References and Resources

www.frc.ri.cmu.edu/sunsync

AIAA paper

Princeton paper

iSAIRAS paper 1

iSAIRAS paper 2

Planning paper

Summary paper ICRA

Summary paper IROS

Today's presentation

The Little Prince by Antoine de Saint Exupery

Candidate Coatings and Dry Traction Drives for Planetary Vehicles

Robert Fusaro and Fred Oswald of the Mechanical Components Branch discussed "Candidate Coatings and Dry Traction Drives for Planetary Vehicles". Vehicles to be designed for exploration of planets and moons of the solar system will require reliable mechanical drives to operate efficiently. Long-term operation of these drives will be challenging because of extreme operating conditions. These extreme conditions include: very high and/or very cold temperatures, wide temperature ranges, dust, vacuum or low-pressure atmospheres, and corrosive environments.

Most drives used on Earth involve oil-lubricated gears. However, due to the extreme conditions on planetary surfaces, it may not be advisable or even possible to use oil lubrication. Unfortunately, solid lubricants do not work well when applied to gears because of the high contact stress conditions and large sliding motion between the teeth, which cause wear and limit life. We believe traction drives will provide an attractive alternative to gear drives. Traction drives are composed of rollers that provide geometry more conducive to solid lubrication. Minimal slip occurs in this contact geometry and thus there is very low wear to the solid lubricant.

The challenge for these solid-lubricated drives is finding materials or coatings that provide the required long-life while also providing high traction. We seek materials that provide low wear with high friction.

Potential Solid Lubricants for Traction Drives

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What is a Solid Lubricant

General Definition

A solid material which,
when interposed between
two relatively moving surfaces
reduces the friction and wear

Why Use a Solid Lubricant?

1. **Used where fluids are not suitable**
   - Where liquids would contaminate
   - At high temperatures (fluids decompose)
   - At Low temperatures (fluids freeze)
   - Chemical reactive environments
     - Liquid oxygen or hydrogen
     - Liquid fluorine
     - Molten alkali metals
2. **Used for mechanical design advantages**
   - Dynamic stability can be improved
     - Solid lubricated air bearings
     - Placing bearings closer to heat sources, allowing the use of shorter shafts
   - Simple, light weight design
     - No cooling required
     - Eliminate pumps, heat exchangers and recirculating oil systems
     - Number of seals can be reduced

Classes of Solid Lubricants

• **Soft Metals** ○ Gold ○ Silver ○ Lead ○ Indium ○ Barium	• **Polymers** ○ PTFE ○ Polyimides ○ UHMWPE ○ Peek ○ Polyacetal ○ Phenolic Resins ○ Epoxy Resins
• **Lamellar Solids** ○ Graphite ○ Molybdenum Disulfide ○ Intercalated Graphite ○ Fluorinated Graphite ○ Cadmium Iodide ○ Lead Iodide ○ Molybdenum Diselenide ○ Pthalocynanine	• **Other Materials** ○ Fluorides of Ca, Li, Ba ○ Rare Earths ○ Sulfides of Bi, Cd ○ Oxides of Pb, Cd, Co, Zn ○ Diamond Coatings ○ Diamond Like coatings

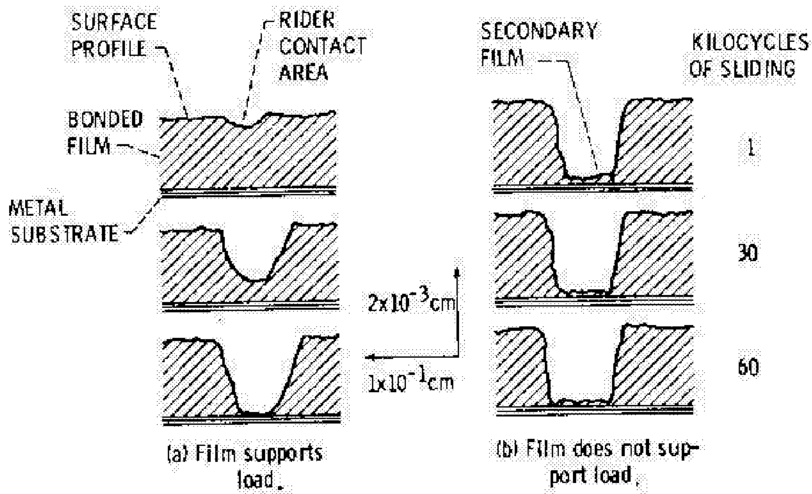
Methods of Employing Solid Lubricants

1. Coatings/Films
   a. Rub or Burnish
   b. Incorporate into a Binder System
      i. Sodium Silicate
      ii. Phenolic Polymer
      ii. Polyimide Polymer
   c. Vacuum Deposition Techniques
   d. Plasma Spraying
   e. Powder detonation
2. Solid Bodies/Composites
   a. Particulate
   b. Fiber Reinforced
3. Oil Dispersions/Greases
4. Powder Lubrication

Factors which Affect Solid Lubricant Performance

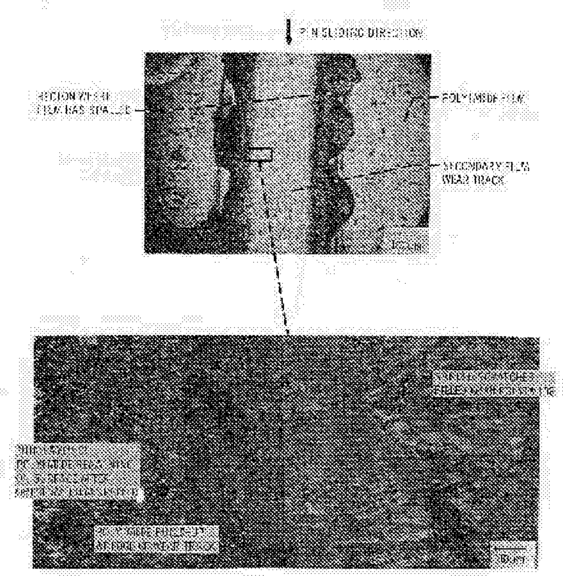
- Type of substrate material to which a film is deposited
- Surface finish of the substrate material
- Type of counterface material
- Surface topography of the counterface
- Hardness of substrate material
- Hardness of counterface material
- Surface or surfaces to which a solid lubricant is applied
- Geometry of sliding specimens
- Contact stress or pressure
- Temperature
- Sliding Speed
- Environment
- Atmosphere
- Fluids, Dirt or Dust

Macroscopic Wear Mechanism of Gradual Wear Through Coating



A coating that has structural strength but still has the ability to flow at the interface can support the load and the wear process is one of gradual wear through the coating (left). Coatings without sufficient structural strength can still lubricate by forming a very thin film at the metallic surface. The life of this lubrication mechanism is strongly dependent on the topography of the metallic surface.

Thin Film Lubricating Mechanism



Photomicrograph showing the thin film lubricating mechanism for a polyimide coating that was unable to support the load. A thin film of material at the metallic surface has formed and the roughness (scratches) in the surface helps hold the material in place to provide a long endurance life. Most soft lamellar solid lubricants lubricate by this mechanism. Proper substrate surface preparation is important for obtaining a long endurance life.

Friction and Wear of Sliding Couples

(Experimental Conditions: 50% RH Air, 25 C, 10 N load)

Disk Lubricant Material	Film or Solid	Pin Material	Friction Coeff.	Disk Wear Rate ($mm^3/Nm \times 10^{-9}$)	Pin Wear Rate ($mm^3/Nm \times 10^{-9}$)
Polyphenylene Sulfide Composite	Solid	440C	0.30	6200	0
Polyimide (PI-4701)	Film	440C	0.13	4000	0
Poly(amide-imide) Composite	Solid	440C	0.37	1800	0
Polyimide/Graphite Powder Composite	Solid	440C	0.37	900	0
UHMWPE	Solid	440C	0.10	380	0
Polyimide/Graphite Fiber Composite	Solid	440C	0.19	120	0
Sputtered MoS_2 Vacuum	Film	440C	0.05	70	0
Sputtered MoS_2 Air	Film	440C	0.07	64	0
Polyimide (100° C)	Film	440C	0.02	8	0
Diamond-like Carbon	Film	440C	0.05	2800	0.02
PS-200	Film	Cobalt Alloy	0.28	2100	3000

This table shows the friction and wear of various sliding couples illustrating that low friction and low wear do not always occur at the same time. For traction drives we want high friction and low wear. One should not assume that just because you have high friction you will also have high wear.

Friction and Wear of Composite Materials

(Testing Conditions: Pin-on-Disk, 200 rpm, 1 kg load, Dry Air, 25oC)

Type of Solid Lubricant Composite	Counter-face	Frict. Coeff.	Composite Wear Rate ($m^3/m \times 10^{-15}$)	Test Duration (kc)	Comments
GFRPI	Al_2O_3	0.42	1	1143	
GFRPI	Si_3N_4	0.41	3	2393	
Vespel Polyimide SP-21	440C	0.43	3	2244	
GFRPI	440C	0.12	24	1540	
Vespel Polyimide SP-1	440C	0.35	31	2195	
Vespel Polyimide SP-3	440C	0.40	61	1183	
Torlon	440C	0.35	157	1034	
Vespel Polyimde SP-3	Si_3N_4	0.38	---	157	Ball Crazed
Vespel Polyimide SP-1	Si_3n_4	0.35	---	25	Ball Crazed

This table shows the friction and wear of some commercially available composite materials sliding against various counterface materials in dry air. The table illustrates how the counterface can markedly affect the tribological properties of a composite. Thus it may be possible to develop better traction drive rollers by considering materials that have higher friction when sliding against low wear composites or coatings.

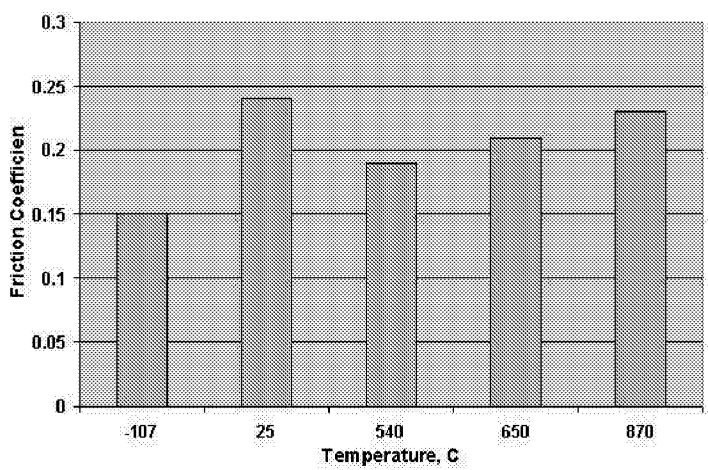
Friction and Wear in Air and Vacuum

(Pin-on-Disk, 440C Pins, 100 rpm, 1 kg load)

Disk Material	Friction Coefficient			Disk Wear Rate ($m^3/m \times 10^{-15}$)		
	Room Air (50% RH)	Dry Air (100 PPM)	Vacuum	Room Air (50% RH)	Dry Air (100 ppm)	Vacuum
PMDA Polyimide	0.50		0.47	120		100
Torlon	0.45	0.35	0.09	20	157	20
GFRPI	0.28	0.12	0.30	0.1	24	18
Polyphenelene Sulfide/Graphite Fibers	0.35		0.04	18		8
Vespel SP-1	0.50	0.35	0.05	300	31	40
PI-4701 Polyimide Film	0.18		0.05	20		80

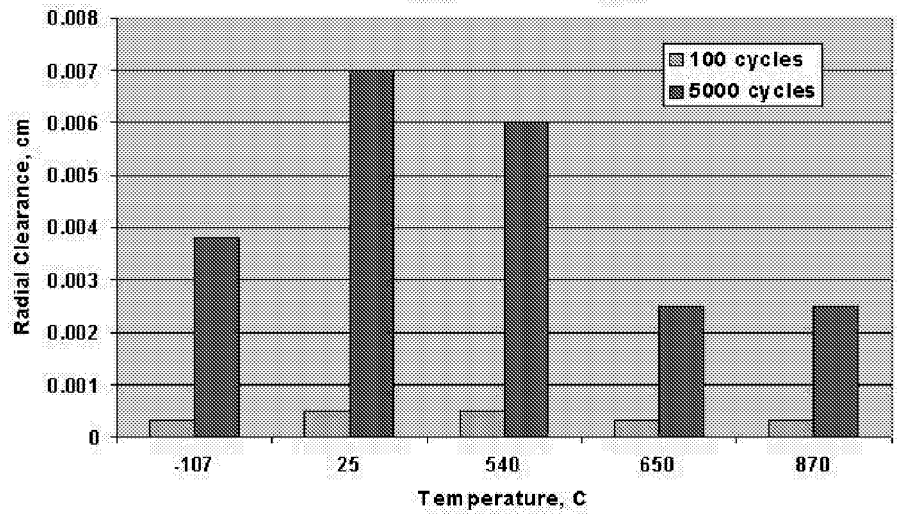
This table compares the friction and wear properties in air and vacuum to illustrate how oxygen and water vapor can affect tribological properties. The results show that the PMDA polyimide or the Graphite Fiber Reinforce Polyimide (GFRPI) have potential for traction drive rollers in a planetary environment.

Friction Coefficient Versus Temperature for PS 101 Coatings in Oscillating Bearing Tests



Plasma Sprayed (PS) coatings were developed for high temperature lubrication applications. This figure illustrates that in oscillating journal bearing tests the friction remains relatively high over a range of temperatures from -107° to +870° C. This high friction characteristic makes these materials candidates for traction drives for space applications on cold planetary surfaces.

Radial Clearance Loss Versus Temperature for PS 101 Coatings in Oscillating Bearing Tests



The loss in radial clearance (wear) for the oscillating journal bearing tests indicates that wear is relatively low at -107°C when compared to room temperature (25°C) indicating that for cold planetary surfaces this could be a good traction drive material.

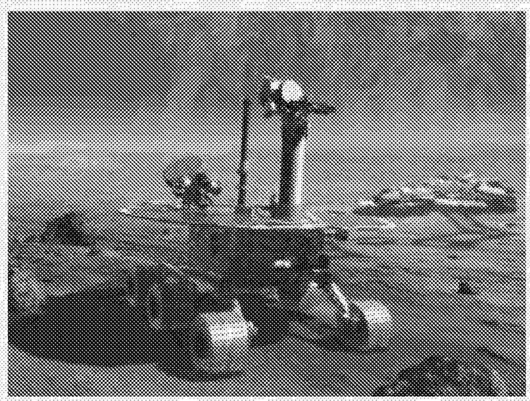
Final Remarks

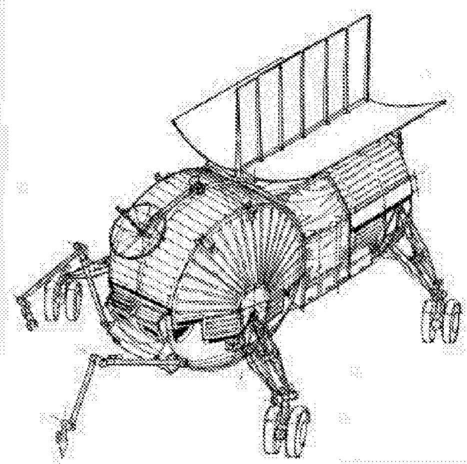
Solid Lubricated Traction Drives

- Desire Solid Bodies or Coatings that have low wear and have the ability to support the loads.
- Desire Solid Lubricants that have relatively high friction coefficients.
- Plasma Sprayed (PS-101) Coatings have been tested at low temperatures and seem to have desirable characteristics.
- Certain types of polyimides used as coatings and fiber reinforced polyimide composites are also possible candidates for this application.

Investigating Dry Traction for Planetary Vehicle Drives

Fred Oswald
NASA Glenn Research Center





Left, Mars Athena '03 rover. Right, Boeing concept for a pressurized Lunar rover.

Investigating Dry Traction for Planetary Vehicle Drives

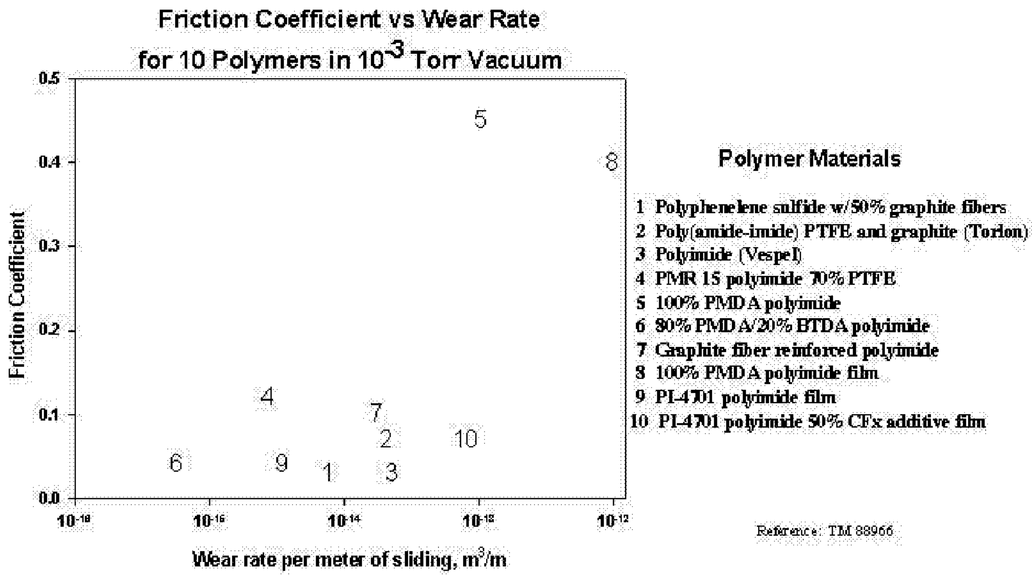
Objective

- Develop solid lubricated traction drive for rover vehicles exploring planetary surfaces
- Provide efficiency & long life in hostile environments

Benefits

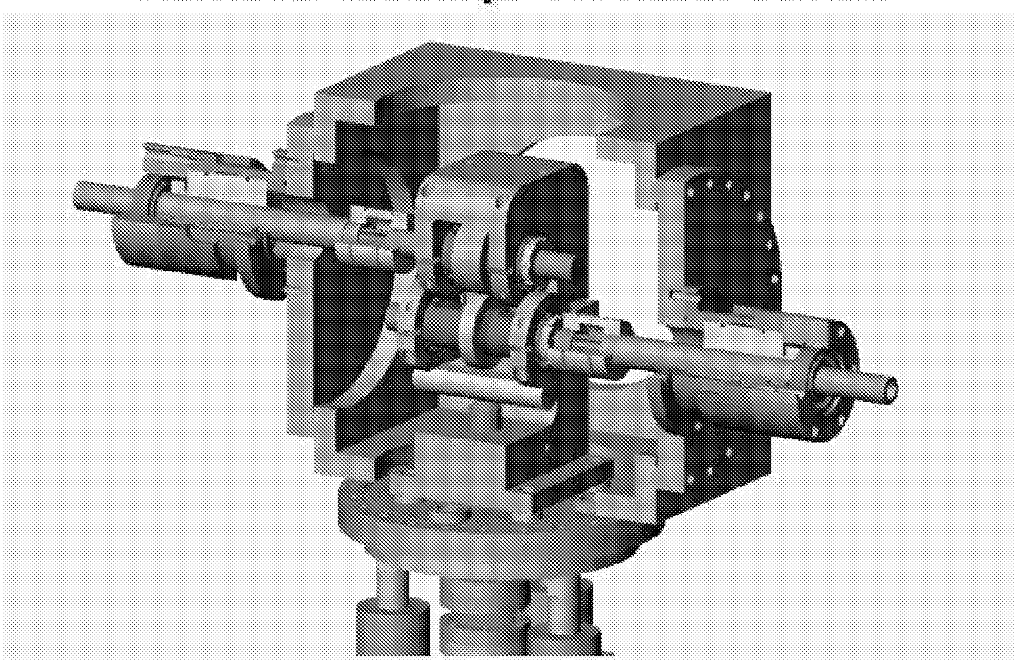
- Higher mechanical efficiency than existing drives
- Provide longer life with high reliability
- Allow operation below ~ -60° C
- Provide robustness to harsh environment
- Minimize weight to save launch cost

Wear Resistant Solid Lubricants



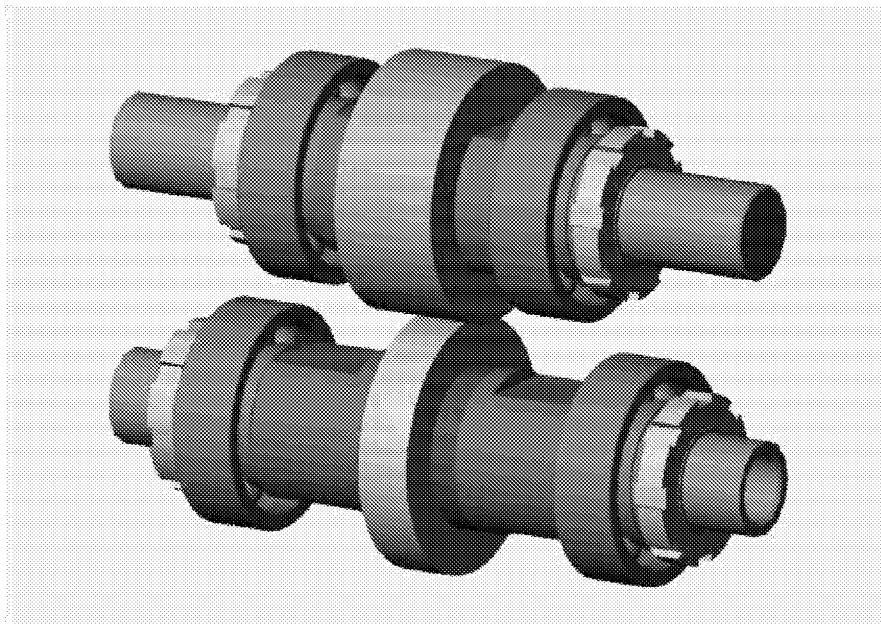
**For a traction drive, we need high friction (traction) with low wear.
The 100% PMDA polyimide solid (#5) and film (#8) materials show promise.**

Proof of Concept Traction Tester



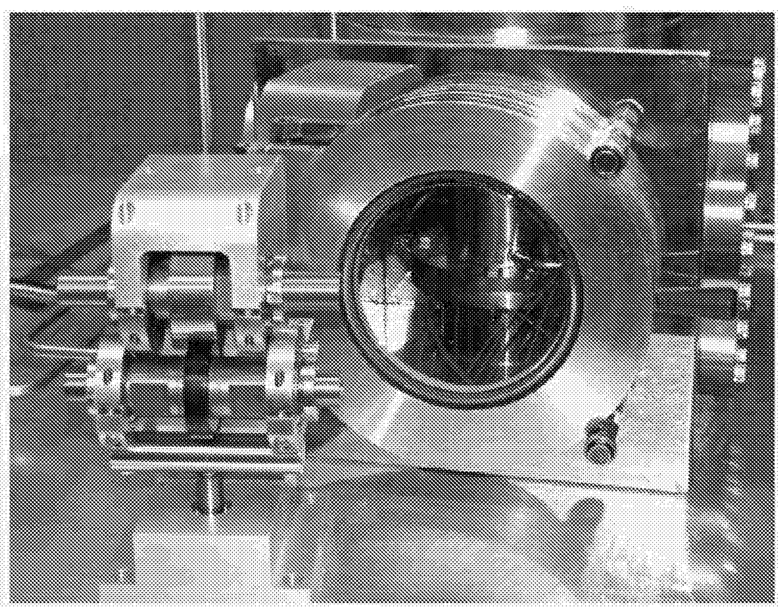
This simple device can test traction roller materials in vacuum. It includes provision to cool the rollers through hollow shafts. With minor modification, it can also test gears.

Detail of Rollers, Shafts & Bearings



Proof of Concept Traction Tester

Roller unit shown with vacuum cube



Partly completed traction drive tester is at left. Project awaits restored funding.