Coatings for Centrifugal Compression*

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Overview

Timeline

- Start: 10/2006
- Completion: 10/2011
- Completion (%): 50 %

Budget

- Total project funding
  - DOE share ($725K)
- Funding FY10 received ($100K)
- Funding FY11 received ($50K)

- Project continuation and direction determined annually by DOE

Barriers

- Barriers addressed
  - Delivery Barrier B – "Reliability and Costs of Hydrogen Compression"
- Targets – Hydrogen Delivery Targets related to Hydrogen Delivery of large compressors for FY2012 are:
  - Reliability – > improved
  - Efficiency - 98%
  - Capital investment - $12M/compressor
  - Maintenance – 7% of TCI

Partners

- MITI – Mohawk Innovative Technologies Incorporated - oil-free, high-speed centrifugal compressor (bearings)
- CSM – test machine development
- John Crane - seals

Relevance

- Overall objective:
  - Develop enabling technology to attain *the cost and reliability* targets for oil-free centrifugal and forecourt compressors by reducing/eliminating downtime or repair costs
- Means to objective:
  - identify, and develop as required, advanced materials and coatings that can achieve the *tribological performance* necessary for durable operation of dry-sliding seals and bearings
- Two-prong technical approach:
  - using commercial or lab materials and coatings (compound, composite, intermetallic, carbon based), test and identify those materials that produce the lowest friction and wear in a hydrogen environment
  - "focus on understanding" the tribological mechanisms by which the best materials produce low friction and wear and optimize the properties
- Objectives FY11:
  - Perform acceptance test of new elevated-temperature hydrogen test machine (tribometer)
  - Perform high temperature tests of candidate materials to eliminate poor performers
  - Conduct longer-term sliding tests on materials used in forecourt compressors

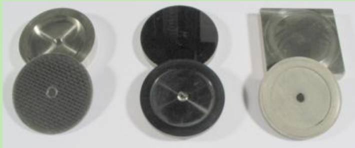
Technical Approach

- Identify critical dynamically loaded compressor components, materials/alloys/surfaces, and operating environments.
- Evaluate tribological performance of commercial or lab materials under well-defined tribological conditions:
  - Temperature, H_2 pressure
  - Speed, load/stress
  - Air/H_2/impurities
- Characterize/identify critical phenomena/mechanisms that control tribological performance.
- Target: constant friction coefficient <0.1 and high durability (able to withstand 500 stop/start cycles with 25 lb load) before repair needed
- Engineer and validate solution(s) into compressor design.

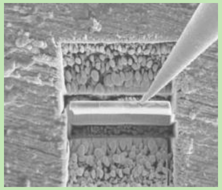
Testing

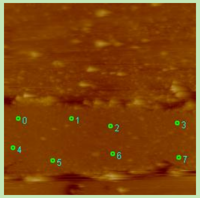
Understanding mechanisms

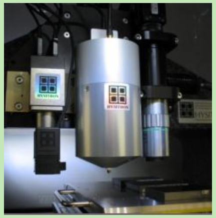
Laboratory testing of friction and wear under simulated service conditions



Post-test characterization





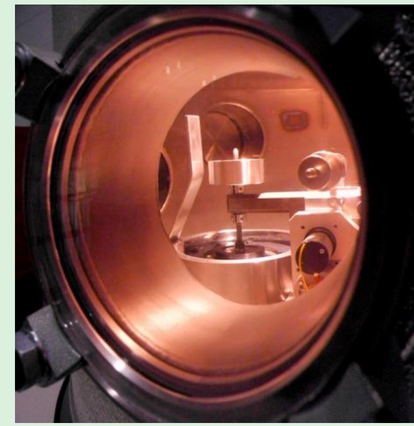


Milestones 2011

Milestones	Progress Notes and Comments	% Comp
(for 11/10) Acceptance test demonstrating 2000 rpm operation for 4 h in 0.9-bar H_2 gas at 500°C with continuous measurement of friction, wear, temperature, and sliding distance.	Acceptance test verified for 2000 rpm operation for 1 hr in 0.9-bar H_2 gas at 500°C with continuous measurement of friction, wear, temperature, and sliding distance.	100%
(for 03/11): Complete durability testing of a NFC7 compressor foil bearing material and demonstrate a coefficient of friction that meets the desired compressor design requirements of < 0.1 under 14 kPa load, over a temperature range of 100 – 500°C, and in 99.999% H_2.	Room temperature, 100°C, 200°C, 300°C tests, on compressor foil-bearing material producing coefficients of friction <0.1, at 5.6 kPa load, in 99.999% hydrogen. Friction and wear are excessive at 400°C.	90%
(for 4/11) Complete ball-on-disk tests on the test materials from inventory (N3FC, NFC6, MoS_2/graphite, X-750, boride, carbon composite) at temperatures up to 400°C for durations up to 12 hours or to point where materials fail.	Preliminary testing has been completed using room temperature test rig in early part of FY 2011.	10%
(for 6/11) Obtain and examine failed forecourt compressor parts from reciprocating compressor partner to identify failure mechanisms and possible remedies.	Some pump manufacturers and a compressed H_2 deliver station operator were contacted, but no parts were obtained.	0%

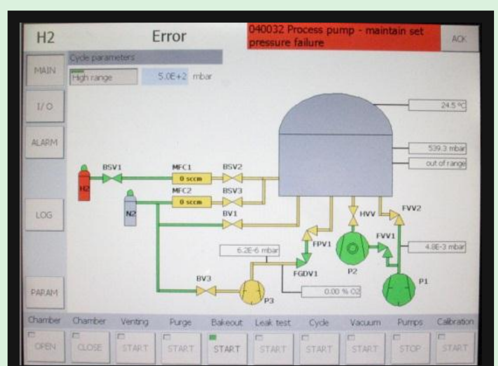
Technical Accomplishments 2011

Successful acceptance test verified 2000 rpm operation for 1 hr in 0.9-bar H_2 at 500°C with continuous measurement of friction, wear, and temperature.



Problem with loading arm limits. Motor does not raise and lower arm – repair in progress.

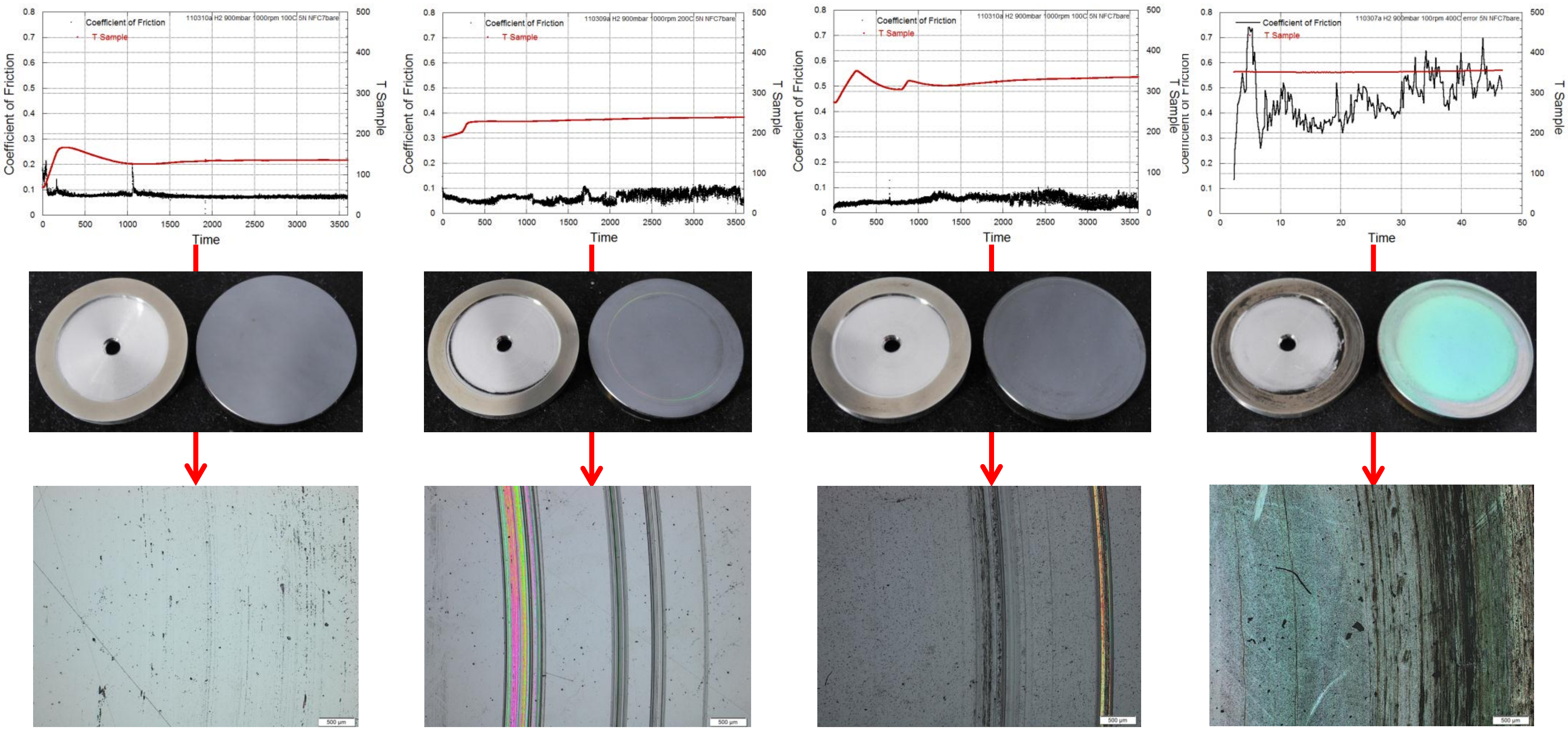
Problem with H_2 pressure regulation limits operation in certain hydrogen pressure regimes – repair in progress.



Technical Accomplishments 2011

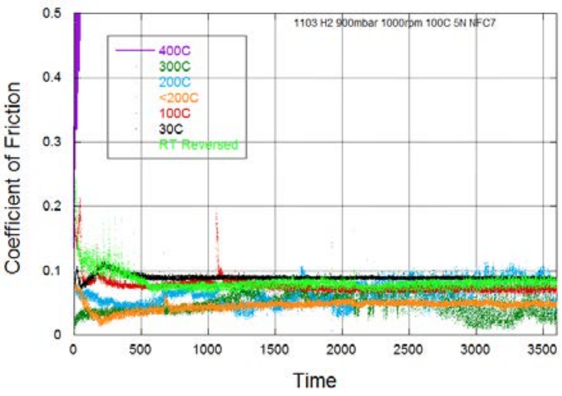
- Tests at different temperatures show limitation of candidate NFC7.

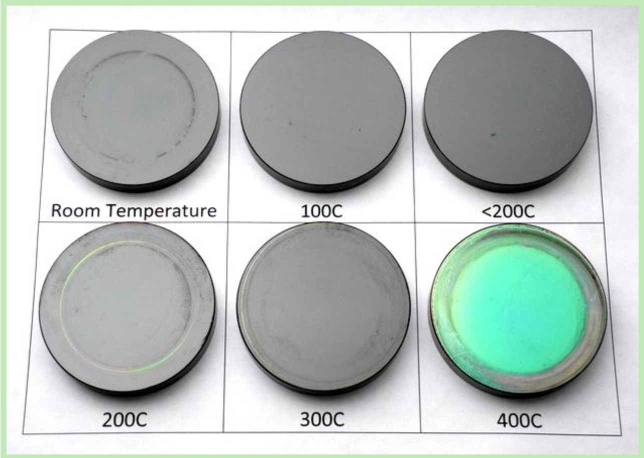
100°C 200°C 300°C 400°C



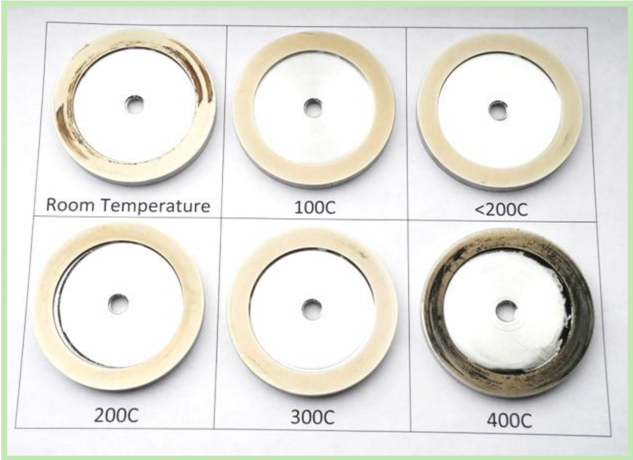
Technical Accomplishments 2011

- Milestone of hydrogen tests at different temperatures accomplished.
- Total loss of material at 400°C and above.





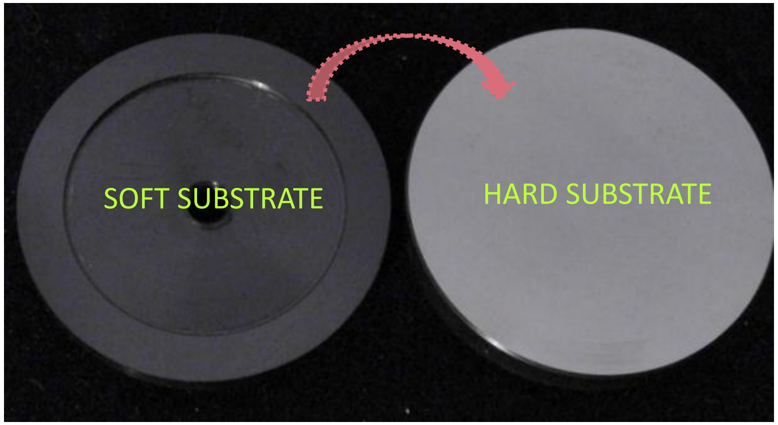
Post-test examination

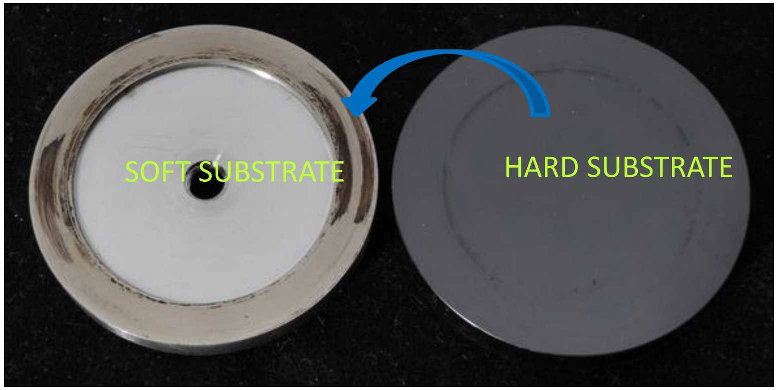


Post-test examination

Technical Accomplishments 2011

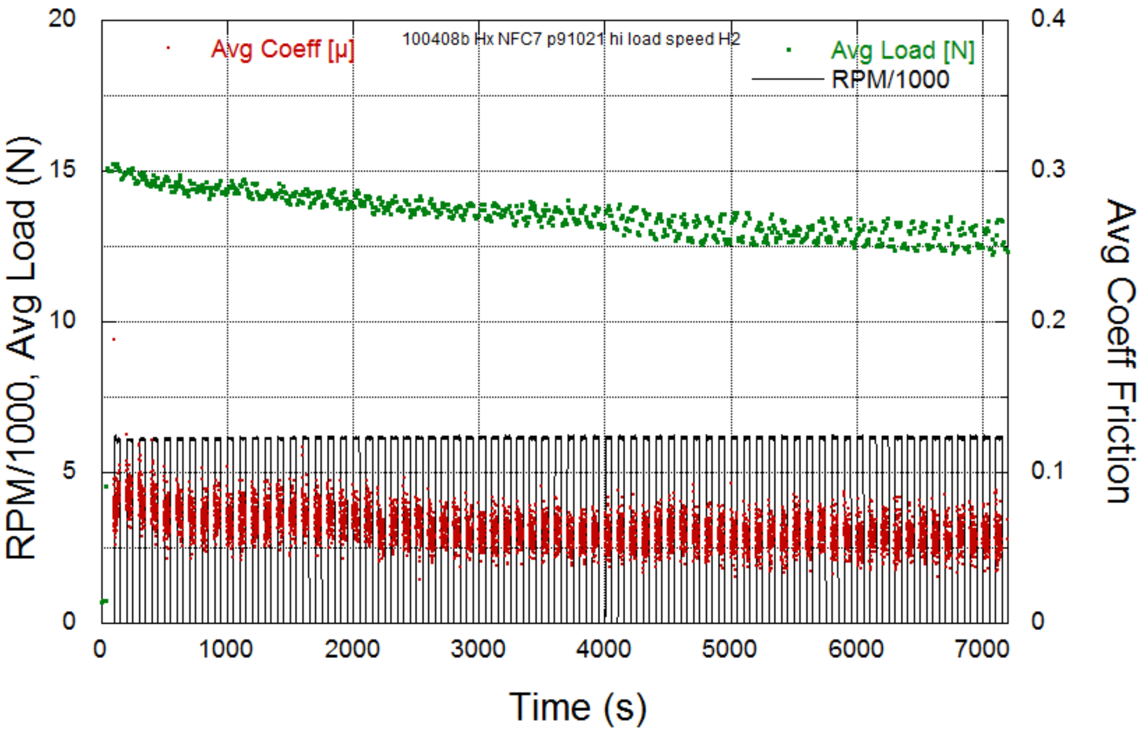
- Examination of sliding surfaces from room temperature tests revealed that transfer film occurs from hard coating to soft counterface, but not from hard coating to hard counterface after 60,000 cycles in H_2. Friction does not seem to be significantly affected.

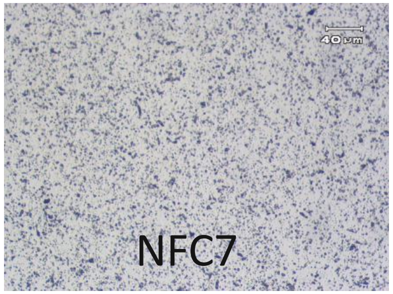


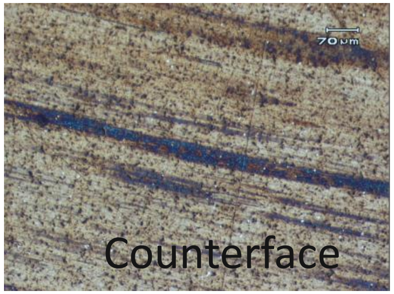


Technical Accomplishments 2011

- High load tests at room temperature on carbon NFC7
- Two-hour test at 6,000 rpm, 2 minute 50% duty cycle
- 56 km sliding distance
- No visible or measurable wear
- Low coefficient of sliding friction

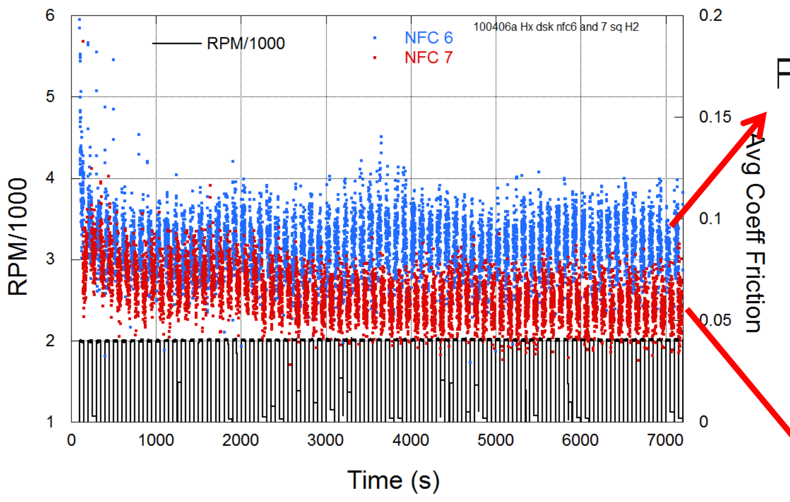




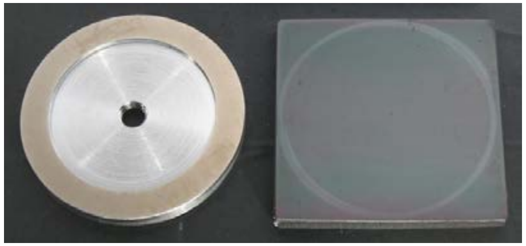


Technical Accomplishments 2011

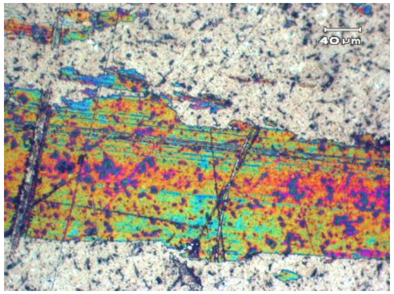
- New Argonne NFC7 carbon performs better than former leader NFC6. Tests are harsher with 2-hr duration at 6,000 rpm, 50% duty cycle, up to 15 N load.



NFC6

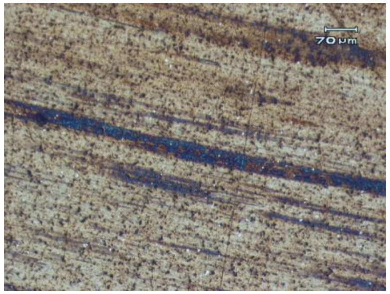


NFC6



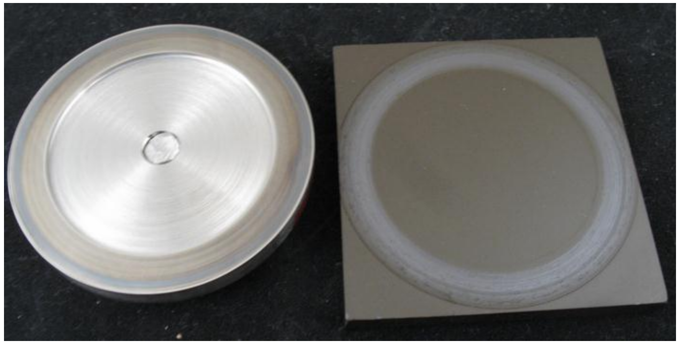
NFC7

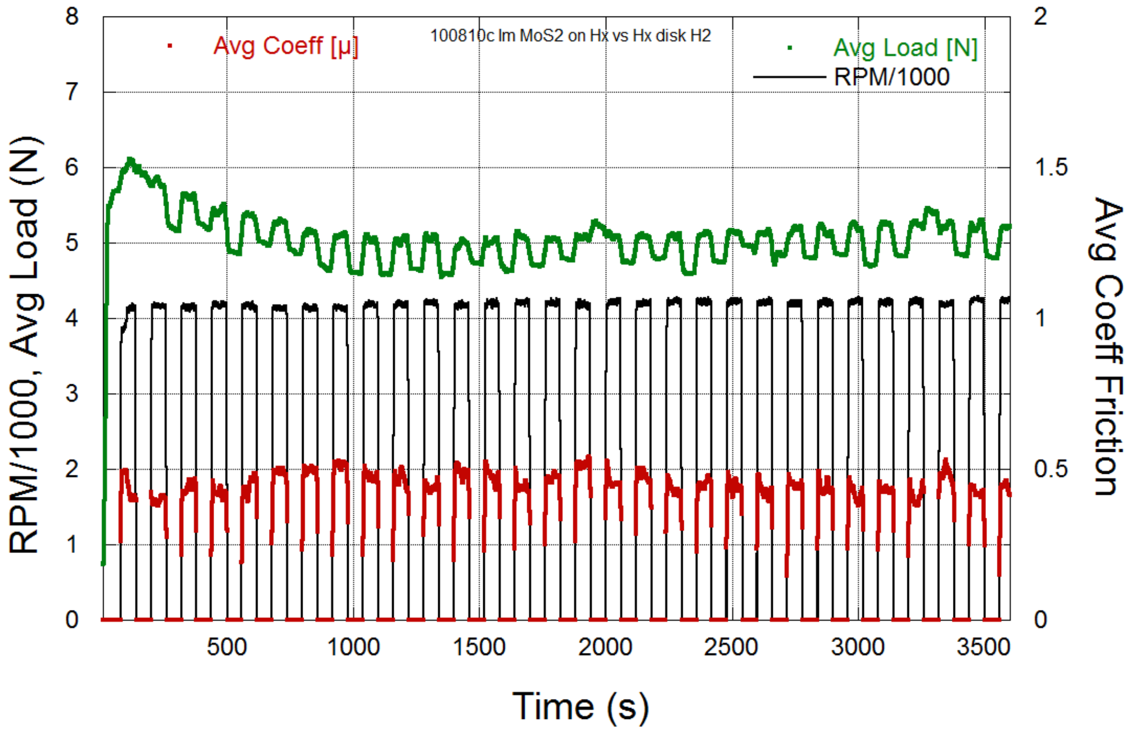
NFC7

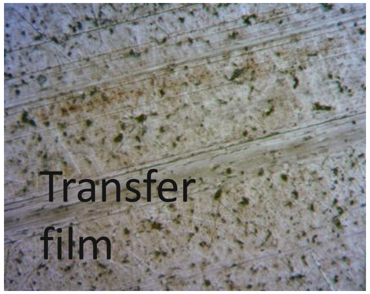


Technical Accomplishments 2011

- New MoS_2-based coating, which is compatible with H_2 to 700°C, and air to 350°C, exhibits improved durability compared to other MoS_2 materials.
- 18 km sliding distance.

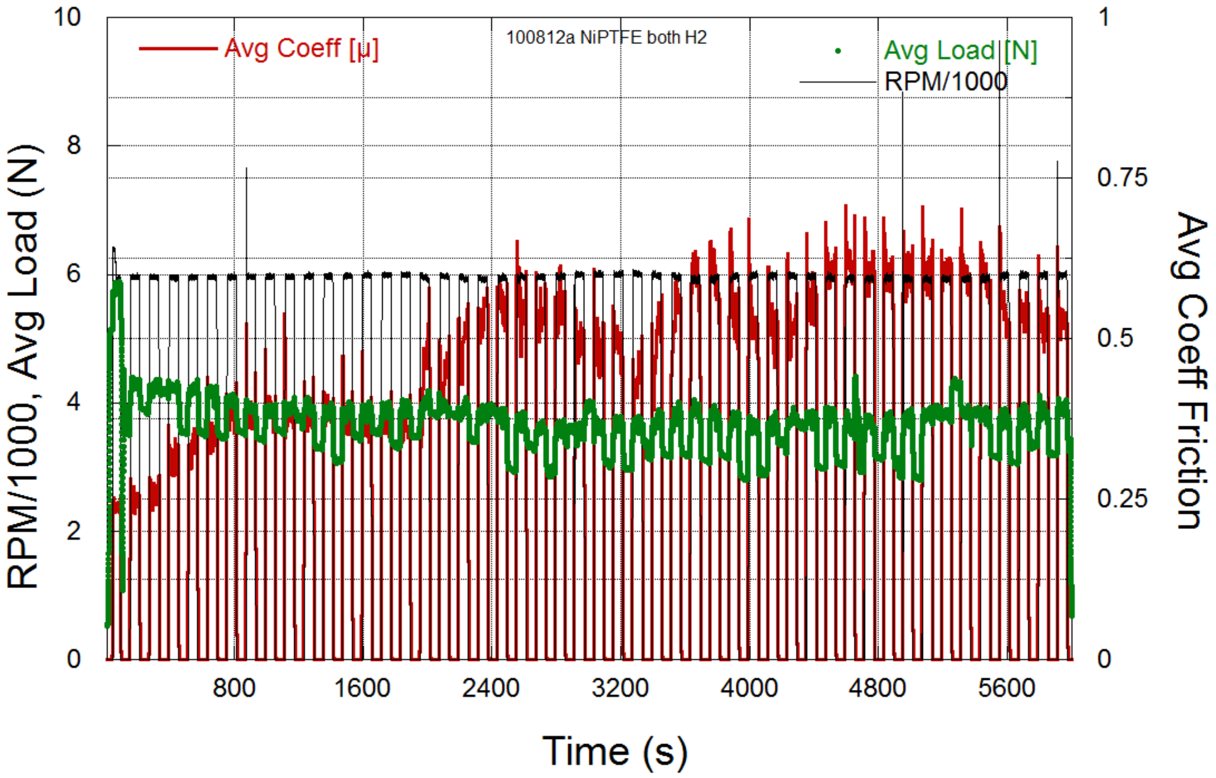


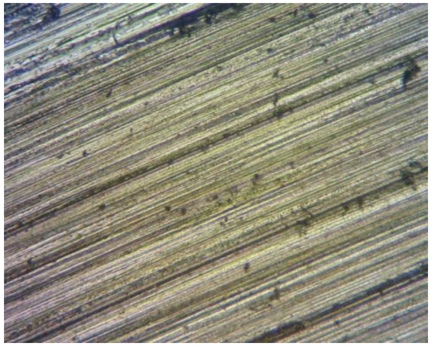


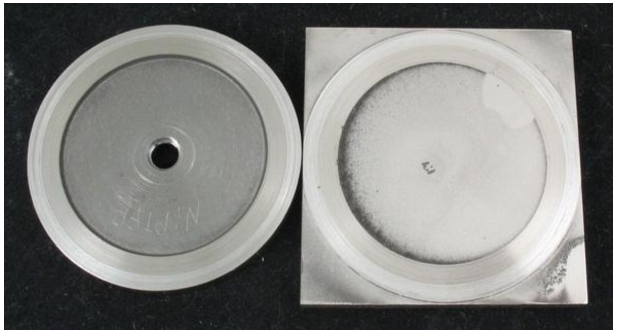


Technical Accomplishments 2011

- New NiPTFE coating evaluated.
- Short lifespan and high friction found.

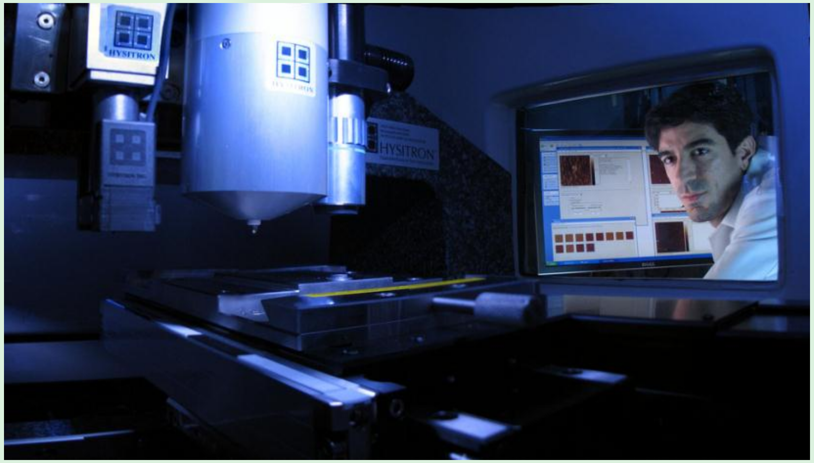


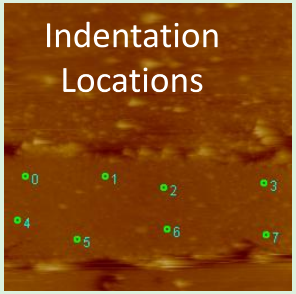


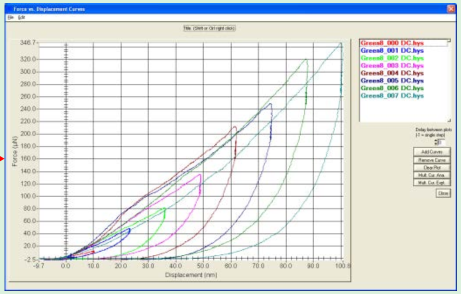


Technical Accomplishments 2011

- First tests of mechanical properties of specimens that had been tested in hydrogen were performed with nanoindenter .
- Force/displacement curves of carbon films (either new or worn) are extremely elastic (lower graphs) in comparison to transfer film or metal substrate. Tests are ongoing to understand this unusual behavior.



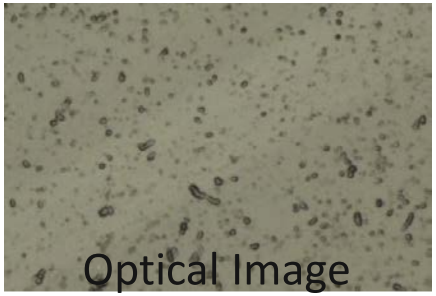


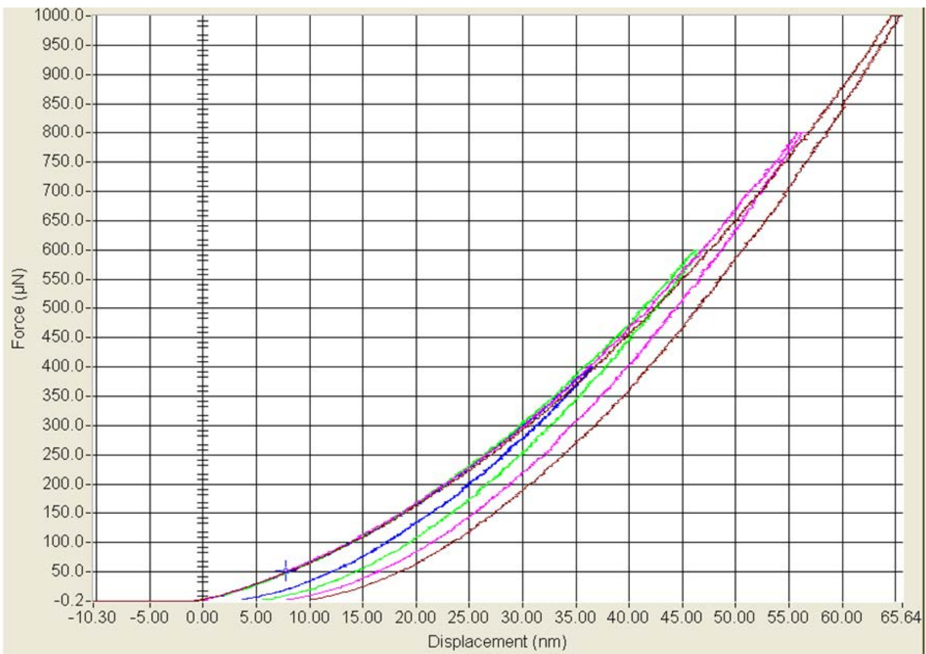


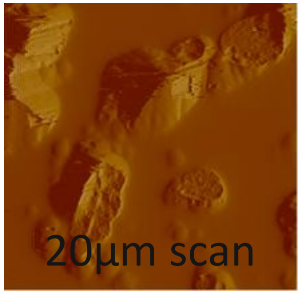
Sample and region of probing	Hardness (GPa)	Elastic Modulus (GPa)
Plain 4118 steel	13.8±1.3	234±20
Transfer film of H_2 tested N3FC DLC	1.7±0.42 1.7±0.5	60±14 30±5
N3FC tested in H_2	5.3±2.5	35±15
N3FC DLC	6.4±2.6	44±22
N3FC12	9	66
NFC7 (area 1) NFC7 (area 2)	17.3±0.5 16.6±0.5	122±1 111±3
NFC6	7.8±0.8	69±4

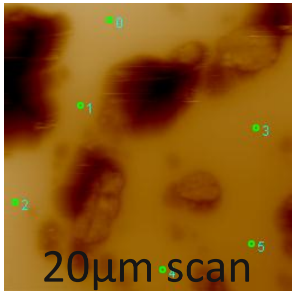
Technical Accomplishments 2011

- Nanoindentation performed late 2010/early 2011 finds smooth featureless NFC7 surface is extremely elastic and has approximately double hardness and modulus than NFC6.





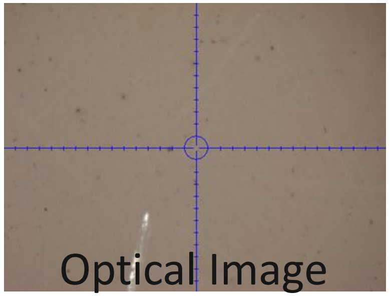


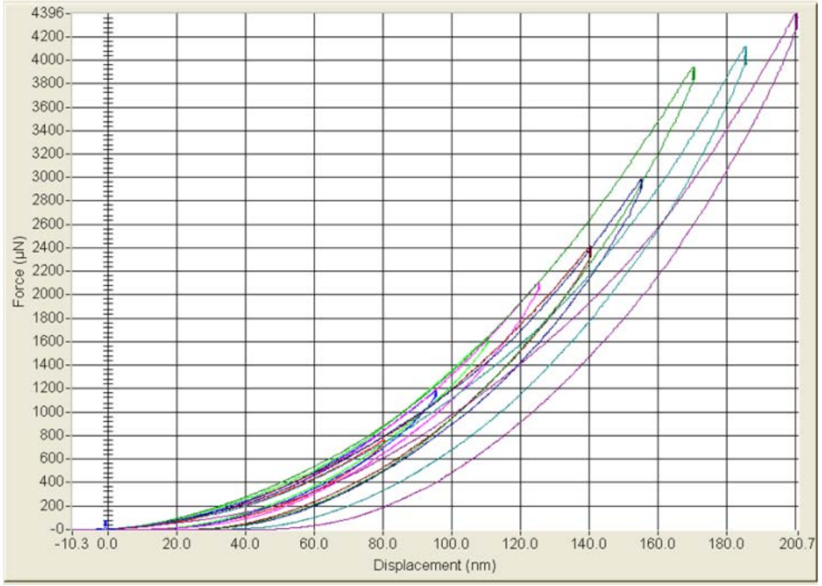


Sample and region of probing	Hardness (GPa)	Elastic Modulus (GPa)
NFC7 (area 1)	17.3±0.5	122±1
NFC7 (area 2)	16.6±0.5	111±3

Technical Accomplishments 2011

- Nanoindentation performed late 2010/early 2011 finds smooth featureless surface of NFC6 is extremely elastic and has modest hardness and modulus.

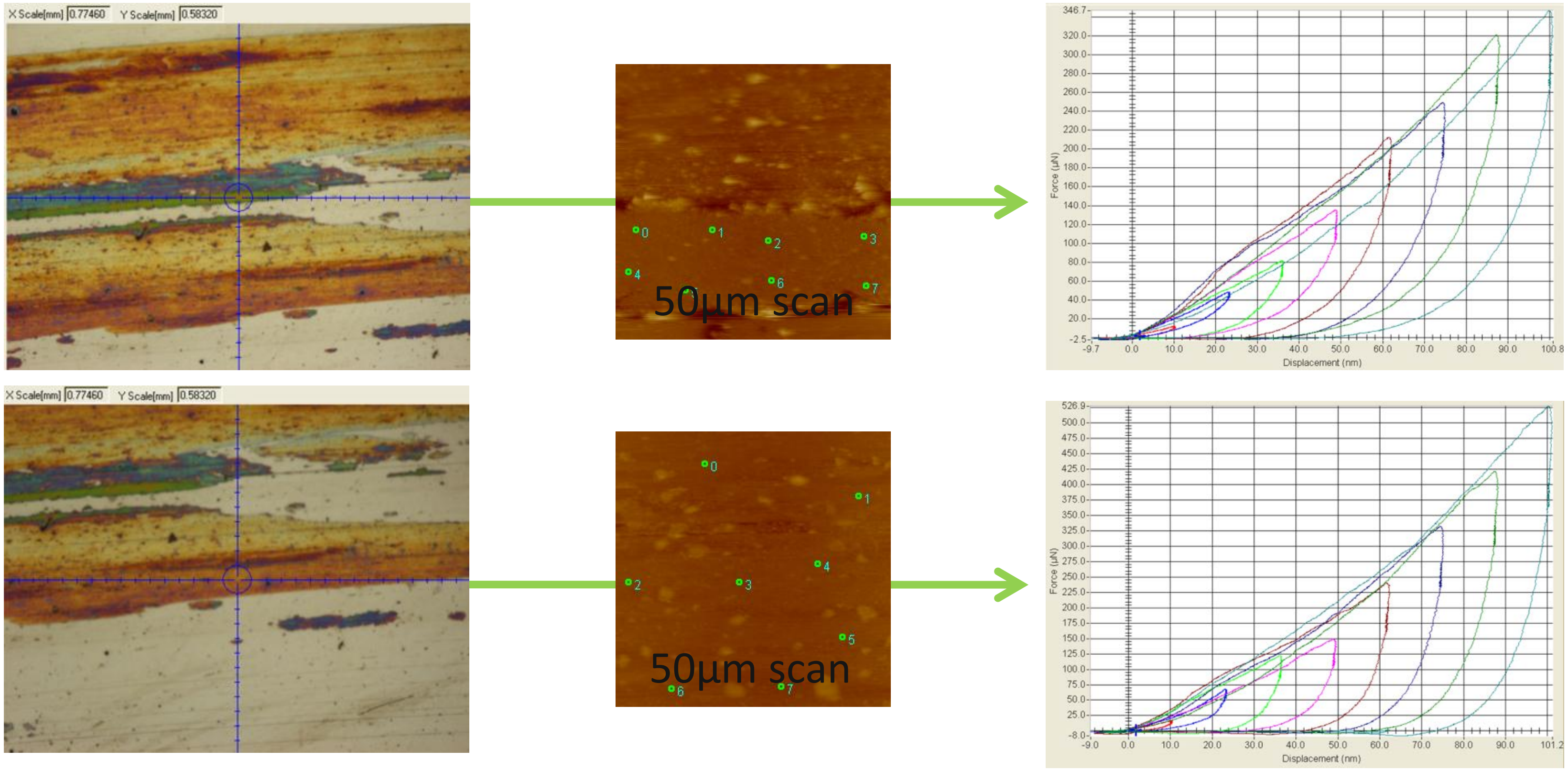




Sample and region of probing	Hardness (GPa)	Elastic Modulus (GPa)
NFC6	7.8±0.8	69±4

Technical Accomplishments 2011

- Nanoindentation performed late 2010/early 2011 finds N3FC6 transfer films showed high elastic modulus but low hardness.



Sample and region of probing	Hardness (GPa)	Elastic Modulus (GPa)
Transfer film of H_2 tested N3FC DLC	1.7±0.42	60±14
Transfer film of H_2 tested N3FC DLC	1.7±0.5	30±5

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)**

Proposed Future Work

- Finish up required milestones at elevated temperatures.
- Obtain and examine failed forecourt compressor parts from reciprocating compressor partner to identify failure mechanisms and possible remedies
- Conduct longer-term sliding tests on materials used in forecourt compressors for “bone dry” use [e.g., polyether ether ketone (PEEK) and carbon tetrafluoroethylene (TFE) instead of nickel alloys, as has been done so far].
- Continue nanoprobe/nanoindentation studies to elucidate possible relationship of surface mechanical properties to tribology friction and wear.
- Use focused-ion-beam method to understand how H_2 can impact near-surface and subsurface failure.
- Study embrittlement and crack behavior.

Summary

- Project initiated to address concern over potential impact of hydrogen on friction, wear, and embrittlement of dynamically loaded components (bearings and seals)
  - Despite limited funding, longer-duration room-temperature testing was performed of existing (NFC6) and new (amorphous carbon and Argonne NFC7) materials at start of FY2011.
  - Our new elevated temperature tribometer was accepted, and tests to 500°C have been performed, but some load arm function and pressure regulation issues are ongoing.
  - A sequence of tests from room temperature to 400°C was performed with NFC7.
  - First tests of mechanical properties of tested specimens obtained using nanoindenter show very soft carbon films and transfer films, but much harder NFC7.
  - Development and testing of amorphous carbon coatings containing hydrogen (the Argonne NFCX series) showed excellent friction and wear behavior.

Presentations and Publications

- Friction and Wear of Metals and Coatings Used in Hydrogen Service, Robert Erck, George Fenske, and Osman Eryilmaz, Effects of Hydrogen on Materials, *Proc. 2008 Intl. Hydrogen Conf*., Brian Somerday, Petros Sofronis, Russell Jones, eds., pp. 405-412.
- Friction and Wear Properties of Materials used in Hydrogen Service , R. A. Erck, G. R. Fenske, and O. L. Eryilmaz *Materials Innovations in an Emerging Hydrogen Economy,* G. G. Wicks, J. Simon, eds., Ceramics Transactions, **202**, pp. 181-186, (2009).
- Impact of Friction Reduction Technologies on Fuel Economy, G. R. Fenske, Presentation to Chicago Section STLE, Mar 2009.
- Hydrogen Pipeline Compressors, George Fenske, Robert Erck, 2009 Progress Report for the DOE Hydrogen Program.

Critical Assumptions and Issues

- The reliability and durability of current hydrogen compressors (pipeline or forecourt) are not sufficient to meet future needs.
  - Solution – advances in materials and coatings to address the reliability and durability issues.
- Hydrogen will impact the tribological performance of materials used in the construction of dynamically loaded compressor components such as seals, bearings, pistons and rider rings.
  - Solution – develop hydrogen-tolerant materials.
- Initial nominal room temperature tests on common alloys raise concerns about the reliability and durability of current compressor materials in hydrogen environments.
  - Solution – find materials which work *better* in hydrogen than other gases, and obtain and understand *why* such materials work better in hydrogen.