III.16 Hydrogen Pipeline Compressors

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Fiscal Year (FY) 2011 Objectives

- Develop advanced materials and coatings for hydrogen pipeline compressors.
- Achieve greater reliability, increased efficiency, and lower capital investment and maintenance costs in hydrogen pipeline compressors.
- Research existing and novel hydrogen compression technologies that can improve reliability, eliminate contamination, and reduce cost.

Technical Barriers

The project addresses the following technical barrier from the Hydrogen Delivery section (3.2.4.2) of the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Reliability and Costs of Hydrogen Compression

Technical Targets

This project is directed toward the study of fundamental mechanisms associated with the tribology of hydrogen pipeline compressors (friction, wear, and degradation). The goal of the research is to identify materials and engineered surface treatments that provide low friction and wear resistance required to achieve the energy efficiency and reliability targets for pipeline compressors. Accordingly, the project tasks address the challenges associated with meeting the DOE hydrogen delivery performance and cost targets for 2017 in Table 1.

TABLE 1. Hydrogen Delivery Performance and Cost Targets for 2017

Technical Targets for Hydrogen Delivery		
Category	**FY 2012 Targets**	**2010 Status**
Reliability	Improved	Low
Energy Efficiency	98%	<98%
Total Capital Investment	\$12M	>\$15M
Maintenance	7%	>10%
Contamination	Varies	Unknown

FY 2011 Accomplishments

- Prior year accomplishments have been in the nature of finding a low-friction coating that can stand up to the conditions of unlubricated sliding in H_2. These tests were initially conducted with a modified in-house tribometer that could operate at room temperature.
- Candidate materials that were obtained in-house and from commercial companies were studied in detail and the general nature of each was characterized with the room-temperature tribometer.
- The design specifications and procurement of new high-temperature hydrogen tribometer was started in 2008, and the installed machine was accepted in 2010.
- The leading materials were found to be thin film carbon coatings, particularly hydrogenated carbon known as near-frictionless coating (NFC) 7, which shows very small wear in tests.
- Other counterface materials studies were MoS_2, carbon fiber, iron boride, sp^3 diamondlike carbon (DLC), Ni-poly-tetrafluoroethylene (PTFE), and carbon-carbon.
- Initial tests using the new elevated tribometer found the NFC7 carbon functioned to 300°C, but apparently has a temperature limit of 400°C in H_2 gas.

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Introduction

Compressors are critical components used in the production and delivery of hydrogen. Current reciprocating compressors are costly, are subject to excessive wear, have poor reliability, and often require the use of lubricants that can contaminate the hydrogen (used in fuel cells).

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 DOE Strategic Directions for Hydrogen Delivery Workshop identified critical needs in the development of advanced hydrogen compressors – notably, the need to minimize moving parts and to address wear through new designs (centrifugal, linear, guided rotor, and electrochemical) and improved compressor materials. The DOE is supporting several compressor design studies on hydrogen pipeline compression, specifically addressing oil-free designs that demonstrate compression in the 0-500 psig to 800-1,200 psig range with significant improvements in efficiency, contamination, and reliability/durability.

One of the designs by Mohawk Innovative Technology, Inc. (MiTi®) involves using oil-free foil bearings and seals in a centrifugal compressor, and MiTi® identified the development of bearings, seals, and oil-free tribological coatings as crucial to the successful development of an advanced compressor. MiTi® and Argonne have developed potential coatings for these rigorous applications; however, the performance of these coatings (as well as the nickel-alloy substrates) in high-temperature, high-speed hydrogen environments is unknown at this point.

Approach

The approach that is being undertaken is to evaluate the tribological performance of candidate seal and bearing materials under consideration by compressor manufacturers and provide data required to select the optimum seal and bearing material/coating configuration for a 300-kg/min centrifugal compressor and high-pressure, low-flow positive displacement compressor. This effort will include a) evaluating the effects of a hydrogen environment on the mechanical properties of Ni alloys, b) evaluating the feasibility of coating suitable substrates with Argonne's NFC and outside vendor coatings, c) establishing the requirements and testing needs for NFC and a series of foil seal coatings, and d) evaluating foil seal and bearings under conditions prototypic of the proposed MiTi® hydrogen compressor.

The research uses facilities and expertise at Argonne – notably the ability to deposit advanced high-performance coatings (e.g., NFC), to test and evaluate coatings under extreme conditions, and to characterize and understand friction, wear, and surface degradation phenomena that determine component lifetime and reliability.

Different contact stress/sliding speed regimes were 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

Based on the range of contact stresses and sliding speeds anticipated for these compressors, we will replicate lab conditions to encompass nominal contact stresses between 2 and 1,500 psi, with sliding speeds from 0.1 to 10 m/s. Operating temperatures up to 500°C due to working-gas adiabatic heating and 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. The coating deposition is focused on NFC and commercial coatings based on conventional solid lubricants. The substrates chosen are stainless steels, nickel alloys, and Cr-Mo steels.

Results

New Test Machine

In the past year, the main focus was the acceptance and first tests using a new high-temperature test rig, which is shown in the photograph in Figure 1. The test machine exhibited deficiencies in operation which were repaired under warranty. Further deficiencies in the pressure control system were overcome in June 2011. Because the prescribed tests call for a low pressure sliding condition the machine needed to be modified from pin-on-disk to thrust washer configuration.

Continuing Tests to Evaluate Materials

In FY 2011, the FY 2011milestones were largely met. Milestone 1 required a satisfactory acceptance test demonstrating 2,000 rpm operation for 4 h in 0.9-bar H_2 gas at 500°C with continuous measurement of friction, wear,

FIGURE 1. Photograph of new high-temperature hydrogen test machine in open position for loading of test specimens.

temperature, and sliding distance. This milestone was met 100%. Figure 1 shows a photograph of the test machine installed and operational. Milestone 2 was to 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 gas. This milestone was met 90% by obtaining 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. Figure 2 shows that the coefficient of friction is below 0.1 at all test temperatures up to 300°C, meeting the target value. However, this was not the case at 400°C for which the coefficient of friction jumped to unacceptably high values. Figure 3 shows

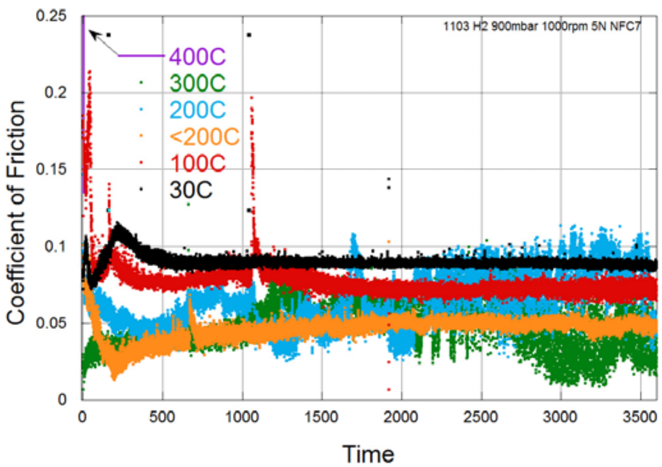

FIGURE 2. Graph showing coefficient of sliding friction as a function of test time for the NFC7 material sliding in H_2 gas against Hastelloy X at various indicated temperatures.

post-test images of the test coupons and reveals adequate durability for the NFC7 material at test temperatures up to 300°C, but failure at 400°C. Milestone 3 was to 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. This was 10% completed by completed using the room temperature test rig in early part of FY 2011.

Most Recent Results

Table 2 shows the most recent tabular results for the most recent thrust washer tests, omitting those not run in H_2 gas. Most tests, except for those terminated early due to extreme wear, were for up to two hours duration with a 50% duty cycle, 50s on and 50s off at speeds up to 6,000 rpm. Typical results for a nickel-PTFE film are shown in Figure 4.

Conclusions and Future Directions

Longer-duration room-temperature testing was performed on existing (NFC6) and new (proprietary DLC and Argonne NFC7) materials, with excellent results for the latter. Final problems with the new elevated temperature tribometer were worked out, and initial tests showed the limitation of carbon-based materials may be 400°C. We will finish up testing of promising materials at typical in-service temperatures. The knowledge that is being gained will also be directly applicable to unlubricated forecourt compressors. The original goal of “Large Compressors: Transmission, Terminals, Geological Storage” is being broadened to include the section “Forecourt Compressors: Forecourt,” and discussions have been started with two manufacturers of non-centrifugal hydrogen compressors who have products in the field that are exhibiting the need for frequent scheduled

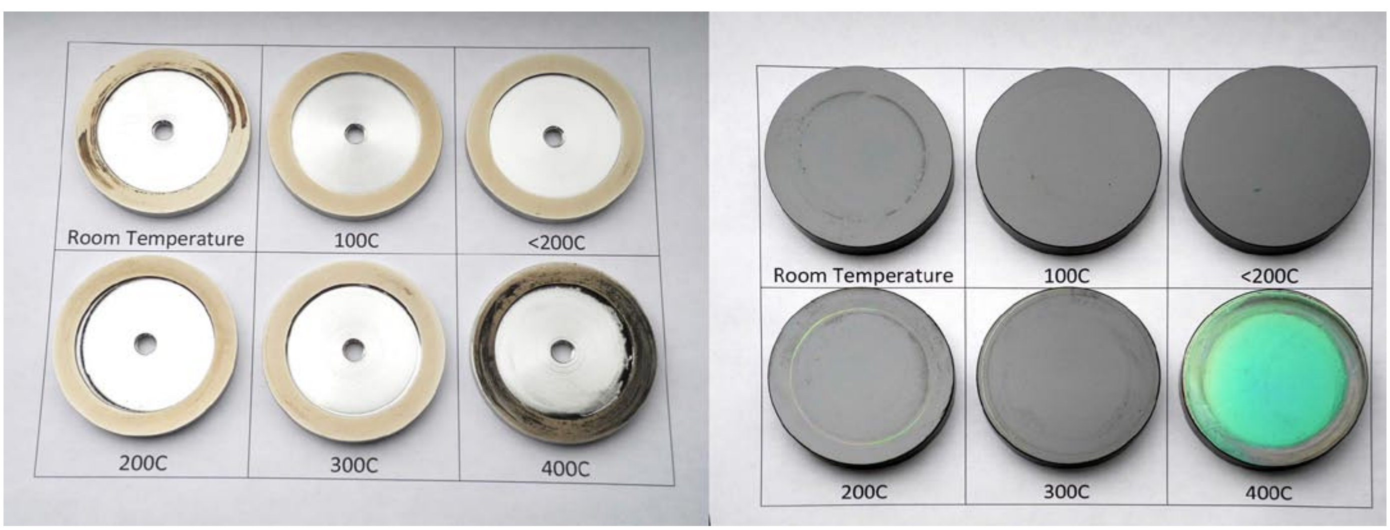

FIGURE 3. Photographs of worn thrust-washer test pairs (stationary bottom samples coated with NFC7-right, rotating Hastelloy X top samples-left) after 1 hr sliding at indicated test temperatures in H_2 gas.

TABLE 2. Most Recent Results From Thrust-Washer Tests

Rotating Face	Stationary Counterface	Environment	Friction	Wear Face	Wear Counterface
MK MoS_2	X750	Hydrogen	Medium 0.4	High abrasion	Low
Fe/Mo/Boride	316ss	Hydrogen	Med high 0.6	Low abrasion	Low
CF composite	X750	Hydrogen	Medium 0.4	Low	Low
N3FC	4118 steel	Hydrogen	Low 0.15	Low	Immeasurable
NFC6	Hastelloy X	Hydrogen	Low 0.1	None	Very low
Hastelloy X	Diamonex	Hydrogen	Medium 0.4	Low	Medium
NFC7	Hastelloy X	Hydrogen	Low 0.06	None	Immeasurable
SP3 DLC	4118 steel	Hydrogen	Low 0.05	Large	Large
Ni/PTFE	Ni/PTFE	Hydrogen	High 0.6	Large	Large
Hastelloy X	Im MoS2	Hydrogen	Medium 0.4	Low	Low

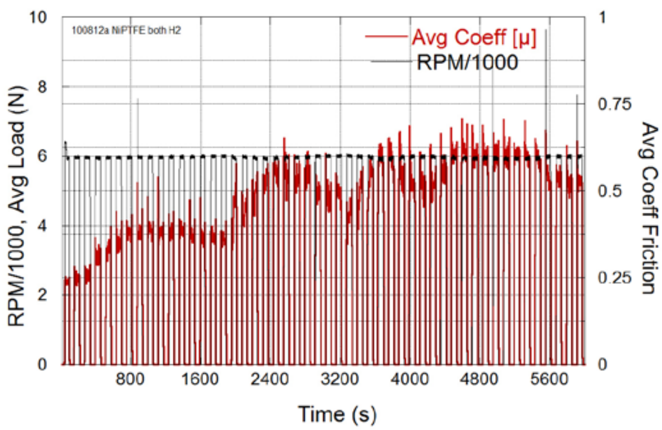

FIGURE 4. Graph showing coefficient of sliding friction as a function of test time for a Ni/PTFE composite sliding against itself in H_2 gas with 50% on/off duty cycle for 6,000s.

and unscheduled maintenance. This revised goal will involve conducting longer-term sliding tests on materials used in forecourt compressors for "bone dry" use (e.g., polyether ether ketone and carbon-tetrafluoroethylene instead of nickel alloys, as has been done so far). We will continue nanoindentation studies to elucidate the possible relationship of surface mechanical properties to tribology friction and wear. This research leverages facilities and expertise at Argonne used to develop advanced materials and coatings for dry sliding conditions – notably the ability to deposit advanced high-performance coatings, test and evaluate coatings under extreme conditions, and characterize and understand friction, wear, and surface degradation phenomena that determine component lifetime and reliability. Concurrently we will to initiate discussions with point-of-delivery compressor users and manufacturers to obtain and examine failed forecourt compressor parts from reciprocating compressor partner to identify failure mechanisms and possible remedies.

FY 2011 Publications/Presentations

1. Coatings for Centrifugal Compression, G. Fenske, R. Erck, and O. Eryilmaz, presented at 2010 DOE Hydrogen Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., May 9–12, 2011.