NASA/CP—2002-211882

Space Mechanisms Technology Workshop

September 2002

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NASA/CP—2002-211882

Space Mechanisms Technology Workshop

Proceedings of a conference held at and sponsored by
NASA Glenn Research Center
Cleveland, Ohio
May 14, 2002

National Aeronautics and
Space Administration

Glenn Research Center

September 2002

Acknowledgments

There were many people whose contributions made this workshop possible. It started with the organizing committee: Robert Fusaro (now retired), James Zakrajsek, Rebecca Kwiat, Wilfredo Morales, Mark Siebert, and Fred Oswald. Our invited speakers made an interesting workshop possible: Fred Crosno, Robert Fusaro, Lois Gschwender, Geoffrey Landis, Wilfredo Morales, Fred Oswald, Frank Ruhle, Mark Siebert, Scott Starin, William (Red) Whittaker and Jim Zakrajsek. Finally, we acknowledge the participation by our guests. They really made the Workshop a success.

The Aerospace Propulsion and Power Program at
NASA Glenn Research Center sponsored this work.

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Summary

The Mechanical Components Branch at NASA Glenn Research Center hosted a workshop on Tuesday, May 14, 2002 to discuss space mechanisms technology. The theme for this workshop was "Working in the Cold," a focus on space mechanisms that must operate at low temperatures. We define "cold" as below –60 °C (210K), such as would be found near the equator of Mars. However, we are also concerned with much colder temperatures such as in permanently dark craters of the Moon (about 40K).

Introduction

This was the second in a planned series of space mechanisms technology workshops sponsored by the Mechanical Components Branch at NASA Glenn Research Center. The previous workshop in November 2000 considered space drives, mechanical transmissions that perform as speed reducers to match the high speed, low torque output, typical of electric motors, to the low speed, high torque required to operate machinery. This workshop focused on space mechanisms that must operate at low temperatures. We define "cold" as below –60 °C (210K), such as would be found near the equator of Mars. However, we are also concerned with much colder temperatures such as in permanently dark craters of the Moon (about 40K).

These low temperatures present challenges for mechanisms design. At extreme temperatures, conventional liquid lubricants (including grease) may not be feasible, therefore either solid lubricants must be used, provision must be made to heat lubricants, or some unconventional lubricant may be considered. The goal is to identify the problems caused by these conditions and to project what resources will be needed to support future missions.

This report summarizes the nine presentations on space mechanisms technology given at the workshop.

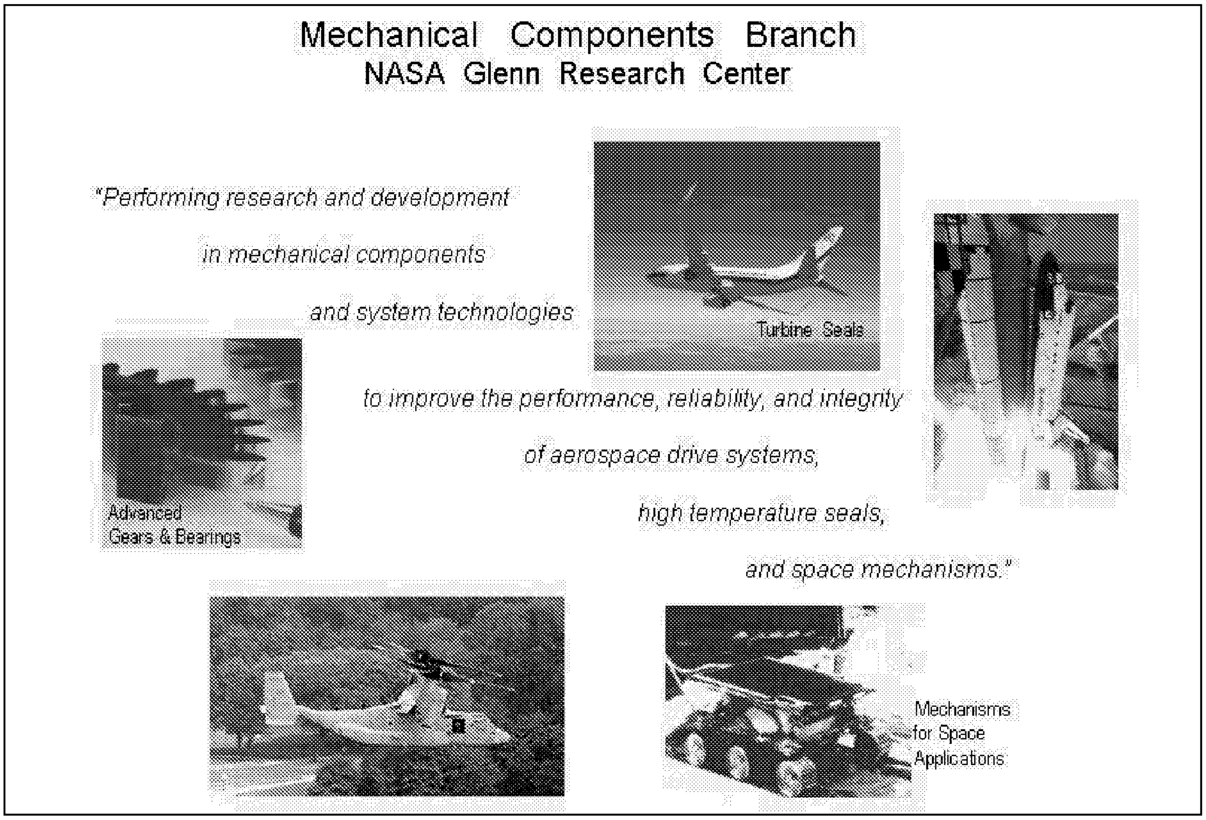
Overview of Glenn Mechanical Components Branch Research

Mr. James Zakrajsek, chief of the Mechanical Components Branch, gave an overview of research conducted by the branch. Branch members perform basic research on mechanical components and systems, including gears and bearings, turbine seals, structural and thermal barrier seals, and space mechanisms. The research is focused on propulsion systems for present and advanced aerospace vehicles.

For rotorcraft and conventional aircraft, we conduct research to develop technology needed to enable the design of low noise, ultra safe geared drive systems. We develop and validate analytical models for gear crack propagation, gear dynamics and noise, gear diagnostics, bearing dynamics, and thermal analyses of gear systems using experimental data from various component test rigs.

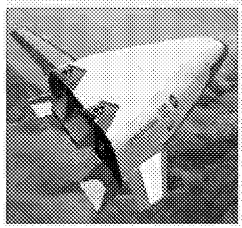
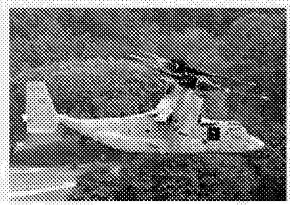
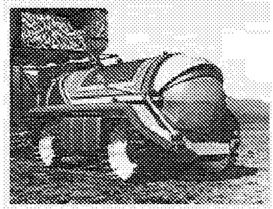
In seal research we develop and test advanced turbine seal concepts to increase efficiency and durability of turbine engines. We perform experimental and analytical research to develop advanced thermal barrier seals and structural seals for current and next generation space vehicles.

Our space mechanisms research involves fundamental investigation of lubricants, materials, components and mechanisms for deep space and planetary environments.



Mechanical Components Branch

Core Technologies

Seals	Drive Systems	Space Mechanisms
		

Seals

non-contacting turbine seals

self adapting seals

thermal barrier seals development

acoustic seals development

structural seals development

Drive Systems

drive systems lubrication and thermodynamics

drive system health management

fracture mechanics

drive systems dynamics and noise

gear fatigue

Space Mechanisms

lubrication in space environment

space mechanisms design guidelines

coatings research

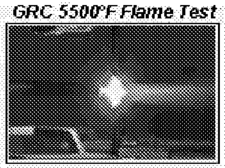
mechanical drives for planetary rovers

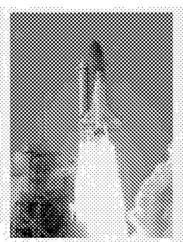
Mechanical Components Branch

Seal / Thermal Barrier Development for Space Transportation Programs

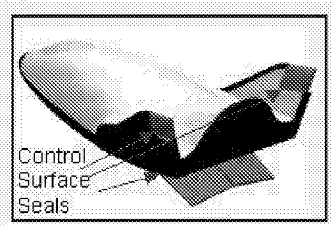
Developed thermal barrier to block hot gases from damaging Viton O-rings in Space Shuttle Solid Rocket Motor

GRC 5500°F Flame Test



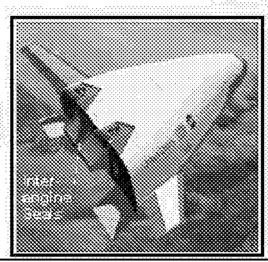


Assist JSC in developing control surface seals to prevent hot, re-entry gas ingestion/damage of control surface hardware



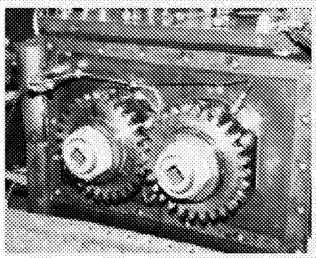
X-38 CRV

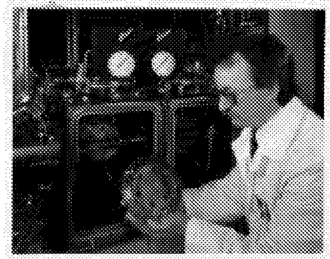
Developed conceptual design of inter-engine seal showing promise of accommodating large deflections in hot flow environment between aerospike engine modules

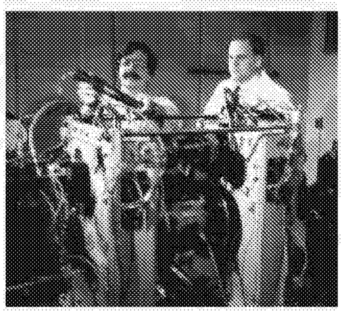


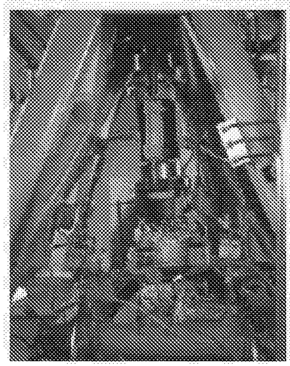
Mechanical Components Branch

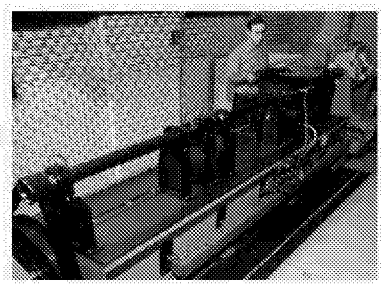
Drive Systems Experimental Facilities - NASA Glenn Research Center





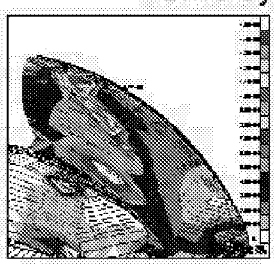




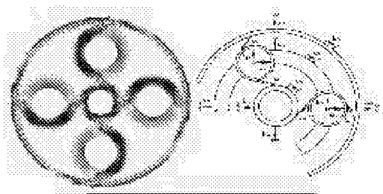


Mechanical Components Branch

Drive Systems Analytical Capabilities

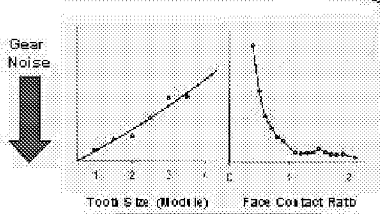


Finite Element Based Structural - Thermal

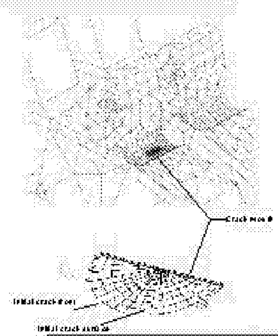


Planetary Gear Dynamics

Physics-Based Models



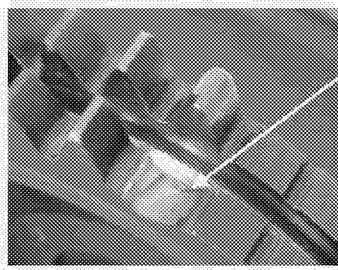
Helical Gear Dynamics

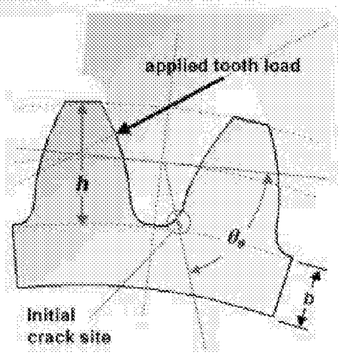


Fracture Mechanics - BEM

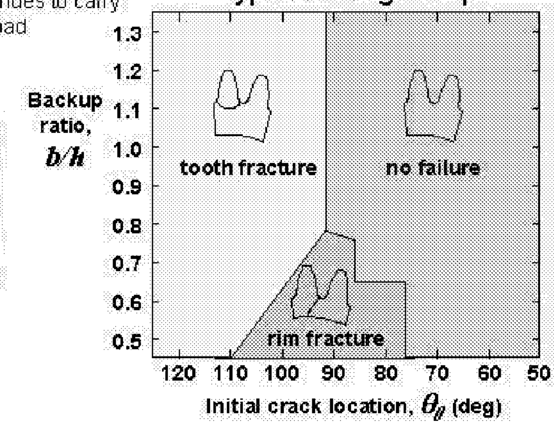
Mechanical Components Branch

Gear Design Guide for Failsafe Operation





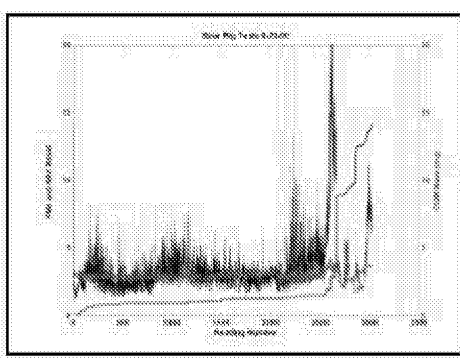
Typical Design Map



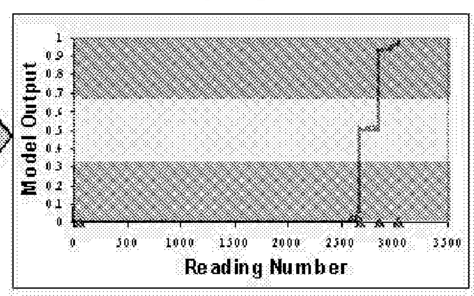
Mechanical Components Branch

Drive System Sensor Fusion for Increasing Reliability of Health Monitoring Systems

Vibration and Oil Debris Data



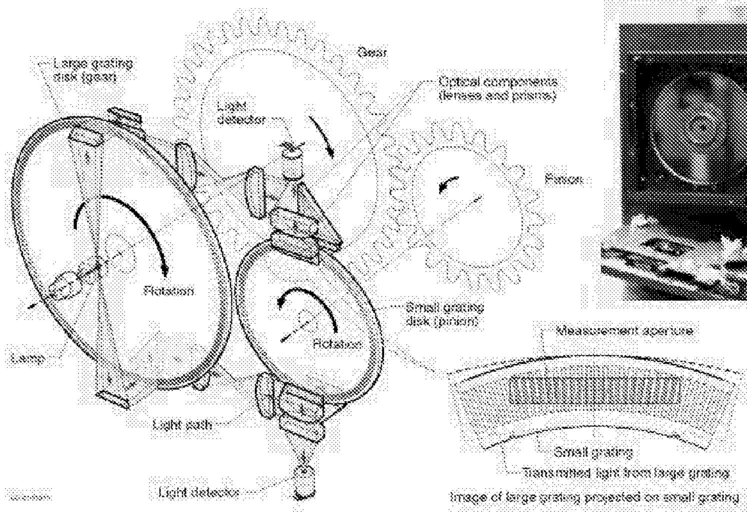
Output of Fuzzy Logic Model

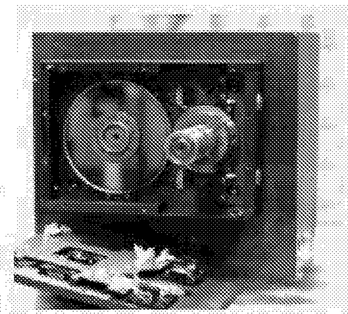


Mechanical Components Branch

Technologies to Reduce Gear Noise at the Source

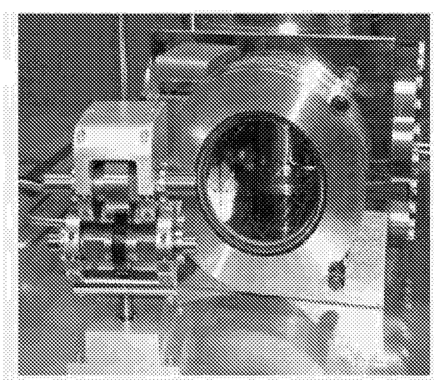
High Speed Gear Transmission Error Measurement System



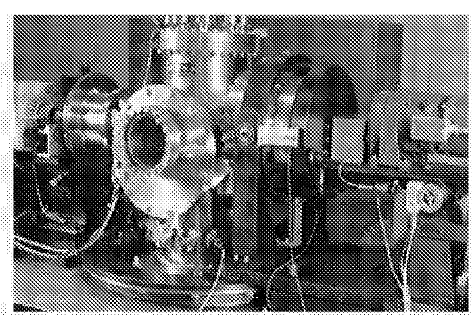


Mechanical Components Branch

Space Mechanisms Experimental Facilities - NASA Glenn Research Center



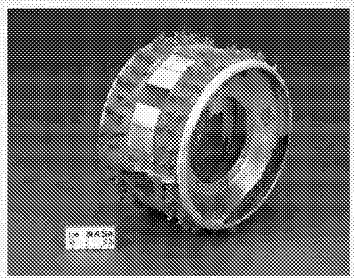
New proof-of-concept traction drive test unit with vacuum cube



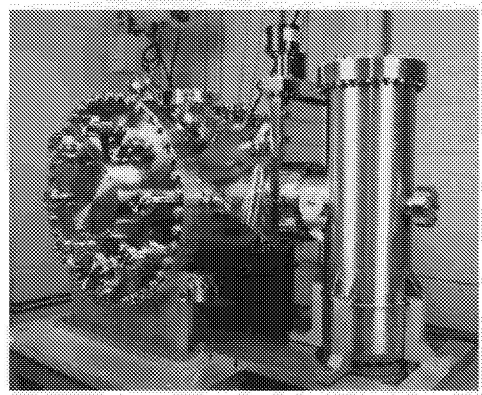
Vacuum roller test rig

Mechanical Components Branch

Space Mechanisms Research
Mars Pathfinder Abrasive Wheel Experiment Test



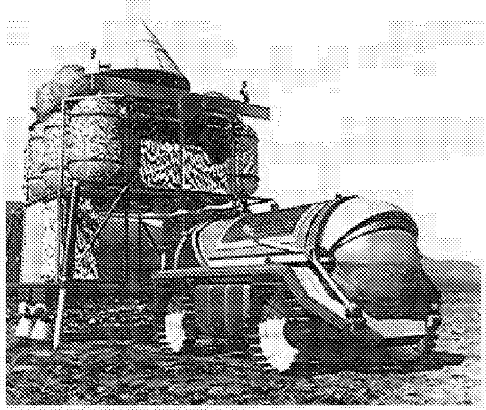
GRC test chamber with simulated Martian atmosphere and simulated Martian soil



Space Mechanisms Pathfinder

Mechanical Components Branch

Space Mechanisms Research - Initiative for Horizon
Advanced Space Drives Research



Human Exploration of Mars:
The Reference Mission of the NASA Mars Exploration Team
NASA SP 6107, July 1997

Investigating new concepts in solid lubricated traction drives for future planetary exploration vehicles

- 16.5 Metric ton rovers planned for future manned Mars missions
- Must be capable of reliable operations on 500Km, 10 day excursions
- Must be lightweight and power efficient
- Must be "oil-free", and capable of operating in extreme cold and dusty conditions

Crossing Mars: Past and Future Missions to a Cold, Dry Desert

Dr. Geoffrey A. Landis of the Photovoltaics and Space Environment Effects Branch presented an overview of recent discoveries about the environment of Mars. He covered missions from the 1966 Mariner IV that returned those first grainy close-up pictures of Mars showing an ancient cratered terrain to the Mars Odyssey mission with its tantalizing evidence of recent water flows on Mars.

Mars is one of the most interesting planets in the solar system, featuring enormous canyons, giant volcanoes, and indications that, early in its history, it might have had rivers and perhaps even oceans. Five years ago, in July of 1997, the Pathfinder mission landed on Mars, bringing with it the microwave-oven sized Sojourner rover to wander around on the surface and analyze rocks. Pathfinder is only the first of an armada of spacecraft that will examine Mars from the pole to the equator in the next decade, culminating (someday, we hope!) with a mission to bring humans to Mars.

Mars is the next planet out from the Sun, so it gets a little bit less sunlight than we do, and so it is a cool planet. Mars is a bit smaller than the Earth. The first thing you notice when you look at it is that it's a very red planet -actually more of a muddy orange color, but it’s much redder than the Earth, which is why they call it the red planet.

The fact that we think of it as being a small planet is a little bit misleading. In fact, the land area of Mars is greater than the entire land area of the planet Earth. It's really a big place. There's a lot to explore on the planet Mars.

You can see Mars from the Earth, and even from here, about fifty million kilometers at the closest, with a telescope we can see a lot things about Mars. It has clear dark and light features; you can see it has a polar cap. Like the Earth, Mars has an axis that's tilted, and therefore it has seasons, winter and summer, and the polar caps grow in the winter and shrink in the summer. It also has clouds, so you can tell that it has an atmosphere.

But to really get a good look at Mars, you need a spacecraft. You need to get up close, and now we can see really interesting things about Mars. The first thing that spacecraft learned when they visited Mars in 1964 was that it has a lot of craters. It's a lot like the Moon. It's been heavily bombarded, which is reasonable because it's closer to the asteroid belt than we are, so you do get asteroids that hit the planet Mars. From these first spacecraft to visit Mars we also learned that its atmosphere is very thin-- less than 1% as thick as Earth’s atmosphere.

After the first spacecraft, which just flew past the planet, we put spacecraft into orbit. Viking looked at it more carefully and saw that Mars has what appears to be dry river beds. These look like dry rivers. So Mars once had water. Today, Mars is a very cold and dry world, so what happened to the water? Where is it now? As we know, water is very important. It's important for life - all of us drink it. We also know that as soon as the planet Earth has a surface cool enough that water could condense on it, life formed on Earth. That was a few billion years ago. But once, perhaps several billion years ago, Mars also had water. So it seems very probable that it might once have had life. We do have a pretty good guess that underneath the soil on Mars, there is still water in the form of permafrost.-- the Mars Odyssey mission will tell us about this.

Mars is the planet of extremes. It has the largest canyon the solar system, the Valles Marineris, a canyon that extends almost a third of the way across Mars. They named it Valles

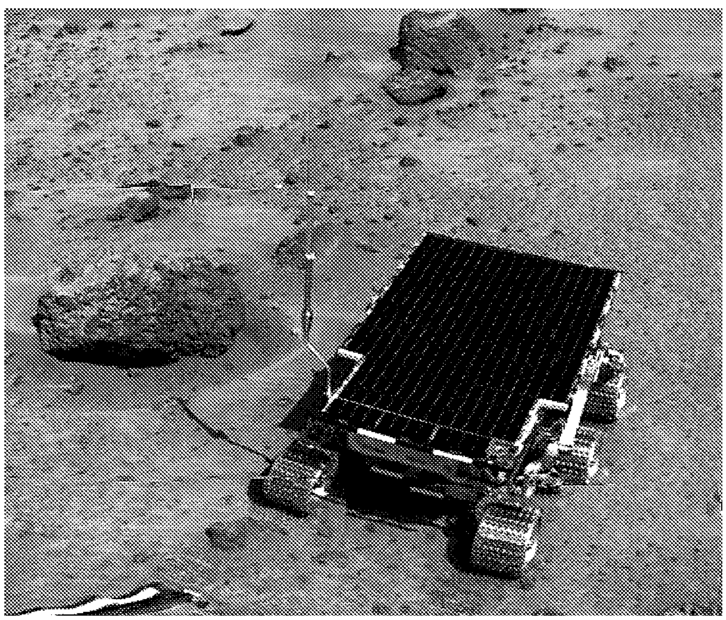
Marineris, the "Canyon of the Mariner", because it was discovered by the Mariner spacecraft. This is a canyon four thousand kilometers long, and in places nearly ten kilometers deep. (In my novel, my characters spend much of their time exploring and climbing through Valles Marineris.)

Mars has the largest mountains in the solar system as well. Olympus Mons, the largest, rises up twenty-five kilometers. It's a volcano so tall that the top of it is in vacuum and outside the atmosphere. It is far taller than Mount Everest.

The Pathfinder Mission and Landing on Mars

Pathfinder was a solar-powered spacecraft. Before Pathfinder nobody had used solar power on Mars before; Pathfinder was a first. Analyzing the operation of solar power systems on Mars was a project that I worked on, and I am very proud that some of my work helped in the design of the power system for this spacecraft.

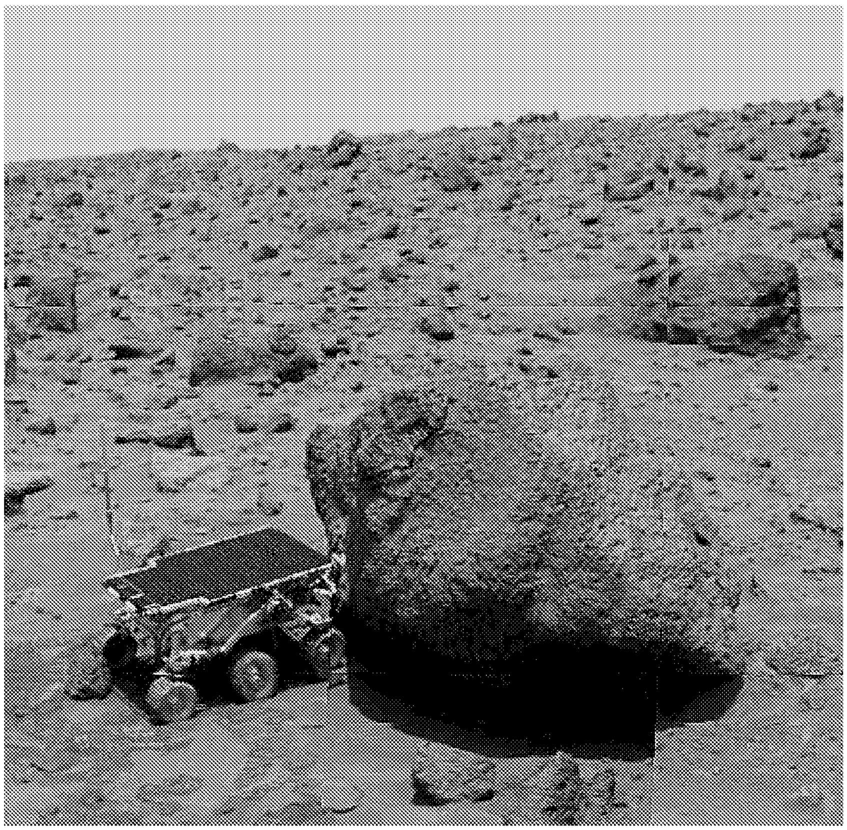
Pathfinder came down in a parachute, and then the airbags inflated. It bounced on the surface, as high as a five story building, and at least eighteen times. That was just as many as they counted; it probably bounced more than that. Then it opened up, like a flower unfolds, and the blue solar petals on the inside were revealed, and we got to see the Sojourner rover.



Six Wheels on Soil!

The Sojourner rover really was the real star of the show. This is the first time that anybody has operated a wheeled vehicle on another planet, and I'm pleased to tell you that it set a world speed record for the fastest vehicle ever to go on the world of Mars. The speed record was a little bit under half a meter per minute--that's about one-fiftieth of a mile per hour--but that is faster than anybody has ever gone on Mars before. It has six wheels that enable it to run over different kinds of terrain, and walk over rocks. The suspension is articulated to allow it to crawl over very large rocks. If a car had the same sort of wheel systems, it could drive over something a rock a meter and a half tall, as tall as a dining room table. So it gives it a good amount of ability to go over very rough terrain.

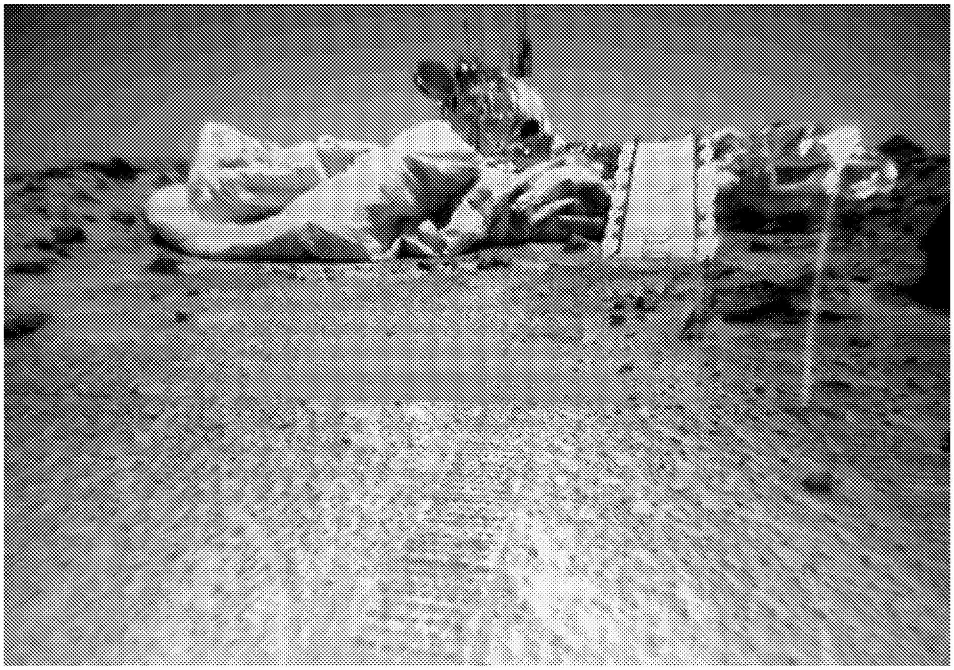
To pick a name for the Pathfinder rover, they held a contest for schoolchildren. The name was chosen by Valerie Ambroise, a school girl from Connecticut. "Sojourner" means "wanderer," and the Sojourner rover wanders around on Mars, so it's a very appropriate name. The Sojourner rover is stowed on one of the petals covered with solar panels. To drive off the petal and onto the surface, they have to deploy rolled-up ramps. These ramps to get the rover to the surface are spring-loaded, so they deploy with an enthusiastic bing.



The Sojourner rover and the rock "Yogi," viewed by the Pathfinder lander. (This image is a mosaic of several dozen individual frames taken by the Pathfinder "IMP" camera; close inspection reveals many seams where individual frames do not perfectly overlap.)

Most of the scientists on the mission were geologists, and geologists love to talk about rocks. They decided to name all the rocks that they can see, so that when they talk about rocks, they remember which one is which. So the first thing they did when they got the pictures down was to make a mural of the surface of Mars as seen by the lander camera. They stuck the mural on the wall of the conference room and said anybody could name a rock. So if you have a name for a rock, you just write it on a little yellow piece of paper, and stick it on to the picture. If everybody likes it, they'll leave it up, and if they don't like it, some body else will name the rock. I'm very proud of one rock, "Yogi," which I named, and which was featured very prominently in the news coverage! Pathfinder mission had other instruments on it as well, including the APXS

("Alpha Proton X-ray Spectrometer") that could actually sniff the rocks and find out what they are made out of. It was a very capable instrument.



The Pathfinder lander, surrounded by deflated airbags, as viewed by the Sojourner rover's camera.

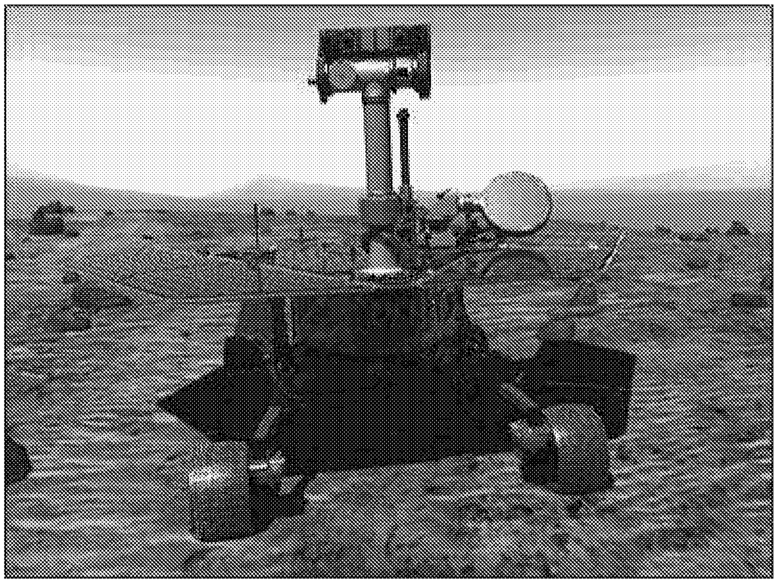
Future Missions to Mars

Pathfinder is not the end of Mars exploration. We have a whole armada of spacecraft going to the red planet. The Mars Global Surveyor is in orbit around Mars right now and has a mapping camera that shows very detailed close-up pictures of the surface of Mars from orbit.

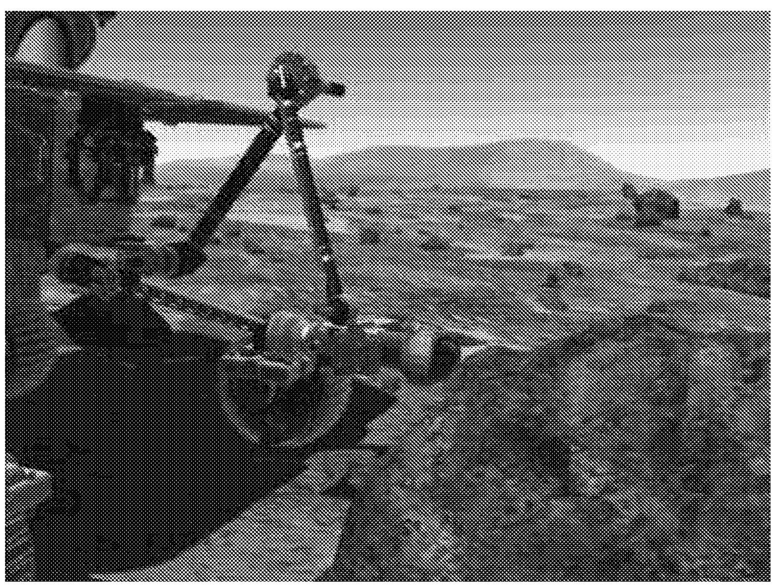
I worked on another mission, which was intended to launch in 2001, called the 2001 Surveyor lander. Unfortunately in 1999 two missions to Mars both failed, and because of those failures, the 2001 lander mission was postponed and then cancelled. We were all very disappointed. Another mission did launch to Mars in 2001, an orbiter, the Mars "Odyssey" mission. The Odyssey spacecraft is in orbit around Mars right now, and taking measurements of Mars from orbit.

Many future missions are now being planned. The next mission to land on Mars is the Mars Exploration Rovers, two rovers each one much larger than the Sojourner rover, to launch in the summer of next year. 2003. At the same time, the British are heading to Mars with a small lander named the Beagle-2, a spacecraft which "hitchhike" to Mars with the ESA "Mars Express" orbiter. And then in 1005, the "Mars Reconaissance Orbiter" is going to fly.

Further in the future, in 2007 we will fly the Mars "Scout" missions. This is a solicitation for new concepts in Mars exploration, and several new ideas have been proposed. Some people that I work with would like to fly an airplane in the atmosphere of Mars. This is very difficult, because the atmosphere is so thin. Some people have suggested flying a balloon, and other people have suggested landing a spacecraft on the ice of the polar cap, and melting down through the ice to see the layers under the ice. Another group is proposing a long-range rover to drive across the fascinating layered terrain around the polar cap.



The Mars Exploration Rover. Two of these rovers will launch to Mars in the summer of 2003.



Rock drilling tool on the 2003 Mars Exploration Rover

We would like to actually get samples back to Earth in a future mission, probably in the year 2015, which is only thirteen years from now, and blast them all home so we can take a look at them and look for fossils and for other interesting things.

All of these robotic flights are precursors to the most important future exploration: a mission to Mars with people on board. But right now there is no mission planned, so this is more science fiction than science.

In my science fiction novel, Mars Crossing, I picture such an expedition to Mars—in fact, several expeditions. The difficult part of sending people to Mars is not how to send them to Mars—the difficult part is bringing them home. (And most of my novel is about how the characters work at coming home). In the novel, the expeditions to Mars manufacture rocket fuel from resources found on Mars to bring the expedition home. One of the expeditions lands on the polar cap, and makes rocket fuel out of the carbon dioxide and water ice in the cap, and the other expeditions lands near the equator, and manufactures fuel out of the atmospheric carbon dioxide. I think that this is very realistic, and that when we do send humans to Mars, that this is the logical way to do it—we should make the rocket fuel on Mars, instead of bringing it from Earth. Of course, in my story, the characters have tremendous difficulties, and are in great danger. I hope that in the real world, they will not have so many problems! The best expedition is one that is not very exciting. But perhaps this is one of the functions of science fiction, to show what the problems might be.

I do think that eventually people will go to Mars. It is our sister planet, and we should go explore it!

References

1. "The Rover Team" (J. Matijevic, D. Bickler, D. Braun, H. Eisen, L. Matthies, A. Mishkin, H. Stone, L. Sword, L. van Niewstadt, L-C. Wen, B. Wilcox, D. Ferguson, G. Landis, L. Oberle et al.) "Characterization of the Martian Surface Deposits by the Mars Pathfinder Rover, Sojourner," Science, Vol. 278, 1765–1768, Dec. 5 1997.
2. "The Rover Team" (J. Matijevic, D. Bickler, D. Braun, H. Eisen, L. Matthies, A. Mishkin, H. Stone, L. Sword, L. van Niewstadt, L-C. Wen, B. Wilcox, D. Ferguson, G. Landis, L. Oberle et al.) "The Pathfinder Microrover," J. Geophysical Research, Vol. 102, No. E2, 3989–4001 (1997).
3. G. Landis, "Water, Pink Salt and Cold Dry Gullies: Halobacteria and the Case for Life on Mars," Analog, April 2001.
4. G. Landis, "Adventures in the Mars Business," Analog, July 1998.
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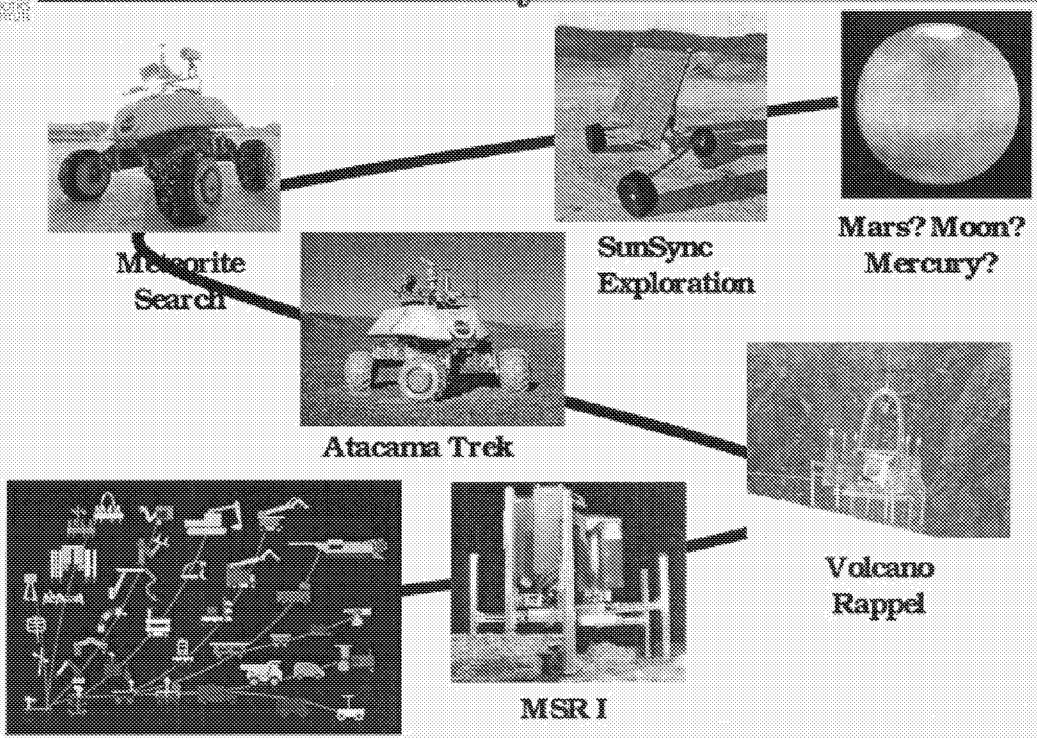
6. P. Jenkins, G. Landis, and L. Oberle, "Materials Adherence Experiment: Technology," paper IECEC–97339, Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Vol. 1, 728–731, July 27–Aug. 1 1997, Honolulu HI.

Robots in the Planetary Cold

Dr. William (Red) Whittaker, director of the Field Robotics Center of the Robotics Institute at Carnegie Mellon University, discussed operation of robotic explorers in challenging environments, including the Moon and Mercury. He gave historical background from the Russian Lunokhod tele-operated rover, the American Apollo manned rover vehicle and terrestrial robots including Nomad, which found meteorites in Antarctic and Pioneer, the robot that explored the damaged Chernobyl nuclear plant in Russia.

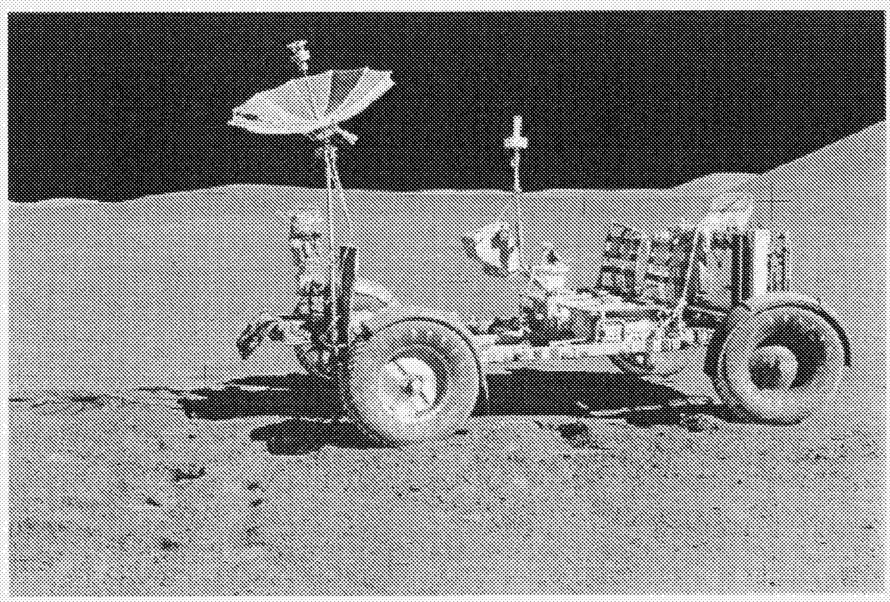
The main emphasis of the presentation was on autonomously controlled, sun-synchronous robots that are continuously operated by solar power. These are practical on slowly rotating bodies such as the Moon (28 days rotation) and Mercury (187 days) or on bodies with a tilted axis that allow continuous sunshine at polar regions during summer, such as Earth and Mars. Issues impacting sun synchrony are shown in the charts reproduced below.

Robots in the Planetary cold

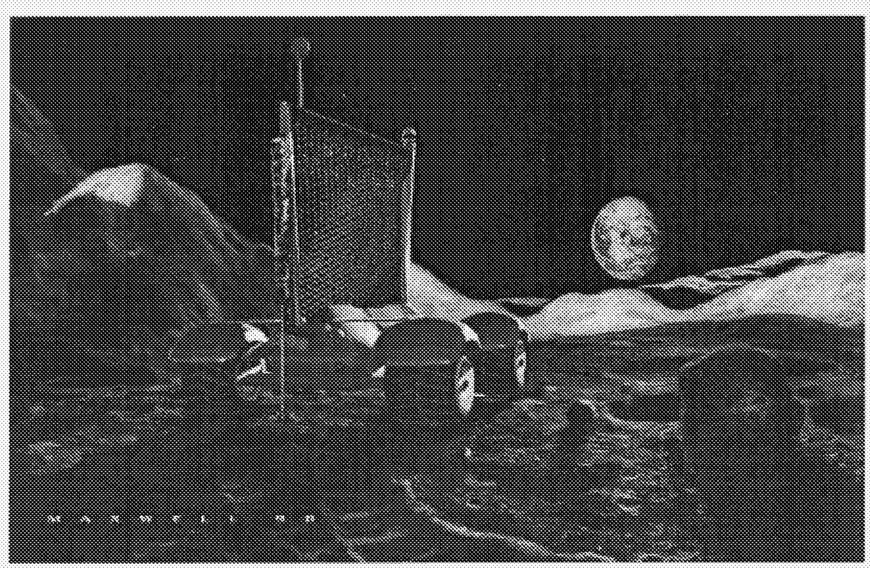


Antarctica

Lunar Day

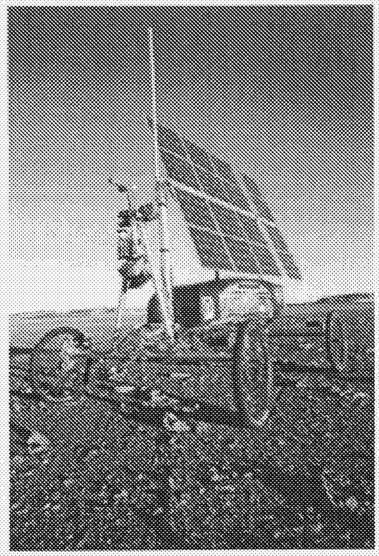


Lunar Night

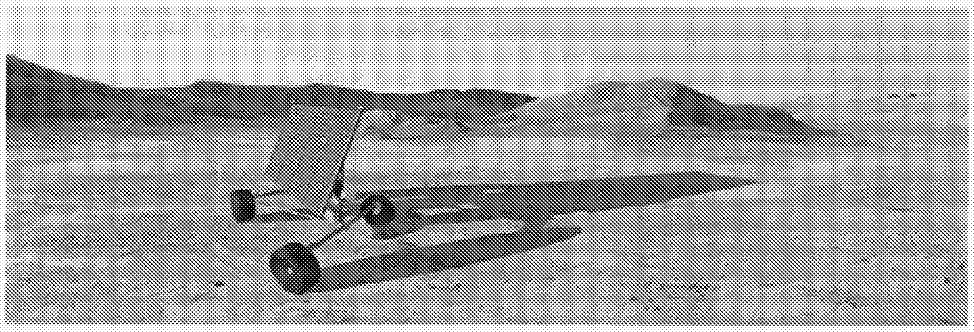


Sun-Synchronous Robotic Exploration

- Sun-synchrony and solar dwell
- Sun-synchronous navigation
- Solar-powered robot Hyperion
- Field experiment on Devon Island
- Toward persistent solar exploration



Sun-Synchronous Exploration

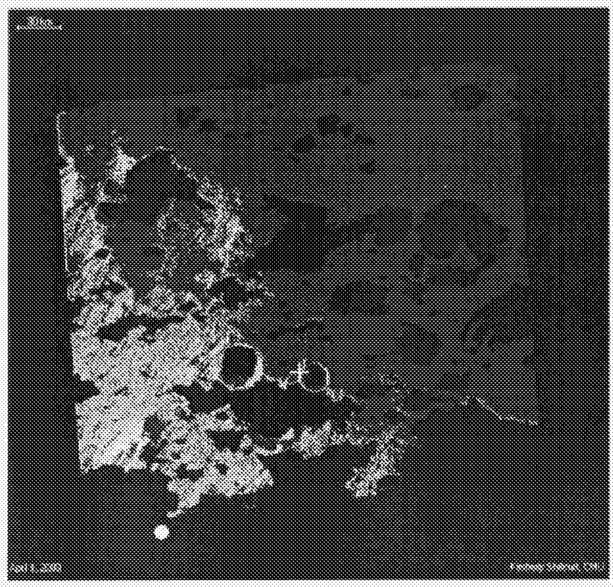


Concept: **Perpetual planetary exploration through synchronization with the motion of the Sun**

Technical Goal: **Robotic navigation with reasoning about resources for continuous operation**

Sun-Synchrony on the Moon

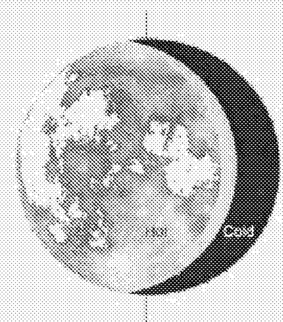
Sunlt Shadowed Unknown Terrain



Lunar South Pole

Circumnavigation

Remain in favorable sun position by following the dawn

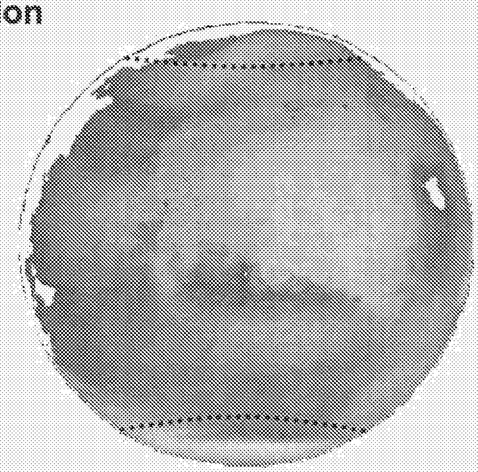


Sun-Synchrony on Earth/Mars

Operate at polar latitudes using the sun position to dictate orientation

- **Fixed solar panel: daily circuit that spirals into new regions**
- **Actuated solar panel: heading unrestricted, dodge shadows and remain in sunlight**

Relevant to resource planning at equatorial latitudes



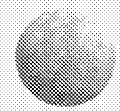
Sun-Synchrony

Sun-Synchrony is advantaged by:


Earth

High solar flux
Providing abundant solar energy

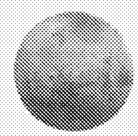
Moderate gravity
Resulting in lower locomotion power


Mercury

Small planetary diameter
Long rotational period
Less speed required for planetary circumnavigation

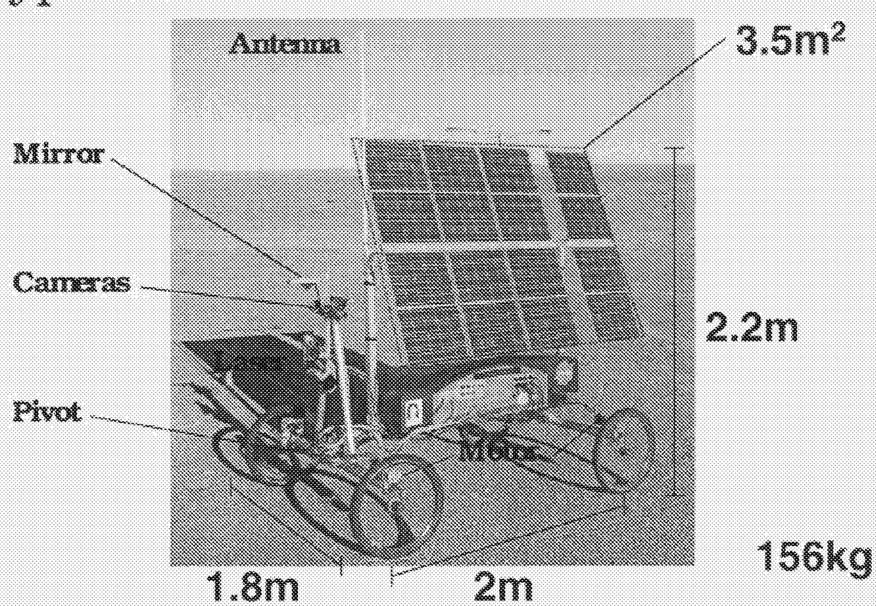

Moon

No planetary axial tilt
Perpetual polar exploration

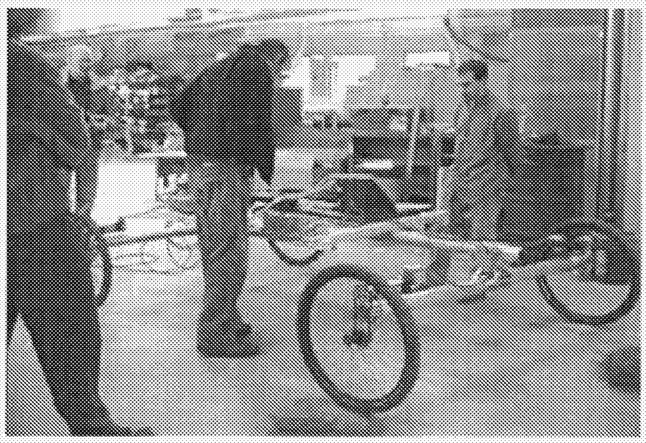

Mars

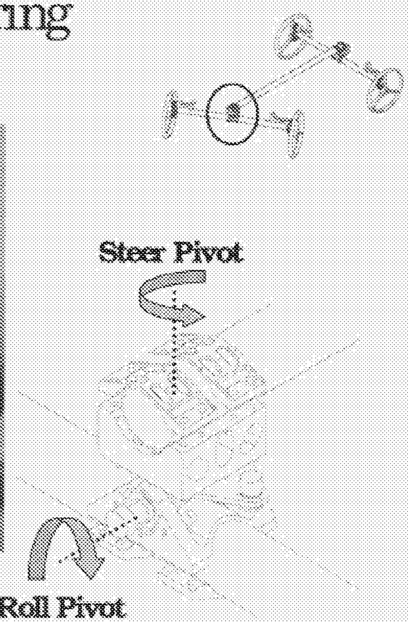
High planetary axial tilt
Long summer for polar exploration

Hyperion

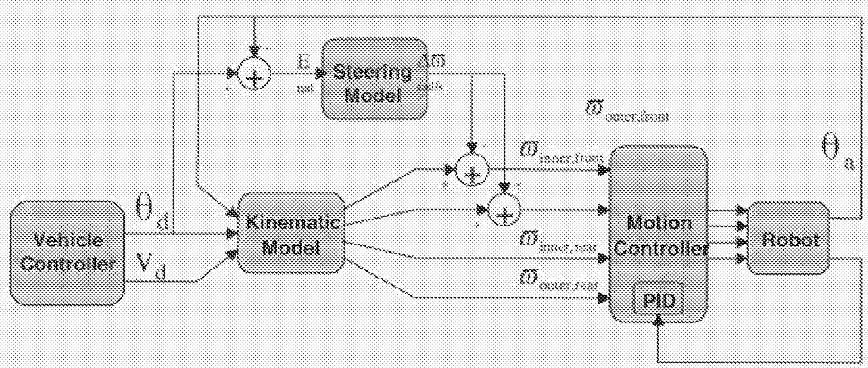


Passively Articulated Steering





Control of Passive Steering



Four wheel drive, no steering actuator, no skidding

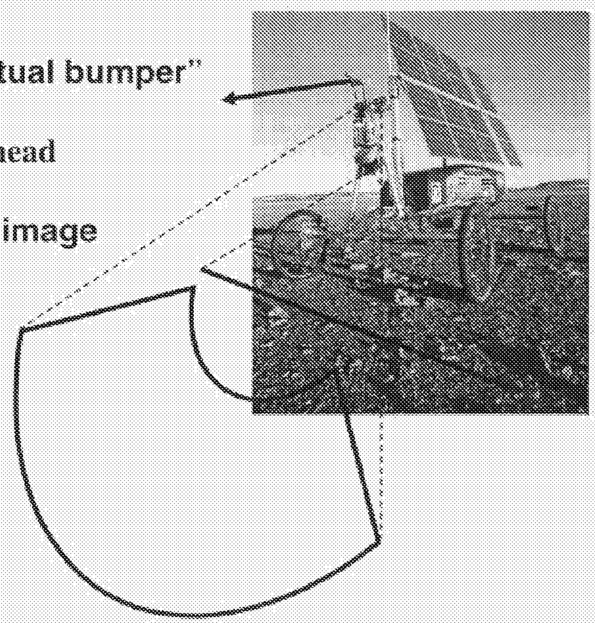
- **Proportional control of front axle angle**
- **Front wheel velocities based on desired axle angle + differential velocity term**
- **Rear wheel velocities based on actual axle angle**

Perception

Laser line scanner as "virtual bumper" for emergency stop
- Field of view: 3m at 1m ahead

Stereo cameras for depth image
- Field of view: 60°
- Baseline: 20cm
- Range: 1m to 7m
- Resolution: 12.5cm at 7m

Panoramic camera for operator

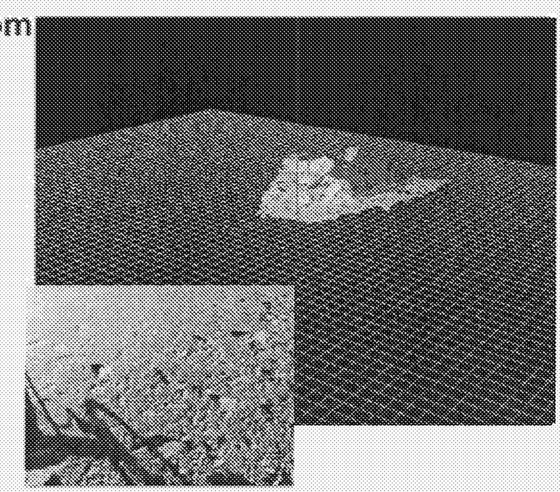


Terrain Evaluation with Stereo Vision

Terrain model developed from depth image using region-based correlation method

Terrain evaluated by fitting vehicle footprint to terrain
- Slope
- Elevation discontinuity
- Roughness (residual)

Each metric linearized [0,1] and maximum metric assigned to terrain



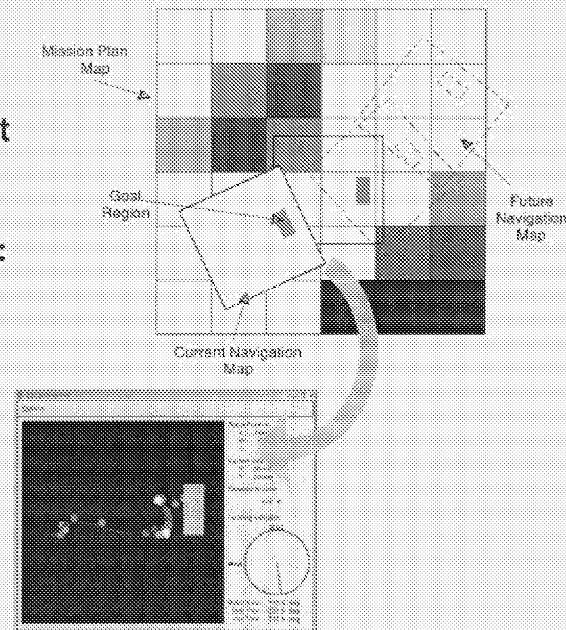
Local Navigation

Navigator plans path to next mission goal region

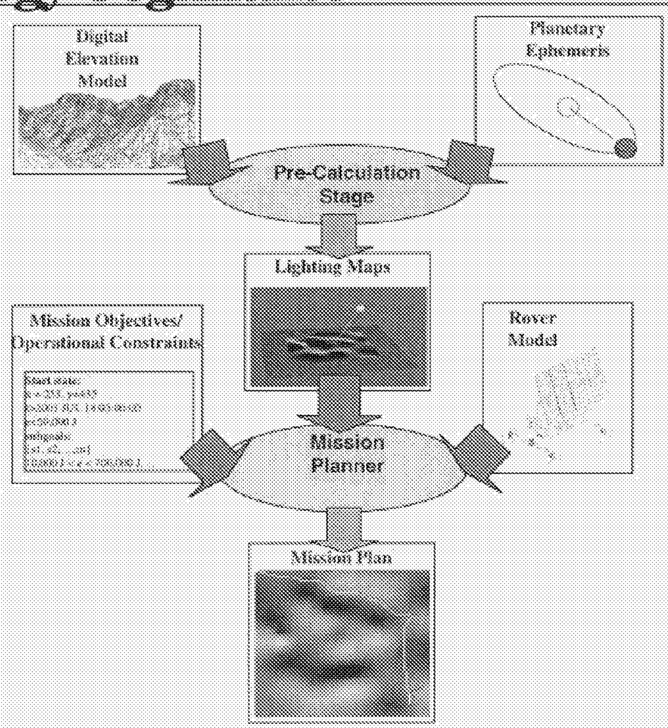
Optimal search (D*) applied:
- Terrain evaluation
- Expected cost to goal

Steering arcs in 15 steps between -4m and +4m selected at ~1Hz

Continuous at 30cm/sec

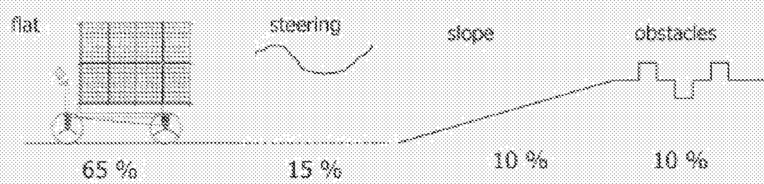


Energy Cognizance



Locomotion Power

Locomotion Power Draw		
Speed = 0.28 m/s		
	torque per wheel	total power
	Nm	Watts
Straight Driving	17	60
15 deg slope	23 per rear wheel	75
	10 per front wheel	
Dead lift	332/4 = 83	290
Skid steering	90 per outer wheel	150

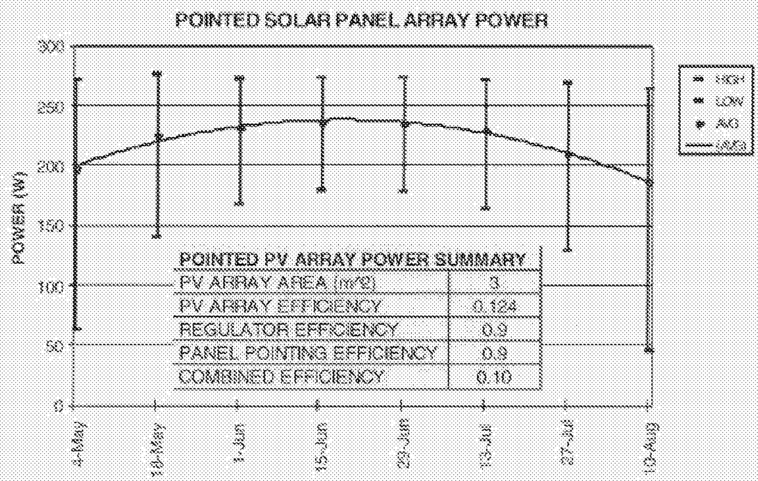


Steady State Power

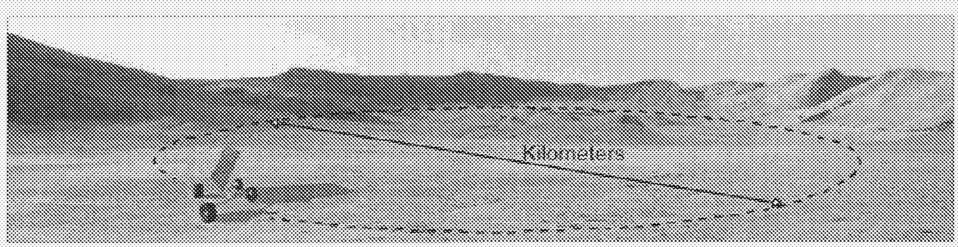
System	subsystem	mfg	model	Power (W)
Computing				
	CPU	PEP	CP302	21.0
	Serial port board	GESPAC	PCISIO-8	2.5
	Firewire	MindReady	OCHI	3.0
	fan	Cosair		5.0
*	PCMCIA adapter	SBS	PCI-PCMCIA	0.5
*	Hard drive	IBM	Microdrive 1 GB	2.2
*	I/O board	custom		2.0
			Subtotal (W)	*36.2*
Sensing				
	stereo cameras (2)	SONY	DFW	6.0
	GPS	Novatel		12.0
	laser rangefinder	Sick		17.0
	proprioceptive			8.0
	PMAD	custom		2.0
			Subtotal (W)	*45.0*
Motion Control				
	motion controller	Galil	DMS-2080	*9.0*
Communication				
	wireless bridge	Cisco	Arian 640	*6.3*
	Non-locomotion power		**Total (W)**	**86.5**

Available Power

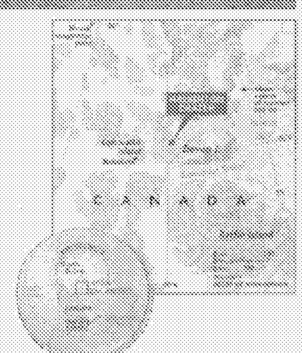
Predicted 220W/m² in arctic region in mid-July



Arctic Field Experiment



Objective:



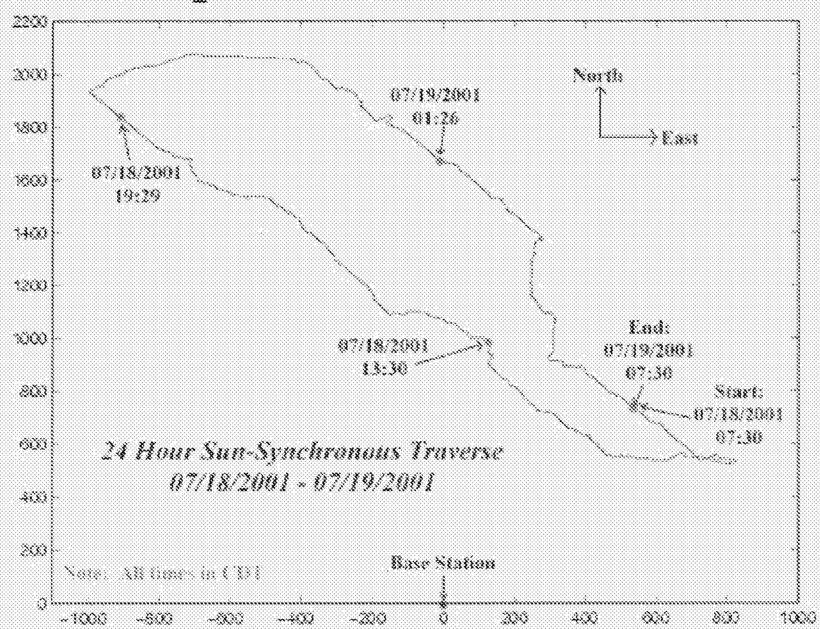
Prove concept of sun-synchronous navigation and quantify performance

Conduct continuous 24-hour sun-synchronous experiments in planetary-analog terrain

Technical Objectives

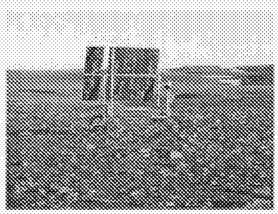
- Verify passive steer, four-wheel drive mechanism
- Analyze locomotive power under terrain and load conditions in relevant terrain
- Quantify solar power effectiveness under varying lighting conditions
- Evaluate reliability of sensing and autonomous navigation in planetary-analog terrain
- Determine navigational efficiency of synchronizing to sun/avoiding shadows
- Ground-truth power input/output, and achievable vehicle speed and endurance (on Earth)
- Quantify performance of 24-hour sun-synchronous circuits

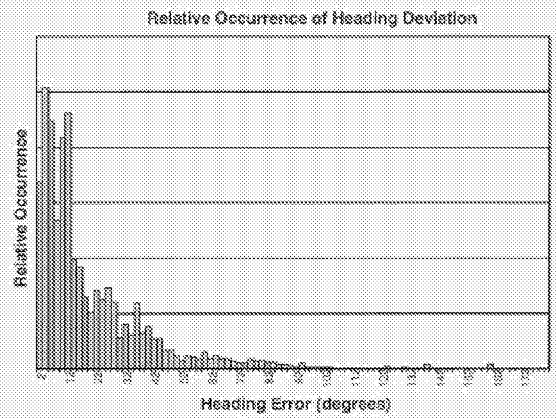
24 Hour Operation



Integrated Experiment

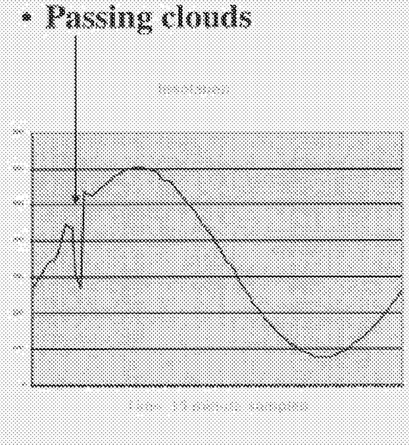
Sun-synchrony
- Average heading tracks path with average near zero
- Some deviation including reversals



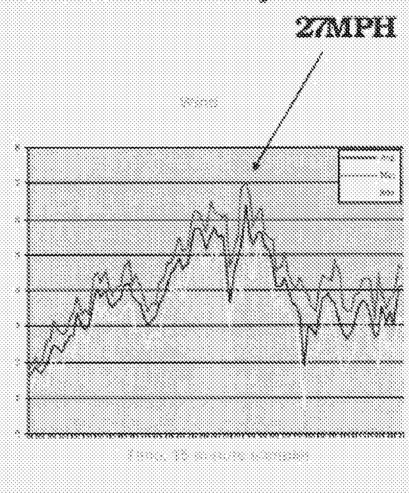


Integrated Experiment

Insolation
- Varied 100-600W/m2
- Passing clouds

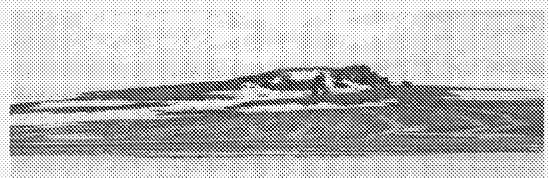


Wind & Stability



Extended Experiment

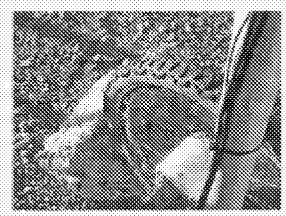
Around Marine Peak



Rough Terrain

Distance: 9.1km
- Challenging terrain
- Recovered from delay and poor sun position

Operation
- One physical intervention
- Multiple remote operator interventions
- Three hour communication dropout
- Unfavorable sun angle



Power
- Completed on schedule with batteries charged

Sun-Synchronous Future

Extended traverse enables fundamentally different exploration

Mars Polar Mission
- Exploration of seasonally varying ice caps and region of possible water permafrost motivates Mars Scout in a summer polar mission

Mars Equatorial Mission
- Reasoning about resources important for any mission
- Ongoing work to develop planning and navigation capabilities for rovers to many destinations and latitudes

Lunar Polar Mission - Magellan Routes
- Possibility of frozen volatiles in lunar cold traps motivates polar circumnavigation in search of water ice

Mercury Circumnavigation - the ultimate circumnavigation?

Summary

Vision of persistent exploration with reasoning about resources for persistent presence

Technology implementation for terrestrial sun-synchrony

Conducted 24-hour sun-synchronous navigation experiments to quantify performance

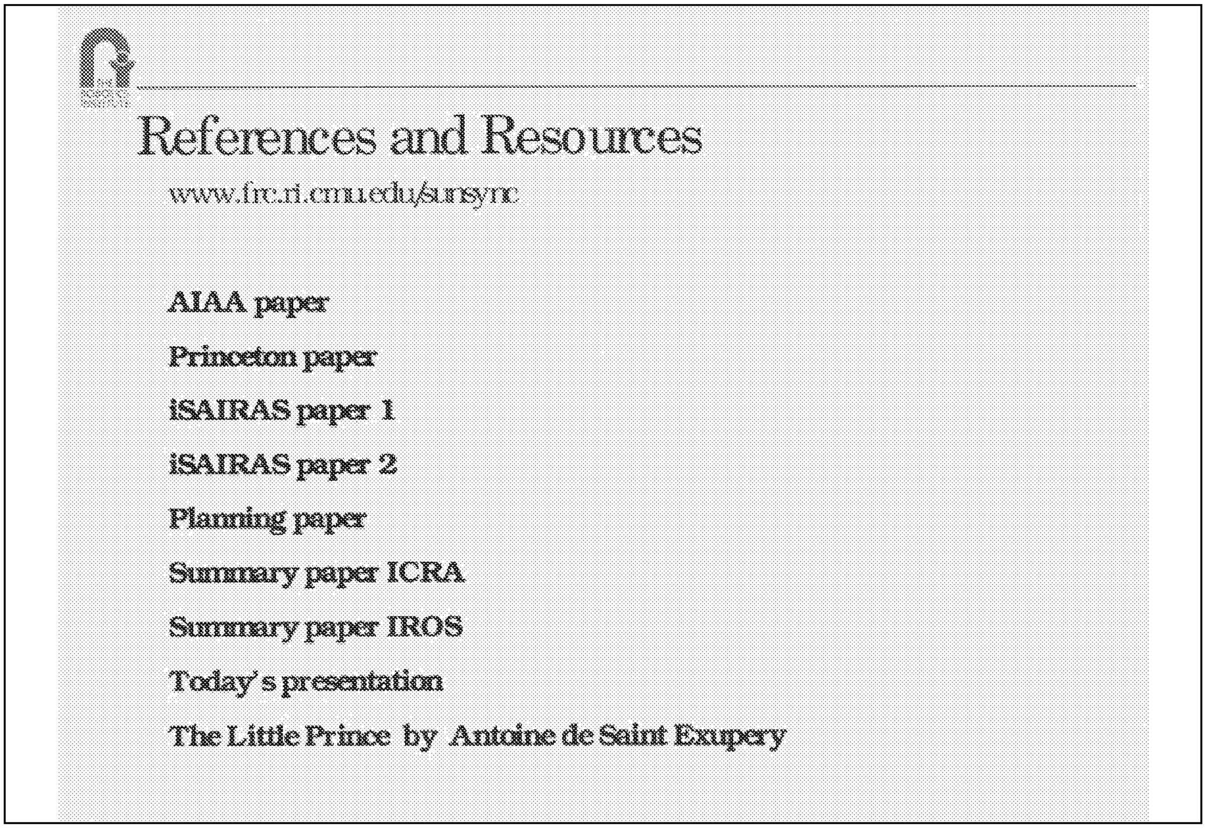
Next step is onboard slam, kinodynamic nav, resource planning, and unattended long-duration operation

Results scale to planetary success

Science opportunities include poles of Mars, Moon and equator of Mercury

Team

Bernardine Dias	Ph.D. Student, Navigation
Stewart Moorehead	Ph.D. Student, Laser
Ben Shamah	Hyperion Mechanical Designer
Jim Teza	Hyperion Electronics Designer
Paul Tompkins	Ph.D. Student, Mission Planning
Chris Urmson	Ph.D. Student, Perception & Localization
Mike Wagner	Software Engineer
David Wettergreen	Co-Investigator
Red Whittaker	PI
David Wilkinson	M.S. Student, Mechanical



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

Robert L Fusaro
Retired
NASA-Glenn Research Center
Cleveland, Ohio

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

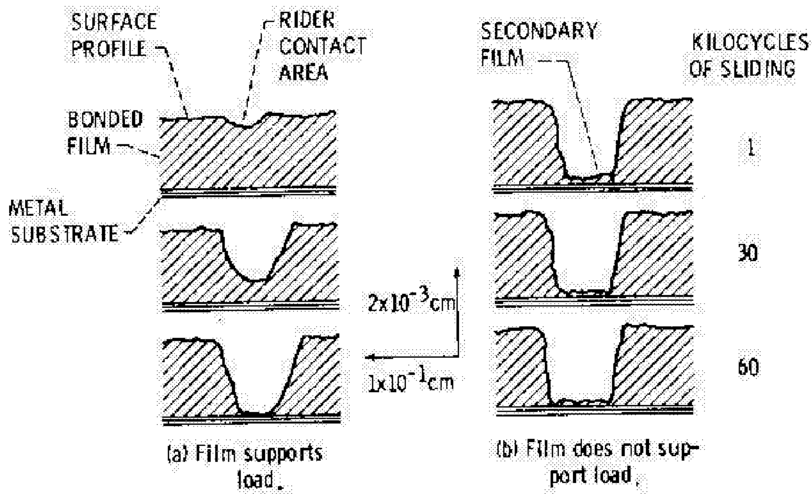
Methods of Employing Solid Lubricants

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

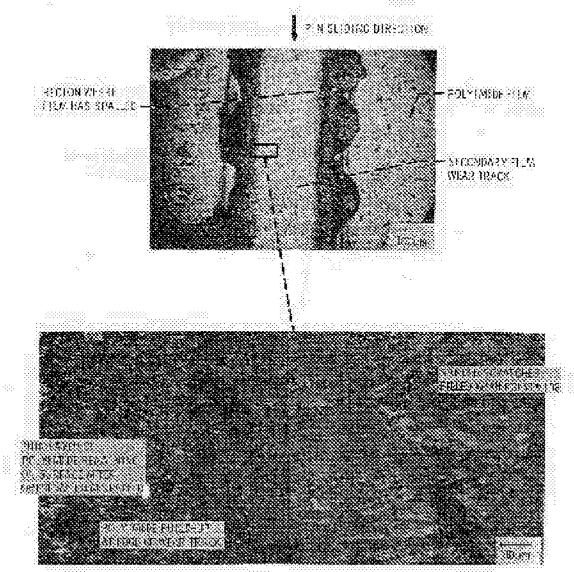
- Type of substrate material to which a film is deposited
- Surface finish of the substrate material
- Type of counterface material
- Surface topography of the counterface
- Hardness of substrate material
- Hardness of counterface material
- Surface or surfaces to which a solid lubricant is applied
- 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.

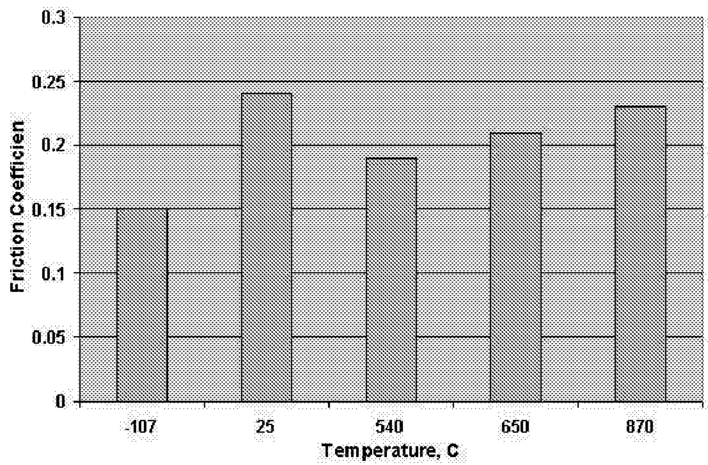
Friction and Wear in Air and Vacuum

(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

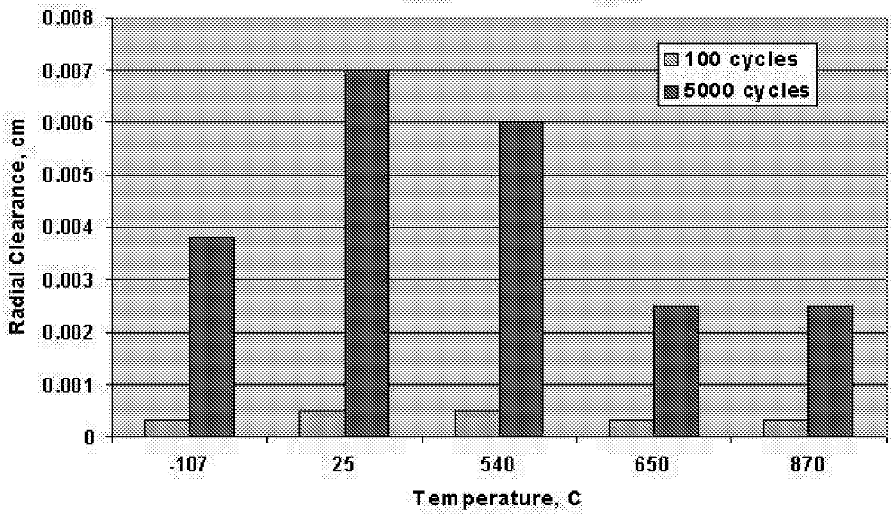
This table compares the friction and wear properties in air and vacuum to illustrate how oxygen and water vapor can affect tribological properties. The results show that the PMDA polyimide or the Graphite Fiber Reinforce Polyimide (GFRPI) have potential for traction drive rollers in a planetary environment.

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.

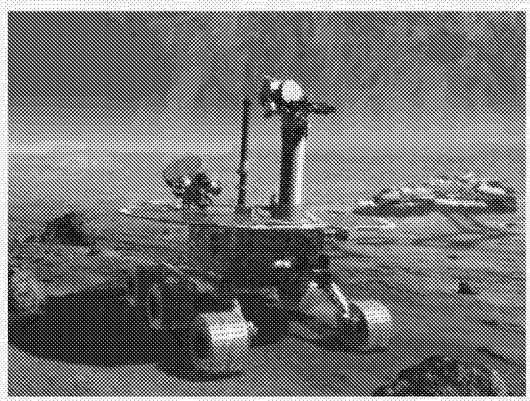
Final Remarks

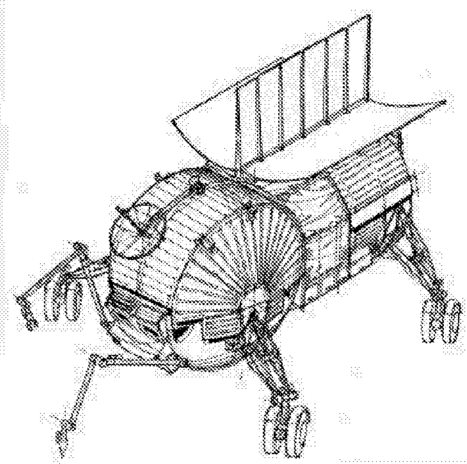
Solid Lubricated Traction Drives

- 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

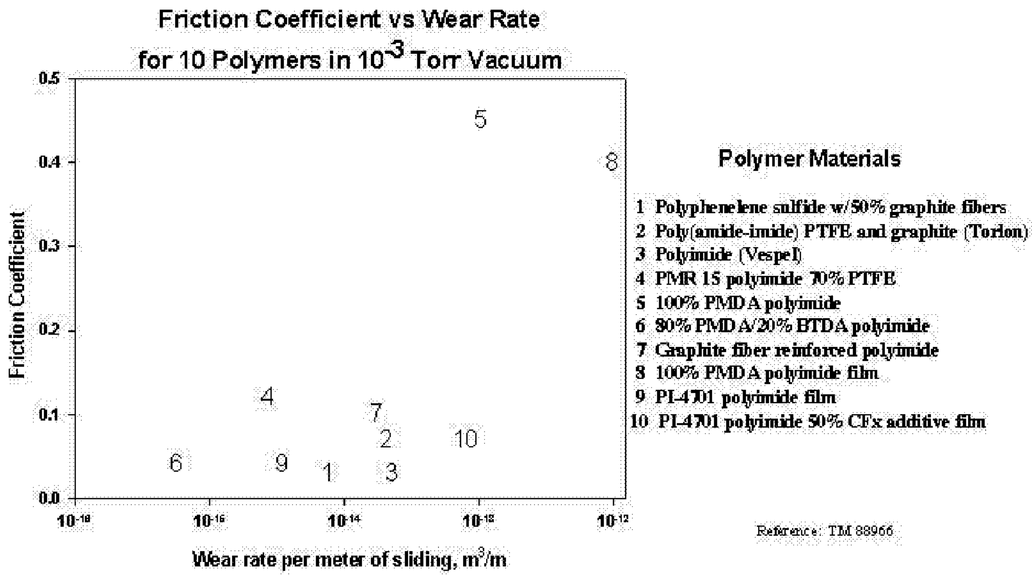
Objective

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

Benefits

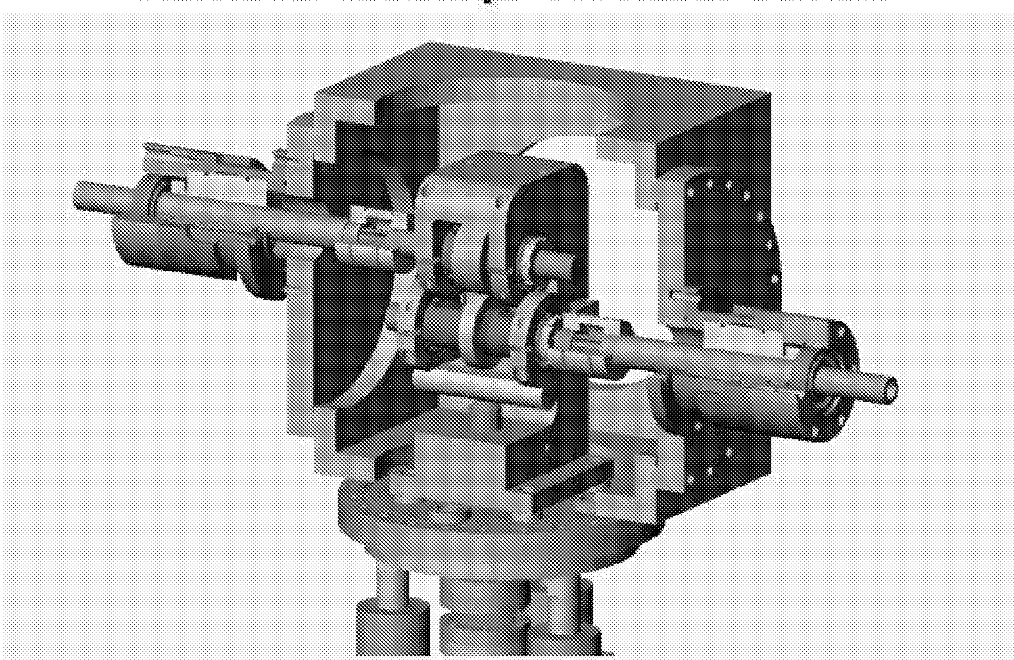
- Higher mechanical efficiency than existing drives
- Provide longer life with high reliability
- Allow operation below ~ -60° C
- Provide robustness to harsh environment
- Minimize weight to save launch cost

Wear Resistant Solid Lubricants



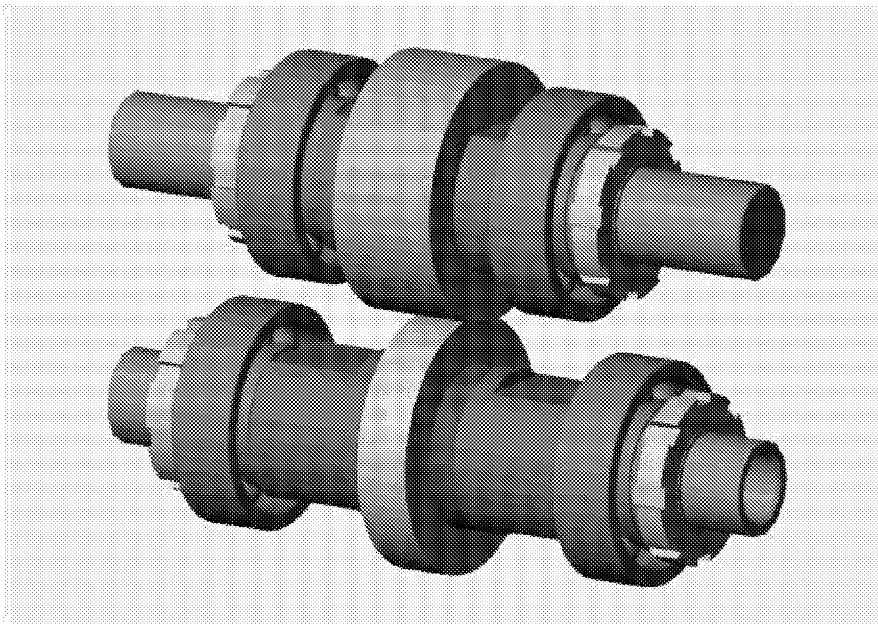
For a traction drive, we need high friction (traction) with low wear.
The 100% PMDA polyimide solid (#5) and film (#8) materials show promise.

Proof of Concept Traction Tester



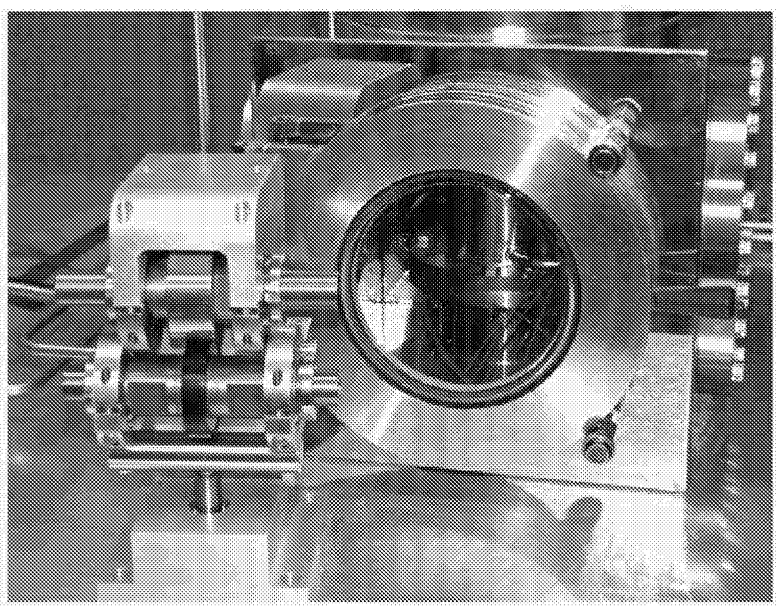
This simple device can test traction roller materials in vacuum. It includes provision to cool the rollers through hollow shafts. With minor modification, it can also test gears.

Detail of Rollers, Shafts & Bearings



Proof of Concept Traction Tester

Roller unit shown with vacuum cube



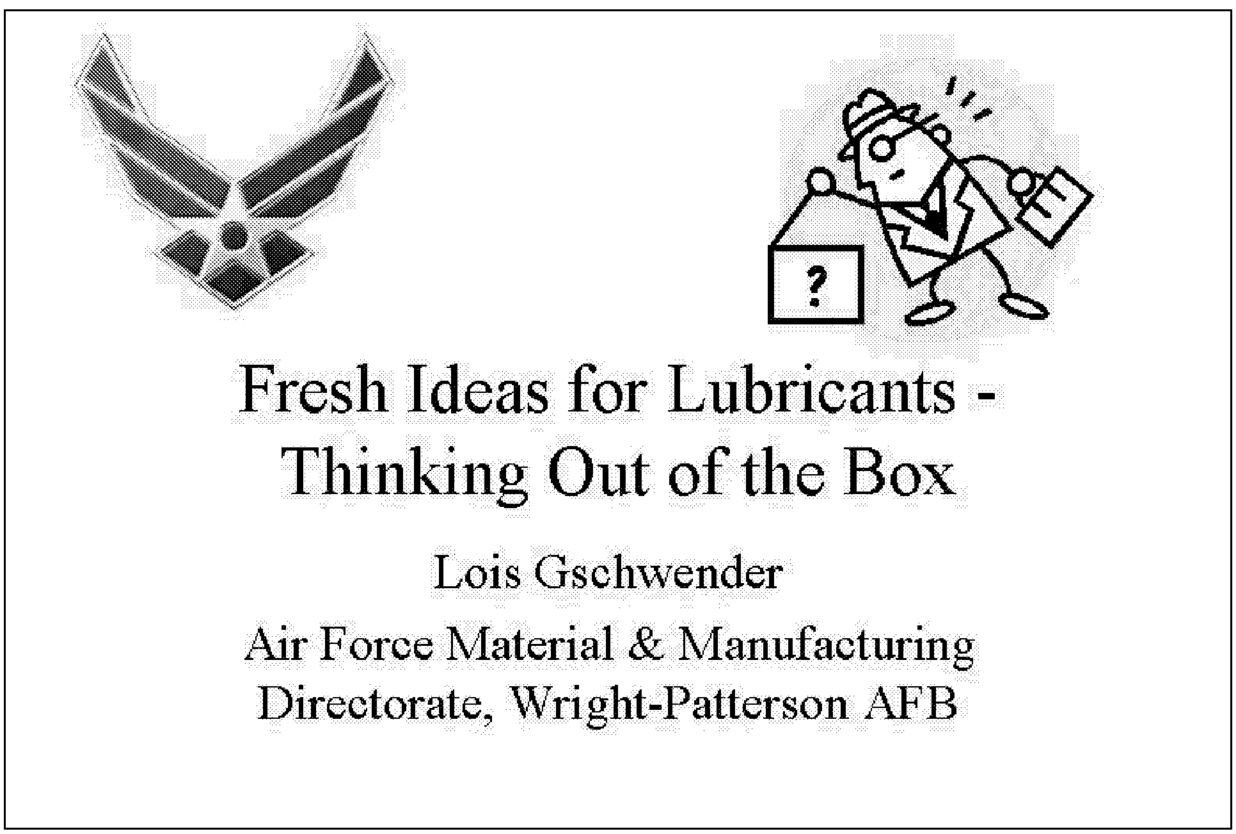
Partly completed traction drive tester is at left. Project awaits restored funding.

Fresh Ideas for Lubricants, Thinking Out of the Box

Lois Gschwender of the U.S. Air Force Research Laboratory, Materials Directorate, at Wright-Patterson Air Force Base discussed new and novel lubricants including Perfluoropolyalkylether (PFPAE), Multiply Alkylated Cyclopentane (MAC), Silahydrocarbon (SiHC) and some solid coatings.

Synthetic lubricants are replacing mineral oils because of their lower volatility and better low temperature performance. PFPAE fluids are the best liquids regarding viscosity temperature properties (can be used to –54 °C and lower) and low volatility, but can only be used a low loads and may cause tribocorrosion. MAC fluids have many attractive properties, but are limited to –40 °C. SiHCs have excellent low volatility and can be used to –54 °C. Some extended bearing tests with these lubricants have been successfully conducted at ITT and Lockheed, but long-term results are pending.

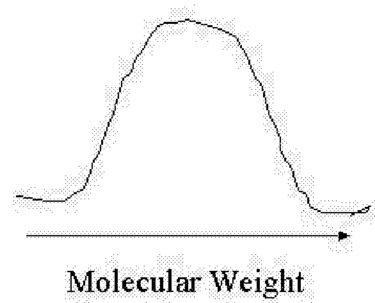
A filtered-arc TiCN coating process has had very promising results in bench tests at Wright-Patterson and UES, Inc. under Air Force contracts. See the presentation charts for more details on these new lubricant materials.



Outline

- Background
- Perfluoropolyalkylether
- Multiply Alkylated Cyclopentane
- Silahydrocarbon
- Durable Coating

Background



- Liquid/Grease Lubricants
  - MineralOil - Original lubricants
    - ~-20°C low temperature limit
    - Broad molecular weight distribution
    - High volatility issues
    - Lubricant thickened as it evaporated creating higher torque

Perfluoropolyalkylether

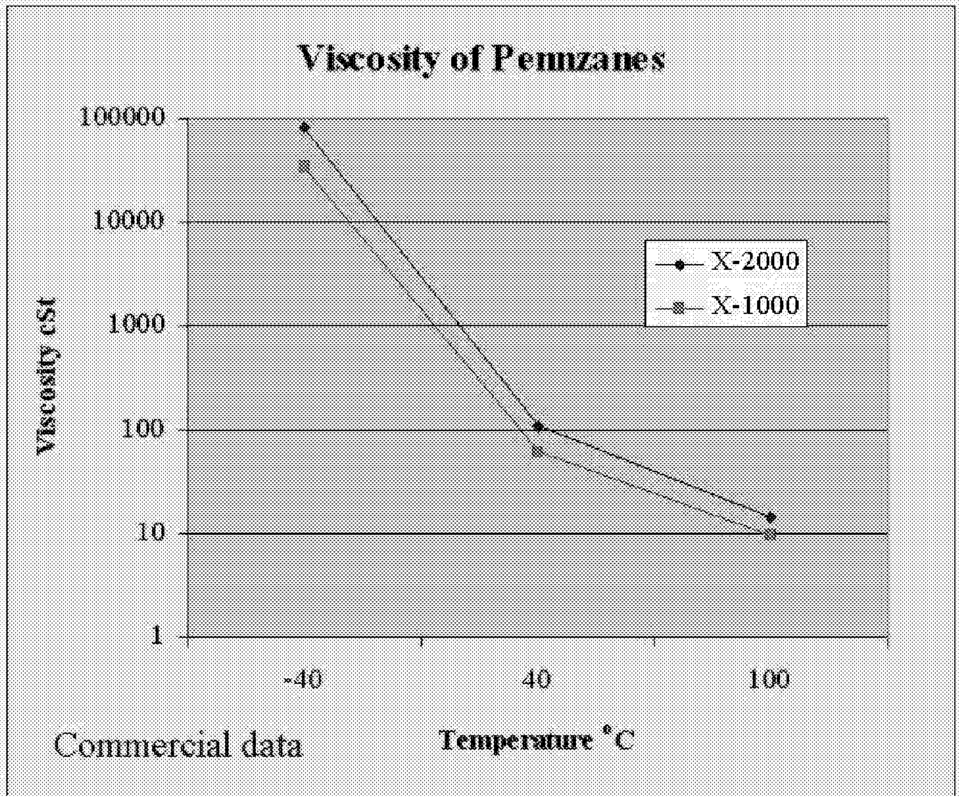
- Branched (Krytox) - Original
- Linear (Brayco) - Improved, excellent volatility, viscosity index , low temperature capability (-66°C pour pt, Z-25)
- All limited
  - ~100ksi Hertzian contact pressure
  - Tribocorrosion (brown sugar)
  - Few soluble additives

Multiply Alkylated Cyclopentane (Pennzane)

- Pennzane 2000 & Pennzane 1000*
  - Good viscosity index
  - Good low temperature (-45°C pour pt, 2000)
  - Additive receptivity, but low solubility
  - Low volatility

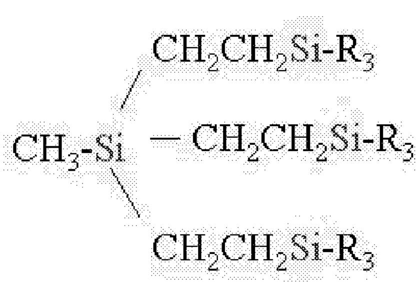
*Awaiting EPA approval

Pennzane is being used more and more in spacecraft and has many advantages over mineral oils or perfluoropolyalkylether oils.



Silahydrocarbons

Silahydrocarbon Structure



Kinematic Viscosity @ -40°C = 34,9104 cSt for R=n-$C_{10}H_{21}$

Kinematic Viscosity @ -40°C = 14,870 cSt for R=n-C_6H_{13}

Silahydrocarbons

- Advantages -
  - Excellent VI
  - Unimolecular - constant viscosity with evaporation
  - Low volatility
  - Low traction
  - Hydrocarbon chemistry - additive receptive, but low solubility
  - Tailor-able molecular weight

Silahydrocarbons

- Disadvantages -
  - Not commercially available, but industry interest (Nye Lubricants)
  - Little vacuum bearing data
  - No history in spacecraft

Silahydrocarbons

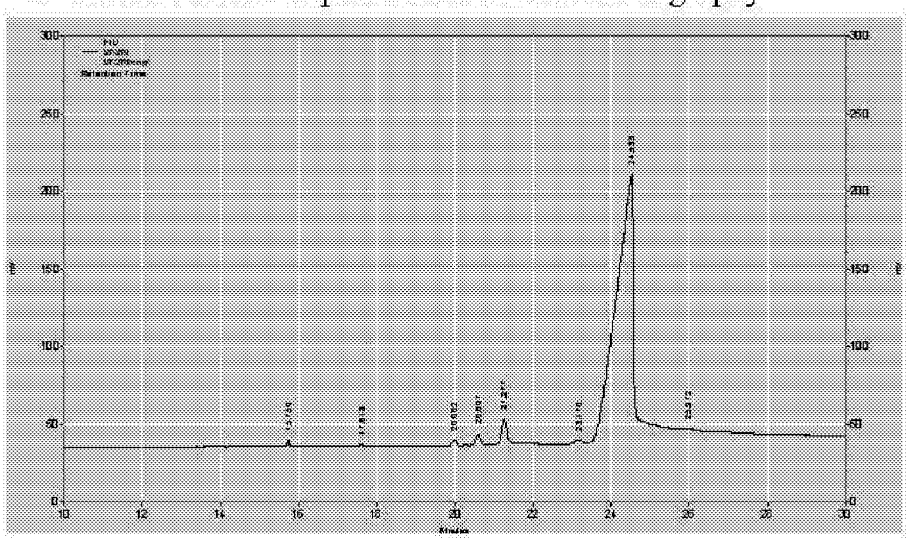
- Excellent viscosity index

Pennzane	Silahydrocarbon
139	170
Polyalphaolefin	Linear PFPAE, Z-15
145	320

Viscosity index is an indication of the fluid's liquid temperature range.
The higher the number the larger the temperature range.

Silahydrocarbons

- Unimolecular - Supercritical fluid chromatography



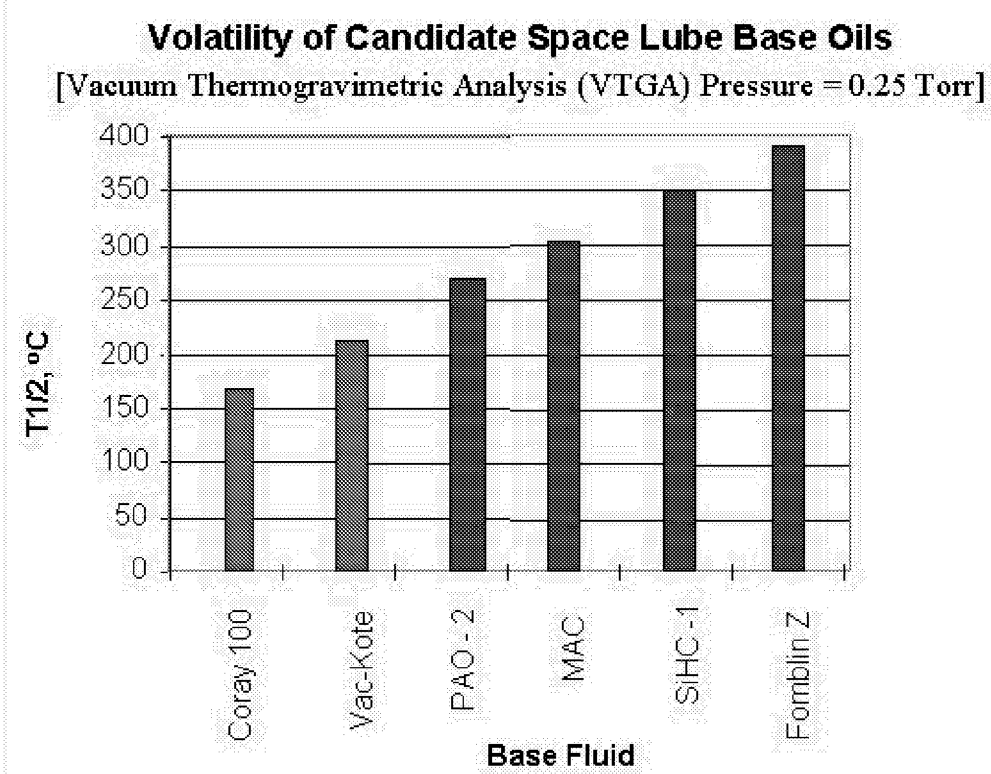
Shows a super critical fluid chromatogram of a silahydrocarbon fluid.
It is essentially unimolecular.

Silahydrocarbons

- Low Volatility - using vacuum TGA (thermogravimetric analysis)

Sample heated at a constant rate under 0.25 torr vacuum, to suppress thermal decomposition.

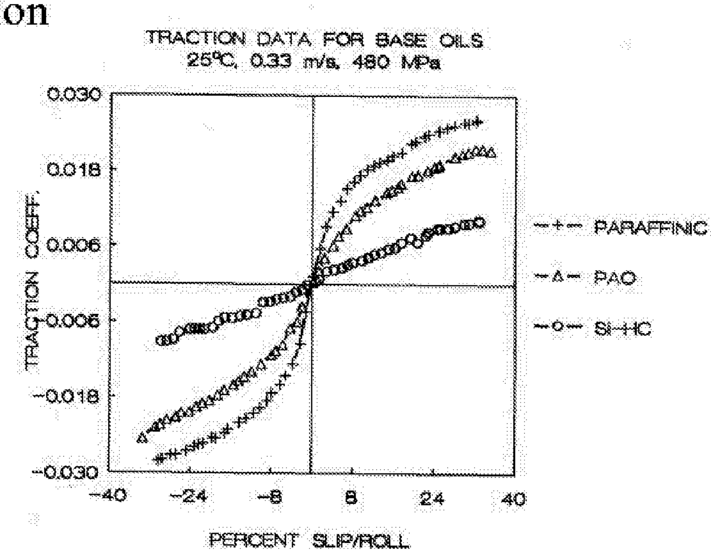
$T_{1/2}$ = temperature half of the oil has evaporated.



Shows T1/2, as described above, of several space lubricants.

Silahydrocarbons

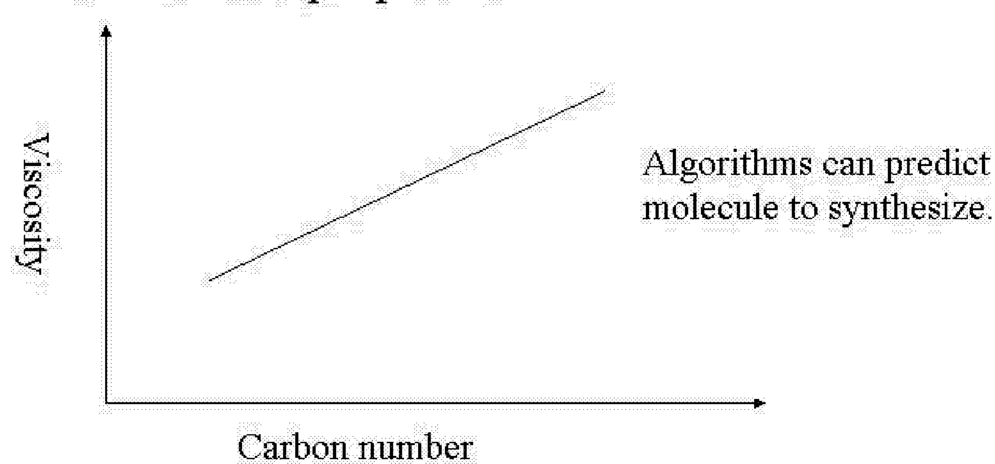
- Low Traction

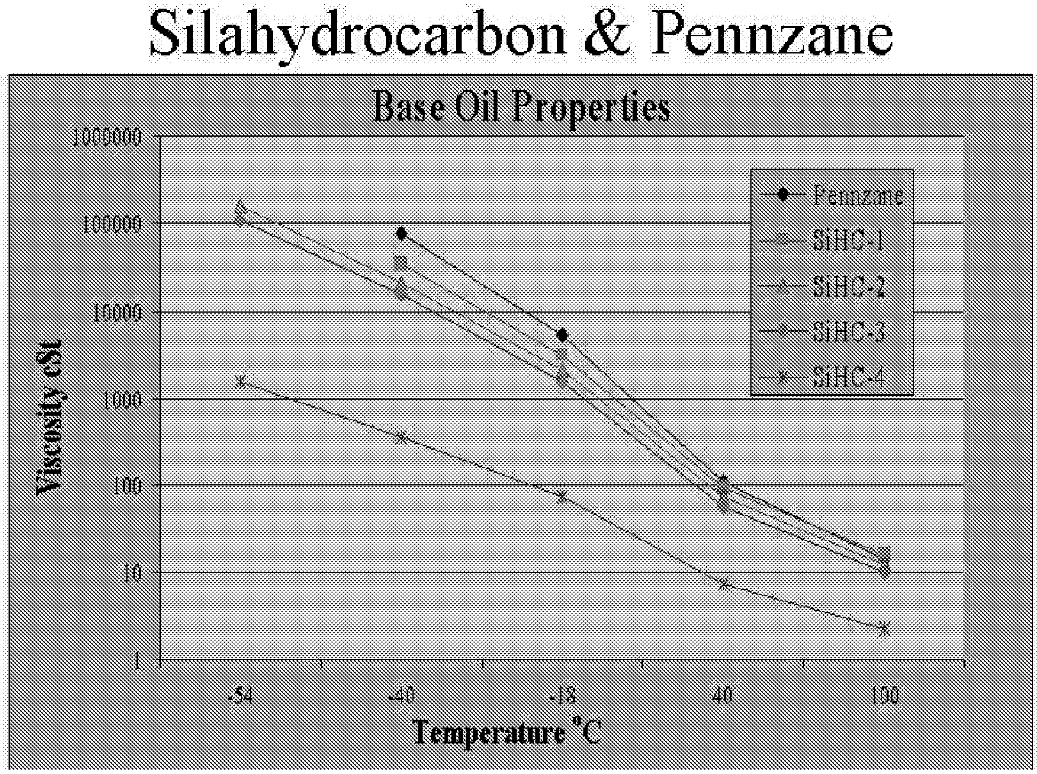


Shows a twin disk traction (torque) profile for three space lubricants.

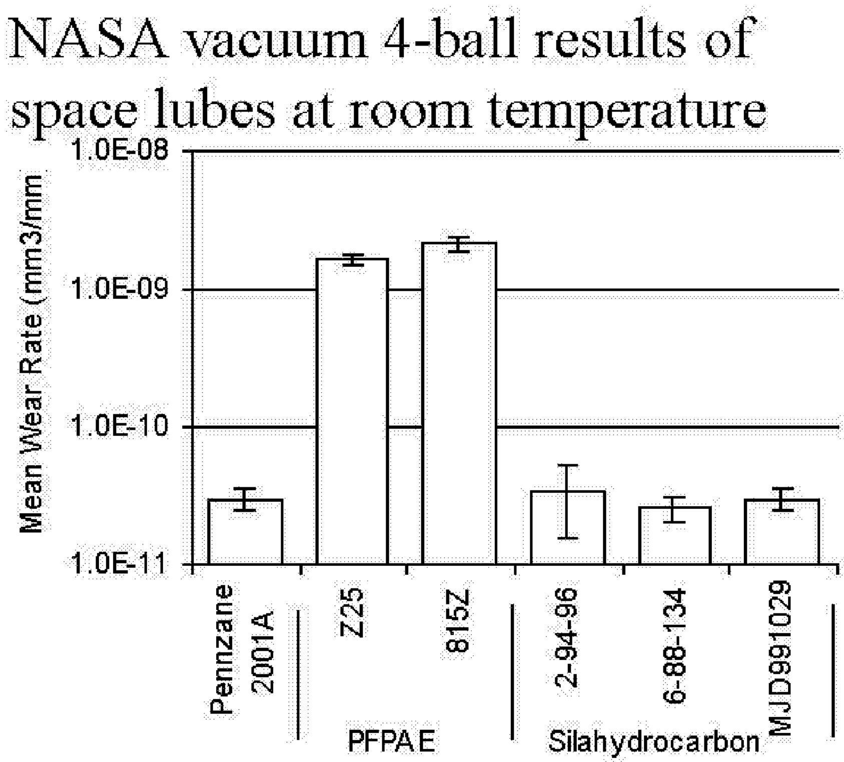
Silahydrocarbons

- Tailor-able properties



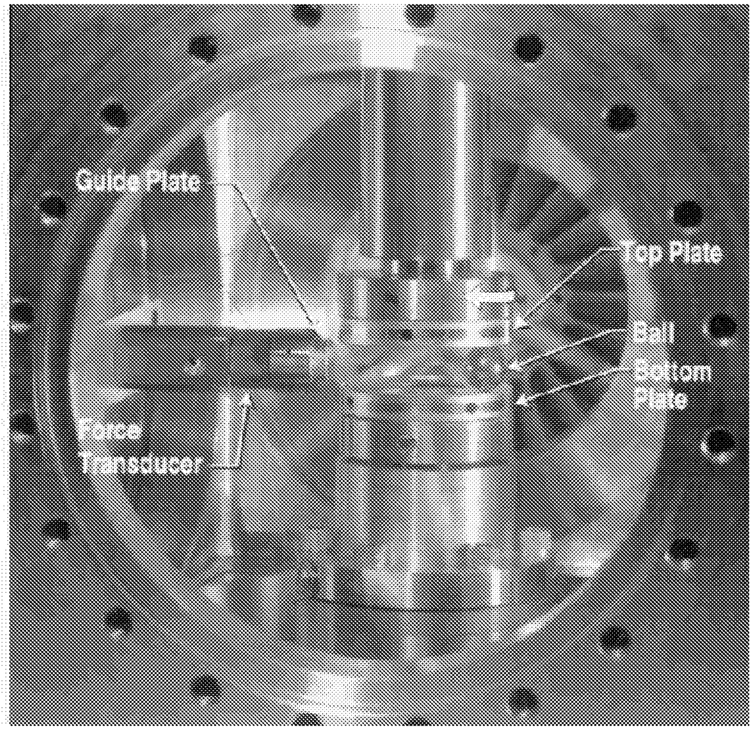


Shows viscosity temperature properties for silahydrocarbon and Pennzane lubricants.

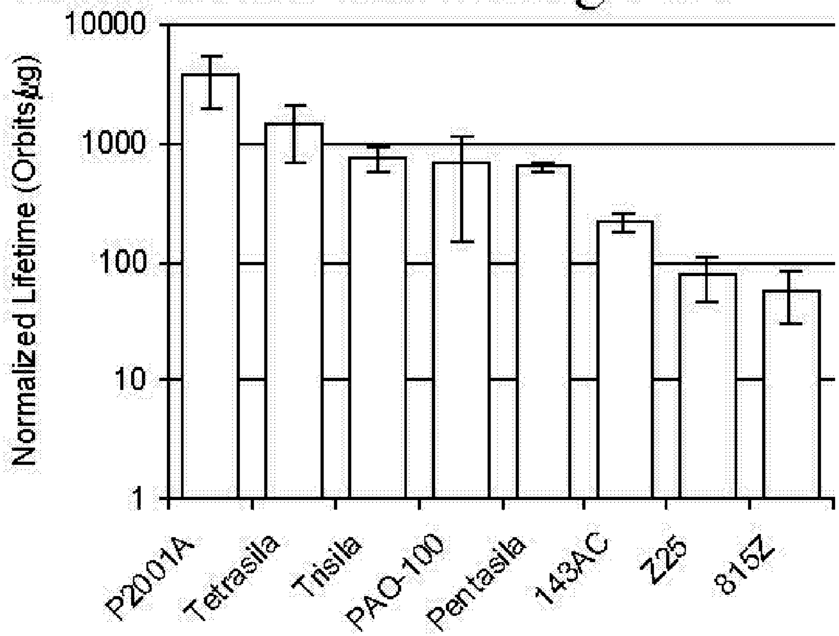


Shows wear rates for different space lubricants in vacuum 4-ball testers.

NASA Glenn Spin Orbit Tribometer (SOT)



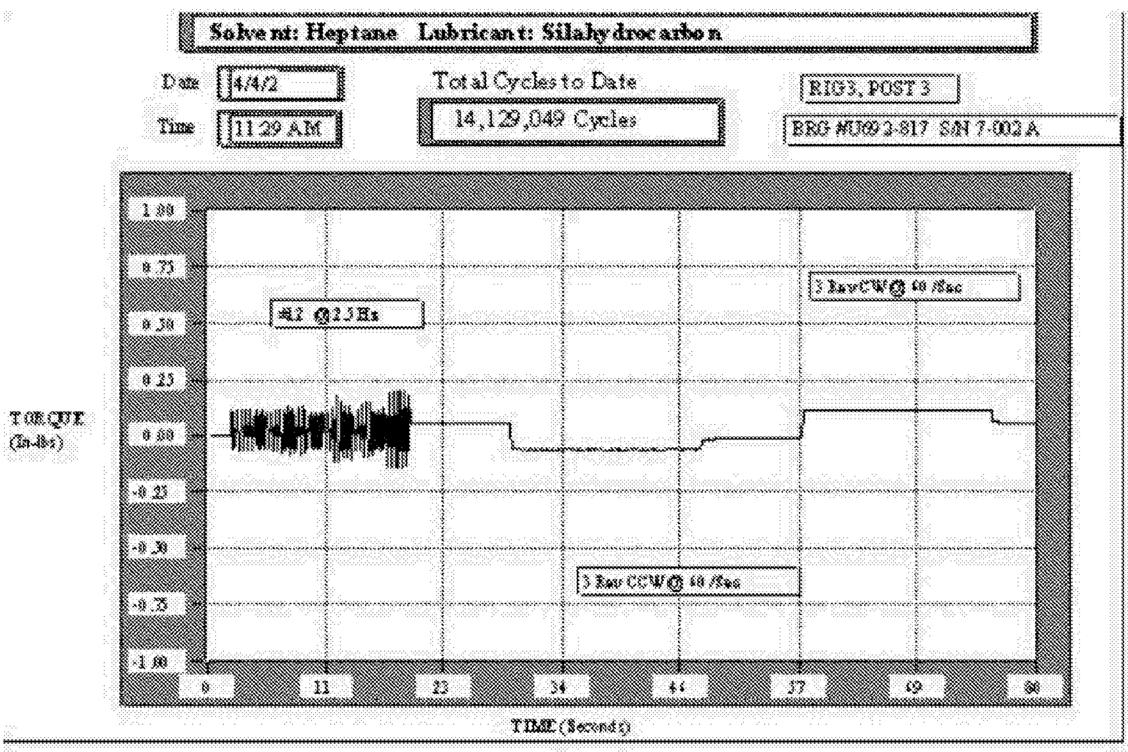
Relative lifetime at a mean Hertzian stress of 1.5 GPA using SOT



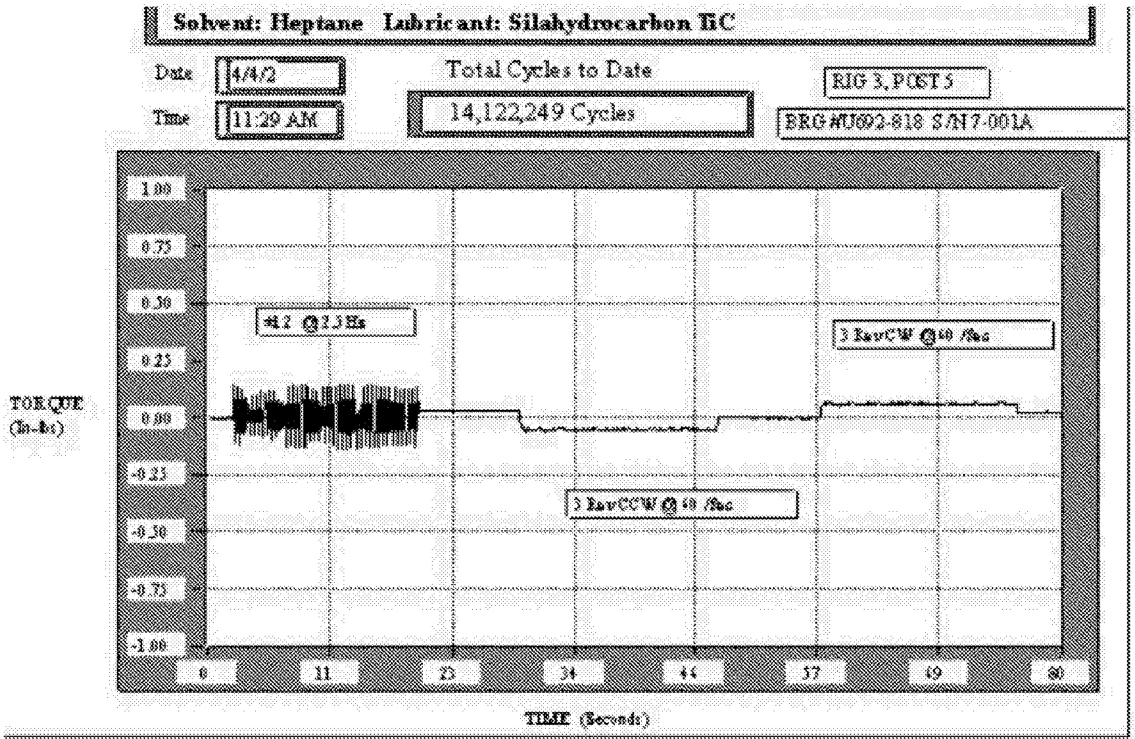
Shows results of Spin Orbit Tribometer tester at NASA Glenn for various space lubricants.

Lockheed Scanner Instrument Bearing Life Test

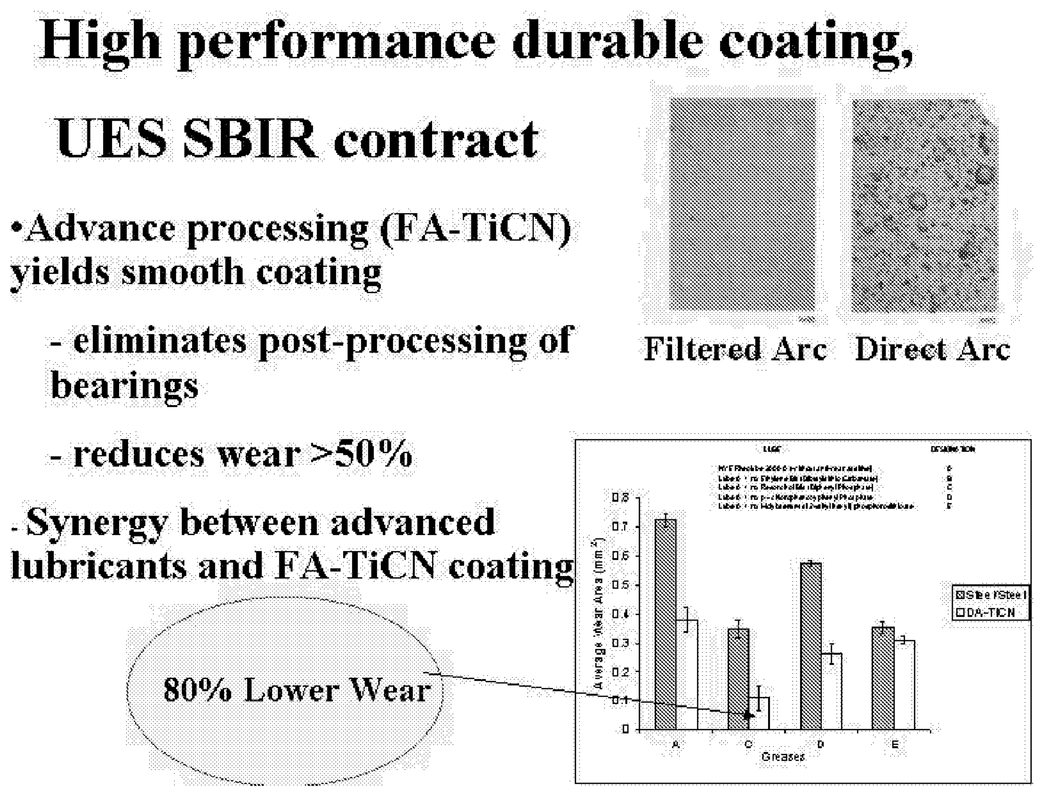
- Fluid: SiHC (-40°C visc 14,870 cSt) with antiwear and antioxidant additives
- Bearings: Angular contact duplex, 440C races, PTFE toroid separators
  - 2 pairs -TiC coated balls, 1 pair - steel balls
- Conditions: Gimbaling $\pm$ 12 deg, 2.5 Hz, 10^{-6} torr
- Test started 12/01, 14M cycles as of 4/4/02, smooth torque performance to date



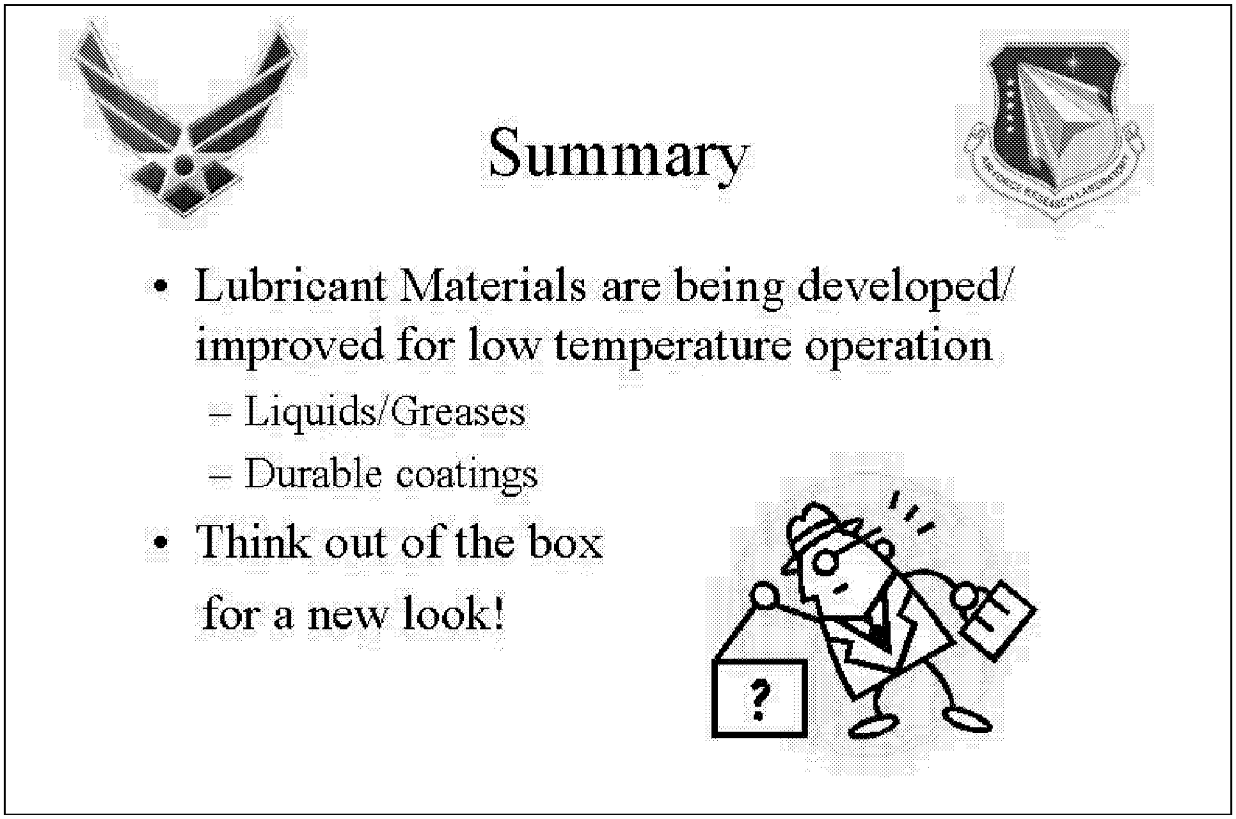
Torque readout of tester explained above showing smooth running of silahydrocarbon oil.



Torque readout of tester explained above showing smooth running of silahydrocarbon oil.



Favorable results from hard coatings on steel surfaces.



Using Condensed Gasses and Novel Liquids for Lubrication on the Martian Surface

Wilfredo Morales of the NASA Glenn Mechanical Components Branch discussed using condensed gasses as lubricants or working fluids for Martian exploration.

The future use of various land vehicles on the Martian surface is inevitable. These vehicles must be designed to function under the extreme conditions of the Martian climate. One critical design challenge is the lubrication system.

Lubricating oils, as we use them on Earth, will be useless on Mars unless extensive heating systems are employed to ensure flow. But the thought occurs, many common substances that are gases on Earth will be liquids on Mars. In particular, carbon dioxide will be a liquid in the cold Martian temperature with a moderate increase in pressure. This property of carbon dioxide along with its ability to dissolve a number of substances may allow the design of simple, reliable lubricating systems.

USING COMPRESSED GASES AND NOVEL LIQUIDS FOR LUBRICATION ON THE MARTIAN SURFACE

WILFREDO MORALES
MECHANICAL COMPONENTS BRANCH
GLENN RESEARCH CENTER

THE MARTIAN CLIMATE

- **Average temperature about –60 °C**
- **Summer highs about +20 °C**
- **Polar nights about -120 °C**
- **Principal atmospheric constituent CO_2**
- **Average atmospheric pressure 8 millbars**

SOJOURNER ROVER

- Afternoon of July 30th, temperature reached –13 °C
- At night temperature dropped to –73 °C
- Sojourner designed for –100 °C
- Batteries and electronics heated by radioisotope units
- Wheel drives used ball bearings consisting of plastic balls, aluminum races and no lubrication
- Spent 3 months traveling over Mars, 12 times longer than originally designed.

The Martian Surface

- Did running water cause the erosion features (channels, gullies and valleys) on the Martian surface?
- Kenneth Tanaka and co-workers have provided evidence that liquid CO_2 was responsible for Martian erosion.

Liquids of Interest for Lubrication Studies

- Isopropanol: liquid down to –85 °C. Vapor pressure 40 mbars at 20 °C
- 2-Butoxyethyl Acetate: liquid down to –64 °C. Vapor pressure 0.2 mbars 20 °C
- Fluoro-compound: liquid down to –70 °C. Vapor pressure 2.9 mbars at 25 °C

CO2 GELLATION

- Yale research team succeeded turning supercritical CO2 into gel form. Discovered a molecule that gelled supercritical CO2.
- This gellation process increased the viscosity of CO2 ten-fold.
- New research under way to extend gellation to gaseous and liquid CO2
- Thickener molecules consisting of CO2-philic functionalities including siloxanes, fluoroethers, and fluoro-acrylates.

Passive Magnetic Bearing Development

Mark Siebert, NASA Glenn Mechanical Components Branch discussed magnetic bearings for use on flywheel energy storage systems that are being considered as efficient energy storage devices for use on unmanned, low earth orbit satellites. These systems are expected to provide five to ten times improvement in specific energy storage capacity with longer life than current battery systems.

Low-loss magnetic bearings will be needed to support the flywheel rotor. For smaller satellites, we are investigating a simple system that uses only passive magnets for radial bearing support and jewel bearings for axial support.

This presentation describes a study on a 100 percent passive magnetic bearing flywheel rig with no active control components. The objective was to determine whether the bearing system has sufficient stiffness and damping built in to allow performance over the required speed range.

PASSIVE MAGNETIC
BEARING DEVELOPMENT

Mark Siebert
University of Toledo
NASA Glenn Mechanical Components
Branch
May 14, 2002

INTRODUCTION

- Active magnetic bearings are used by industry for rotor levitation
- Active magnetic bearings are also being considered for energy storage flywheels for space
- Active magnetic bearings requires complicated control hardware, such as digital signal processors, amplifiers, digital-to-analog converters, analog-to-digital converters, and software
- The control current for active magnetic bearings is proportional to the square of the rotor-stator gap
- Passive magnetic bearings do not require this control hardware

INTRODUCTION
(continued)

- Passive magnetic bearings have the disadvantage of lower stiffness and lower damping than similar size active magnetic bearings.
- Passive magnetic bearing systems must have sufficient stiffness and damping built in to allow them to perform over their entire operating range.
- Few studies have been performed on stiffness and damping of passive magnetic bearings using permanent magnets

OBJECTIVES

- Determine percent critical damping of system
- Determine stiffness of magnetic bearings
- Compare analytical stiffness and experimental stiffness results

BACKGROUND

- Passive magnetic bearings can be constructed using:

  -permanent magnets

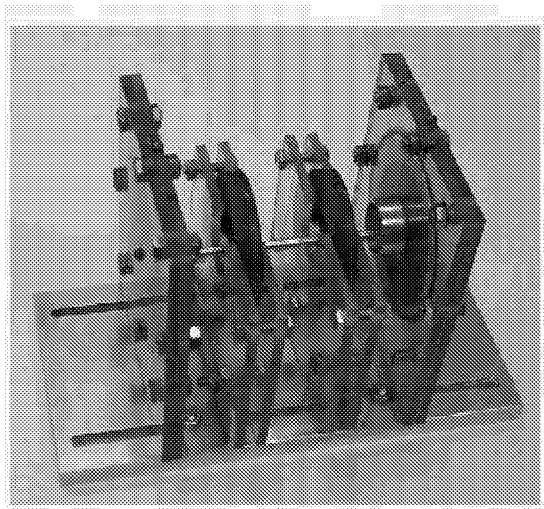
  -electrodynamic effects

  -superconductors

  -diamagnetic materials

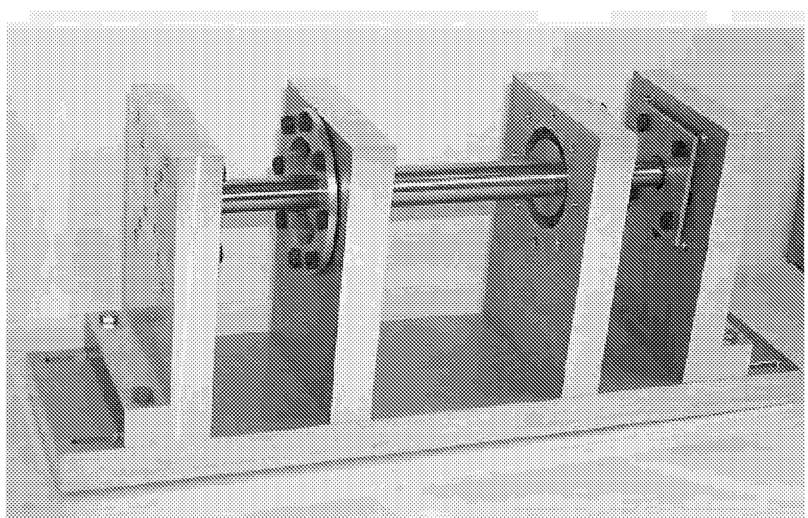
  -ferrofluids
- Earnshaw's theorem says that at least one axis must be unstable in three dimensional problems if using only static ferromagnetic fields
- Current design is based on two earlier passive magnetic bearings built at Glenn Research Center

FERROFLUID-STABILIZED BEARING



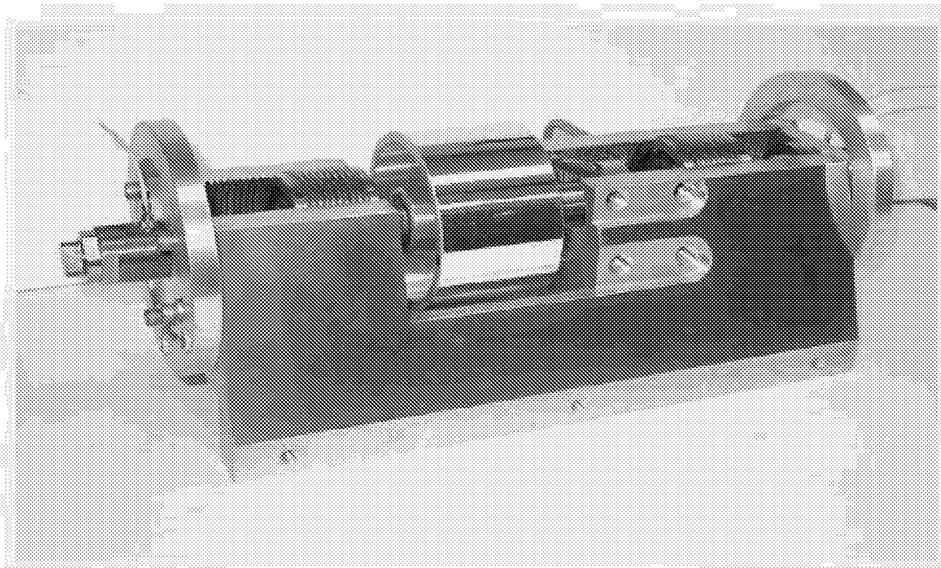
The rotor is suspended radially by two pairs of axially magnetized permanent magnets and axially by disk-shaped magnets in a ferrofluid-filled cavity.

PERMANENT MAGNETIC BEARING WITH AXIAL JEWEL BEARINGS



The rotor is suspended radially by two pairs of axially magnetized permanent magnets and axially by jewel bearings on both ends of the rotor.

REDESIGNED PERMANENT MAGNETIC BEARING



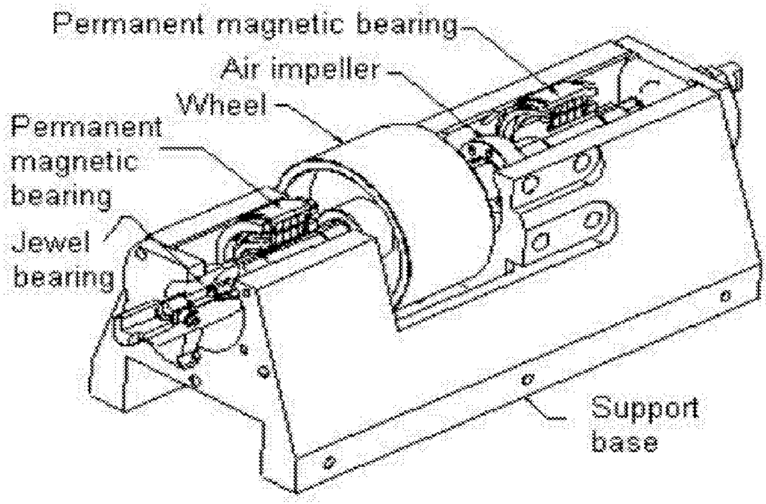
This rig is the result of improvements in the two designs shown above.

REDESIGNED PERMANENT MAGNETIC BEARING

IMPROVEMENTS FROM TWO PREVIOUS BEARINGS

- Load cells to measure axial load
- Air impeller to drive rotor
- Greater stiffness of magnetic bearings to support a heavier rotor
- Threaded stator magnets to adjust axial force

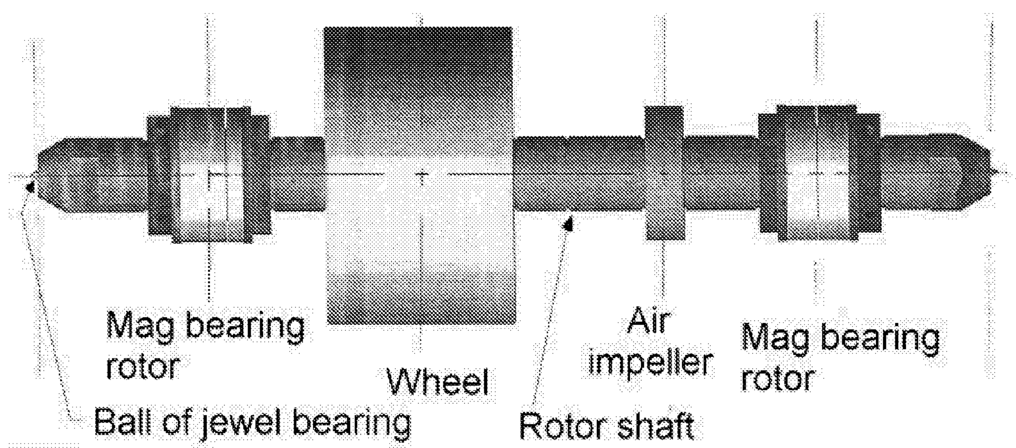
PERMANENT MAGNETIC BEARING



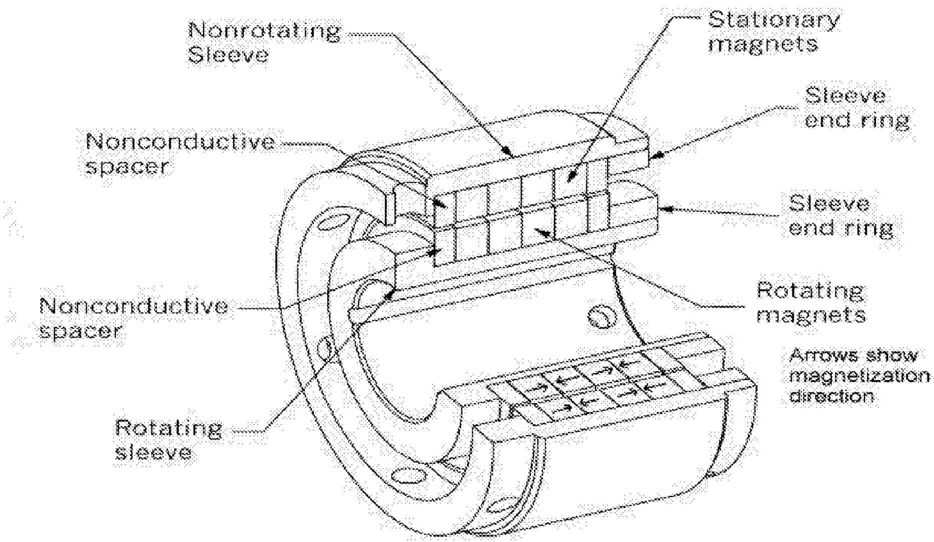
ROTOR

rotor mass=2.26 kg

rotor length=12.6 inch



SECTIONED VIEW OF PERMANENT MAGNETIC BEARING

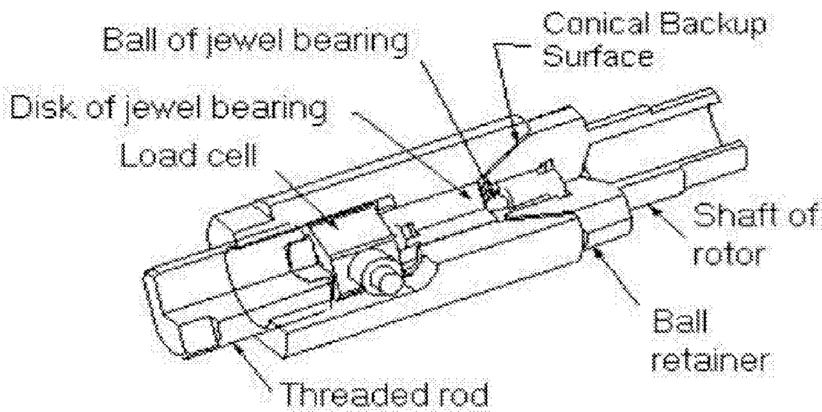


The magnets are stacked with like poles adjacent to each other.

PERMANENT MAGNETIC BEARING

- Neodymium-Iron-Boron magnets used in bearing
- Magnets have an energy (BH) product of 35 MGOe (MegaGauss-Oersted)
- Bearings operate in repulsion mode
- Four laminations of magnets on rotor and stator
- Magnets stacked with like poles adjacent
- Rotor and stator magnets have a nominal 1.27 mm (0.05inch) gap

JEWEL BEARING ASSEMBLY



The ball of the jewel bearing is a 3.175 mm (0.125 inch) silicon nitride ball.
The disk of the jewel bearing is 440C stainless steel.

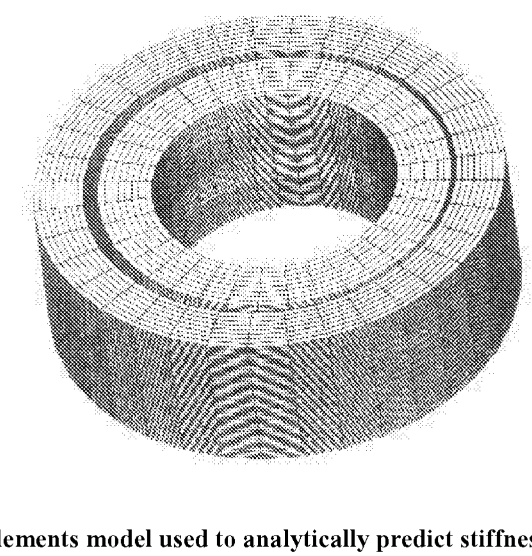
JEWEL BEARING

- Jewel bearings on both ends of rotor
- Jewel bearing consists of silicon nitride ball on 440C stainless steel disk
- Retainer holds ball in center of rotor and 1.27mm (.050inch) of ball extends beyond retainer surface
- Piezoelectric load cell to measure axial load on both ends of rotor behind disk of jewel bearing

RADIAL STIFFNESS BY FINITE ELEMENT METHOD

- 77760 node brick elements in finite element model
- Magnetostatic solver used to solve for distribution of magnetic field
- Maxwell stress tensor integrated over surface of inner ring magnets
- Finite element method stiffness was found to be 1.87 $\times 10^5$ N/m (1.07×10^3 lb_f/in)

FINITE ELEMENT MODEL OF RING MAGNETS OF MAGNETIC BEARING

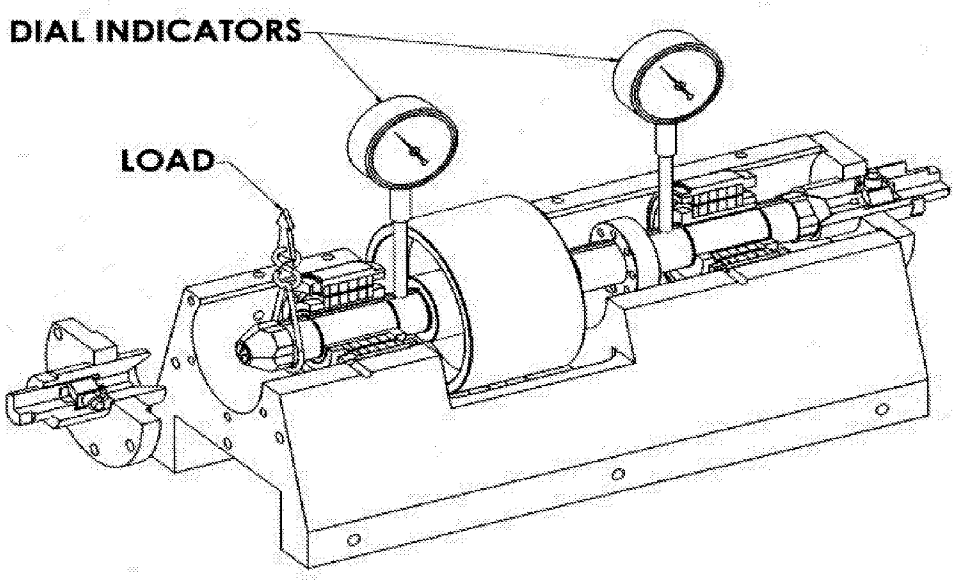


Schematic of finite elements model used to analytically predict stiffness of magnetic bearing.

PROCEDURE FOR MEASURING RADIAL STIFFNESS

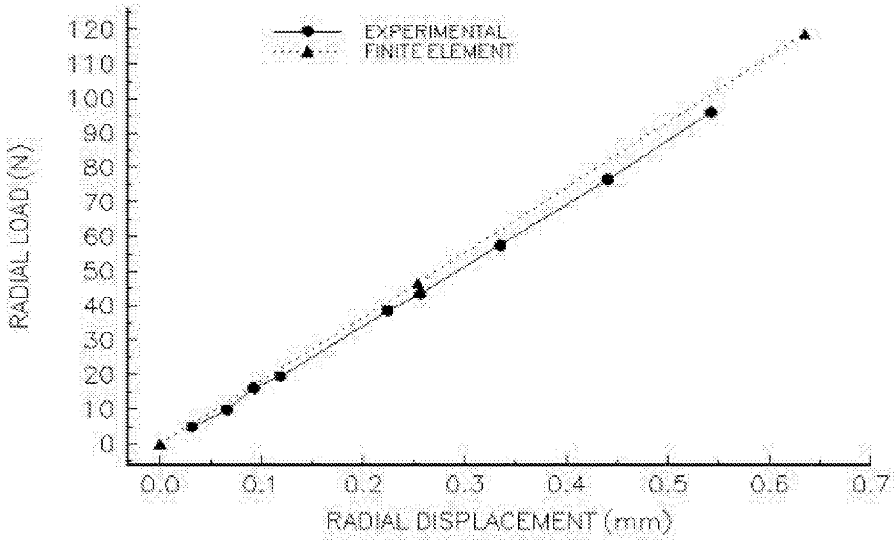
- Rotor was loaded against one jewel bearing
- Disk of unloaded jewel bearing was removed
- Radial stiffness was determined by loading a series of weights on the shaft near the free end and measuring the displacement
- Experimental radial stiffness was found to be 1.78×10^5 N/m (1.02×10^3 lb_f/in)

RADIAL STIFFNESS MEASUREMENT



Experimental measurement of magnetic bearing radial stiffness.

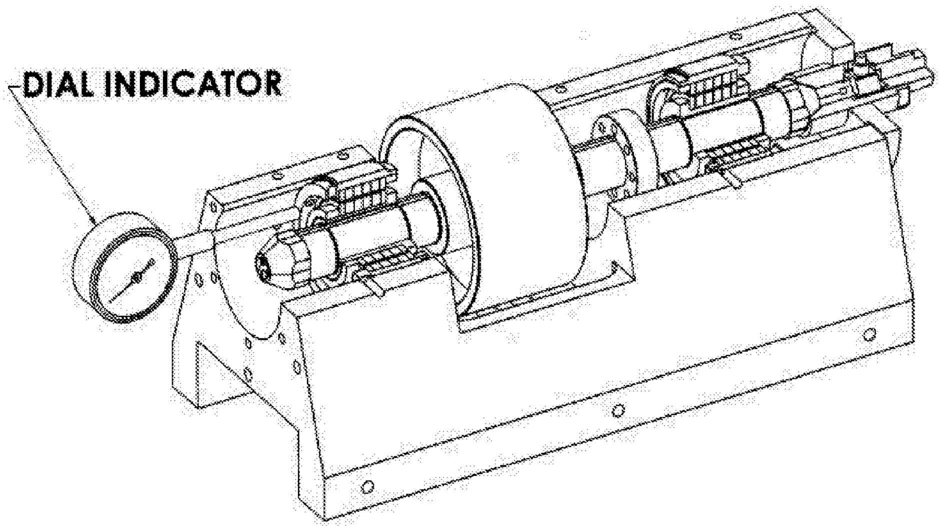
RADIAL LOAD VERSUS DISPLACEMENT FOR ONE MAGNETIC BEARING



PROCEDURE FOR MEASURING AXIAL STIFFNESS

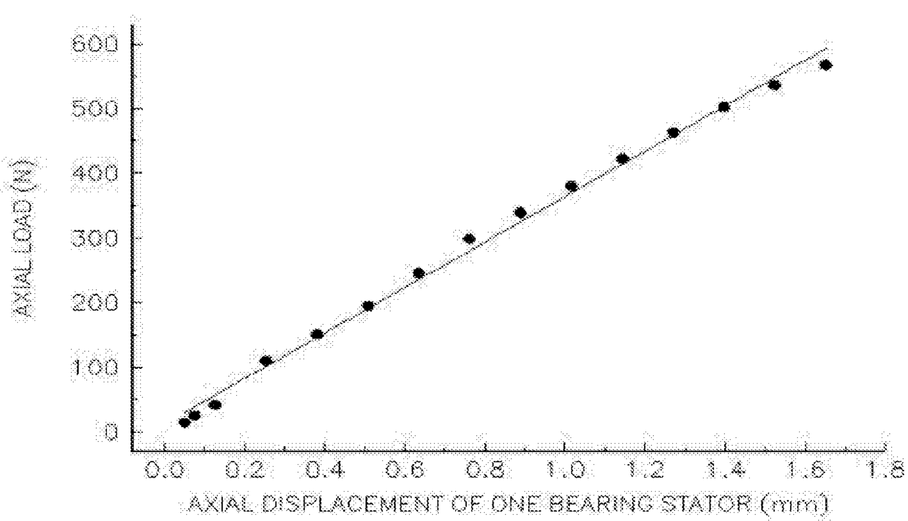
- Rotor was loaded against one jewel bearing
- One magnetic bearing stator was rotated while measuring the axial load against the loaded jewel bearing with piezoelectric load cell
- The bearing stator was incrementally rotated to produce a series of axial loads
- Experimentally measured axial stiffness was found to be 3.52×10^5 N/m (2.01×10^3 lb_f/in)

AXIAL STIFFNESS MEASUREMENT



Experimental measurement of magnetic bearing axial stiffness.

AXIAL LOAD AS A FUNCTION OF DISPLACEMENT



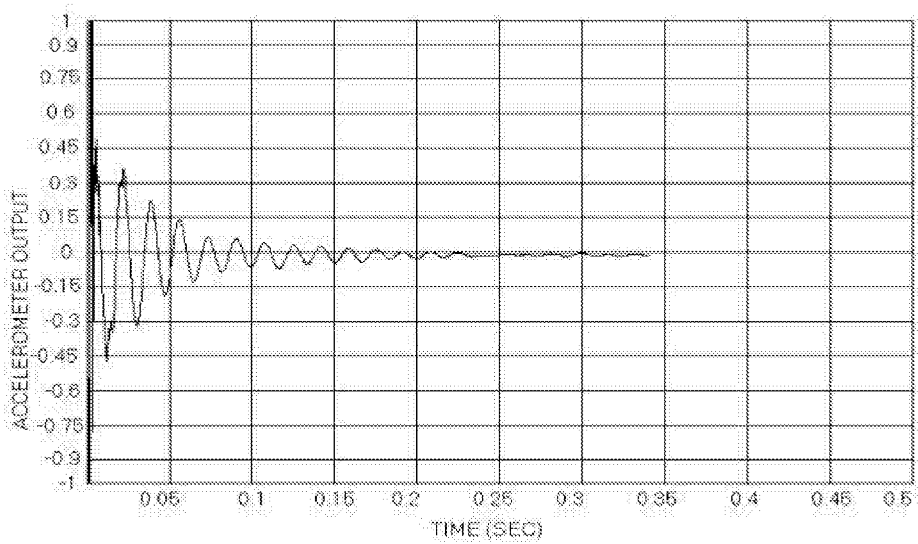
IMPACT TEST PROCEDURE AND RESULTS

- Rotor was loaded against one jewel bearing
- The disk of the non-contacting jewel bearing was removed to allow the rotor to vibrate about the loaded jewel bearing end
- A frequency analyzer was used to record the time history of rotor after it was struck with the instrumented hammer
- From the time history of the rotor, the frequency response was determined
- From the frequency response, the first natural frequency was found to be 55.6 Hz

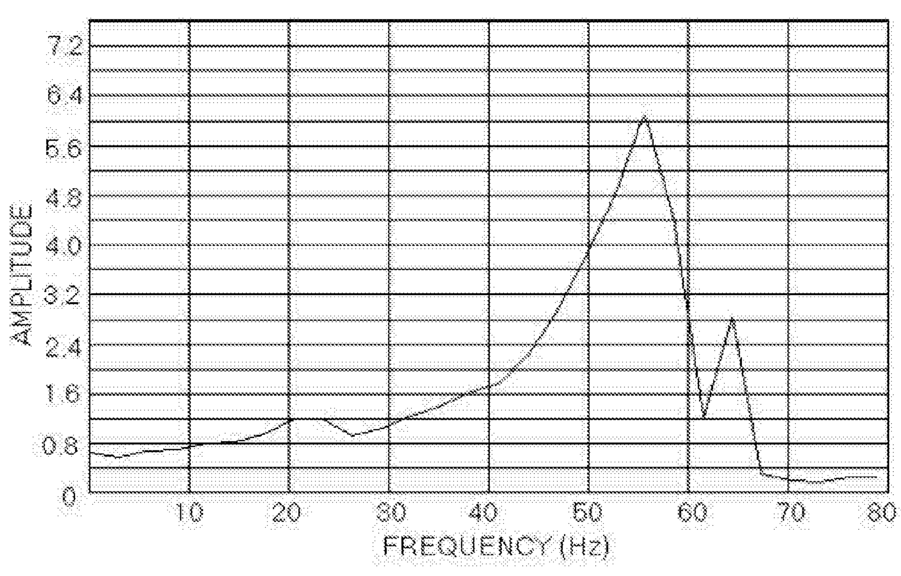
DAMPING

- The log decrement is a measure of the damping factor and gives a convenient method to measure the damping of a system
- The damping coefficient was calculated by two methods: (1) log decrement and (2) half-power bandwidth

TIME HISTORY OF ROTOR FROM IMPACT TEST



FREQUENCY RESPONSE OF ROTOR



DAMPING RESULTS

- The damping coefficient calculated by using the log decrement method was 6.5 percent
- The damping coefficient calculated by using the half-power bandwidth method was 6.9 percent
- The two values are in good agreement

SPIN TESTING

- 120 psig air line connected to air impeller
- Rotational speed measured with timing light
- Ran through first critical speed to 5500 rpm
- 65 percent more than first critical speed

CONCLUSIONS

- A permanent magnetic bearing was designed, built, and successfully operated to 5500 rpm, 65 percent above first critical
- First critical is 3336 rpm from first peak of frequency response
- Radial stiffness of one magnetic bearing is within 5 percent of finite element prediction, so FEM can be used to design the magnetic bearings
- Radial damping coefficient of first fundamental is 6.5 percent
- Experimentally measured axial stiffness is twice radial stiffness within 1 percent--a consequence of Earnshaw's theorem

Eddy Current Damper for Cryogenic Applications

Scott Starin and Fred Crosno of CDA Intercorp discussed the advantages of the use of eddy current dampers. Eddy current dampers offer reliable, repeatable damping characteristics over a wide temperature range. The test results proved the low static friction eddy current dampers may be used as a direct replacement for fluid dampers (form, fit, and function) with much higher reliability.

Eddy Current Damper for Cryogenic Applications

Presented at Space Mechanisms Technology Workshop
May 14th, 2002
NASA, Glenn Research Center

by: Scott Starin, Fred Crosno
CDA InterCorp
Deerfield, FL

Overview

- Need for Cryogenic Energy Absorption
- Eddy Current Damper Theory of Operation
  - High Speed Damper Characteristics
  - Gearbox Characteristics
  - What is Needed for Cryogenic Operation
- Operating over Temperature
  - Theoretical Analysis
  - Empirical Results

The Need for Cryogenic Energy Absorption

- Fluid Damper Limitations
- Desire to Eliminate Temperature Regulation for Passive Deployables
- Out-gassing in Critical Applications
- Extreme Thermal Applications
  - NGST
  - MESSENGER

High Speed Damper Characteristics

- Determine:
  - Damping Rate of High Speed Damper (slope of line)
  - Temperature Coefficient
  - Mechanical Static Friction
  - Magnetic Coulomb Friction
  - Lubrication Effects

    - Refer to "*Eddy Current Damper Simulation and Modeling*" presented at 9th ESMATS, Liege 2001

High Speed Damper (HSD) Characteristics

- Damping Rate of HSD = 4.6 E-04 N*m*s/rad
- Mechanical Static Friction of HSD = 0.2 mNm
- Magnetic Coulomb Friction of HSD = 1.0 mNm
- Temperature Coefficient of Damping = -0.4% / K
- Lubrication: Solid Film – Vacuum Stable
  - -188 C to +500 C Operating Temperature Range

Gearbox Characteristics

- As reaction torque of ECD increases with speed, so does the reaction torque contribution from the Gearbox.
- Determine:
  - Damping Rate of Gearbox (slope of line)
  - Temperature Coefficient
  - Coulomb Friction
  - Lubrication Effects

Gearbox Characteristics

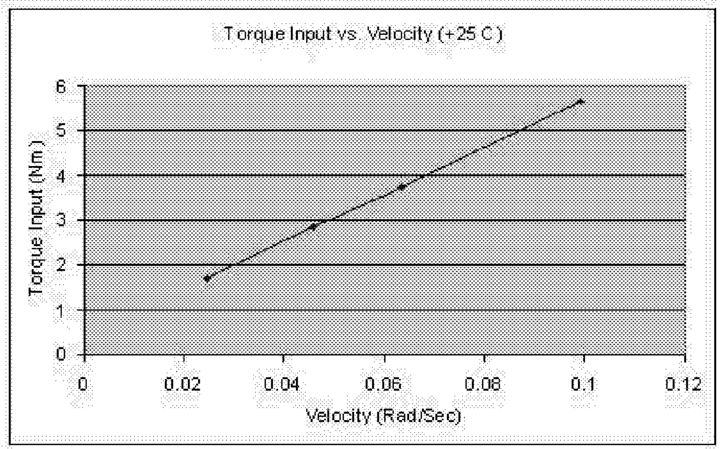
- Data:
  - About 25% of Damping of High Speed Damper
  - Temperature Coefficient of Damping = -0.1% / K
  - Coulomb Friction = 0.2 mNm reflected to high speed damper
  - Gear Ratio = 305:1 for this example
  - Lube effects
    - Vacuum Stable
    - Temperature Invariant

Composite Assembly Characteristics (for this example)

- Dynamic Damping Rate of ECD @ 3.5 Nm : 61 N*m*s/rad
- Mechanical Static Friction of ECD : 0.055 Nm
- Magnetic Coulomb Friction of ECD : 0.34 Nm
- Total Coulomb Friction ($F_{\omega \to 0}$) : 0.395 Nm
- Temperature Coefficient of Damping : -0.5% / K
- Mass : 275 grams (<9.75 Oz)

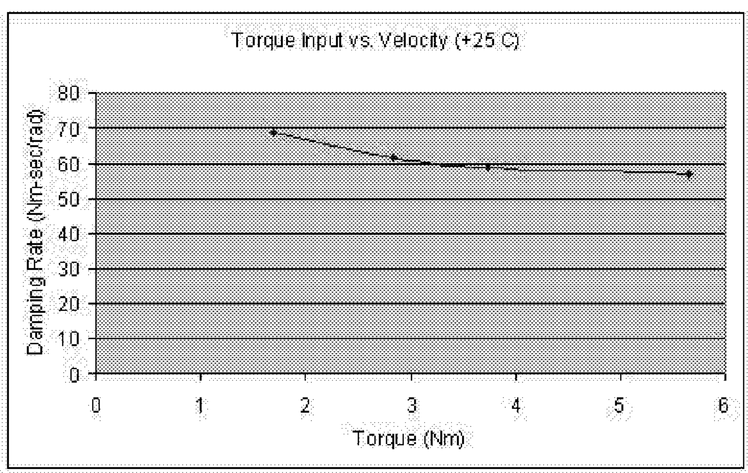
Composite Assembly Characteristics

- Damping Rate at Low Speed Input Shaft = slope of T vs ω Curve
- Coulomb Friction at Low Speed Input Shaft = Y intercept



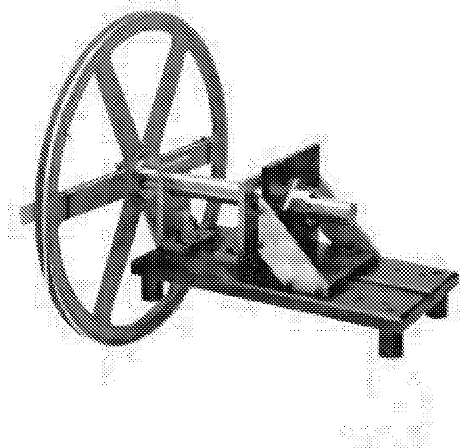
Composite Assembly Characteristics

- Dynamic Damping Characteristic – Non-linear due to Magnetic Coulomb Offset



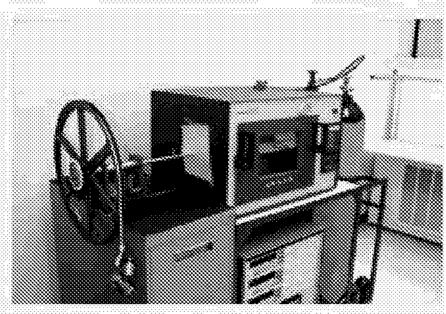
Testing an ECD Assembly

- Apply Pure Torque
- High Torsional / Radial Stiffness
- Tight alignment tolerances (axial, perpendicular etc…)
- Easily accommodate different torque values

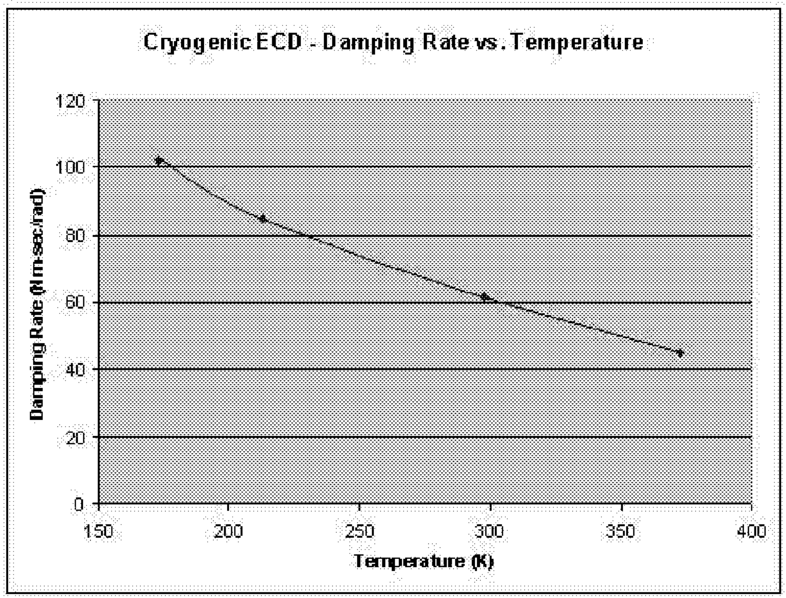


Conducting The Test

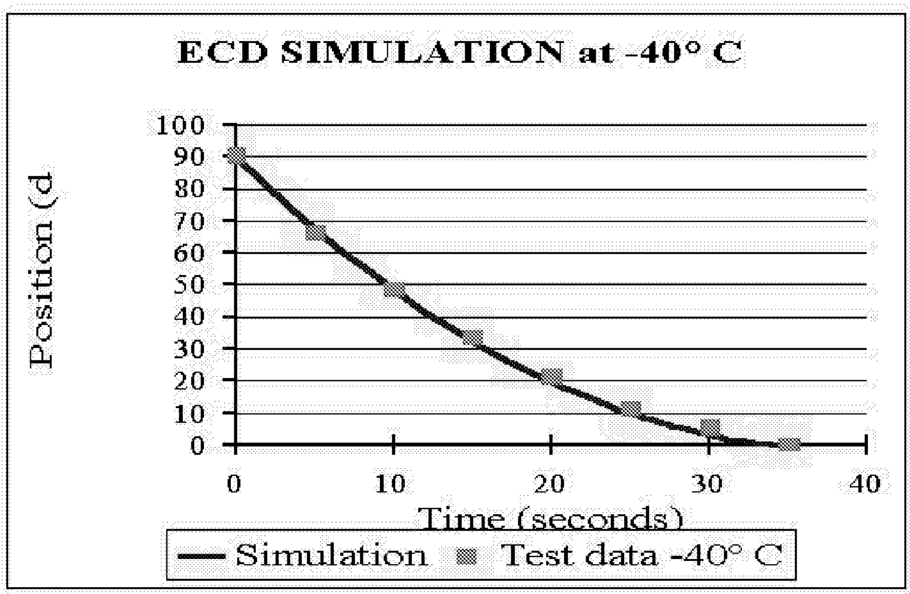
- Mass on Flywheel
- Record Angular Displacement vs. Time
- Tested in temperature chamber from -100° C to +100 ° C



Test Results



Test Results vs. Simulation (for ESMATS Paper)



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13. ABSTRACT *(Maximum 200 words)*

The Mechanical Components Branch at NASA Glenn Research Center hosted a workshop on Tuesday, May 14, 2002, to discuss space mechanisms technology. The theme for this workshop was "Working in the Cold," a focus on space mechanisms that must operate at low temperatures. We define "cold" as below –60 °C (210 K), such as would be found near the equator of Mars. However, we are also concerned with much colder temperatures such as in permanently dark craters of the Moon (about 40 K).

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