Coatings for Centrifugal Compression

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Argonne National Laboratory
May 18-22, 2009

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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)

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

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

Timeline

<table>
<thead>
<tr>
<th>Target</th>
<th>Status</th>
<th>FY 2010</th>
<th>FY 2012</th>
<th>FY 2015</th>
<th>FY 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pipeline</td>
<td>Low</td>
<td>Low</td>
<td>Improved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- ForeCourt</td>
<td>Low</td>
<td>Low</td>
<td>Improved</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capital Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Pipeline (200K kg/day)</td>
<td>$15M</td>
<td>$4.6K</td>
<td>$12M</td>
<td>$3.0K</td>
<td>$9M</td>
</tr>
<tr>
<td>- ForeCourt (1500 kg/day)</td>
<td>$4.6K</td>
<td>$4.0K</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contamination</td>
<td>Varies by design</td>
<td>none</td>
<td>none</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forecourt Fill Pressure</td>
<td>5ksi – 6+ksi</td>
<td>5 ksi – 6+ksi</td>
<td>10ksi – 12ksi</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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, O₂, inert gases, H₂, CH₄, 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, H₂ pressure
  - Speed, load/stress
  - Air/inert/inert-H₂/CH₄/H₂/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
**Approach/Milestones**

- **COMPLETED** Initiate low-temperature tests to evaluate tribological properties of materials and coatings in hydrogen (and baseline gases – air, inert, CH\(_4\)).
  - Low-speed, high stress
  - Medium speed, low stress

- **COMPLETED** Develop design specs and initiate procurement of a high speed, high temperature hydrogen tribometer.  
  
- Rank promising materials and coatings  
  
- Site preparation for high temperature hydrogen tribometer.

- Operation of hydrogen tribometer and high temperature tests

- March 2008
  - July 2008
  - September 2009
  - August 2009
  - February 2010
Technical Accomplishments 2009

- Tribometer developed and made operational with capability to test candidate materials and coatings in hydrogen and methane 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 (H₂ vs. CH₄)
Technical Accomplishments 2009

- Started tests on new, 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

![](image1)

![](image2)
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)

$H_2$ → Air

Both light and dark marks are raised above the surface

Fe/Ni/B
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.
Technical Accomplishments 2009

- Performed preliminary tests on a commercial high-temperature, MoS₂/Graphite based coating in air and hydrogen
- No impact of environment on friction-response during short-duration room temperature tests
Technical Accomplishments 2009

- Commercial, high-temperature, MoS₂/Graphite composite coating tested in air and hydrogen
  - Short duration tests showed unexpected high (0.4) friction for MoS₂/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 high temperature test 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)

260°C
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.

![Graph showing friction coefficient over time for NFC6 hydrogen, Carbon fiber, and Zr - hydrogen.](image)
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
New friction results tabulated

<table>
<thead>
<tr>
<th>Rotating face</th>
<th>Stationary counterface</th>
<th>Environment</th>
<th>Friction</th>
<th>Wear face</th>
<th>Wear counterface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molykote</td>
<td>X750</td>
<td>Air</td>
<td>Medium 0.4</td>
<td>High - abrasion</td>
<td>Low</td>
</tr>
<tr>
<td>Molykote</td>
<td>X750</td>
<td>Hydrogen</td>
<td>Medium 0.4</td>
<td>High - abrasion</td>
<td>Low</td>
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<tr>
<td>Zr</td>
<td>Zr</td>
<td>Air</td>
<td>Medium 0.5</td>
<td>High - galling</td>
<td>High - galling</td>
</tr>
<tr>
<td>Zr</td>
<td>Zr</td>
<td>Hydrogen</td>
<td>Medium 0.5</td>
<td>High - galling</td>
<td>High - galling</td>
</tr>
<tr>
<td>Fe/Mo/Boride</td>
<td>316ss</td>
<td>Air</td>
<td>Med high 0.6</td>
<td>Low - abrasion</td>
<td>Low</td>
</tr>
<tr>
<td>Fe/Mo/Boride</td>
<td>316ss</td>
<td>Hydrogen</td>
<td>Med high 0.6</td>
<td>Low - abrasion</td>
<td>Low</td>
</tr>
<tr>
<td>CF composite</td>
<td>X750</td>
<td>Air</td>
<td>Medium 0.4</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>CF composite</td>
<td>X750</td>
<td>Hydrogen</td>
<td>Medium 0.4</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td>CF composite</td>
<td>X750</td>
<td>Methane</td>
<td>Medium 0.4</td>
<td>Low</td>
<td>Low</td>
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<tr>
<td>N3FC</td>
<td>4118 steel</td>
<td>Hydrogen</td>
<td>Low 0.15</td>
<td>Low</td>
<td>None</td>
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<tr>
<td>N3FC</td>
<td>4118 steel</td>
<td>Methane</td>
<td>Low 0.15</td>
<td>Low</td>
<td>None</td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>Hastelloy X</td>
<td>Hydrogen</td>
<td>Very high &gt;1</td>
<td>High - galling</td>
<td>High - galling</td>
</tr>
<tr>
<td>Hastelloy X</td>
<td>Hastelloy X</td>
<td>Methane</td>
<td>Very high &gt;1</td>
<td>High - galling</td>
<td>High – galling</td>
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<tr>
<td>NFC6</td>
<td>316ss</td>
<td>Air</td>
<td>Low (0.2-0.4)</td>
<td>Low</td>
<td>None</td>
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<tr>
<td>NFC6</td>
<td>316ss</td>
<td>Hydrogen</td>
<td>Very Low (0.04)</td>
<td>Low</td>
<td>None</td>
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<tr>
<td>X-750</td>
<td>X-750</td>
<td>Hydrogen</td>
<td>High 0.6-0.9</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>316ss</td>
<td>316ss</td>
<td>Hydrogen</td>
<td>High 0.6-0.9</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>
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
  - Molykote
  - Tribaloy
  - WC+17%Co
  - BN composite
  - Boride conversion
  - Bodycote
  - ANL NFC6
  - 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