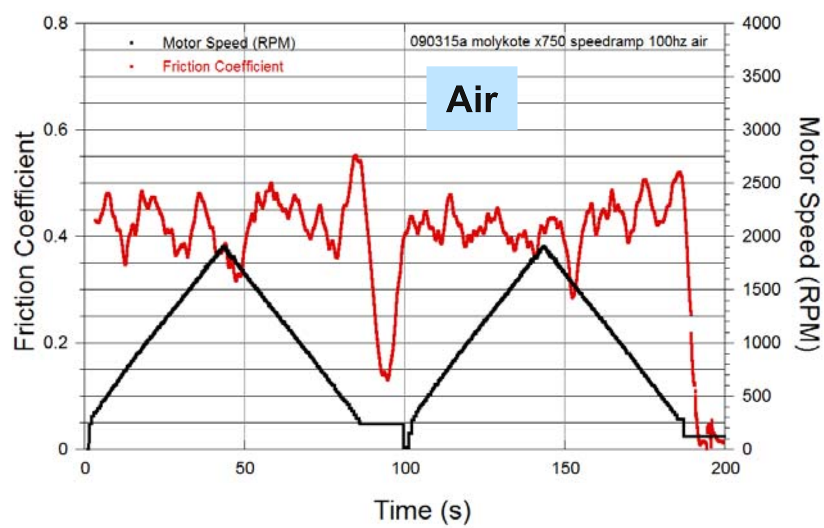


Technical Accomplishments 2009

- **Performed preliminary tests on a commercial <u>high-temperature</u>, MoS_2/Graphite based coating in air and hydrogen**
  - **No impact of environment on friction-response during <u>short-duration</u> room temperature tests**



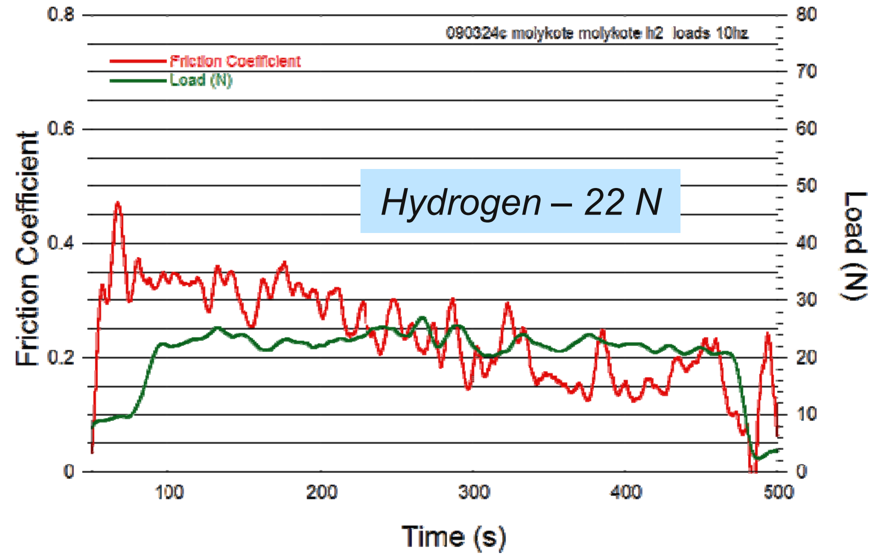


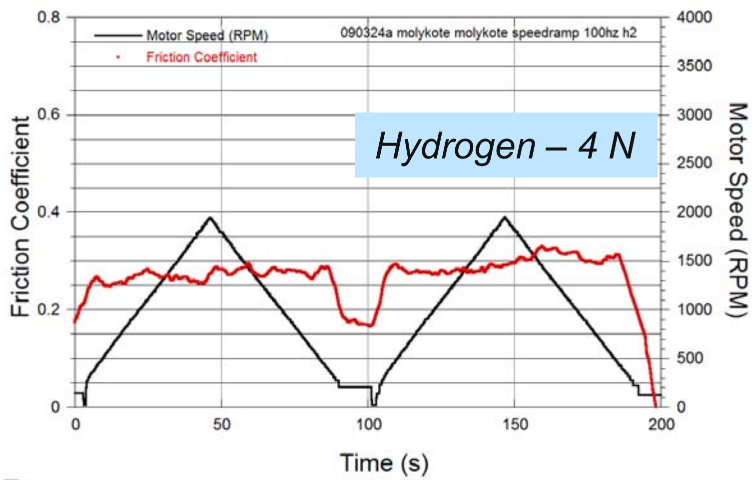


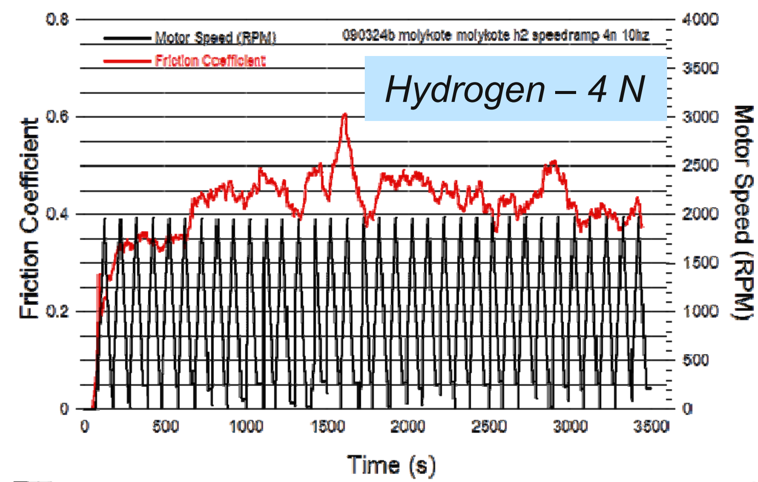
Technical Accomplishments 2009

- Commercial, high-temperature, MoS_2/Graphite composite coating tested in air and hydrogen
  - Short duration tests showed unexpected high (0.4) friction for MoS_2/Graphite coating
  - Long duration testing at light loads did not reduce friction, but…
  - friction was reduced when load was increased factor of X5

  - Further studies scheduled to explore load dependence

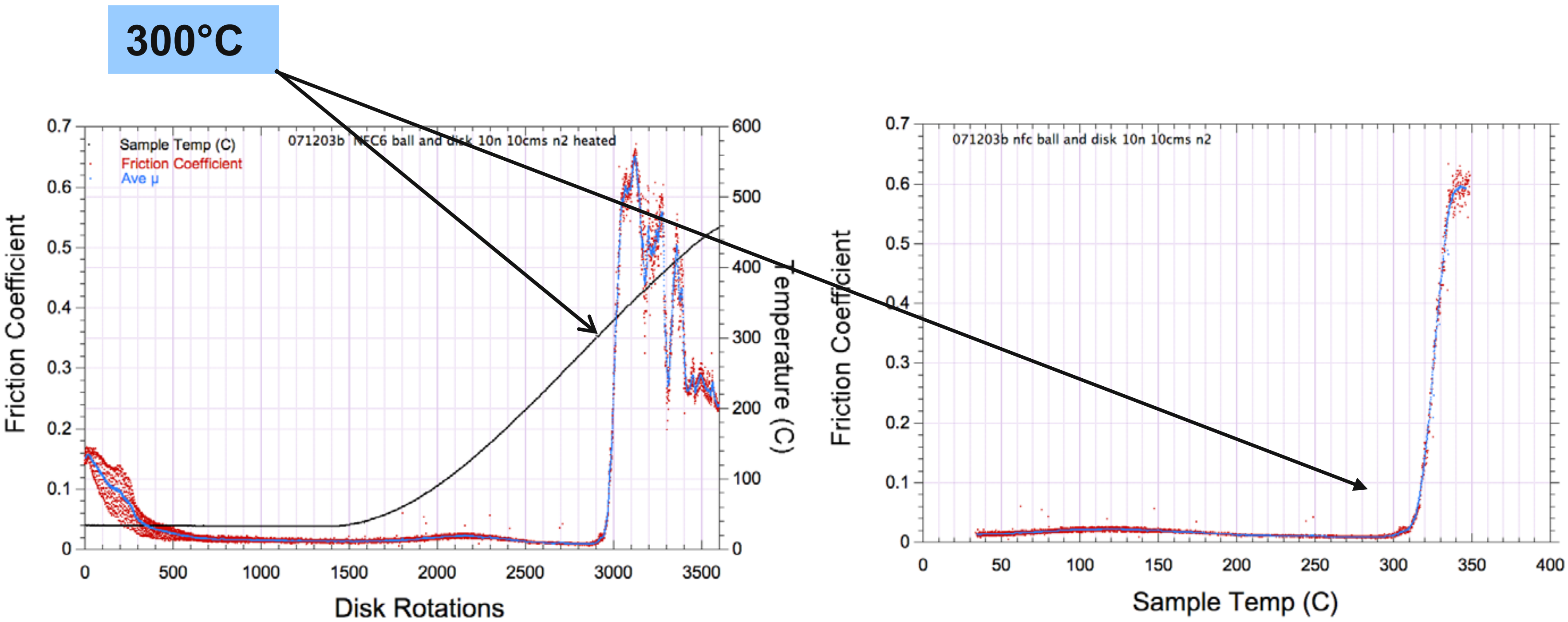






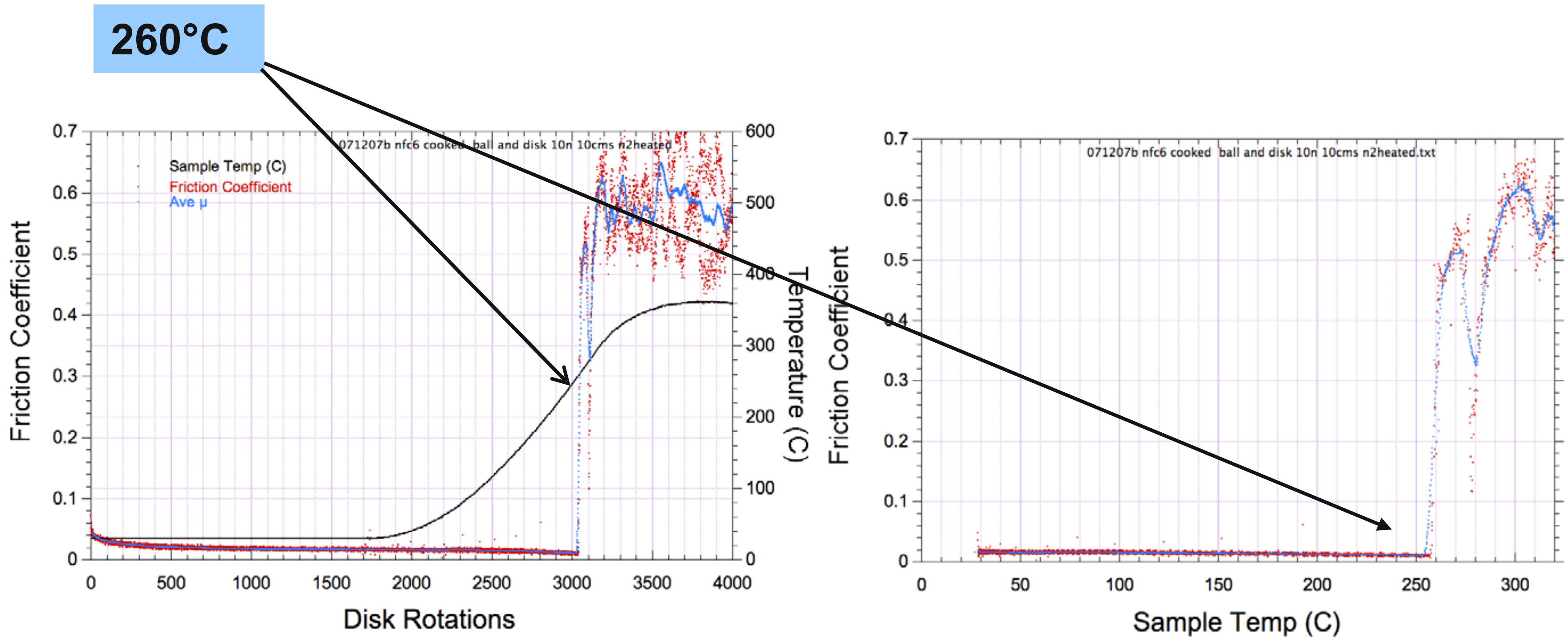
Technical Accomplishments 2009

- **Performed <u>high temperature test</u> of an amorphous diamondlike carbon coating (NFC6) to test upper temperature limits (using nitrogen instead of hydrogen with a ball-on-disc configuration)**
  - **Results demonstrate low friction performance maintained up to 300 C**



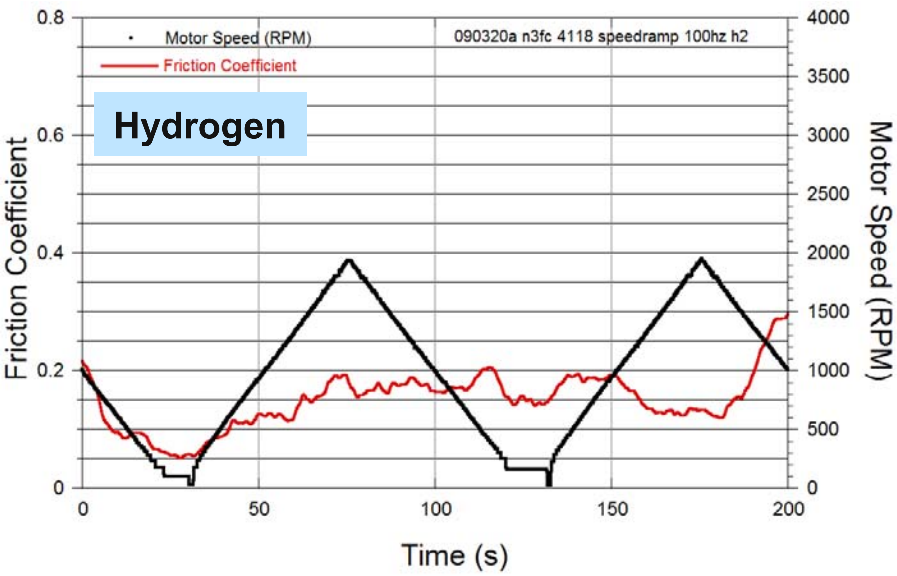
Technical Accomplishments 2009

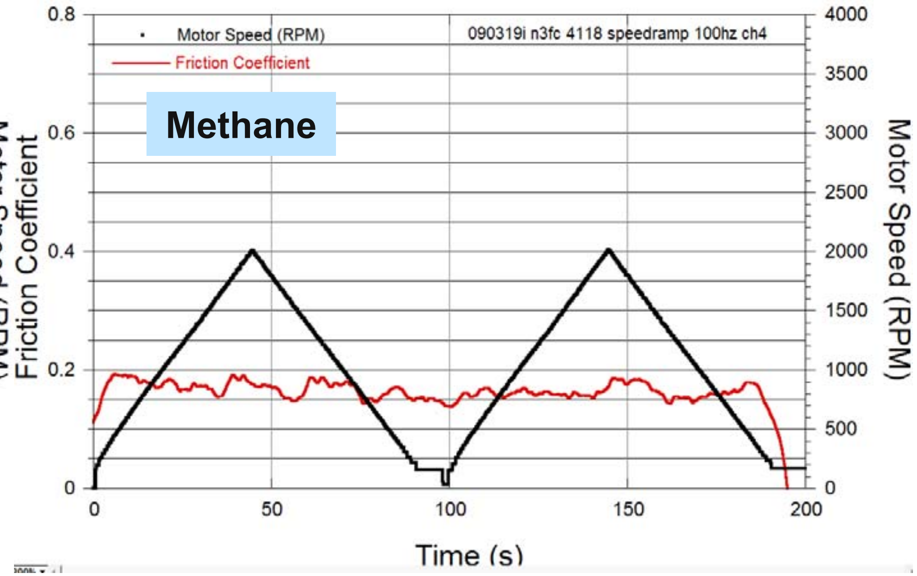
- **Repeated high temperature test of NFC6 (ball on disk) to test upper temperature limits (using nitrogen instead of hydrogen)**
  - **Repeated tests on same sample, but different wear track/region, still show acceptable performance, although they raise concern about potential thermal annealing effect on tribological performance**
  - **Further tests are planned on high-speed, high-temperature hydrogen tribometer (currently under construction)**



N3FC friction behavior

Performed friction tests on N3FC in hydrogen and methane and observed no significant differences in friction.

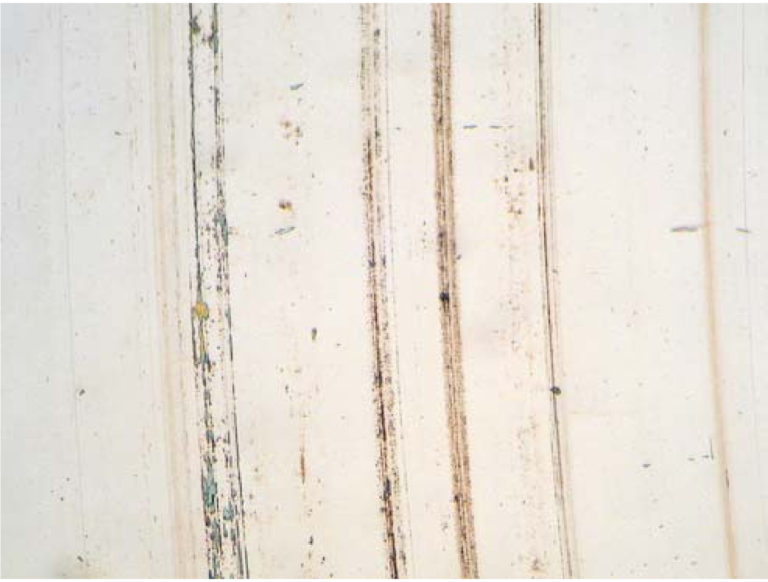




Technical Accomplishments 2009

- **Although friction is comparable, the transfer film associated with low friction is different for hydrogen than methane for N3FC**
  - **Samples scheduled for detailed chemical analysis**
  - **Long-term tests scheduled to determine if a steady-state transfer film will form and impact friction response.**

Methane – weak transfer film

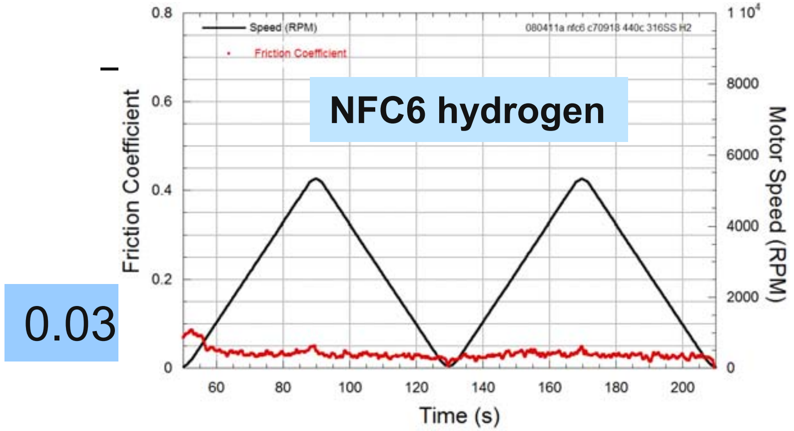


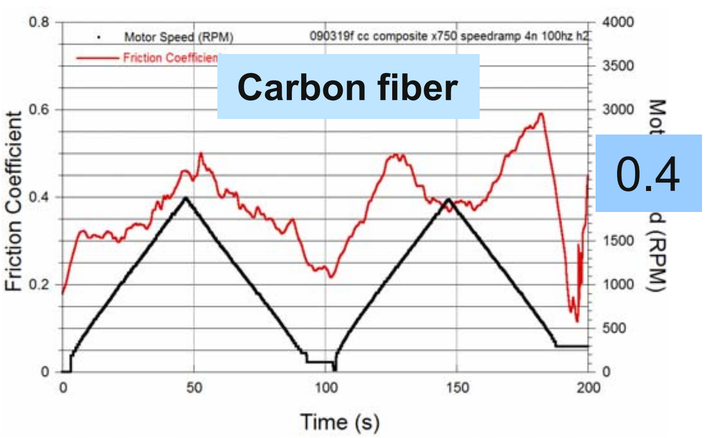
Hydrogen – strong transfer film

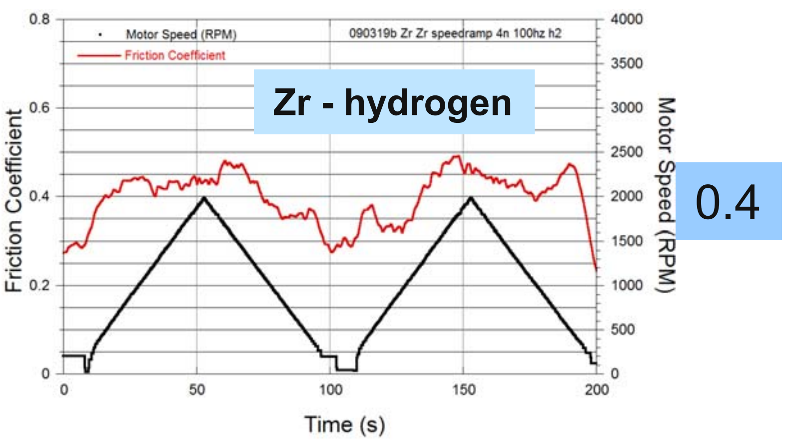
Technical Accomplishments 2009

- **Low friction NFC6 coating material continues to excel in comparison to others**

HIGH PURITY HYDROGEN

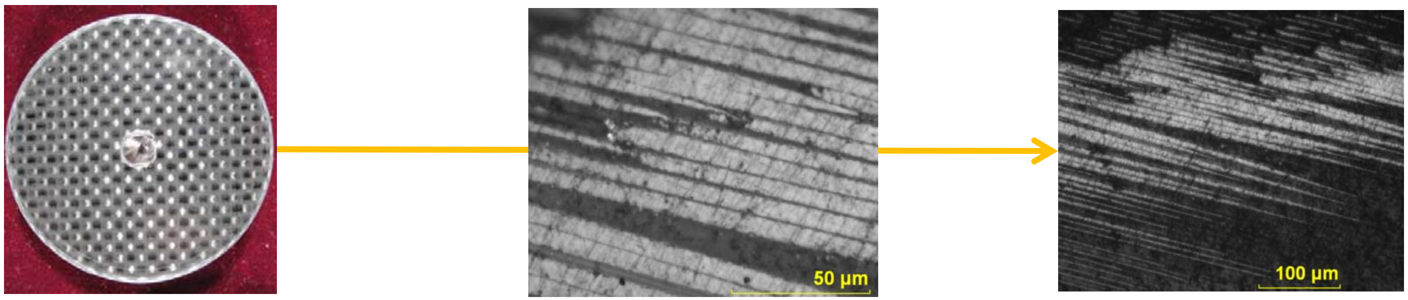


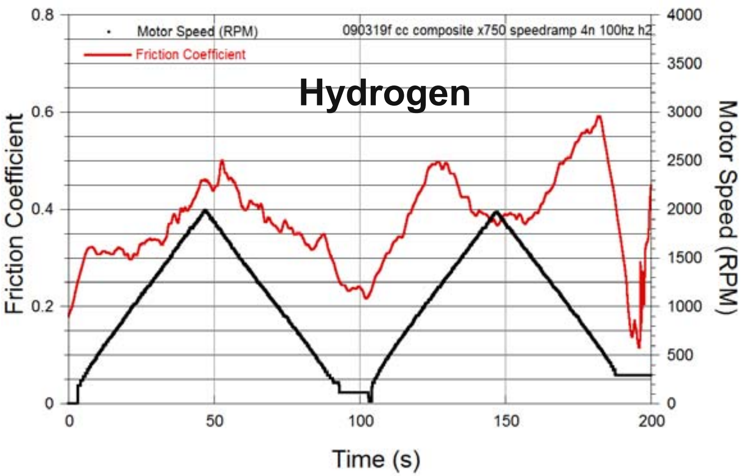


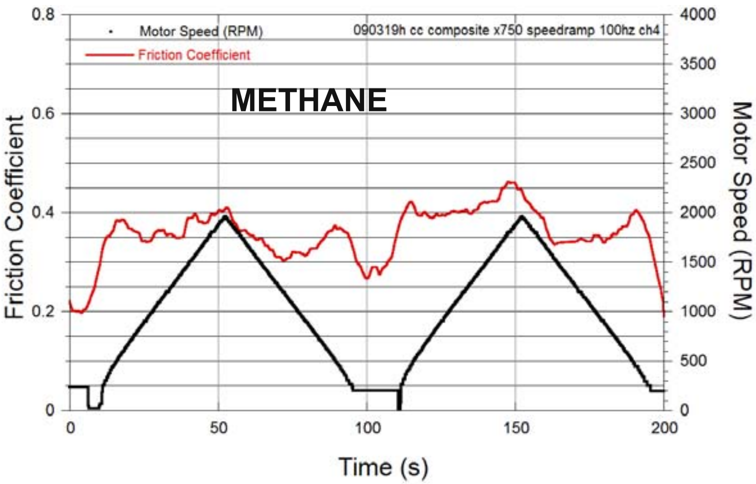


Technical Accomplishments 2009

- **Initial tests of a carbon fiber composite show low wear potential but higher friction**
  - **Future activities to examine role of moisture on friction**







Technical Accomplishments 2009

- **New friction results tabulated**

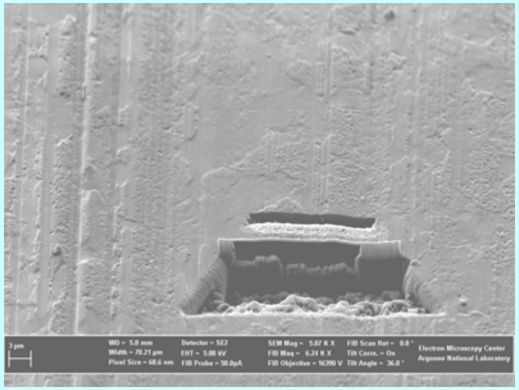
Materials Tests					
Rotating face	**Stationary counterface**	**Environment**	**Friction**	**Wear face**	**Wear counterface**
Molykote	X750	Air	Medium 0.4	High - abrasion	Low
Molykote	X750	Hydrogen	Medium 0.4	High - abrasion	Low
Zr	Zr	Air	Medium 0.5	High - galling	High - galling
Zr	Zr	Hydrogen	Medium 0.5	High - galling	High - galling
Fe/Mo/Boride	316ss	Air	Med high 0.6	Low - abrasion	Low
Fe/Mo/Boride	316ss	Hydrogen	Med high 0.6	Low- abrasion	Low
CF composite	X750	Air	Medium 0.4	Low	Low
CF composite	X750	Hydrogen	Medium 0.4	Low	Low
CF composite	X750	Methane	Medium 0.4	Low	Low
N3FC	4118 steel	Hydrogen	Low 0.15	Low	None
N3FC	4118 steel	Methane	Low 0.15	Low	None
Hastelloy X	Hastelloy X	Hydrogen	Very high >1	High - galling	High - galling
Hastelloy X	Hastelloy X	Methane	Very high >1	High - galling	High – galling
NFC6	316ss	Air	Low (0.2-0.4)	Low	None
NFC6	316ss	Hydrogen	Very Low (0.04)	Low	None
X-750	X-750	Hydrogen	High 0.6-0.9	High	High
316ss	316ss	Hydrogen	High 0.6-0.9	High	High

Collaborations

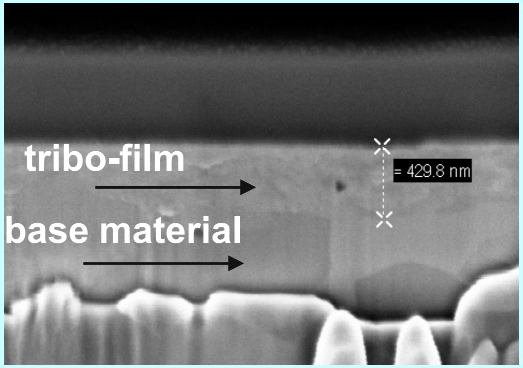
- **MITI – Mohawk Innovative Technologies Incorporated**
  - Oil-free, high-speed centrifugal compressor (bearings)
- **John Crane**
  - Oil-free, high-speed gas lubricated seals
- **Discussions underway with manufacturers of positive displacement compressors (forecourt compressors 10-12 kpsi)**

Future Work - Advanced Characterization

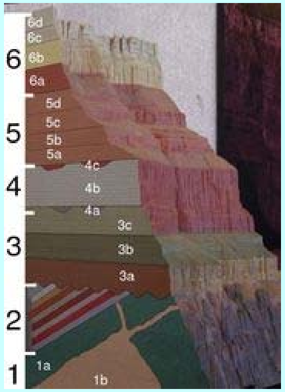
- Electron microscopy for wear mechanism studies
- Focused-ion-beam method to understand how H_2 can impact near-surface and subsurface failure
  - FIB mills down through surface
- Study embrittlement and crack behavior



Example of FIB trench



Example cross section



Example from nature

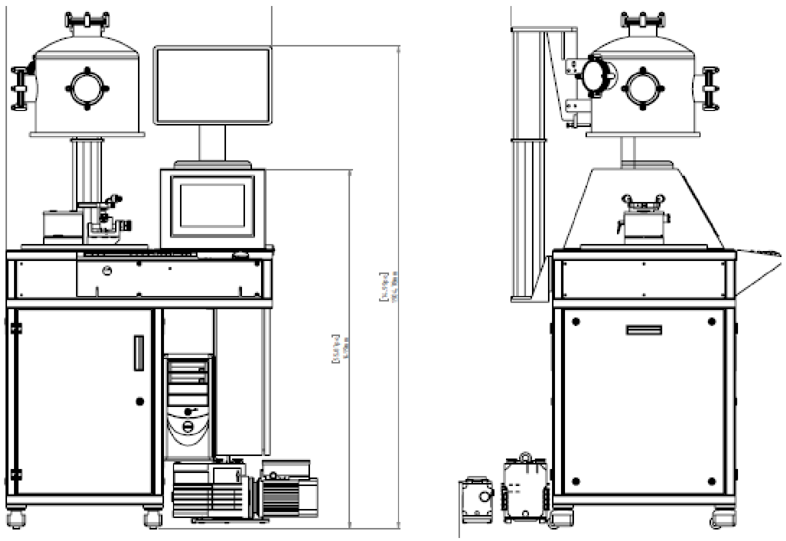
Future Work - Coating and Testing

- **Milestone: Install high-temperature hydrogen tribometer & initiate friction and wear tests in hydrogen**

- **Candidate coatings**

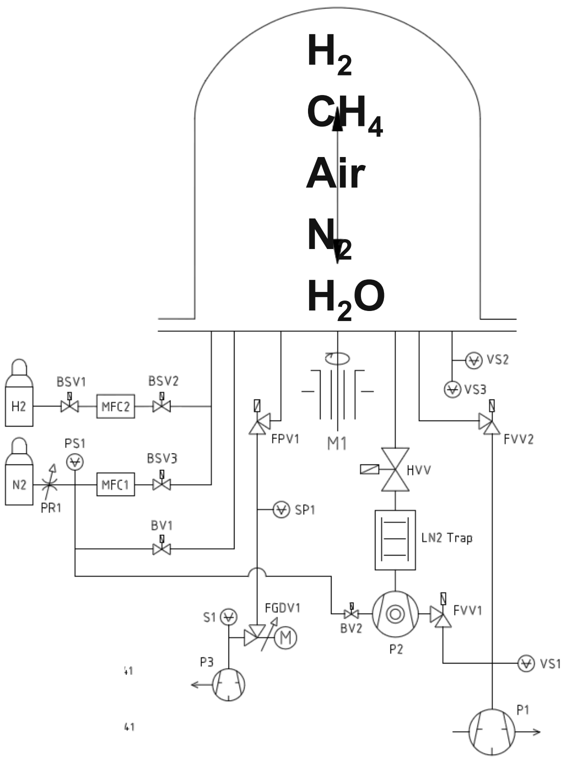
– **Korolon**	Composite
– **Molykote**	
– **Tribaloy**	Intermetallic
– **WC+17%Co**	
– **BN composite**	Compound
– **Boride conversion**	
– **Bodycote**	
– **ANL NFC6**	Carbon based
– **ANL N3FC**	
– **Carbon composite**	
– **Ionbond**	
– **Diamonex**	
– **K-Systems DLC**	
– **Smooth, nanocrystalline diamond**	

- **Upgraded test machine (delivery scheduled for summer ‘09)**

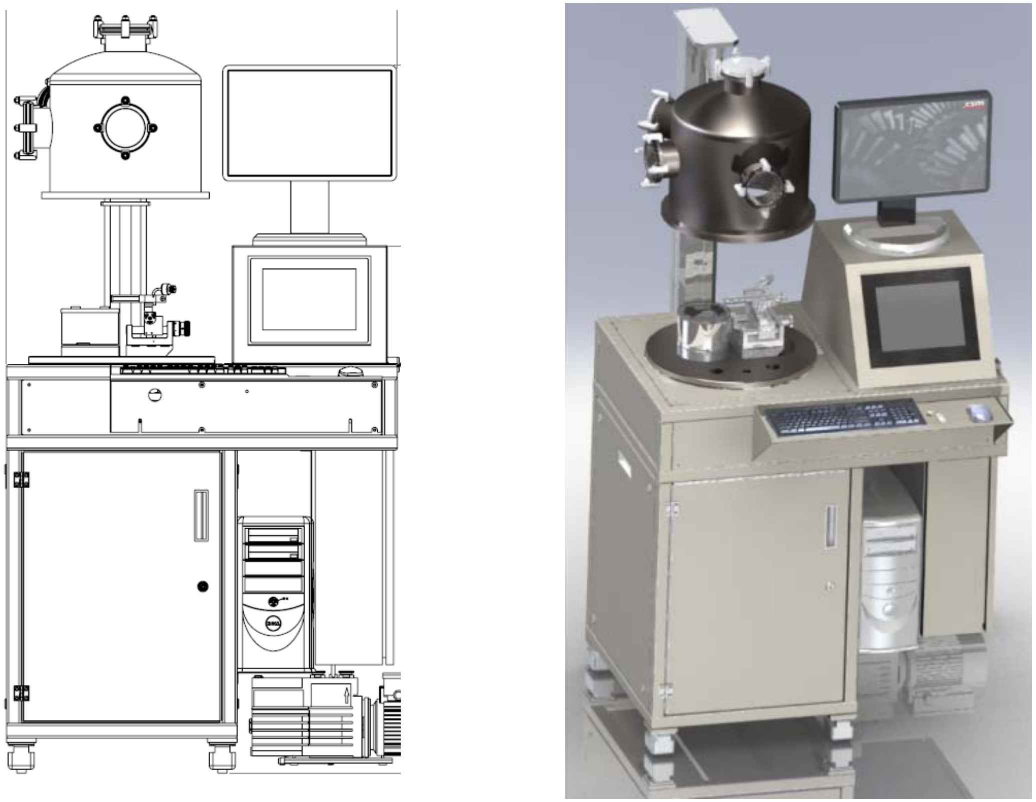


Future Work - Coating and Testing

- **Milestone: Procure high-temperature hydrogen tribometer (under construction)**



Gas handling system



Factory drawing and rendering

Summary

- Project initiated to address concern over potential impact of hydrogen on friction, wear, and embrittlement of dynamically loaded components (bearings and seals)
  - Preliminary tests at room temperature indicate friction of metallic alloys experience significant increases in friction and wear when exposed to reducing hydrogen environments
  - Preliminary studies (room temperature) identified several candidate materials (e.g. non-metallic solid-lubricant composites, and amorphous carbon films
  - Preliminary, short-duration tests of a solid-lubricant composite in hydrogen and methane show no significant differences in the frictional behavior, however, differences in transfer film formation were observed which may influence long-term frictional behavior
  - Development and testing of amorphous carbon coatings showed acceptable friction behavior at elevated temperatures, however, long-term durability studies are required.
- Design, procurement, and fabrication of a high-speed, high-temperature hydrogen tribometer was initiated with delivery anticipated in fall 2009