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DOE Hydrogen Program

Coatings for Centrifugal Compression

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Argonne National Laboratory

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U.S. Department of Energy

UChicago Argonne LLC

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Overview

Timeline

- Start: Oct 2006
- Completion: Sept 2012
- Completion (%): 20 %

Budget

- Total project funding
  - DOE share ($725K)
- Funding for FY07 ($200K)
- Funding for FY08 ($500K)

Partners

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

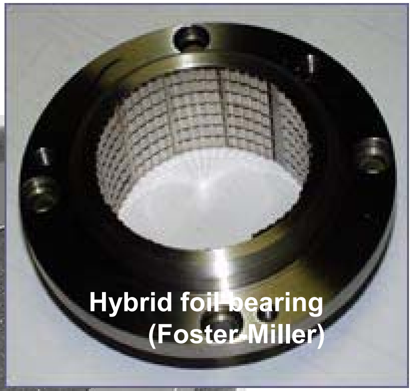
Barriers

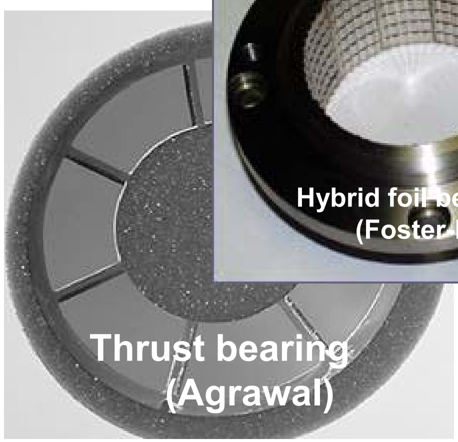
- Barriers addressed
  - Delivery Barrier B – 'Reliability and Costs of Hydrogen Compression'
- Targets – Pipeline and Forecourt Compressors

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

Objectives

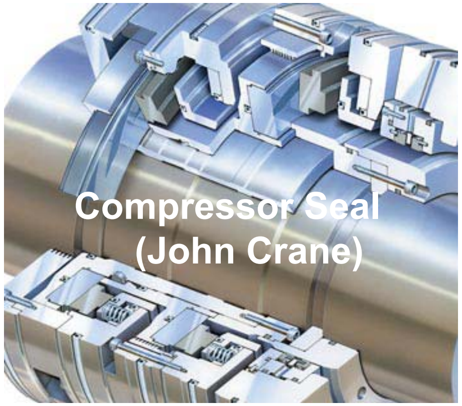
- The primary objective of this project is to identify, and develop as required, advanced materials and coatings that can achieve the friction, wear, and reliability requirements for dynamically loaded components (seal and bearings) in high-temperature, high-pressure hydrogen environments prototypical 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 currently insufficient to design reliable, efficient hydrogen compressors

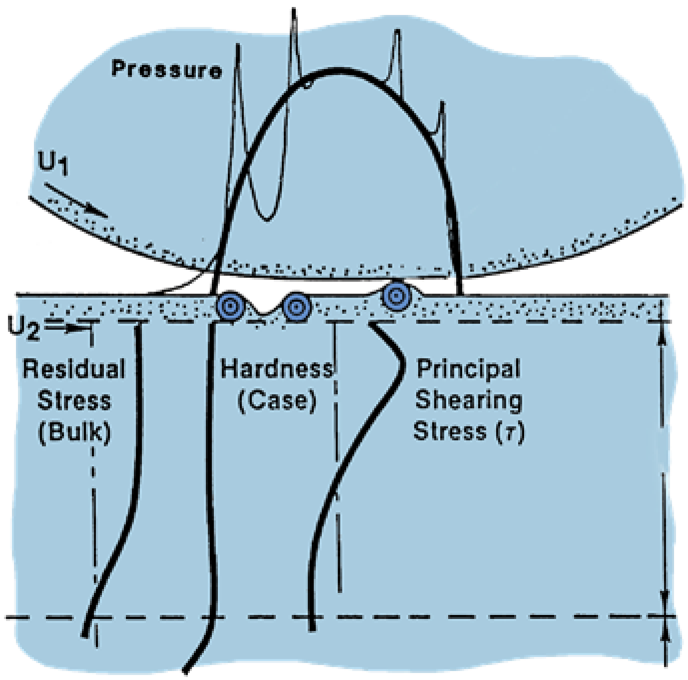
- Rule-of-thumb/target: friction < 0.1



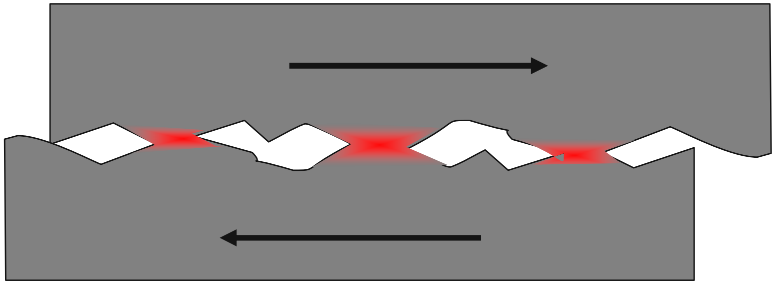
-High reliability,
-Low capital cost

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, ….)



Milestones

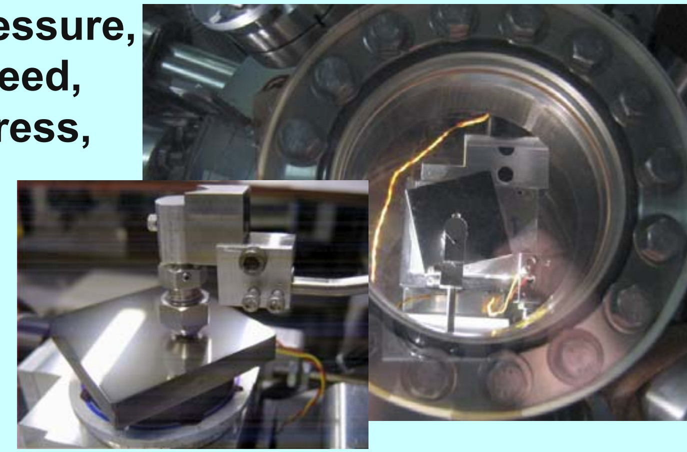
- Identify and characterize candidate seal and bearing materials and coatings. — January 2008
  - Baseline materials & alloys
  - In-house & commercial coatings
- Initiate low-temperature tests to evaluate tribological properties of materials and coatings in hydrogen (and baseline gases – air, inert, CH_4). — March 2008
  - Low-speed, high stress
  - High speed, low stress
- Develop design specs and initiate procurement of a high speed, high temperature hydrogen tribometer. — July 2008
- Install high-temperature hydrogen tribometer & initiate friction and wear tests in hydrogen. — FY 2009

Approach

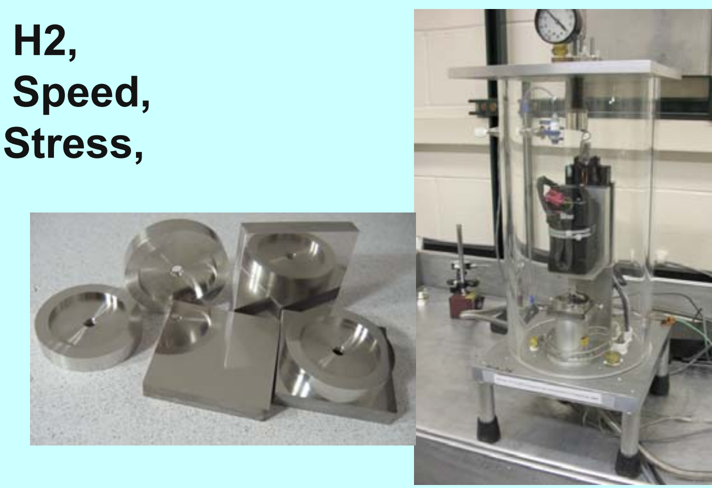
- Identify critical dynamically loaded compressor components, materials/alloys/surfaces, and operating environments.
- Evaluate tribological performance of candidate materials and advanced solutions under well-defined tribological conditions. **[Target: durable friction coefficient < 0.1]**
  - Temperature,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

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

Low-Pressure, Low-Speed, High Stress, RT – H2

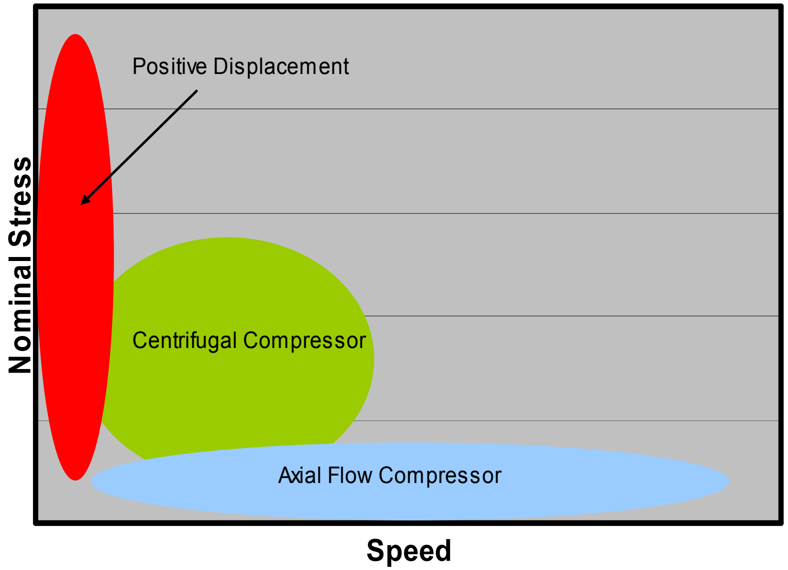


Atm. H2, High Speed, Low Stress, RT



Accomplishment - Identified critical operating parameters impacting material selection/optimization of dynamically loaded compressor components

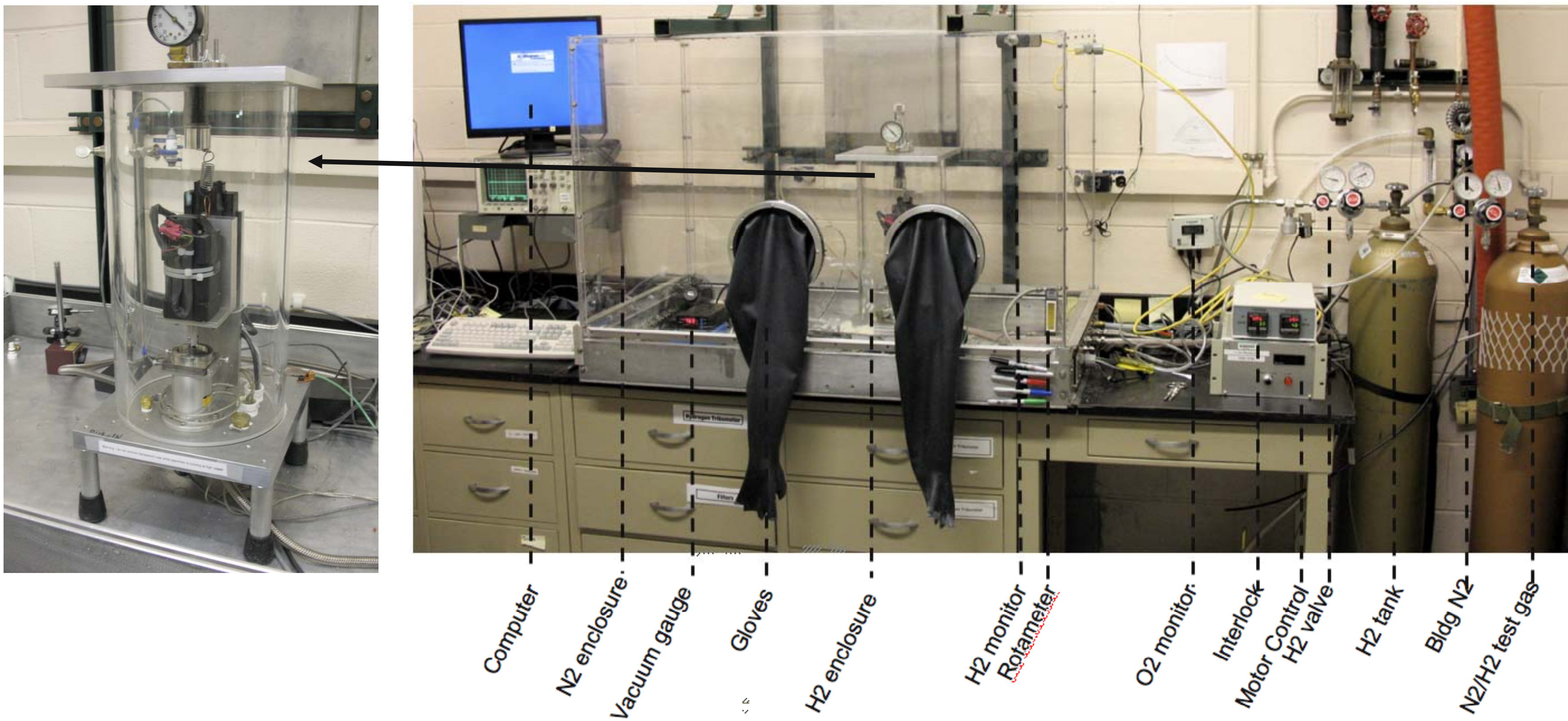
- Different **contact stress / sliding speed** regimes identified depending on compressor design
  - Positive displacement - high contact stress, low sliding speed
  - Axial flow compressors - high speed, low contact stresses
  - Centrifugal compressors - intermediate speeds and contact stresses
  - Lab conditions will encompass the following;
    - *Nominal Contact Stress - 2 to 1500 psi*
    - *Sliding Speed - 0.1 to 10 m/s*
- **Operating temperature up to 500 C**; flash/asperity heating can add an additional 500 to 750 C (depending on load, speed, thermal properties, and friction) to the temperature of near-surface asperities.
  - Lab tests will be performed at bulk temperatures up to 500 C



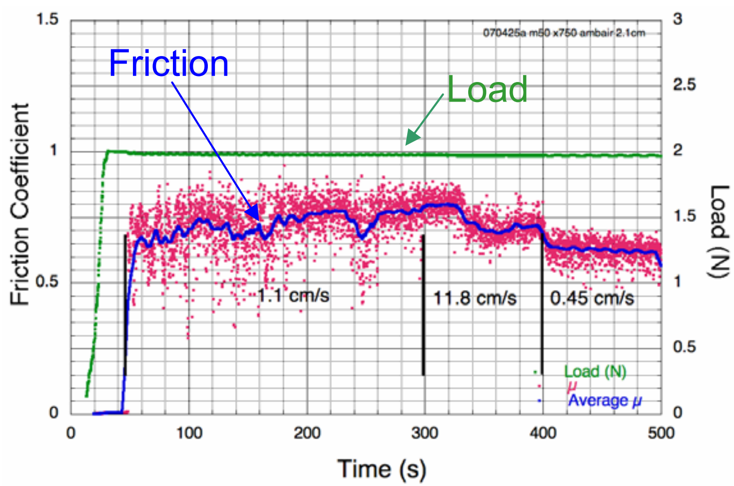
- **Gas composition** has not been defined. Different levels of impurities (moisture, natural gas, contaminants) will impact formation of surface films.
  - Lab tests will be performed with H2 containing different levels of water, and other trace impurities
  - Lab tests will be performed using natural gas to baseline performance of current compressors

Accomplishment - Adapted current (room temperature) tribo-test rigs to operate with H2

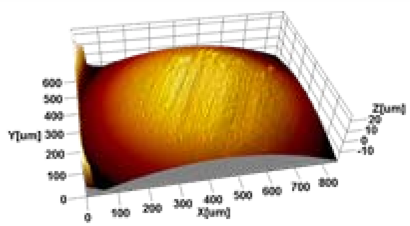
- **Capability to perform tests in hydrogen was needed**
- **Two systems were were developed to perform tests in hydrogen of candidate materials and coatings at high speeds**
  - **Low speed, high contact stress, @ H2 pressures < 0.5 atm.**
  - **High speed, low contact stress, @ H2 pressures up to 1 atm.**



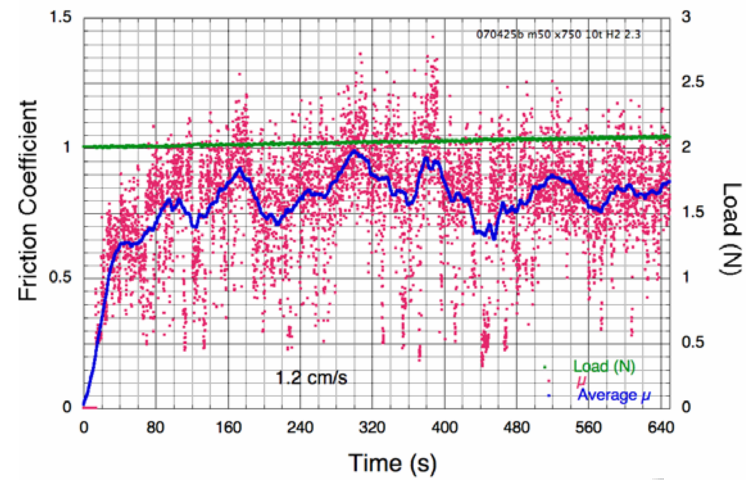
Accomplishment - Low speed, high stress tests in low pressure H2 demonstrate adverse impact of H2 on friction and wear of commercial alloys (x-750) - possible breakdown of protective oxide layers



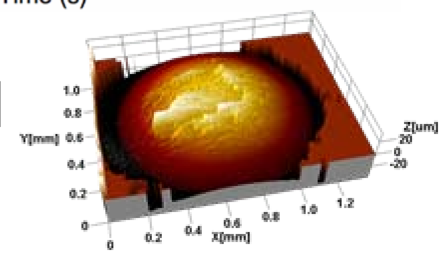
AIR



- Tests in air exhibit typical friction (0.7 - 0.8) and relatively smooth wear scar on mating ball showing formation of fine oxide wear debris.

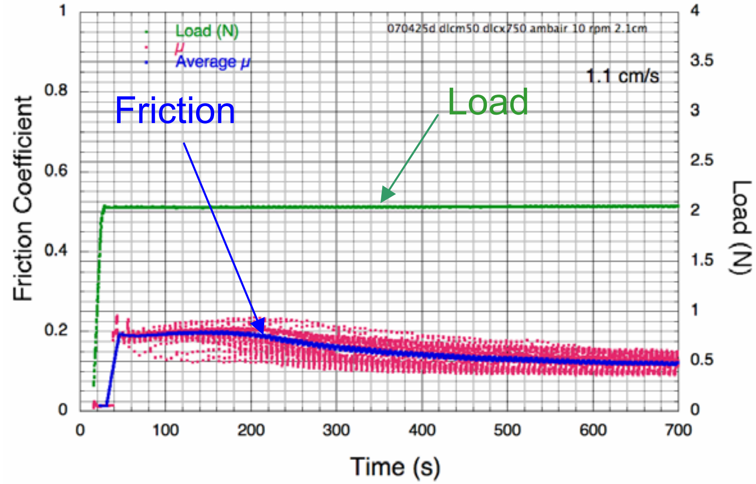


HYDROGEN



- Tests in hydrogen exhibit higher and more erratic friction, and severe transfer of material from one surface to the mating surface - breakdown of oxide films in reducing environment

Accomplishment - Low-speed, high stress in low pressure H2 demonstrate the ability of a low-friction coating (DLC) to reduce friction of Nickel based alloys



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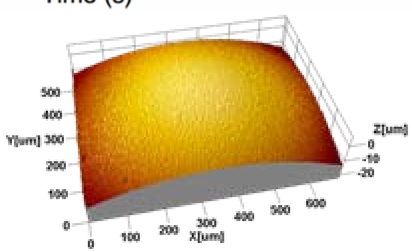
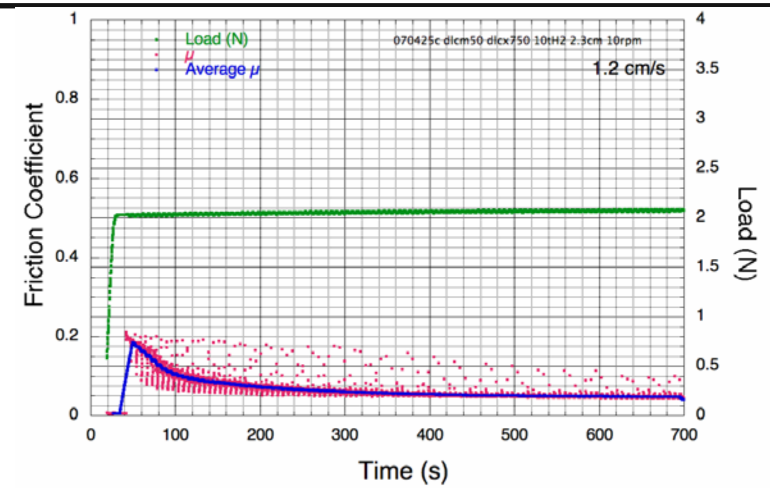
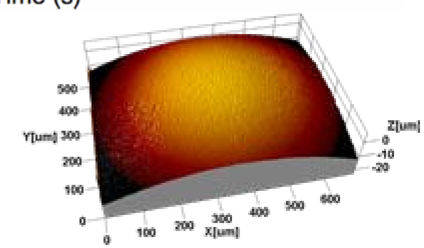


- **Tests in air exhibit greatly reduced friction (0.1-0.15) for DLC coated nickel alloy, and minimal wear**



HYDROGEN

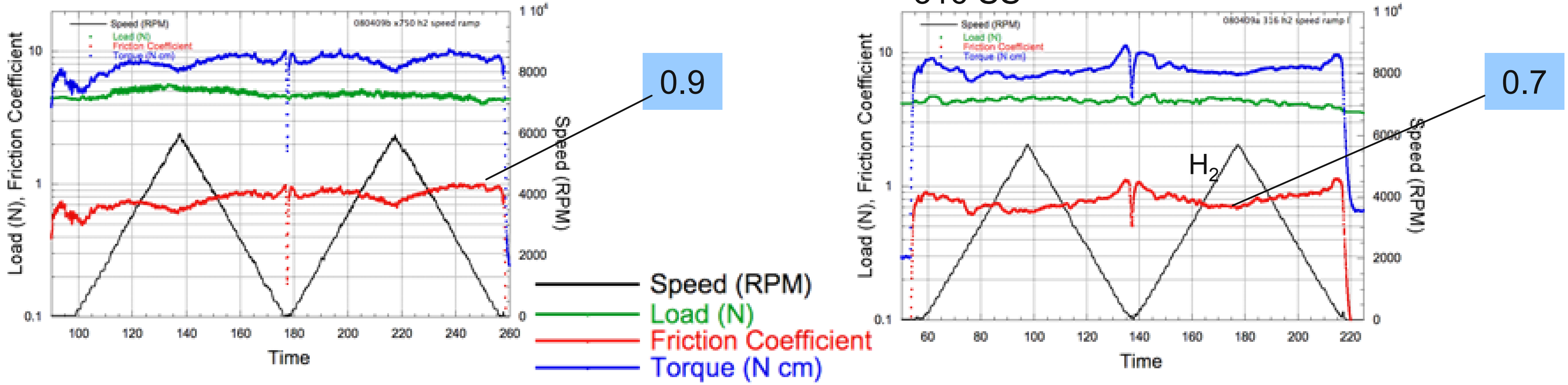


- **Tests in hydrogen show even lower friction (<0.05) for DLC coated nickel alloys; and greatly reduced wear.**

- **Long-term durability of thin (2-5 µm thick) DLC coatings needs to be addressed**

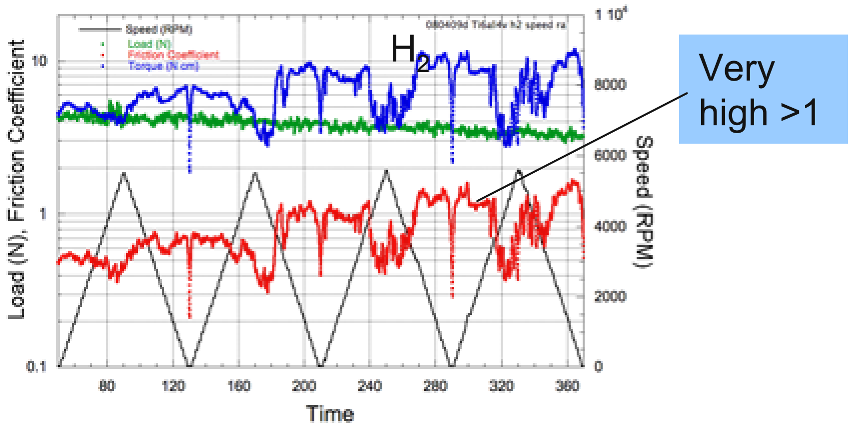
Accomplishment - High speed, low contact stress tests in atmospheric H_2 demonstrate friction of common alloys are too high (> 0.7); Commercial coatings such as MoS_2 are better, but still too high.

X-750 316 SS

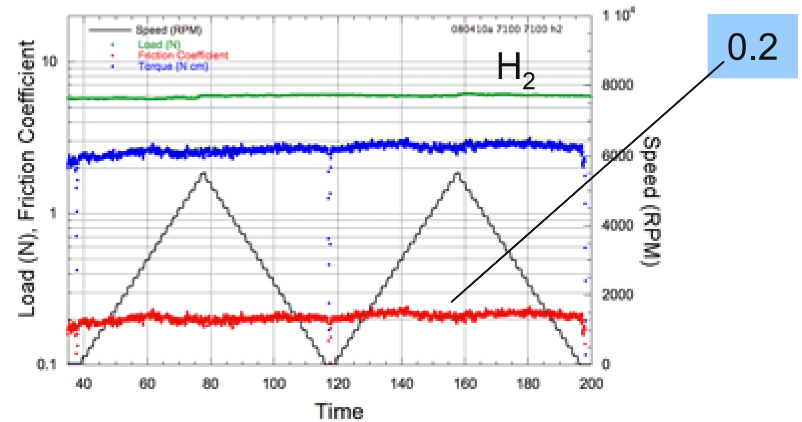


- **Friction torque, friction coefficient, load, and speed traces as a function of time during speed ramp tests where the speed is ramp up then down in speed from o to 6000 rpm**

Ti-6Al-4V

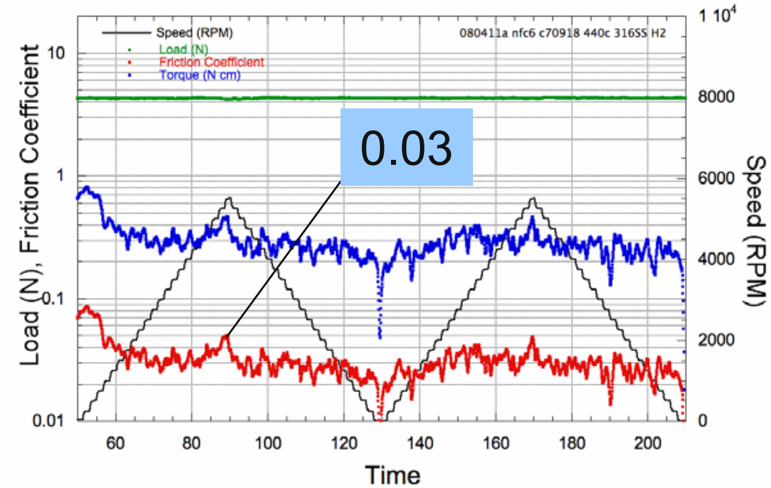


MoS2 conventional

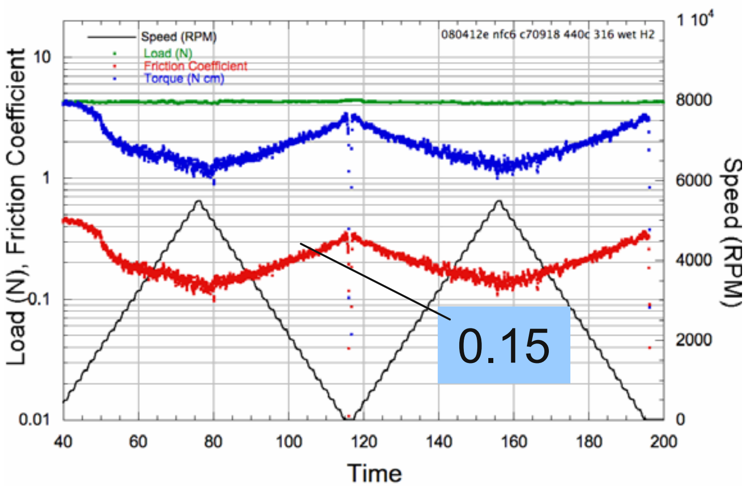


Accomplishment - High speed, low stress tests in air, dry H2, and water-saturated H2 show strong impact of impurities on friction

- Impurities such as water vapor entrained in gases can dramatically impact friction (and wear/durability)
- Tests on DLC coatings applied to 316 SS show a 5-fold increase in friction when tested in saturated H2
- The impact of other trace impurities requires further research



HIGH PURITY HYDROGEN



WATER SATURATED H2

Summary - Initial tests in H2 demonstrate the friction of common alloys unacceptably high. Advanced surface treatments/coatings will be required; however the performance of current coatings may not be adequate and further advances will be required to meet friction and durability targets.

Friction coefficients of candidate materials in specified environments					
Material	**Air**	**N_2**	**N_2/H_2**	**Vacuum**	**H2**
Ni X-750	0.5–0.9	0.5–0.9	0.6–1	0.5–0.9	0.6-0.9
Al 6061	-	1–1.5	0.5– 1	0.8–1.2	
Ti alloy	0.4	~0.5	~0.5	0.5–0.6	0.5-2
316 steel	0.4–0.9	0.6–1	0.6–1	0.5–0.8	0.6-0.9
MoS_2/MoS_2	0.25–0.5	0.3–0.6	0.25	0.3	
MoS_2 bond/ MoS_2 bond	-	0.2–0.25	0.25	0.3	0.2
MoS_2 bond/ 316					0.1-0.2
DLC/316	**0.2-0.4**	**0.03-0.05**		**0.03-0.05**	**0.03-0.04**
DLC/DLC (pt contact)	**0.1**				**0.04**

Future Work - Assess potential of commercial surface treatments, and initiate high temperature (up to 500 C) high-sped tests in H2

- **Candidate coatings**
  - **Korolon**
  - **Molykote MoS_2/graphite**
  - **Tribaloy**
  - **WC+17%Co**
  - **BN composite**
  - **Boride fused**
  - **MoS_2**
  - **Bodycote**
  - **ANL DLC6**
  - **ANL N3FC6**
  - **Ionbond**
  - **Diamonex**
  - **K-Systems DLC**

Composite (Korolon, Molykote MoS_2/graphite)

Intermetallic (Tribaloy)

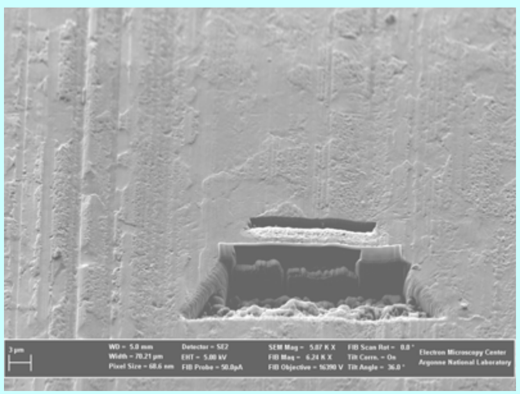
Compound (WC+17%Co, BN composite, Boride fused, MoS_2)

Carbon based (Bodycote, ANL DLC6, ANL N3FC6, Ionbond, Diamonex, K-Systems DLC)

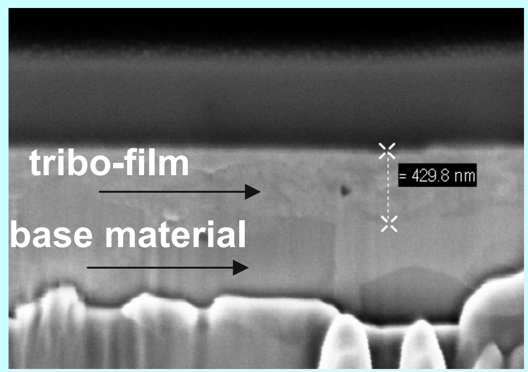
- **Install high-temperature test machine to match prototypic running conditions**

Future Work - Advanced characterization to quantify wear and identify failure mechanisms.

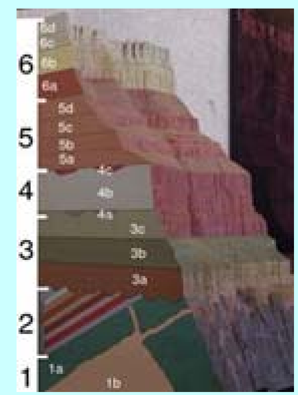
- **Detailed optical microscopy to quantify wear/durability**
- **Electron microscopy for wear mechanism studies**
- **Focused-ion-beam method to understand how H_2 can impact near-surface and subsurface failure**
  - **FIB mills down through surface**
- **Study embrittlement and crack behavior in near surface regions**



Example of FIB trench



Example cross section



Example from nature

Summary

- Transition to hydrogen-based fuels will require an infrastructure to transport and dispense hydrogen at levels far greater than currently available.
- The reliability and durability of current hydrogen compressors are not sufficient to meet future needs.
- Hydrogen will impact the tribological performance of materials used in the construction of dynamically loaded compressor components such as bearings and seals.
- Initial nominal room temperature tests on common alloys raise concerns about the reliability and durability of current compressor materials in hydrogen environments
  - Higher friction in hydrogen environments suggest current seal and bearing solutions may not achieve targets for hydrogen compressors
- Future tests will determine the impact of hydrogen on the tribological properties of current and advanced materials and coatings, and, provide solutions for the design of reliable and durable compressors.

Project Summary

Relevance: Perform testing/development of materials and coatings required for effective hydrogen compressor bearings and seals

Approach: Evaluate tribological performance of candidate and advanced solutions under well defined tribological conditions that encompass range of environments and provide solutions to problems

Technical Accomplishments and Progress: Demonstrated hydrogen testing capabilities/identified key candidate materials. Developed specifications and initiated procurement of high temperature hydrogen tribometer

Technology Transfer/Collaborations: Collaboration with MiTi and others

Proposed Future Research: Procure/Install high-temperature hydrogen tribometer & initiate friction and wear tests. Identify materials for use in dynamically loaded compressor components.