Argonne NATIONAL LABORATORY

ANL-11/30

Hydrogen Pipeline Compressors Annual Progress Report 2009

Energy Systems Division

ANL-11/30

Hydrogen Pipeline Compressors
Annual Progress Report 2009

by
G.R. Fenske and R.A. Erck
Energy Systems Division, Argonne National Laboratory

Work supported by U.S. Department Energy, Office of Hydrogen, Fuel Cells and Infrastructure Technologies under contract DE-FC26-04NT42263

June 2009

III.10 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 R. Gardiner
Phone: (202) 586-1758; Fax: (202) 586-9811
E-mail: Monterey.Gardiner@ee.doe.gov

Technical Advisor: Timothy Armstrong
Phone: (865) 574-7996; Fax: (865) 241-0112
E-mail: armstrongt@ornl.gov

Project Start Date: October 2006

Project End Date: September 2012

Objectives

- Develop advanced materials and coatings for hydrogen pipeline compressors.
- Achieve greater reliability, greater 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 Hydrogen, Fuel Cells and Infrastructure Technologies (HFCIT) 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 2012:

Technical Targets for Hydrogen Delivery		
Category	FY 2012 Targets	2008 Status
Reliability	Improved	Low
Energy Efficiency	98%	<98%
Total Capital Investment	$12M	>$15M
Maintenance	7%	>10%

Contamination	Varies	Unknown

Accomplishments

- Bid requests for a high-speed high-temperature tribometer were sent out, and a satisfactory bid was received.
- Construction on the tribometer was started in February 2009, and delivery to Argonne is scheduled for August 2009.
- The ability to run tests in an environment of pure methane (natural gas) was added.
- Room-temperature tests in pure hydrogen and methane were run to compare the friction and wear behavior of baseline materials and coated materials/novel composites and conversion coatings.

Introduction

Compressors are critical components used in the production and delivery of hydrogen. Current reciprocating compressors used for pipeline delivery of hydrogen 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). Duplicate compressors may be required to assure availability.

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 800-1200 psig range with significant improvements in efficiency, contamination, and reliability/durability.

One of the designs by Mohawk Innovative Technologies 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 [1]. MiTi® and ANL 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

Our approach is to evaluate the tribological performance of seals and bearing materials under consideration by MiTi® and provide them with the data required to select the optimum seal and bearing material/coating configuration for the 300-kg/min centrifugal compressor that was designed in their Phase II studies. This effort includes a) evaluating the effects of the hydrogen environment on the mechanical properties of Ni alloys, b) determining the feasibility of coating-suitable substrates with Argonne, MiTi®, and outside vendor coatings, [2], c) establishing the requirements and testing needs for implementing near frictionless carbon (NFC) and MiTi®'s series of foil seal coatings, and d) testing foil seal and bearings under conditions prototypic of their proposed hydrogen compressor.

The research uses facilities and expertise at Argonne – notably the ability to deposit advanced high-performance coatings (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 compressors - 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. Coating deposition on substrates focuses on NFC and commercial coatings based on conventional solid lubricants. The substrates chosen are stainless steel, nickel alloys, and Cr-Mo steels.

The effect of gas composition has not been defined. Different levels of impurities (moisture, natural gas, contaminants) will affect formation of surface films. Lab tests will be performed with H_2 containing different levels of water and other trace impurities and will use natural gas to establish the baseline performance of current compressors.

Results

During FY2009, a new data acquisition system was installed on the room-temperature tribometer that is being used for ongoing tests of candidate materials for compressors. Various conditions were used to compare sliding in hydrogen vs. methane, determine friction of new thin film coatings, and evaluate a chemical conversion process. Figure 1 shows the upgraded hydrogen/methane tribometer and subsystems.

A large amount of sliding data was obtained in FY2009. The baseline materials studied included a Hastelloy X and Type 316 stainless steel (316ss). Zirconium is reported to form hydrides that have beneficial frictional properties, but no improvement due to sliding in hydrogen was observed. A new carbon fiber material was tested. The hydrogen effect on the carbon was not beneficial as first anticipated.

The high-temperature tolerance of a very promising coating (Argonne's NFC6) was tested and found to be quite good. In addition, a new coating, MoS_2/graphite, was tested, as was a conversion coating, pack boriding.

Figure 2 shows friction coefficient results for the MoS_2/graphite and NFC6. The tribological behavior for long duration (one hour) sliding in hydrogen gas of a commercial MoS_2/graphite coating is shown in Figure 2a. For this test the thrust washer speed was ramped to 2000 rpm and back down every 100 s. The friction coefficient remained fairly high at 0.4. The friction coefficient as a function of test temperature for Argonne's NFC6 tested against itself in an inert environment (N_2) is shown in Fig. 2b for a pin-on-disk test configuration at slow speed. The friction at room temperature retains a low and desirable value with increasing temperature. However, upon reaching 350°C, the friction coefficient increases suddenly by about a factor of sixty, indicating catastrophic change in the surface chemistry. A repeat test on the same sample (second trace), but different wear track/region, still showed acceptable performance, although these results raise concern about a potential thermal annealing effect on tribological performance.

The fabrication method for the new conversion coating, pack boriding, uses a commercially available salt bath to chemically transform the surface without the need for a coating step. Tests showed high friction in both air and hydrogen, with erratic coefficients of friction.

Most of the tested materials were examined by analytical techniques such as optical microscopy and optical profilometry. In the future, the near-surface properties will be examined by nanoindentation. Optical examination of most materials showed clear evidence of material adhesion and transfer as a mechanism by which wear proceeds.

Some of the materials behaved differently, depending on whether they were tested in methane or hydrogen. Although the coefficients of friction are comparable, the Argonne N3FC material tested in methane (Figure 3 – top) produced a much weaker transfer film on the counterface surface than when tested in hydrogen (Figure 3 – bottom). This finding may have implications for incorporating existing natural gas compressor technology (methane) into hydrogen gas compressors.

The diamondlike carbon (DLC) films that were available in FY2009 were conventionally produced plasma-grown NFC from Argonne, and a second type of DLC called "N3FC," which was produced from a solid carbon target. It was believed that N3FC has properties superior to NFC because of some low-speed sliding tests that were done. These tests found that the low friction was attained much quicker for the N3FC. However, for the high-speed and low-pressure tests performed in conditions prototypic of compressor use, the conventional NFC shows low friction and withstands high loads without any obvious distress. In contrast, N3FC displays higher friction and undergoes apparent damage after the load test.

Table 1 summarizes the friction coefficients of several materials studied in this project. The table has been updated with the most recent result, focusing on results in either pure methane or pure hydrogen. MoS_2/graphite is a commercial bonded material, CF comp is a carbon-fiber composite, and N3FC is a Argonne-developed thin hard carbon coating that is produced by sputter deposition. NFC6 is an Argonne-developed thin hard carbon coating that is produced using plasma-enhanced chemical vapor deposition.

Table 1: Friction coefficients of materials in different environments

Rotating face	Stationary counterface	Environment	Friction	Wear face	Wear counterface
MoS_2/graphite	X750	Air	Medium 0.4	High - abrasion	Low
MoS_2/graphite	X750	Hydrogen	Medium 0.4	High - abrasion	Low
Zr	Zr	Air	Medium 0.5	High - galling	High - galling
Zr	Zr	Hydrogen	Medium 0.5	High - galling	High - galling
Boride	316ss	Air	Med high 0.6	Low - abrasion	Low
Boride	316ss	Hydrogen	Med high 0.6	Low- abrasion	Low
CF comp	X750	Air	Medium 0.4	Low	Low
CF comp	X750	Hydrogen	Medium 0.4	Low	Low
CF comp	X750	Methane	Medium 0.4	Low	Low
N3FC	4118 steel	Hydrogen	Low 0.15	Low	None
N3FC	4118 steel	Methane	Low 0.15	Low	None
HX	Hastelloy X	Hydrogen	Very high >1	High - galling	High - galling
HX	Hastelloy X	Methane	Very high >1	High - galling	High – galling
NFC6	316ss	Air	Low (0.2-0.4)	Low	None
NFC6	316ss	Hydrogen	Very Low (0.04)	Low	None
X-750	X-750	Hydrogen	High 0.6-0.9	High	High
316ss	316ss	Hydrogen	High 0.6-0.9	High	High

A number of coatings have been indentified as promising candidates, and each has features attractive for high-speed hydrogen-environment use, but needs to be proven by testing. The coatings fall in the following areas:

- Carbon-carbon composite
- Composites such as Korolon, Molykote MoS_2/graphite
- Intermetallics such as Tribaloy or WC+17%Co
- Compounds such as BN composite, boride fused, MoS_2 or Bodycote
- Carbon-based compounds such as ANL DLC6, ANL N3FC, Ionbond, Diamonex, K-Systems DLC

Conclusions and Future Directions

Progress was made on establishing the tribological properties of baseline materials and coatings in FY 2009, though hampered by the lack of high-speed high-temperature testing capability. A total of 81 separate tests were performed, and baseline materials produced unacceptably high friction and wear, whereas a carbon-based coating, NFC6, looked most favorable.

Bid requests for a high-speed high-temperature tribometer were sent out, and a satisfactory bid was received. Construction of the new tribometer was started in February 2009, and delivery is scheduled for August 2009. Installation of the new test machine will enable tribological testing under conditions more representative of those experienced in actual bearing/seal service.

FY 2009 Publications/Presentations

Impact of Friction Reduction Technologies on Fuel Economy, G. R. Fenske, presented to Chicago Section STLE, March 2009.

Hydrogen Pipeline Compressors, George Fenske (Primary Contact) and Robert Erck, in 2008 Progress Report for the DOE Hydrogen Program.

Friction and Wear Properties of Materials Used in Hydrogen Service, R. A. Erck, G. R. Fenske, and O. L. Eryilmaz, presented at Materials Innovations in an Emerging Hydrogen Economy Conference, February 24-27, 2008, Cocoa Beach, FL.

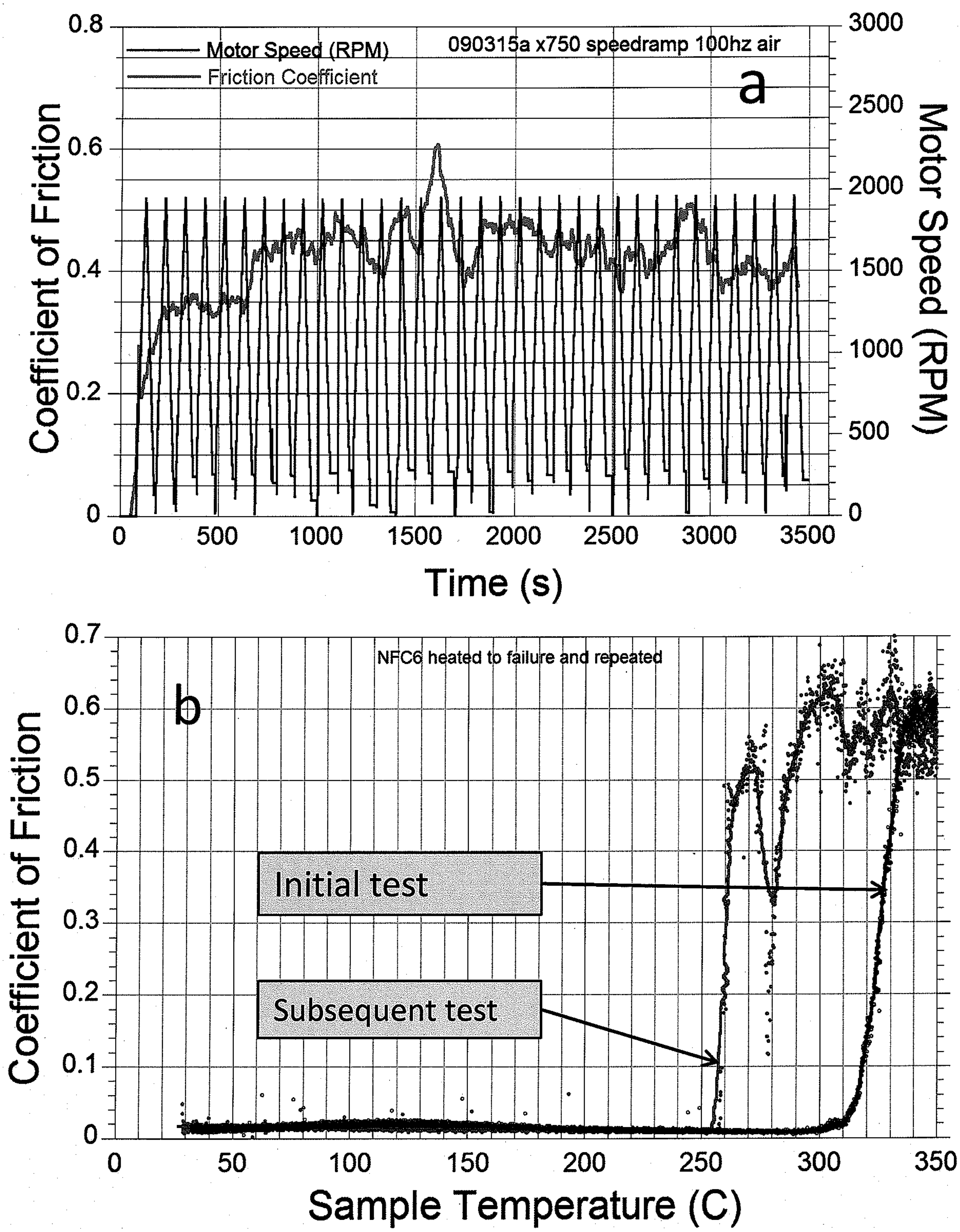
Friction and Wear of Metals and Coatings Used in Hydrogen Service, R.A. Erck, G.R. Fenske, and O.L. Eryilmaz, presented at 2008 International Hydrogen Conference Effects of Hydrogen on Materials, September 7–10, 2008, Jackson, WY.

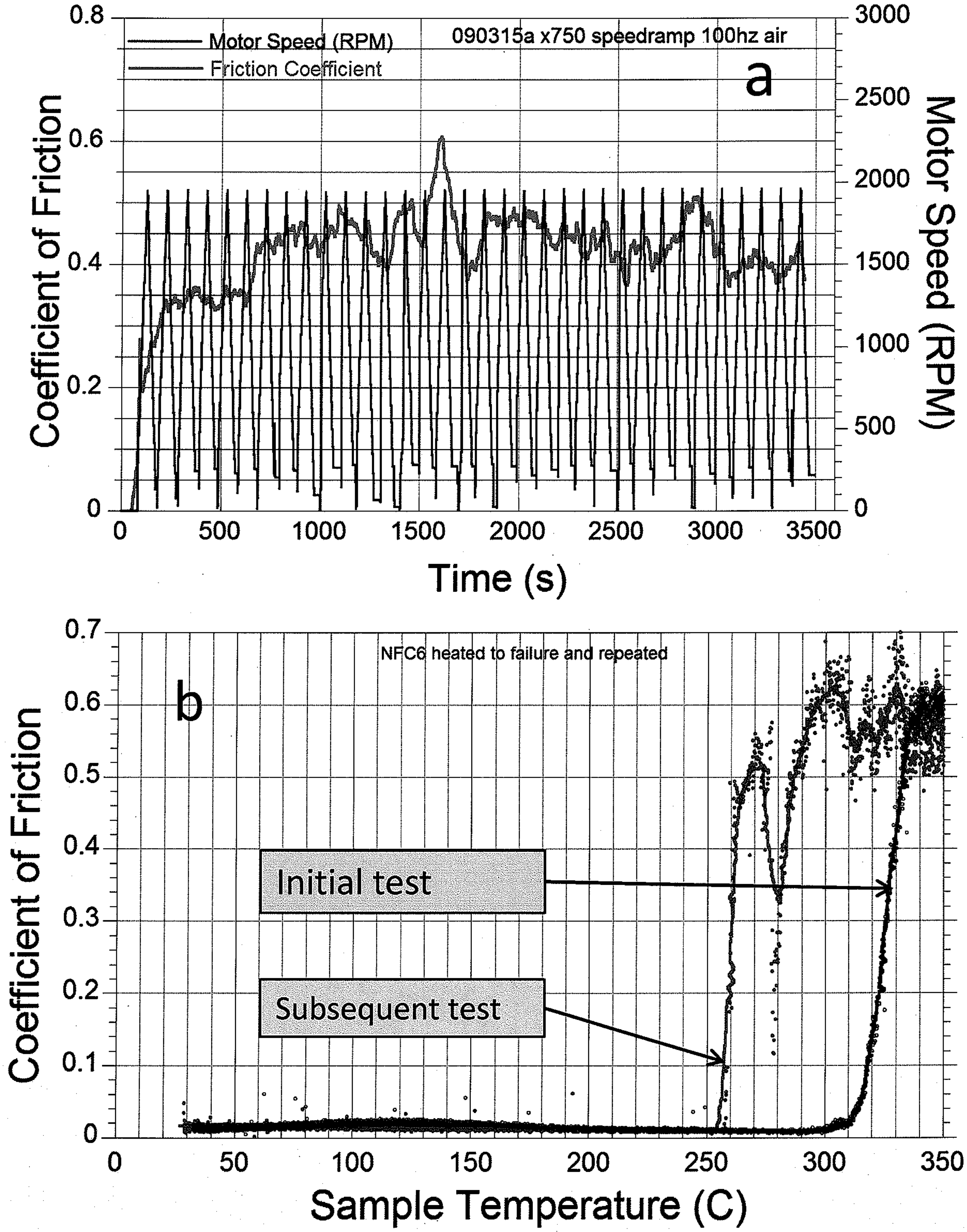
References

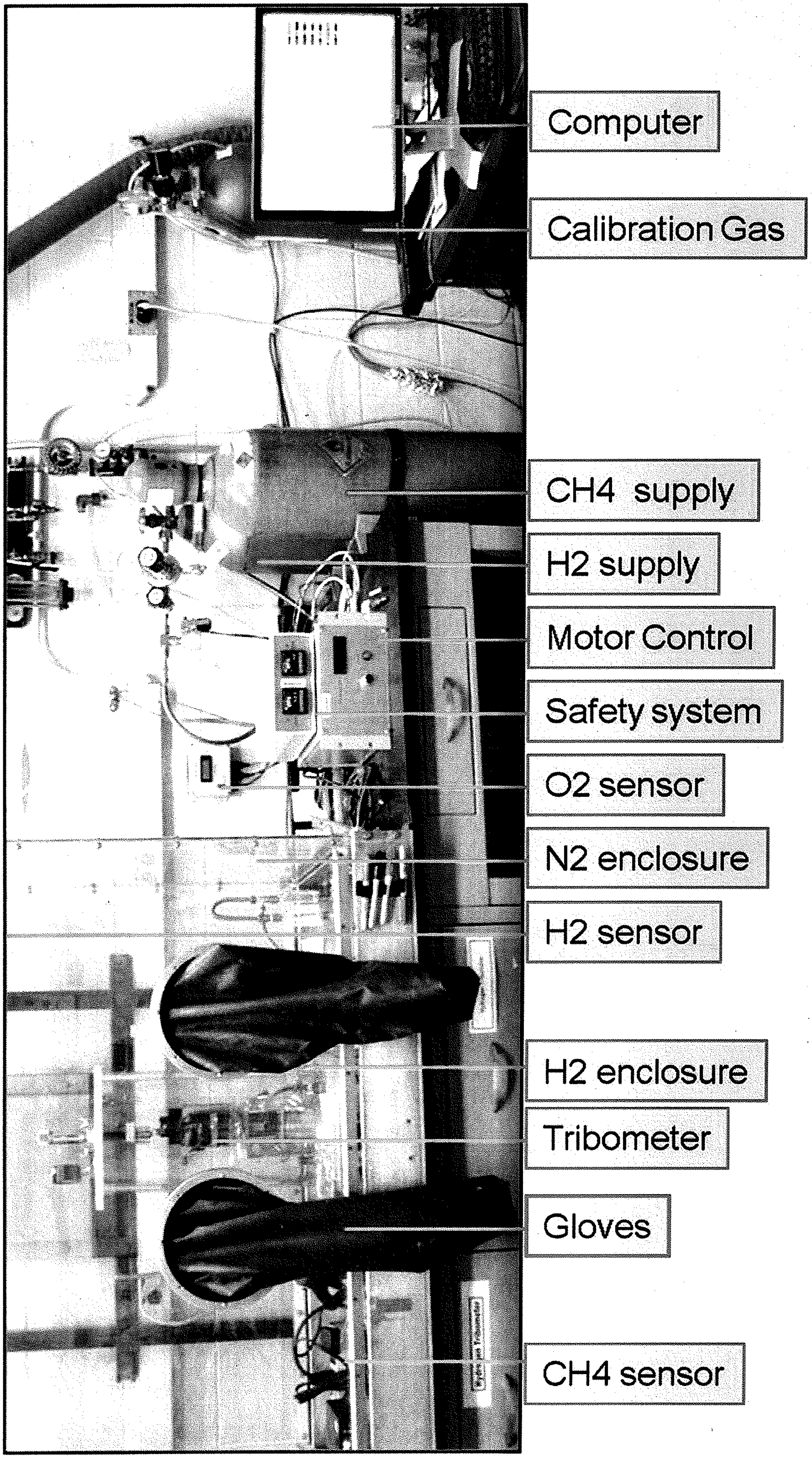
1. H. Heshmat , P. Hryniewicz , J. F. Walton II , J. P. Willis, S. Jahanmir, and C. DellaCorte, Tribol. Intl. **38**, 1059–1075 (2005).
2. A. Erdemir, O. L. Eryilmaz, and G. Fenske, J. Vac. Sci. Technol. A **18**(4), 1987-1992 (2000).

Figure Captions

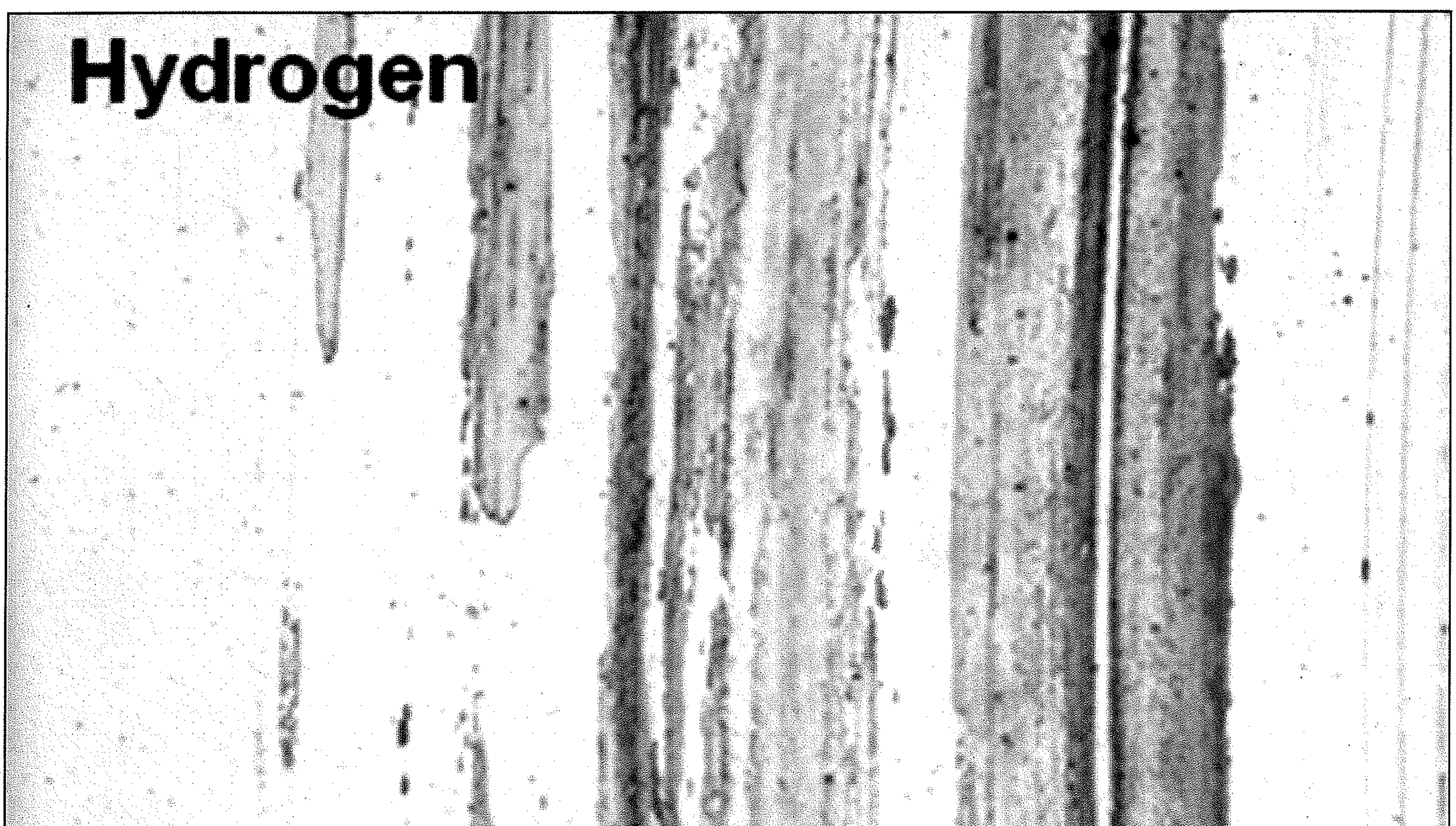
Figure 1. Photograph of room-temperature tribometer and subsystems.
Figure 2. Friction coefficients of (a) one-hour thrust-washer test of commercial MoS_2/graphite coating sliding against bare Hastelloy X750 nickel surface in air and (b) NFC6/NFC6 sliding at elevated temperatures in N_2 (pin-on-disk configuration) .
Figure 3. Optical micrograph of transfer films on surface slid against Argonne N3FC in pure methane (top) and pure hydrogen (bottom) showing weaker transfer film for methane.


Motor Speed (RPM)
Friction Coefficient
090315a x750 speedramp 100hz air
a
Coefficient of Friction
Motor Speed (RPM)
Time (s)
0 500 1000 1500 2000 2500 3000 3500
0 0.2 0.4 0.6 0.8
0 500 1000 1500 2000 2500 3000
NFC6 heated to failure and repeated
b
Initial test
Subsequent test
Coefficient of Friction
Sample Temperature (C)
0 50 100 150 200 250 300 350
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7


Motor Speed (RPM)
Friction Coefficient
090315a x750 speedramp 100hz air
a
Coefficient of Friction
Motor Speed (RPM)
Time (s)
NFC6 heated to failure and repeated
b
Initial test
Subsequent test
Coefficient of Friction
Sample Temperature (C)


Computer
Calibration Gas
CH4 supply
H2 supply
Motor Control
Safety system
O2 sensor
N2 enclosure
H2 sensor
H2 enclosure
Tribometer
Gloves
CH4 sensor


Methane


Hydrogen

Energy Systems Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 362
Argonne, IL 60439-4815

www.anl.gov

U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC