# III.18 Hydrogen Pipeline Compressors

George Fenske (Primary Contact), Robert Erck
Argonne National Laboratory (ANL)
9700 S. Cass Ave.
Argonne, IL 60439
Phone: (630) 252-5910
E-mail: gfenske@anl.gov

DOE Technology Development Manager:
Monterey Gardiner
Phone: (202) 586-1758
E-mail: Monterey.Gardiner@ee.doe.gov

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## 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:

Technical Targets for Hydrogen Delivery

| Category | FY 2012 Targets | 2009 Status |
|---|---|---|
| Reliability | Improved | Low |
| Energy Efficiency | 98% | <98% |
| Total Capital Investment | $12M | >$15M |
| Maintenance | 7% | >10% |
| Contamination | Varies | Unknown |

FY – Fiscal Year

## Accomplishments

- Completion of installation and initial acceptance tests of new high-temperature hydrogen tribometer.
- Identification of new coating material (NFC7) that shows no measurable wear in two-hour test.
- Completion of tests that assessed friction and durability of proprietary diamond-like carbon (DLC) coating.

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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 near frictionless coating (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 receipt and installation of a new high-temperature test rig, as shown in Figure 1. The machine exhibited deficiencies in performance acceptance tests. The operation requirements (speed of 2,000 rpm, test period of 1 hour, pressure of 0.9 bar, temperature of 800°C) with continuous measurement of friction, wear, temperature, and sliding distance were attained in $N_2$ gas but not in $H_2$. Safety interlock switches were installed to limit the maximum pressure to approximately half the specified pressure. The pressure issue is being addressed by using dual redundant differential pressure switches. The specified temperature could not be attained due to excessive convective cooling of the specimen holder as a result of the high heat conductivity of $H_2$, which is approximately seven times that of air. The convection issue is being addressed by the installation of quartz heat shields. During acceptance tests, the $H_2$ pressure regulation was lost because a pirani pressure gauge did not operate correctly in $H_2$ at pressures above 1 mbar. The regulation issue was solved by substituting a capacitance diaphragm gauge, which reads correctly over the complete pressure range, independent of gas species. The reducing nature of $H_2$ on uncoated nickel alloys was dramatized when the new machine jammed and galled during maintenance – necessitating factory repair.


**FIGURE 1.** Photograph of New High-Temperature Hydrogen Test Machine

## Continuing Tests

Additional tribological data were obtained in FY 2010, particularly focusing on extended duration tests (2 hours). Summary results are shown in Table 1. At nominal room temperature, the new Argonne NFC7 carbon performs better than the former best-performing material, NFC6. As shown in Figure 2, the coefficient of friction of NFC7 is substantially less than that of NFC6, and yet the NFC7 shows no measurable wear. Tests were harsher with the NFC7: 2-hr duration at either 2,000 rpm or 6,000 rpm, 50% duty cycle, up to 15 N load. A proprietary DLC coating did not perform as well. A Ni/polytetrafluoroethylene (PTFE) coating was obtained on test coupons, but testing was delayed. A nondisclosure agreement is being negotiated with a company that offers a low-temperature diamond coating process.

## New Characterization Methods

A newly installed Hysitron nanoindenter was used to probe the mechanical properties of unworn and worn surfaces (Table 2). Transfer films, as expected, are quite soft, but the new NFC7 is surprisingly hard with high elastic modulus when compared to the other leading candidate material NFC6, or the lesser-performing N3FC. The NFC7 exhibits surprising constancy in hardness and elastic modulus for various loadings (1-5 mN)

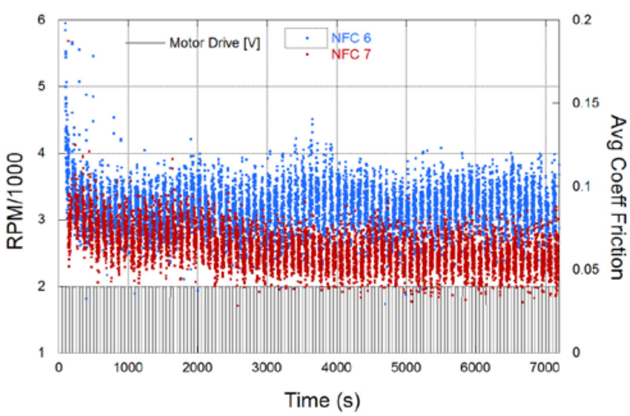


**FIGURE 2.** Graph Showing Results of Two-Hour Test of NFC6 and NFC7 at 50% Duty Cycle in $H_2$

**TABLE 2.** Nanoindenter Measurement of Mechanical Properties of Materials

| 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 | 60±14 |
| Transfer film of $H_2$ tested N3FC DLC | 1.7±0.5 | 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)<br>NFC7 (area 2) | 17.3±0.5<br>16.6±0.5 | 122±1<br>111±3 |
| NFC6 | 7.8±0.8 | 69±54 |

## 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. Installation of the new elevated-temperature tribometer is 80% complete, with shakedown tests performed in $N_2$ but not meeting specifications in $H_2$. Pending successful modifications and acceptance tests, we will finish up testing of promising materials at typical in-service temperatures. A series of tests of newly received Ni/PTFE test specimens will be performed.

**TABLE 1.** Friction Coefficients of Materials in Ambient-Pressure Hydrogen

| Materials Tests in Hydrogen | | | | |
|---|---|---|---|---|
| **Rotating face** | **Stationary Counterface** | **Friction** | **Wear Face** | **Wear Counterface** |
| **$MoS_2$** | X750 | Medium 0.4 | High abrasion | Low |
| **CF composite** | X750 | Medium 0.4 | Low | Low |
| **N3FC** | 4118 steel | Low 0.15 | Low | Immeasurable |
| **NFC6** | Hastelloy X | Low 0.1 | None | Very low |
| **Hastelloy X** | Proprietary DLC | Medium 0.4 | Low | Medium |
| **NFC7** | Hastelloy X | Low 0.06 | None | Immeasurable |
| **$MoS_2$** | X750 | Medium 0.4 | High abrasion | Low |
| **Fe/Mo/Boride** | 316ss | Med high 0.6 | Low abrasion | Low |

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 suppliers of non-centrifugal hydrogen compressors who have products in the field that are exhibiting the need for frequent scheduled 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., poly-ether-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, and will apply the focused-ion-beam method to understand how $H_2$ can affect near-surface and subsurface failure.

## FY 2010 Publications/Presentations

**1.** 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 and J. Simon, eds., Ceramics Transactions, **202**, pp. 181-186 (2009).

**2.** 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., June 7, 2010 – June 11, 2010.