Tribology Research at

Texas A&M University

Surface and Interface Science Laboratory

Director: Hong Liang, PhD

Tribological Evaluation Under Extreme Conditions

-Carlos Sanchez

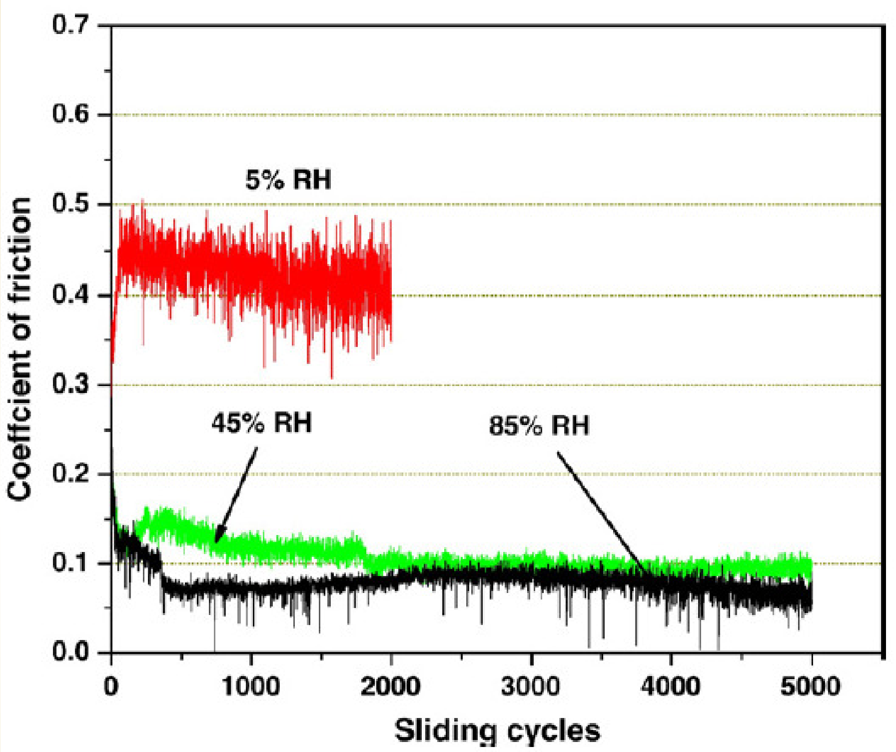
- **PhD Student**
  - Graduate May 2014
  - Topic: Tribo-surface characterization and electrical engineering
- **BS (2009) and MS (2011) from Texas A&M**

Outline

- Introduction
- Testing Equipment
- Testing Methods
- High Temperature/Pressure Testing
- Cryogenic Temperature Testing
- API Friction and Galling Testing
- Conclusions
- Acknowledgements
- Q&A

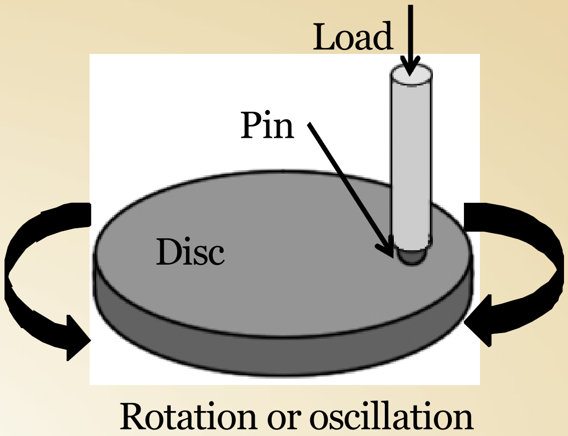
Introduction

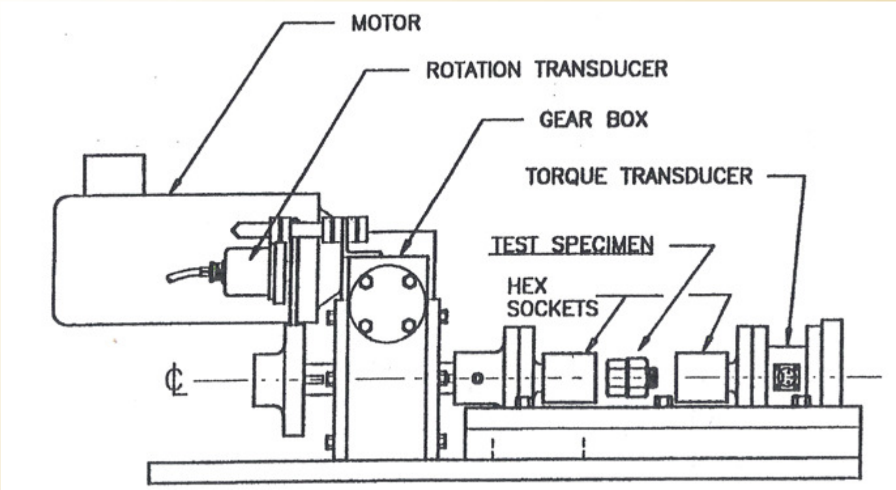
- Traditional tribotesting
  - Room temperature
  - Atmospheric conditions
- Lubricants and coatings are often used under very different conditions
- Testing under extreme environment conditions is necessary



Testing Equipment

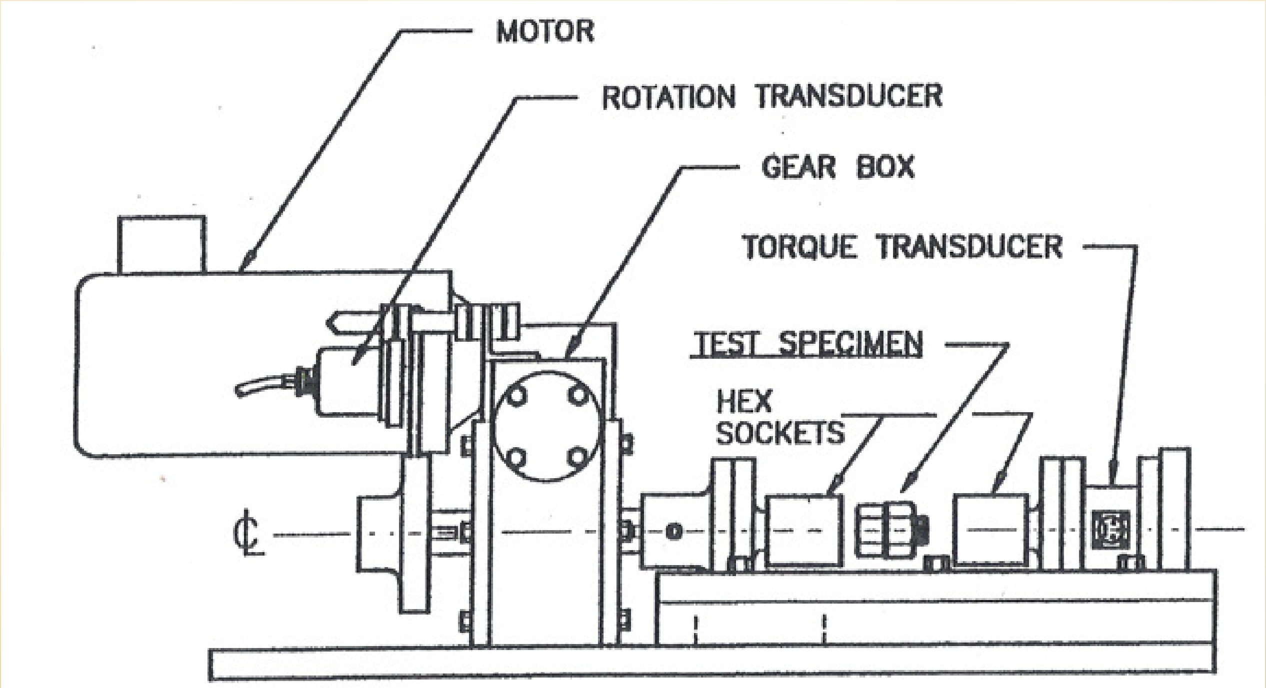
- **Pin on Disc Tribometer**
  - High Temperature (up to 1000°C)
  - Cryogenic Temperatures (>-130°C)
  - High Vacuum pressure (>-100kPa)
  - Controlled humidity (~0% RH)
- **API Galling Tester**
  - High loads (up to 100klbs)
  - High Torques (up to 800ft-lbs)





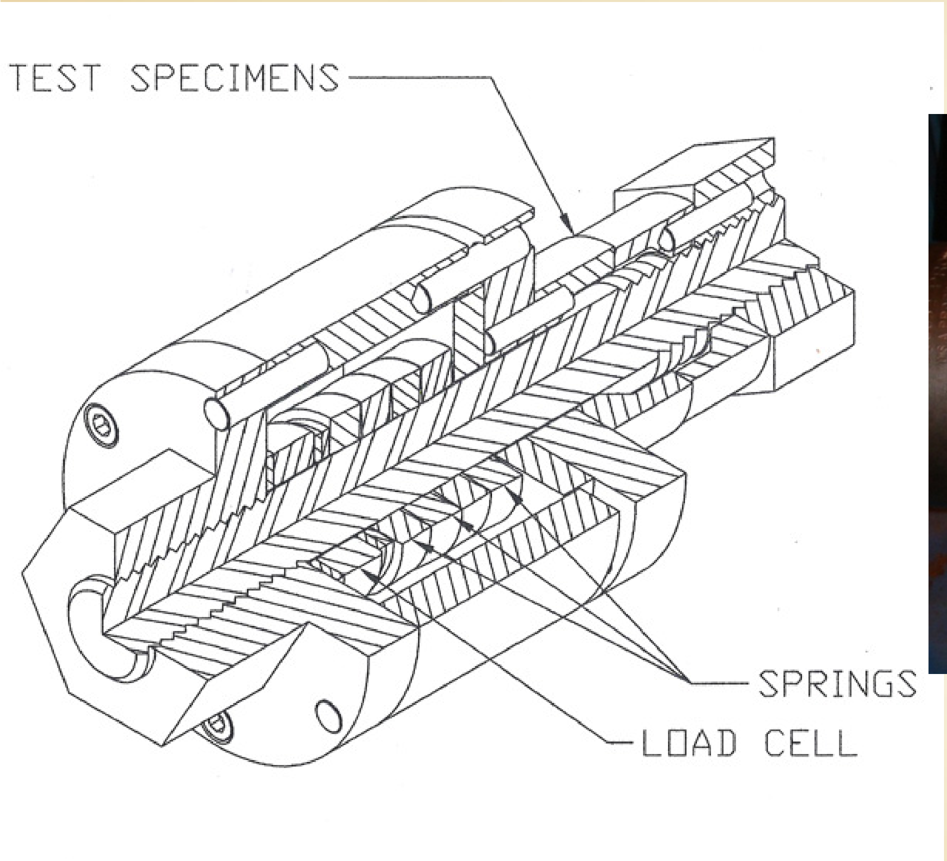
Test Apparatus

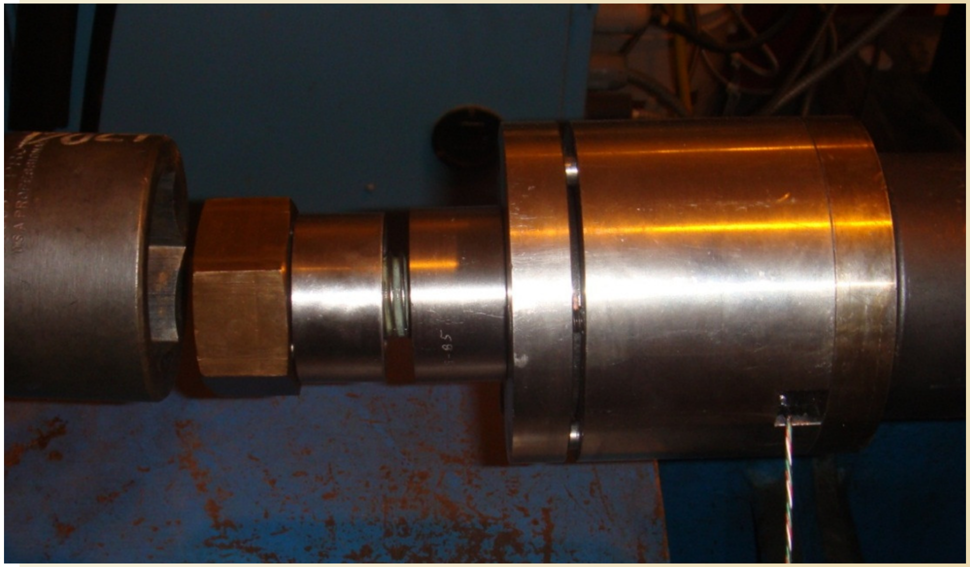
- API RP 7A1 Test
  - Recommended Practice for Testing of Thread Compounds for Rotary Shouldered Connections
  - This method is still being revised and newer methods are being developed.



Test Apparatus

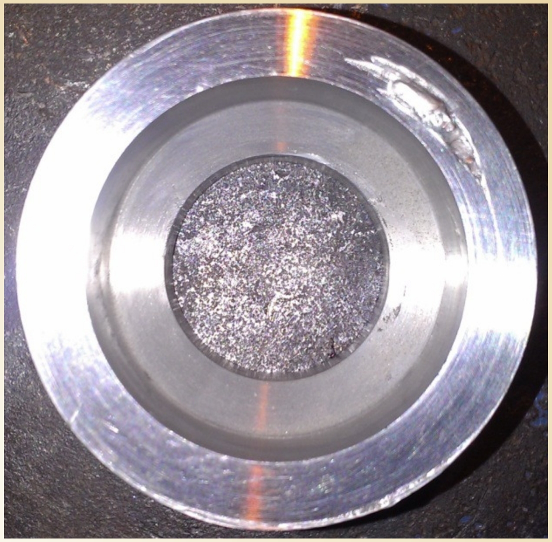
Test Configuration

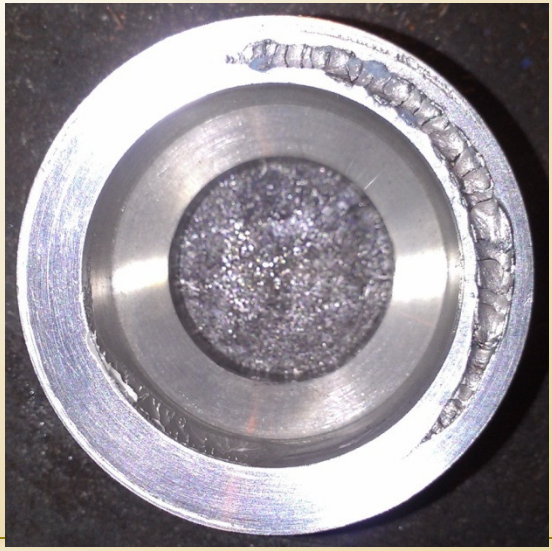




Galling

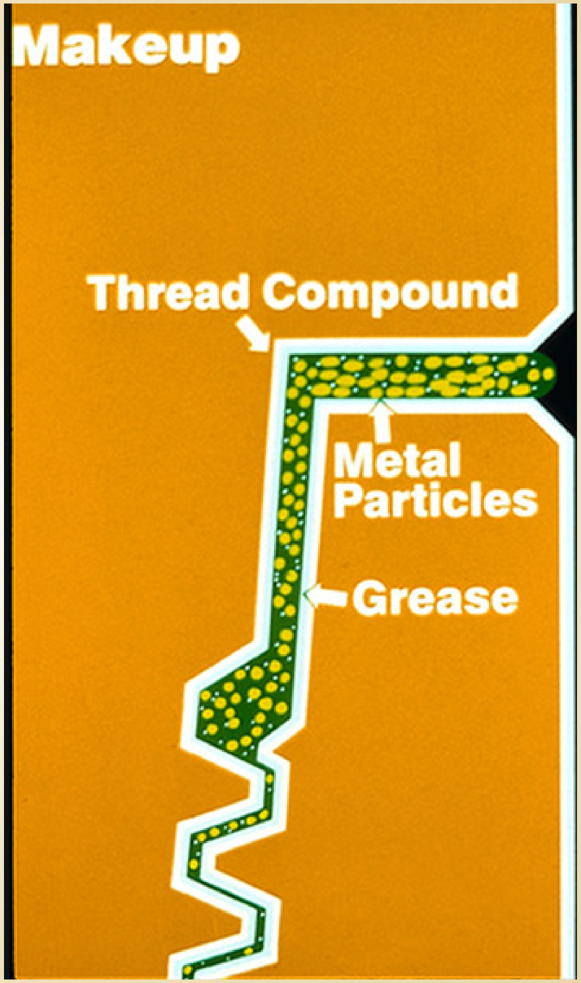
- Severe form of wear
  - localized material transfer, removal, or formation of surface protrusions when two solid surfaces experience relative sliding under load
- There is currently no standard for testing galling under lubricated conditions.
- ASTM G196-Standard Test Method for Galling Resistance of Material Couples
  - "galling will not usually occur under lubricated sliding conditions"
  - API RP 7A1
  - API C1/SC5 test program





Thread Compounds

- Composition
  - Materials that mould into threads, seal, and reduce thread contact
- Spherical-shaped additives
  - Additives are flattened and elongated during torque, bonding together and reducing metal to metal contact
- Particles compact during makeup, separate during breakout

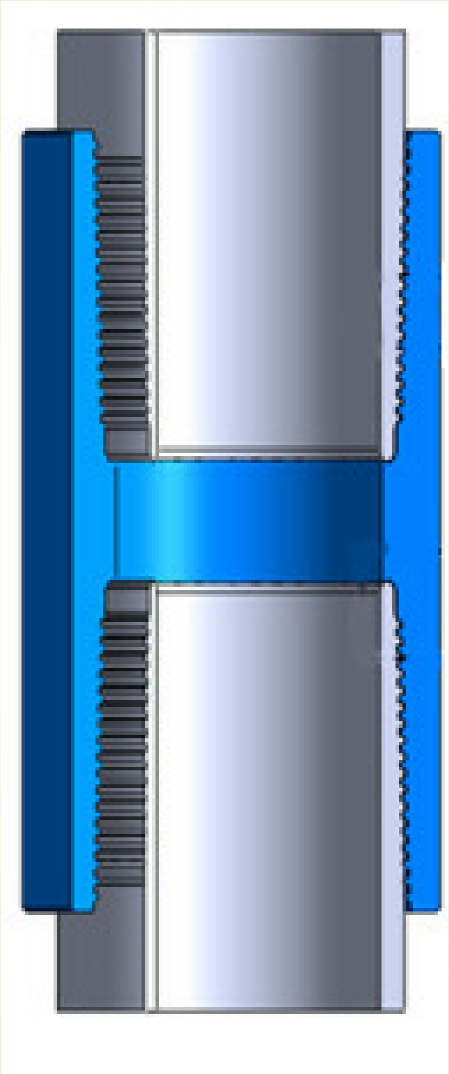


Types of Thread Compounds

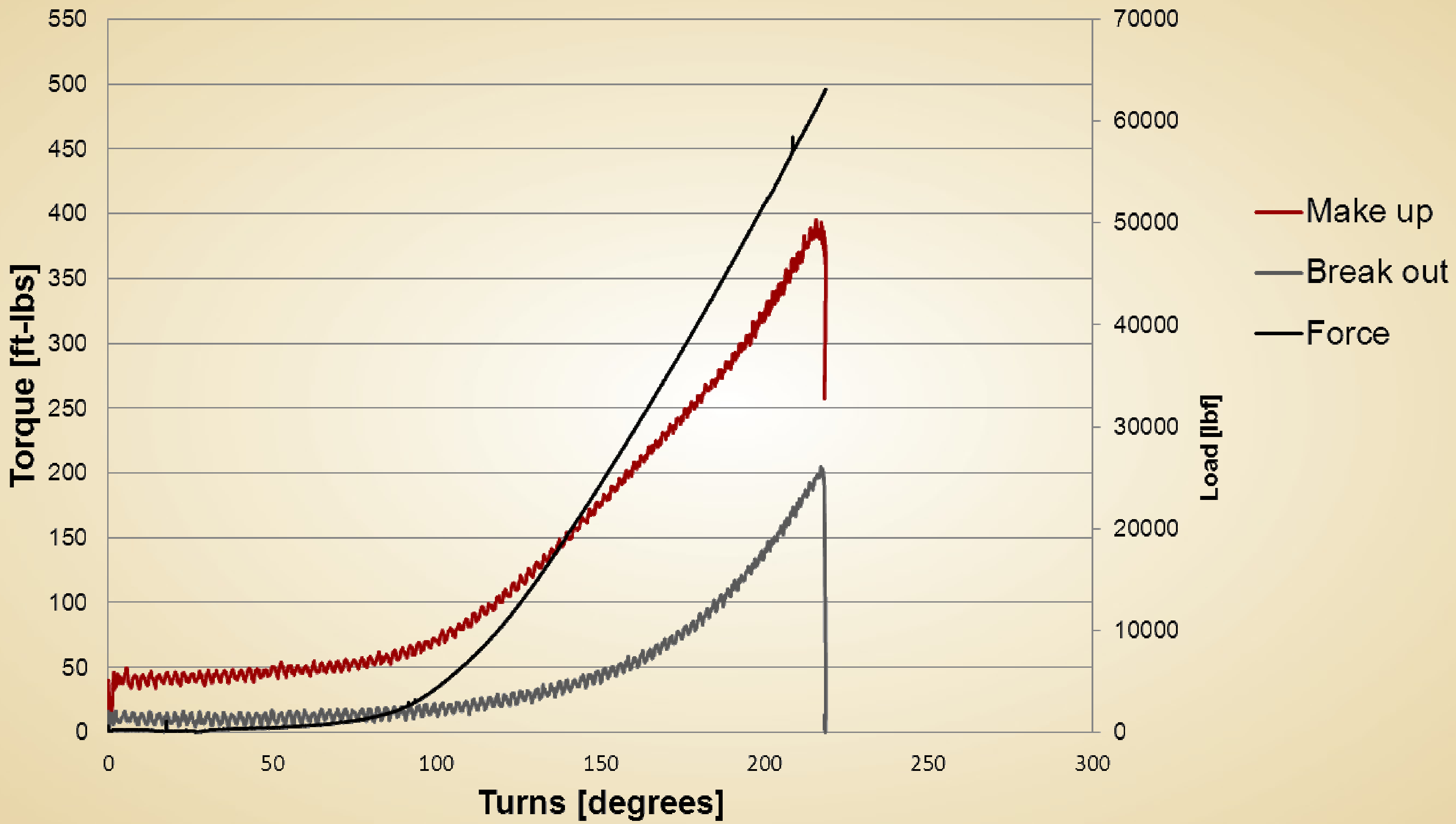
- Metallic
  - Use metallic particles to seal and protect the threads against galling
  - Lead, Zinc, and Copper based
- Non-Metallic
  - Use solids such as graphite, and talc to seal and prevent galling
  - More environment and worker safe
  - Non-hazardous

API Galling & Friction Testing

- Thread compounds are used when pipelines are formed
- Compounds must:
  - protect, seal, and lubricate
- Traditional compounds contained lead as the primary additive
- Legislation was passed to prevent further use of lead based compounds
- A method of comparing new compounds to the standard must be established



Results: Torque vs. Turns



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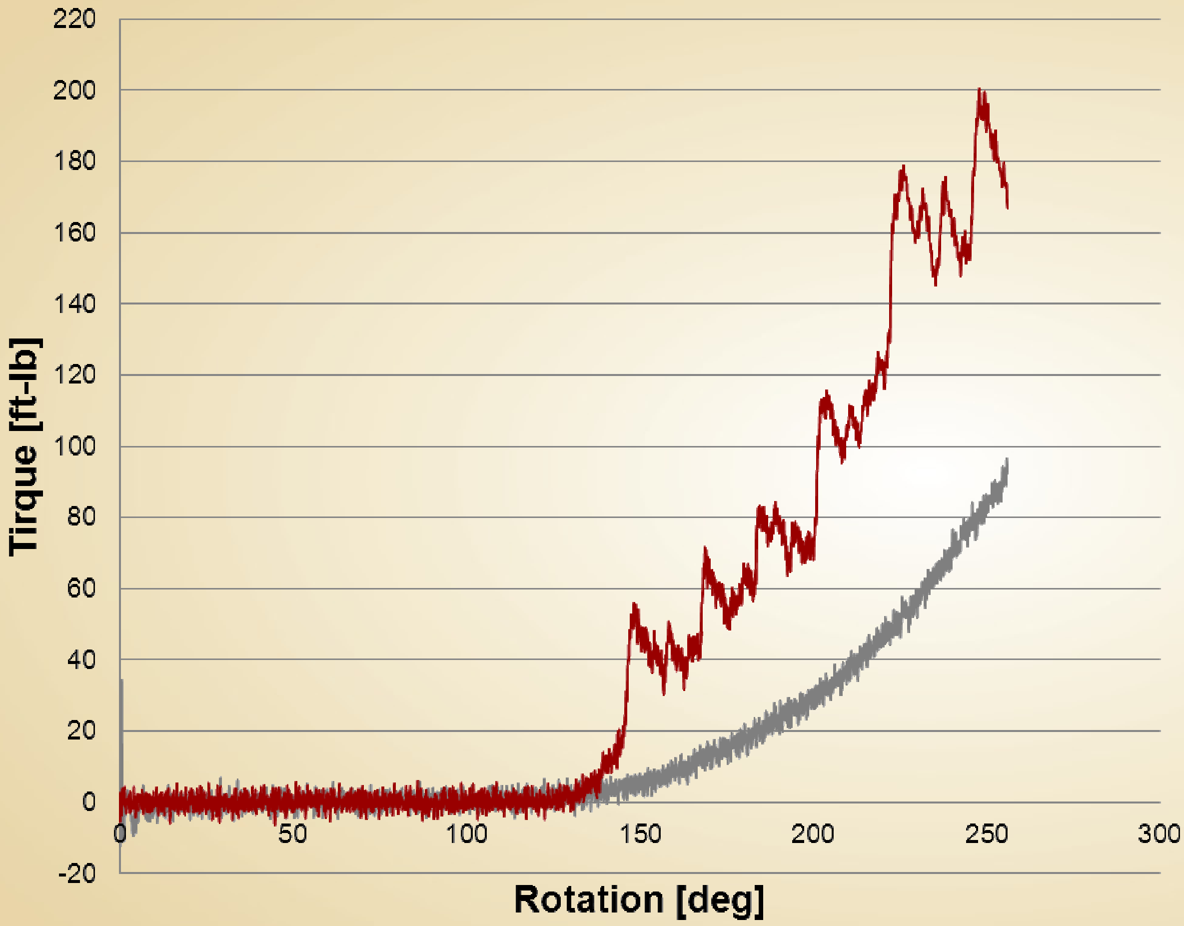

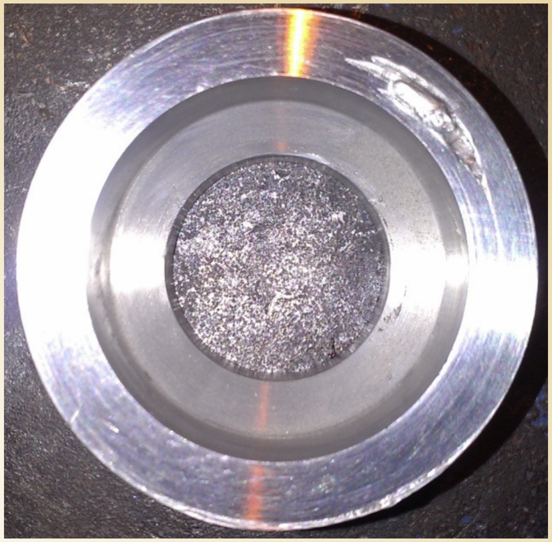

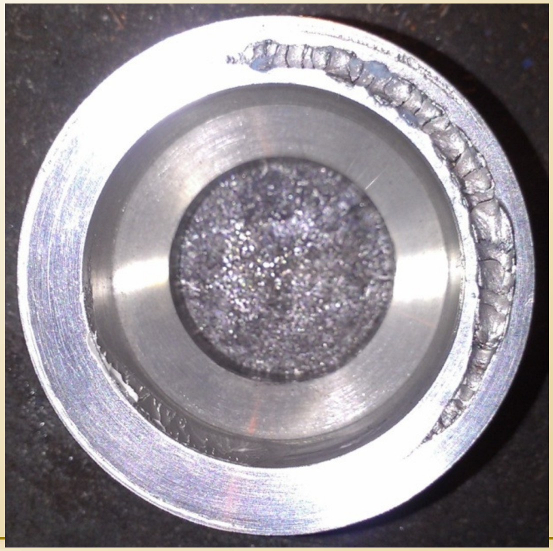

Friction Analysis

- Friction Factor
  - the ratio of the performance of a compound relative to a specific reference
- CaFl Reference Compound
  - a laboratory test compound formulated to produce consistent results from batch to batch that is used as a calibration standard.

Thread Compound	Friction Factor
TiO2 based	0.98
Minearal based, no VOCs	0.84
Non-metallic, no VOCs	0.84
Biodegradable ester	0.78

Testing Equipment

- Pin on Disc Tribometer
  - High Temperature (up to 1000°C)
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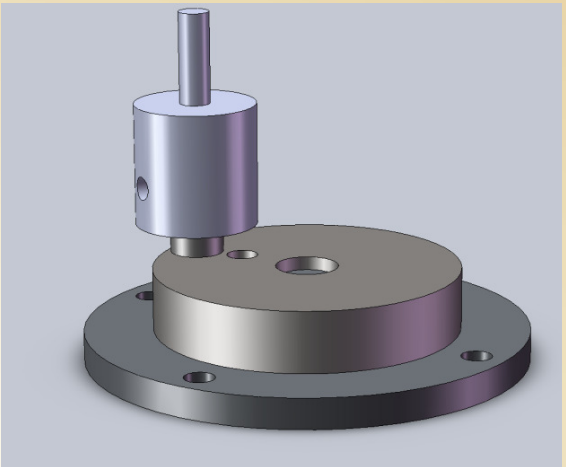
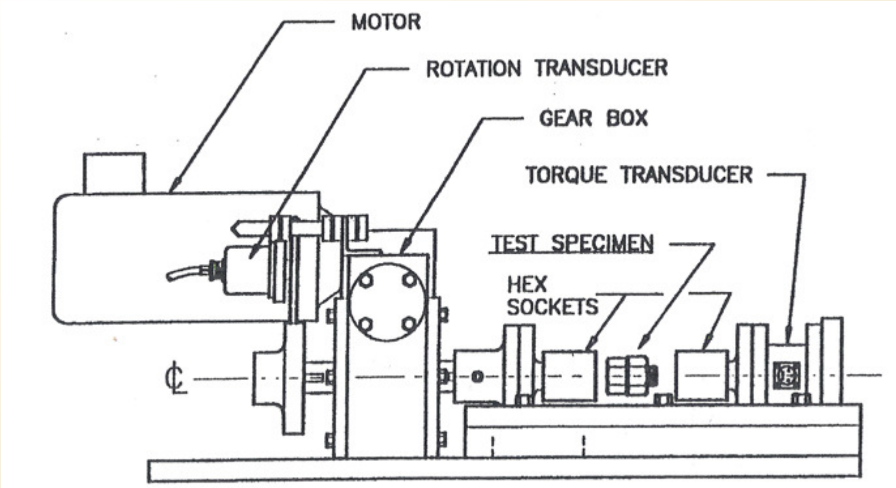




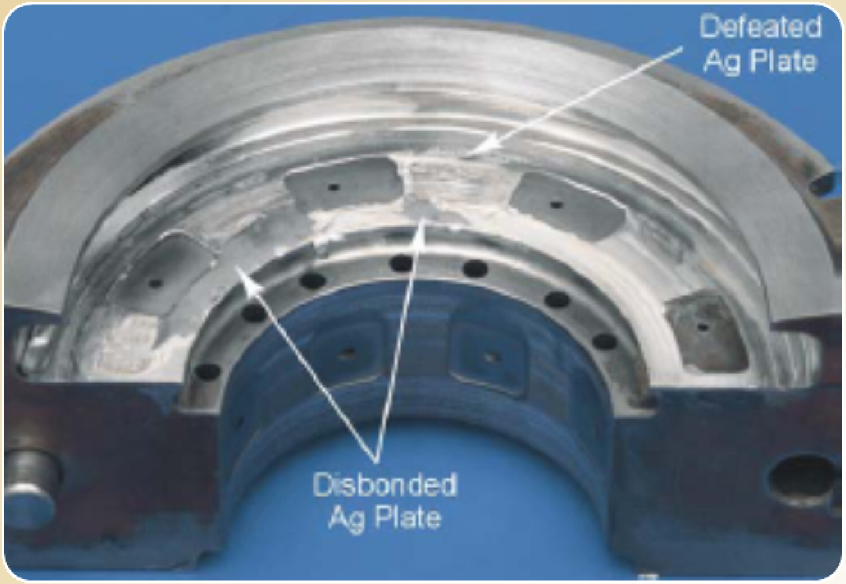
Example I - Cryogenic Temperature Tribotesting

- Determine the influence of cryogenic temperatures (less than -130° C) on the friction and wear characteristics of three proposed bearing coatings on Ti6Al4V substrates.
- Improve wear resistance of bearings under cryogenic conditions.
- Help select best coating for cryogenic applications.

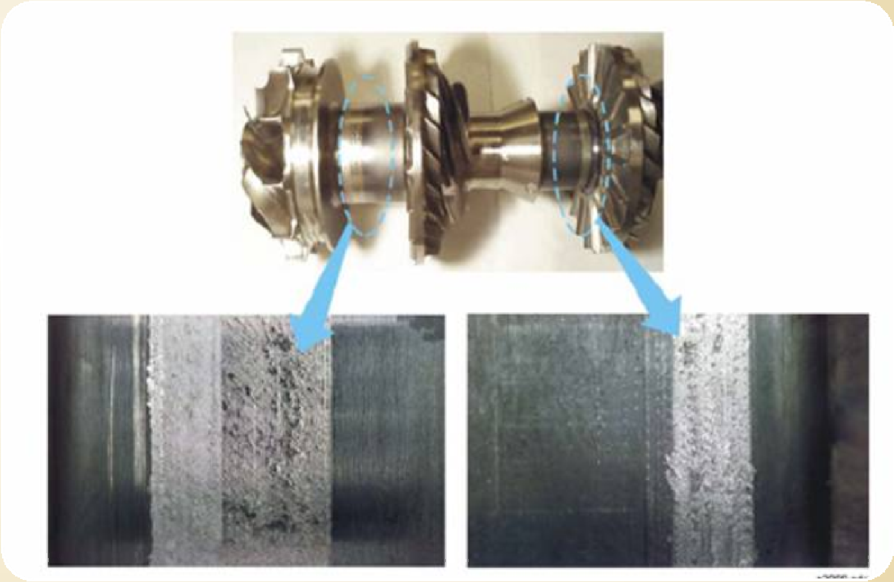
Liquid Hydrogen/Liquid Oxygen Rocket Engines

http://www.allstar.fiu.edu/aero/rocket2.htm

Motivation
Turbopump Wear Examples



Adhesive wear of bearing silver contact surface.



Experimental Setup

- **Pin**
  - Forged Sterling Silver
  - 1.47” radius tip
  - 0.434” dia
- **Disks**
  - Substrate
    - Ti6Al4V
  - Three Coatings
    1. TiSiCN-PEMS
    2. TiN
    3. WC

- Emphasize coating performance, not pin performance
  - Use nitrogen gas environment for room temp tests
  - Lower loads
  - Reduced sliding distance

Unexpected Laminar Pin Debris

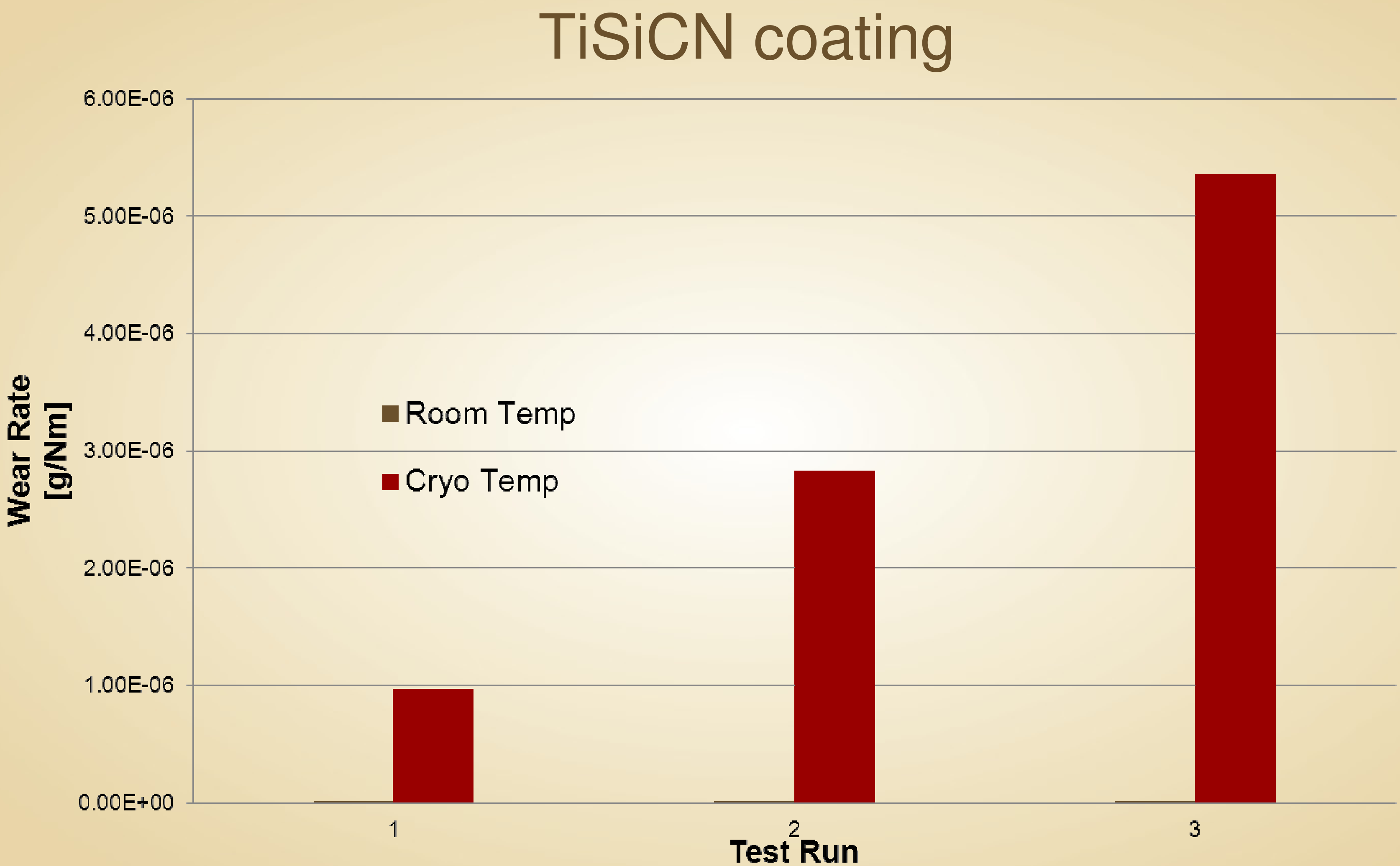
in Cryo Tests

Experimental Setup

- **Variables**
  - Temperatures (27℃, <-130℃)
  - Coating
    - TiSiCN-PEMS
- **Constants**
  - Linear Speed
    - 175 ft/min
  - Sliding Distance
    - 1750 ft
  - Normal Load
    - 1 lb

AMTI Pin-on-Disk Tribometer

Results: Wear Rate

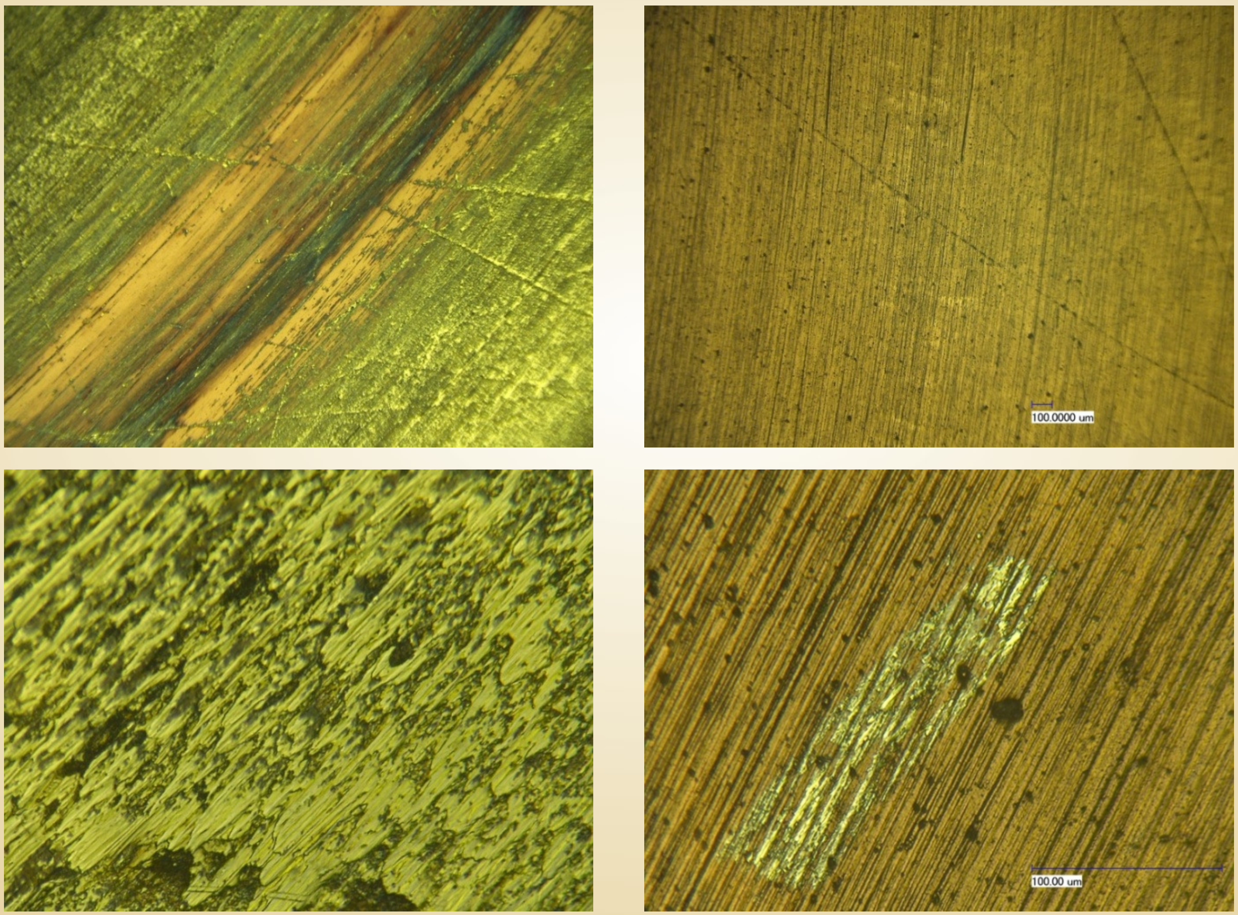


TiSiCN coating

Results: Surface Analysis

TiSiCN coating

Cryo Temp | Room Temp



100x

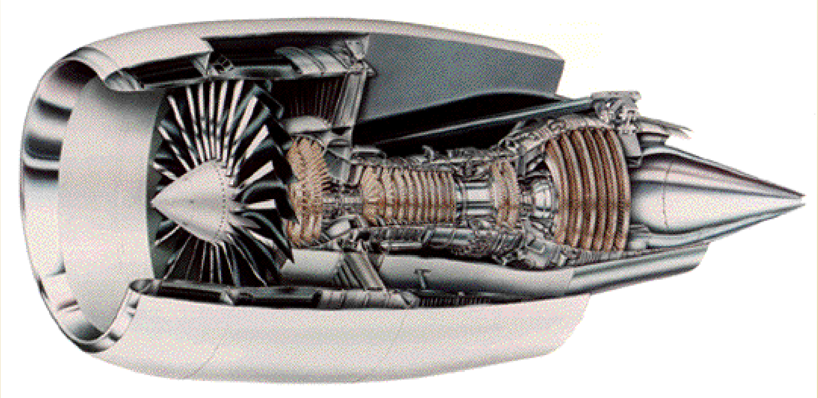
1000x

Summary

- The test setup can evaluate tribological performance at cryogenic temperatures
- The effect of temperature on the coatings is signigicant
- TiSiCN appears to have a higher wear rate at lower temperatures

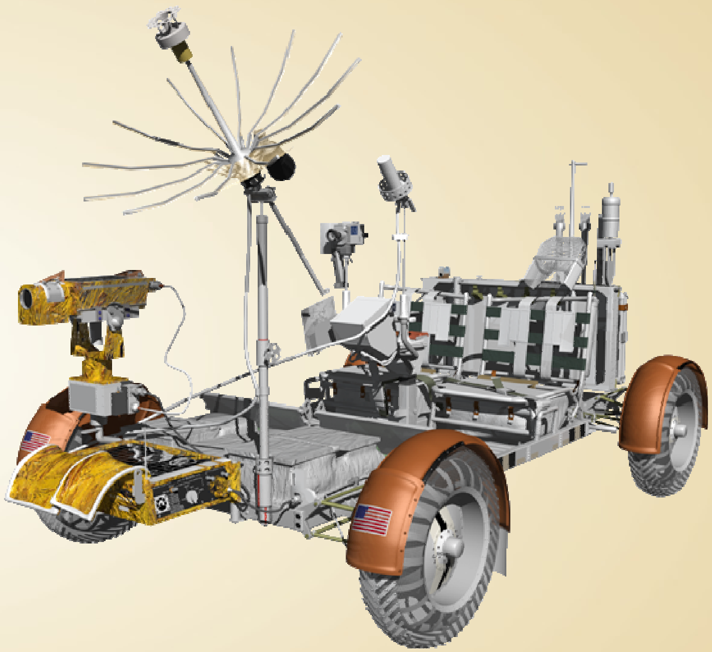
High Temperature/Pressure Tribotesting

- Evaluate the performance of coatings under the influence of temperature and environment
- New solid lubricants are needed for high-temperature and high vacuum applications.
- Applications in industries such as aviation where turbomachinery equipment operate in extreme environmental conditions



Solid Lubricants

- NASA
  - Solid lubricants are essential in space applications
  - Graphite performs poorly in brushed motors at high vacuum, low humidity environments
  - Graphite lubricants in high vacuum cause failure
- When used in high vacuum the high increase in friction always causes failure.

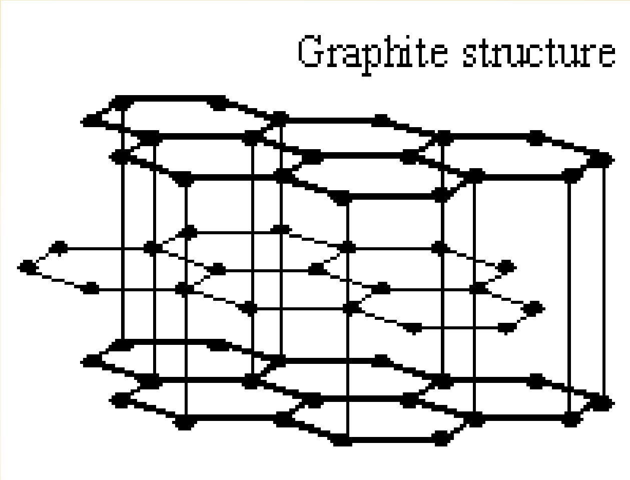


Miyoshi, Kazuhisha. *Solid Lubricants and Coatings for Extreme Environments: State of the art Survey.* Glenn Research Center,. Ohio, NASA 2007

Steele, McCubbin, Fries, Glamoclija, Kater, and H. Nekvasil. Graphite in an Apollo 17 Impact Melt Breccia. Science Vol. 329 5987. 2010.

Carbon Based Solid Lubricants

- Lubricating properties are highly dependent on ambient water vapor
  - Absorbed water molecules on the graphite surface cause further weakening of the bonding between planes
- In a moist environment, CoF can be as low as 0.07
- Typical applications:
  - Sliding electrical contacts (high electrical conductivity)
  - Motor brushes

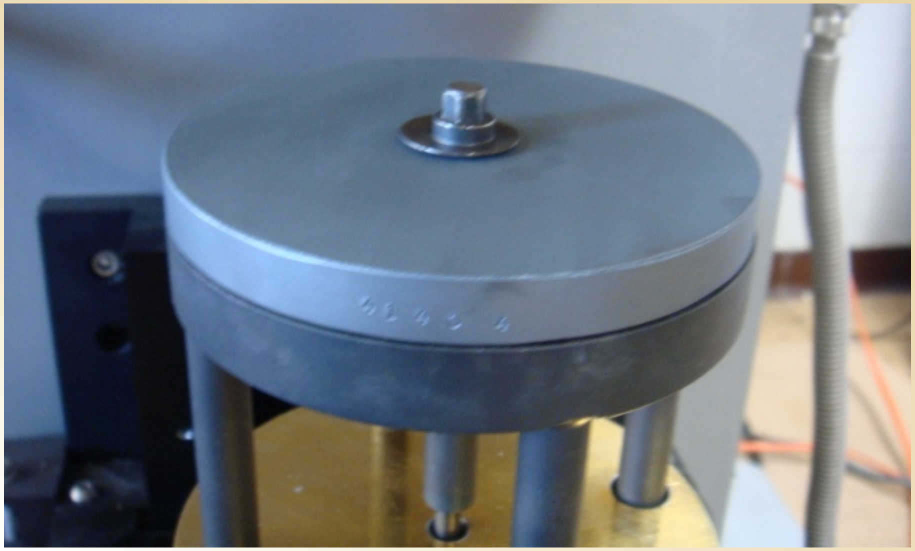


Experimental Setup

- Pin on disc tribometer
- Variables
  - Temperature
  - Vacuum Pressure
    - Relative humidity
- Samples tested under constant load of12lb
  - Oscillatory
  - 3cm path length
  - 2.5 osc/sec

Test Materials

- Disc Samples
  - Perma-Slik® RGE
    - Lube Solid: MoS_2
    - $\rho = 923 \pm 60$ g/L
    - Epoxy binder
    - 0.3mm
  - Perma-Slik® RGAC
    - Lube Solid: C
    - $\rho = 839 \pm 60$ g/L
    - Organo-metallic binder
    - 0.3mm



Test Materials

- Ball Bearings (6mm)
  - 440C Stainless Steel (SS)
  - Tungsten Carbide (WC)

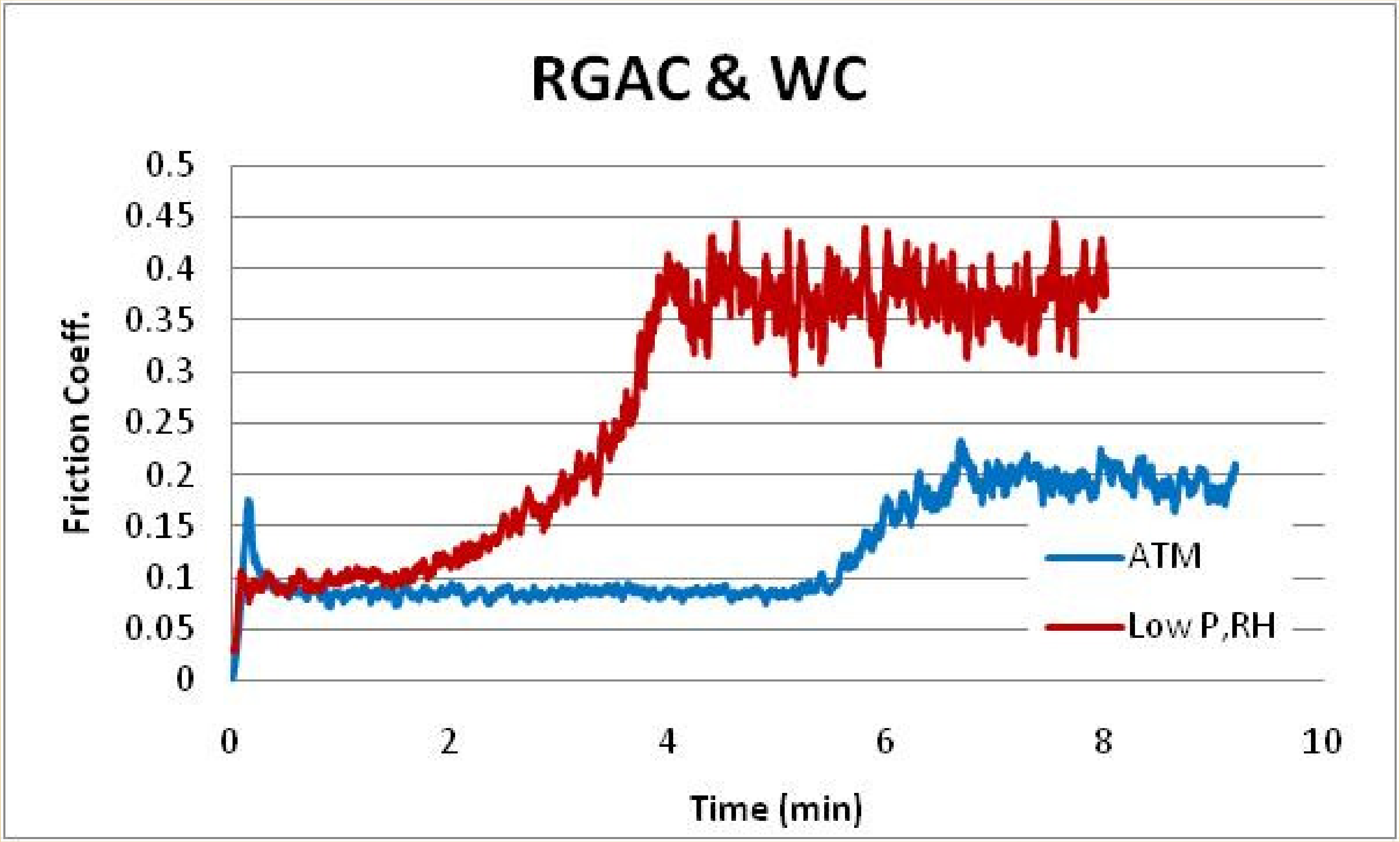
Material	Density [g/cc]	Hardness	Modulus of Elasticity [Gpa]	Tensile Strength [Mpa]
WC	15.7	HRA 90	669	344
440C SS	7.8	HRB 97	215	1365

Testing Matrix

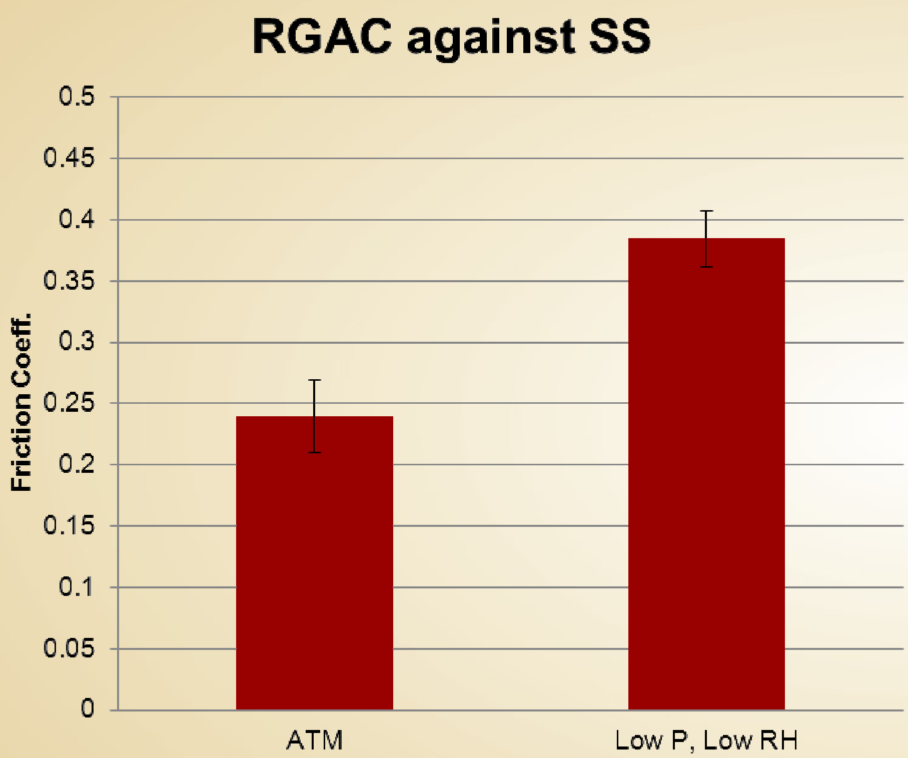
Disc Coating Material	Ball Material	Load [lbf]	Speed [osc/s]	Track Length [cm]	Relative Humidity [%]	Temperature [C]	Pressure [psig]
RGAC	440C	12	2.5	3	40	32	0
RGAC	440C	12	2.5	3	0	200	-12
RGAC	WC	12	2.5	3	40	32	0
RGAC	WC	12	2.5	3	0	200	-12
RGE	440C	12	2.5	3	40	32	0
RGE	440C	12	2.5	3	0	200	-12
RGE	WC	12	2.5	3	40	32	0
RGE	WC	12	2.5	3	0	200	-12

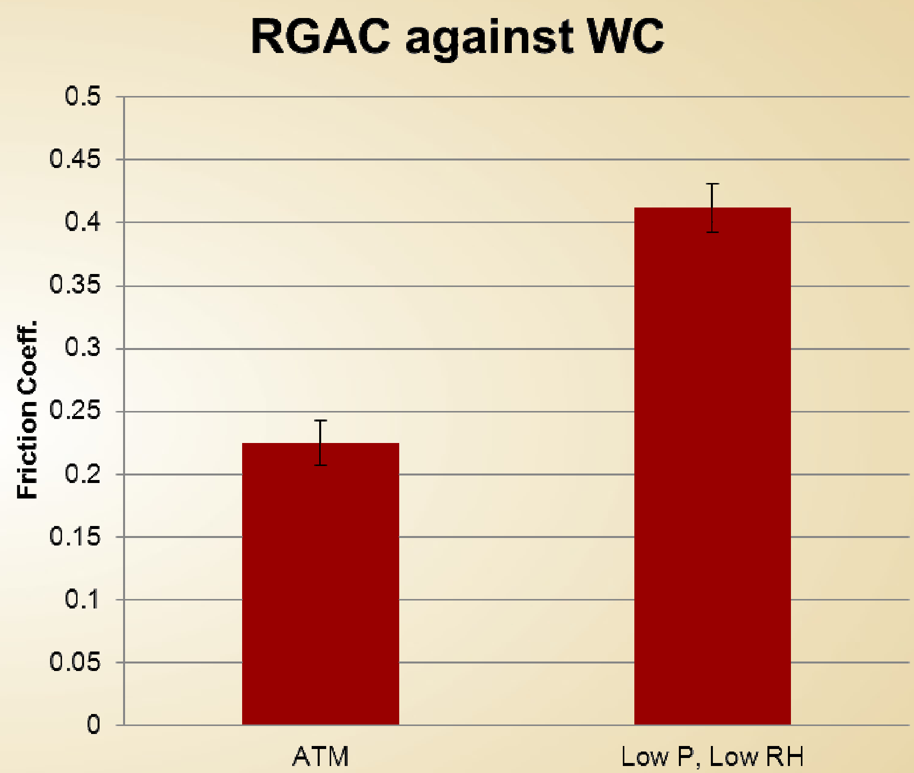
Results: CoF Plots

Graphite based coating



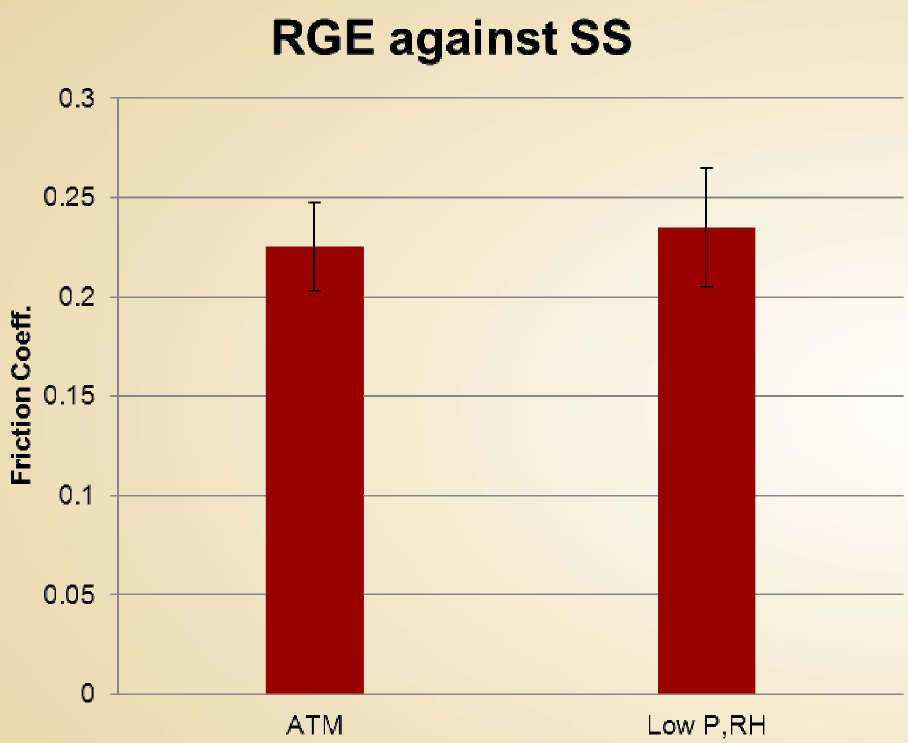
Results: CoF Comparison

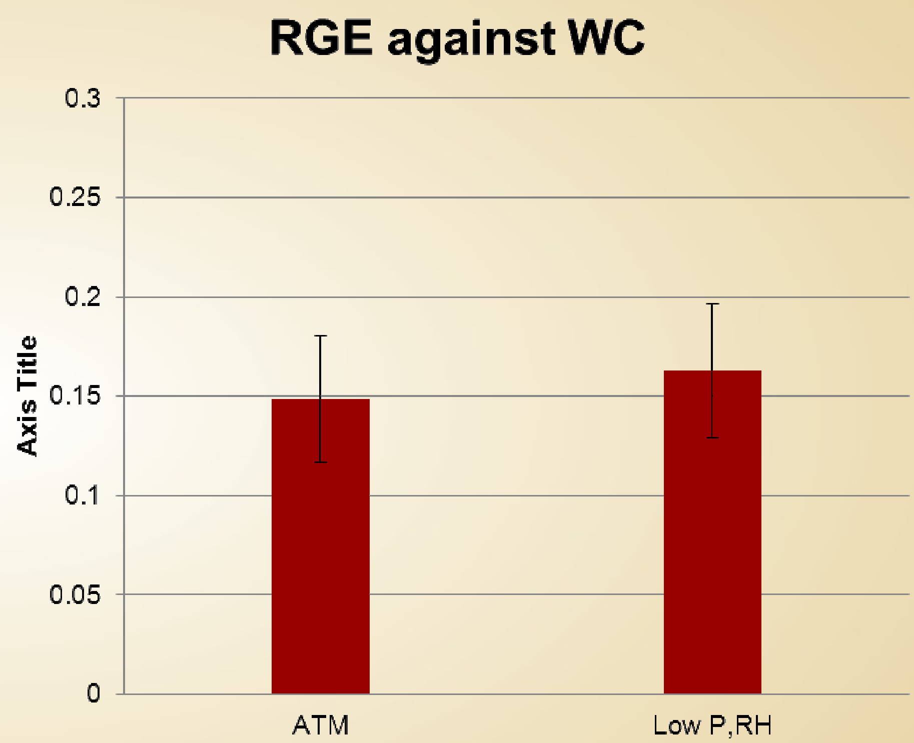




Graphite based coating

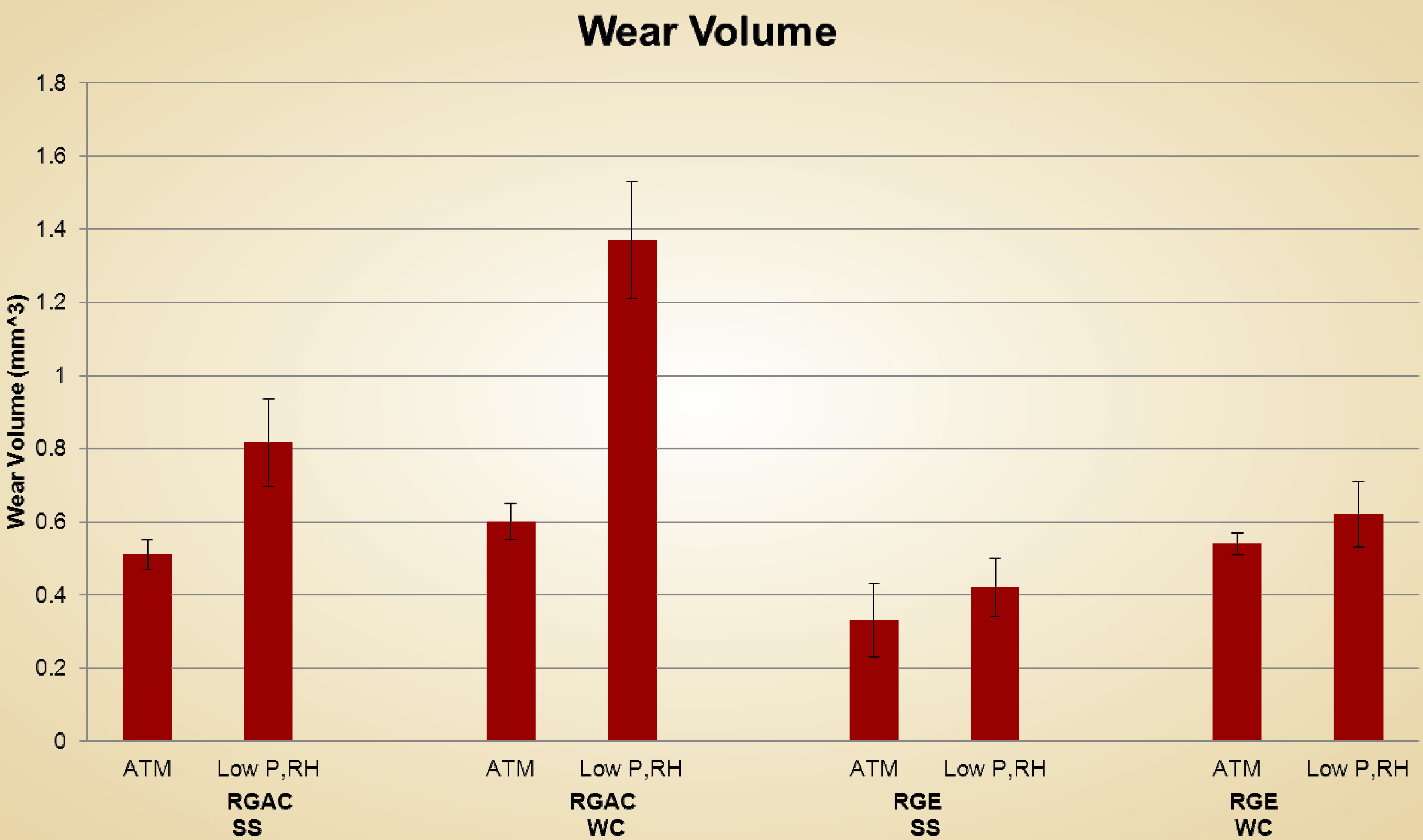
Results: CoF Comparison



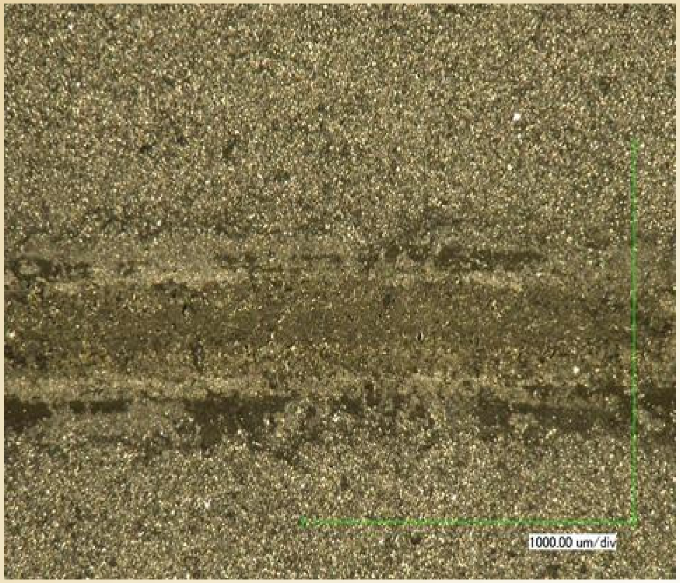


MoS2 based coating

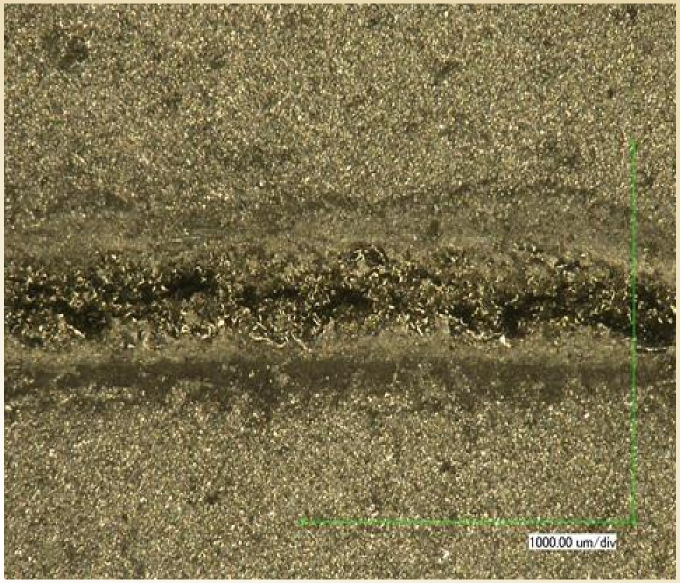
Results: Wear Volume



Wear Track: RGAC against WC



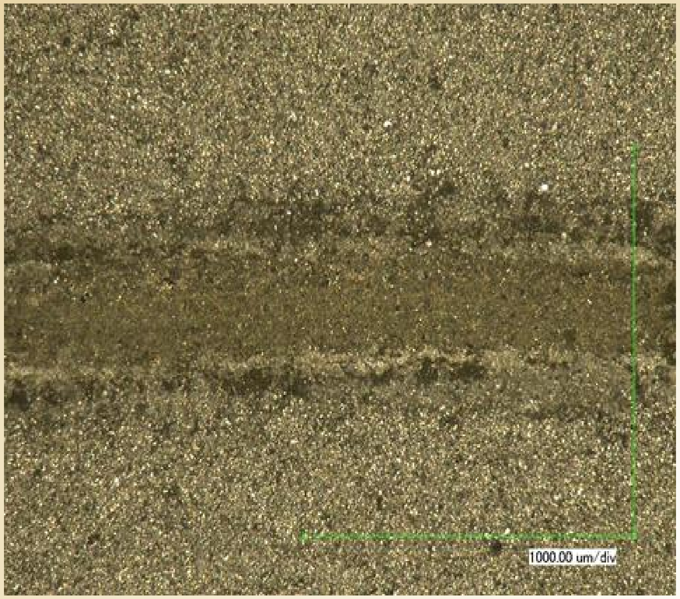
Atmospheric Conditions



Low P,RH & High T

- Abrasion is shown do be the dominant wear mechanism
- Under atmospheric conditions, wear debris remains to serve as a lubricant

Wear Track: RGAC against SS



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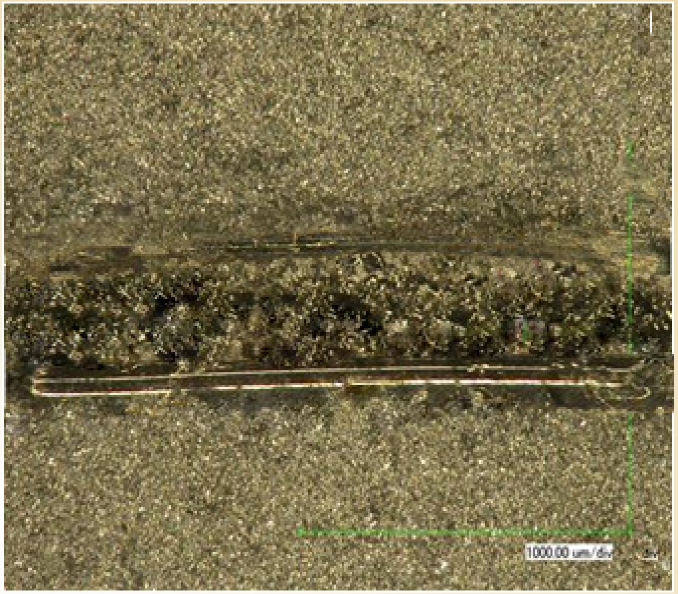

Low P,RH & High T

- Under atmospheric conditions, wear debris remains to serve as a lubricant
- Abrasive wear can be seen at severe conditions

Summary

- Test setup is effective for evaluating the effects of high temperatures and low pressures
- Graphite based lubricant provides higher friction in extreme conditions
  - Not stable at high T, low P
- The durability of the coating is affected by low pressure due to absence of moisture
- Abrasive wear is the dominant wear mechanism
- Molybdenum disulfide coating performed similar at atmospheric and severe conditions

Conclusions

- Extreme environment testing is necessary for the proper evaluation of coatings and lubricants
- New testing conditions and setups have been developed to better evaluate test samples
- Our research has shown significant differences in performance for various coatings and lubricants at such conditions
- New testing parameters continue to be developed in our research lab

Acknowledgements

- Jet-Lube
- Stress Engineering
- GE Aviation
- Houston Chapter STLE

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Q&A