NASA/CP—2001-210971

Space Mechanisms Technology Workshop

Proceedings of a conference held at and sponsored by
NASA Glenn Research Center
Cleveland, Ohio
November 2, 2000

National Aeronautics and
Space Administration

Glenn Research Center

June 2001

Acknowledgments

There were many people whose contributions made this workshop possible. It started with the organizing committee: Robert Fusaro, James Zakrajsek, Rebecca Kwiat, Robert Handschuh, Wilfredo Morales, Mark Siebert, and Fred Oswald. The workshop began with the friendly faces at the registration table: Rebecca Kwiat and Barbara Alexander. It continued with a welcome by Gerald Barna, Acting Deputy Director of Glenn Research Center. Our invited speakers, William (Red) Whittaker and Stuart Loewenthal, shared their expertise and experience in space mechanisms. The Working Group moderators guided small group discussions: Stuart Loewenthal, Robert Fusaro, Romer Predmore, Wilfredo Morales, Red Whittaker, and Fred Oswald. Guides and presenters for the facilities tours were Mark Siebert, James Zakrajsek, Fred Oswald, Robert Fusaro, Wilfredo Morales, Robert Handschuh, and David Lewicki. Finally, we acknowledge the participation by our guests. They really made the Workshop a success.

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Springfield, VA 22100

Available electronically at http://gltrs.grc.nasa.gov/GLTRS

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Summary

The Mechanical Components Branch at NASA Glenn Research Center hosted a workshop to discuss the state of drive systems technology for space exploration. The Workshop was held Thursday, November 2, 2000. About 70 space mechanisms experts shared their experiences from working in this field and considered technology development that will be needed to support future space exploration, for the next 10 to 30 years.

Introduction

Mechanical drives are required to 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 a mechanism. Space exploration applications range from nearly microscopic in size to very large machines that will be needed for mining on alien worlds. Speed requirements range from ultra-slow (stiction) to tens of thousands of rpm.

This report summarizes material presented at the Workshop and the findings of the working groups. These groups attempted to predict what research will be required for the drive mechanisms that will be a crucial part of vehicles needed for future space missions.

Mechanical Components Branch Overview

Mr. James Zakrajsek, chief of the Mechanical Components Branch, presented 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.

In space mechanisms, we conduct fundamental research on lubricants, materials, components and mechanisms subjected to deep space and planetary environments.

Mechanical Components Branch
NASA Glenn Research Center

"Performing research and development

in mechanical components

and system technologies

Thermal Barrier Seals

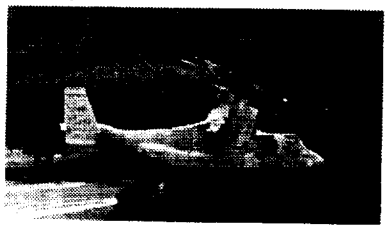
to improve the performance, reliability, and integrity

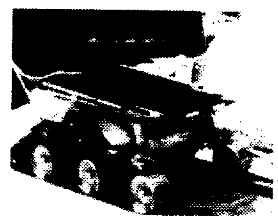
of aerospace drive systems,

high temperature seals,

and space mechanisms."

Drive Systems





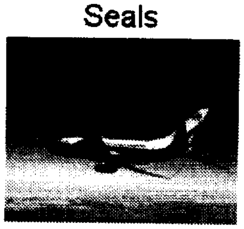
Mechanisms for Space Applications

MCB Overview 10/00

Mechanical Components Branch

Core Technologies

Seals



- *contacting turbine seals*
- *non-contacting turbine seals*
- *thermal barrier seals development*
- *seal thermodynamics and hysteresis*
- *structural seals development*

Drive Systems

- *drive systems lubrication and thermodynamics*
- *fracture mechanics*
- *drive systems dynamics and noise*
- *gear fatigue*
- *gear diagnostics*
- *bearings development*

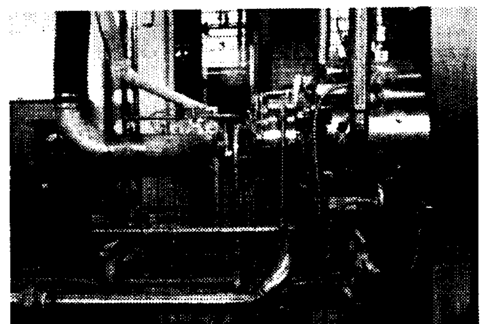
Space Mechanisms

- *lubrication in space environment*
- *space mechanisms design guidelines*
- *coatings research*
- *bearings for space environments*
- *mechanical drives for planetary rovers*

Mechanical Components Branch

Turbine Seals Research and Development

- Advanced brush and finger seals developed and being incorporated into new engine designs
- A unique, world class turbine seal rig developed and installed at GRC
  - 1500 degrees F temperatures
  - 1500 feet/sec surface speeds
  - capable of planned misalignment
- Advanced, non-contacting mechanical seal and acoustic - based seal concepts currently being developed



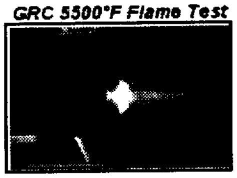
High Temperature Turbine Seal Rig Installation

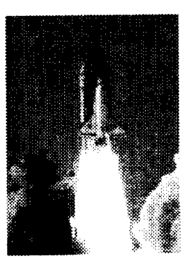
Mechanical Components Branch

Seal / Thermal Barrier Development for Space Transportation Programs

Developed thermal barrier for Thiokol to block hot (5500 F) gases from damaging Viton O-rings in Space Shuttle Solid Rocket Motor

GRC 5500°F Flame Test



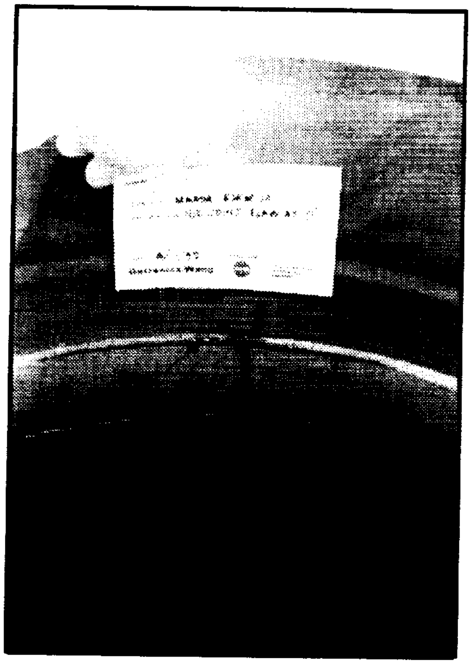


Assist JSC in developing control surface seals to prevent hot, re-entry gas ingestion/damage of control surface hardware

X-38 Control Surface Seal Development

Developed conceptual design of inter-engine seal showing promise of accommodating large 1-3" deflections in hot 3000+ F flow environment between aerospike engine modules

Mechanical Components Branch



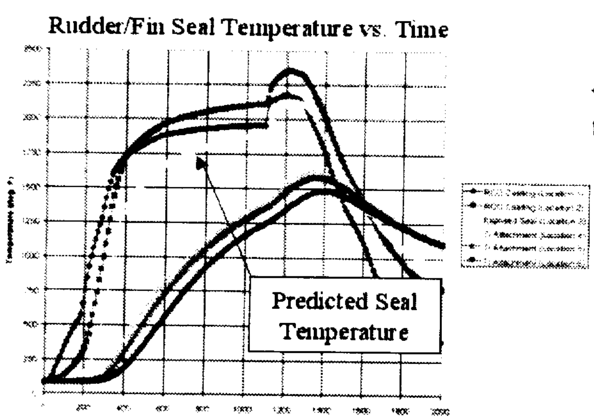
NASA GRC Thermal Barrier Feasibility Proven in MNASA RSRM Motors

GRC Thermal barrier <u>successfully</u> tested in redesigned nozzle-to-case joint with intentional flaw in nozzle insulation in MNASA-10 1/5th scale RSRM motor

Hot combustion gases passed through flaw and impinged on thermal barrier with no damage or erosion to thermal barrier or downstream O-rings

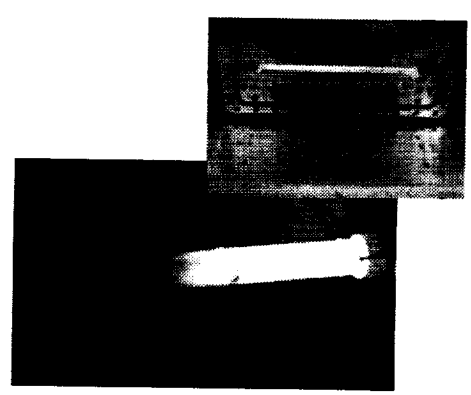
Mechanical Components Branch

X-38 Control Surface Seal Exposure Testing at GRC



🡐 JSC predicts that temperatures for Rudder/Fin Seal will likely reach 1900°F

GRC performs furnace exposure tests on X-38 seal in compressed state at 1900°F, in addition to ambient linear seal flow tests 🡒

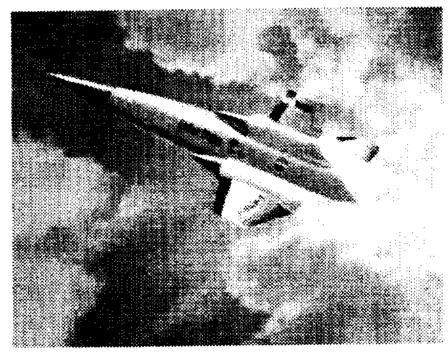


Mechanical Components Branch

Advanced Air-breathing Propulsion Systems Seals

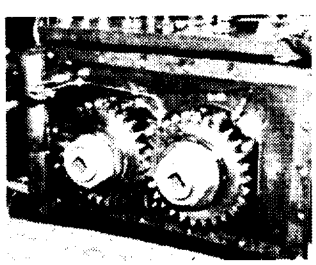
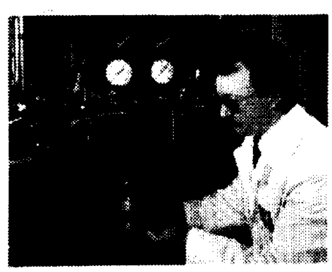
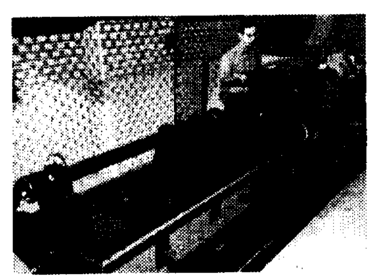
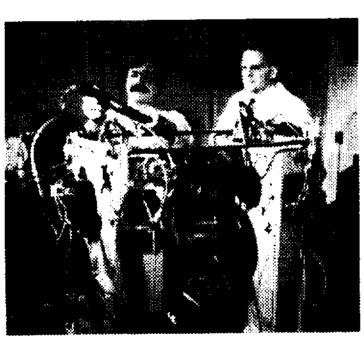
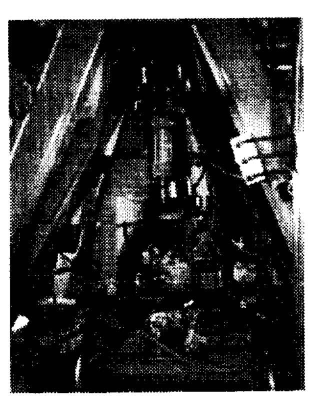
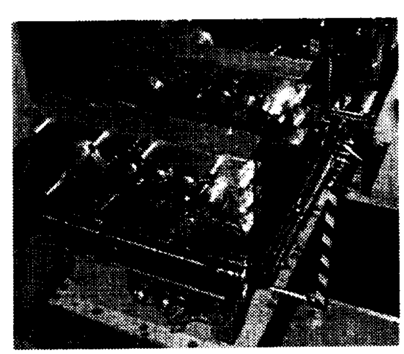
Reusable ram/scramjet engine (RBCC/TBCC) challenges

- Engine structure changes configuration with flight Mach number
- Designers planning on variable geometry for both inlet (inlet door or translating center-body) and moveable nozzle ramp(s)
- Seals must be prime reliable and have adequate life to meet mission goals


Rocket Based Combined Cycle (RBCC) Concept

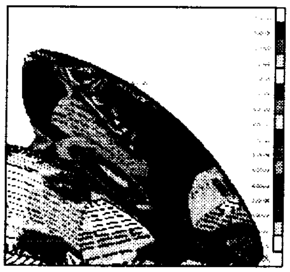
Mechanical Components Branch

Drive Systems Experimental Facilities NASA Glenn Research Center

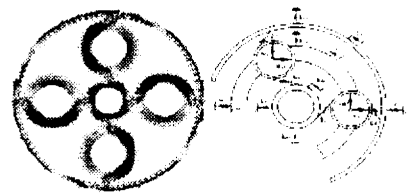







Mechanical Components Branch

Drive Systems Analytical Capabilities

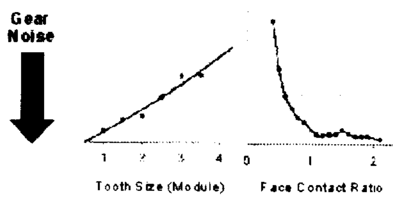


Finite Element Based
Structural - Thermal

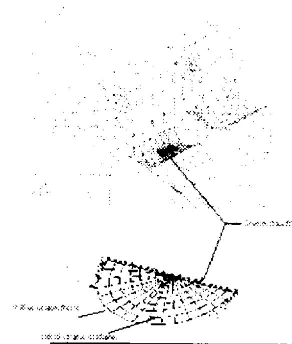


Planetary Gear Dynamics

Physics-Based Models



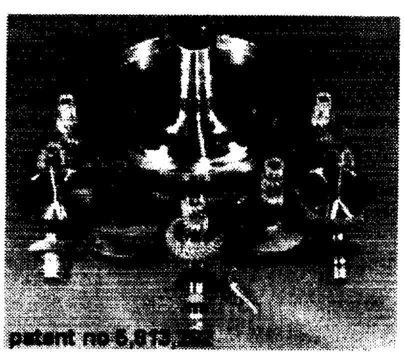
Helical Gear Dynamics

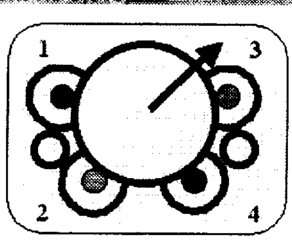


Fracture Mechanics - BEM

Mechanical Components Branch

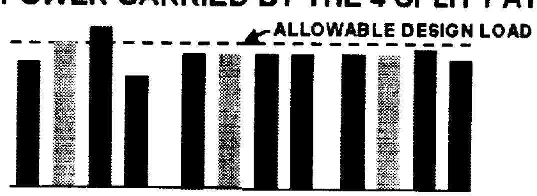
NASA Glenn Research Center Technology Flies On Comanche





NET BEARING FORCE TENDS TO OVERLOAD GEAR NUMBER 3

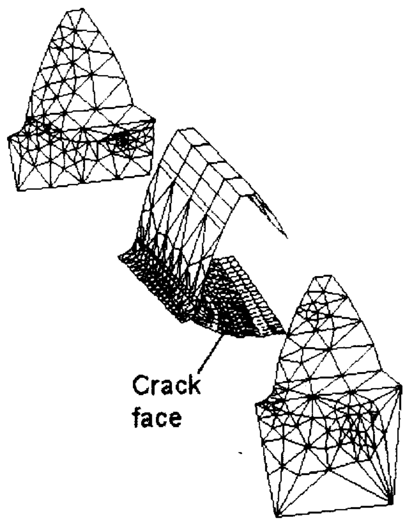
POWER CARRIED BY THE 4 SPLIT PATHS

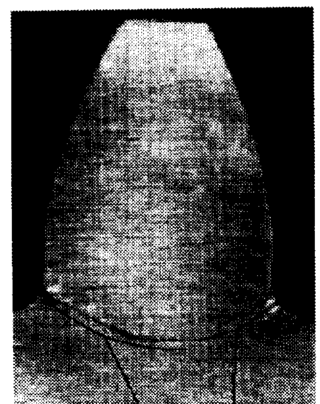


PROTOTYPE (NO INDEXING)   ANALYSIS EXPERIMENTS (REDESIGN WITH INDEXING)

Mechanical Components Branch

Drive Systems Gear Crack Propagation Research

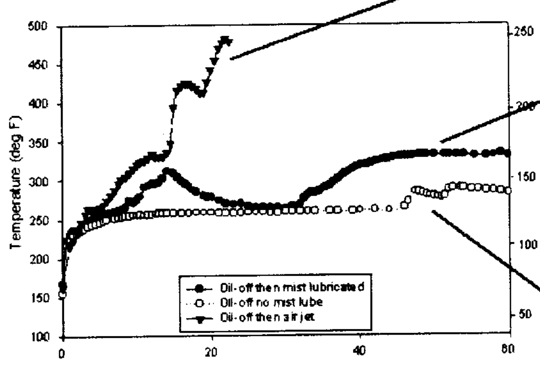


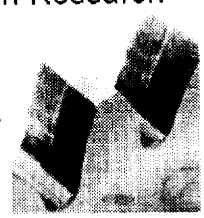


Mechanical Components Branch

Drive Systems Minimal Lubrication Research

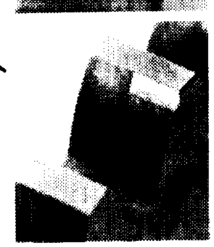
Component test results conducted at 10000 RPM. 248 ksi contact stress (Air / mist out-of-mesh temperature shown versus test elapsed time after primary lubrication system shutdown)





Air jet after primary lube termination

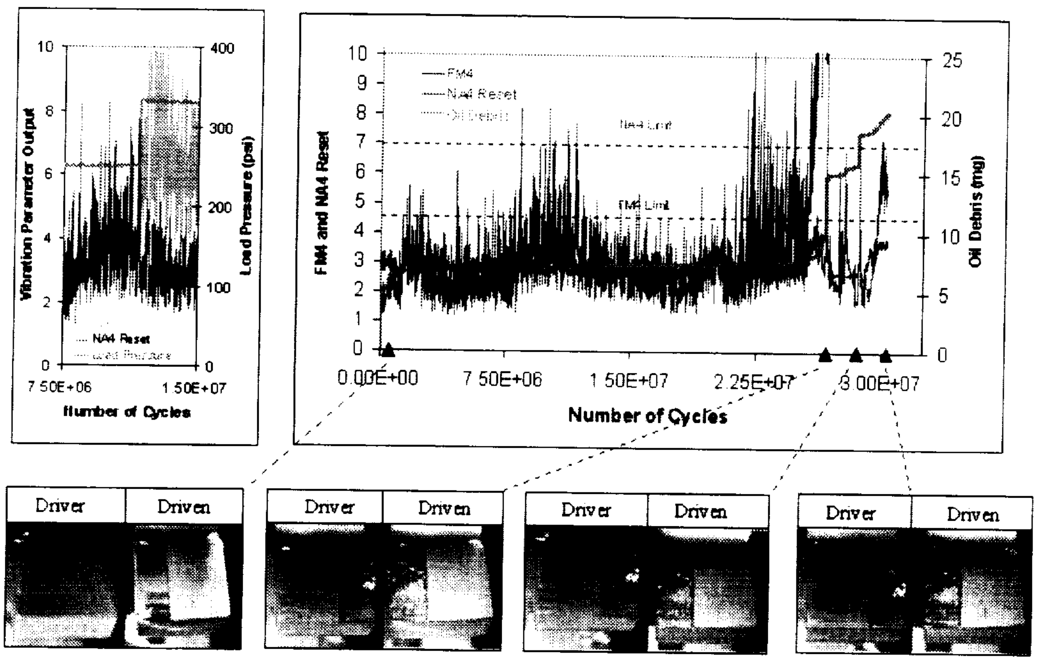
Mist lube after primary lube termination



Residual lube after primary lube termination

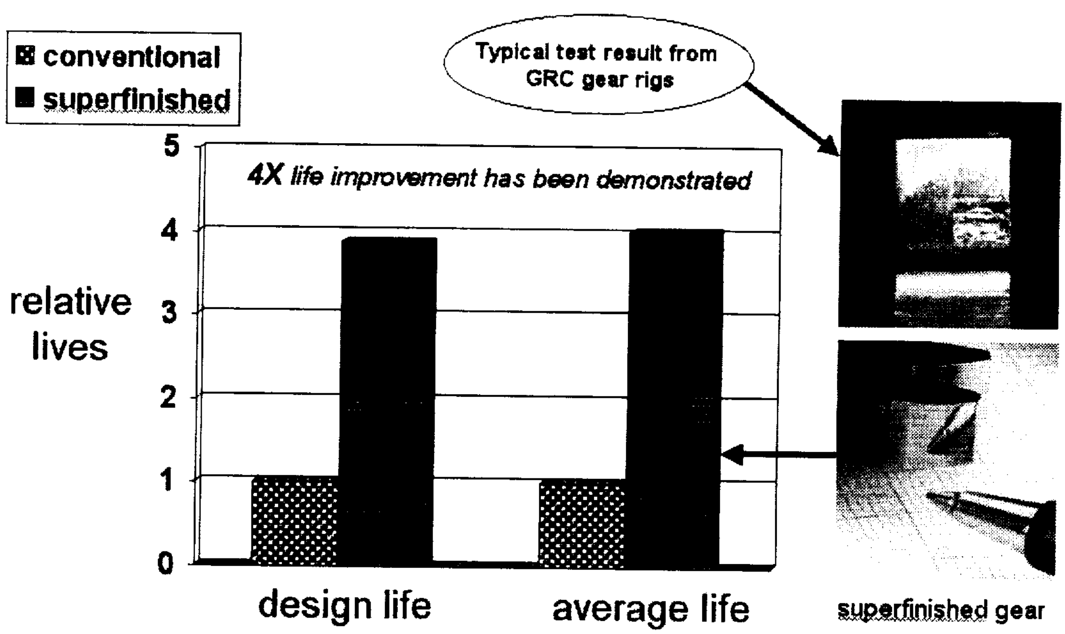
Mechanical Components Branch

Drive Systems Diagnostics / Health Management Research



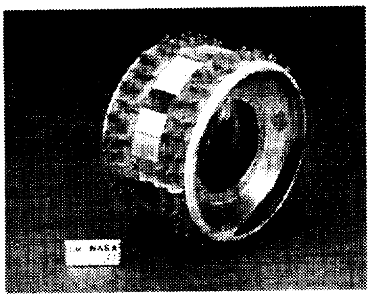
Mechanical Components Branch

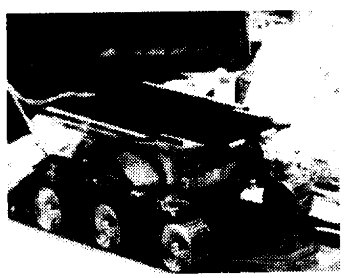
Drive Systems Surface Enhancement Research



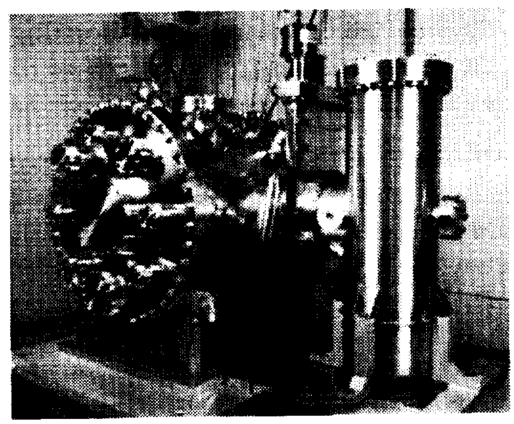
Mechanical Components Branch

Space Mechanisms Research
Mars Pathfinder Abrasive Wheel Experiment Test



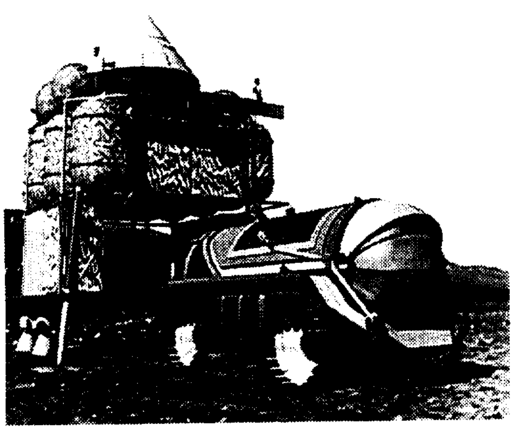


GRC test chamber with simulated Martian atmosphere and simulated Martian soil



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

- *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*

Workshop Goals, History, and Current Programs

Mr. Robert Fusaro, coordinator for the Glenn Research Center Space Mechanisms program, presented the goals of the workshop, history of previous workshops and gave an overview of current space mechanisms work performed by Glenn Research Center. Highlights of his presentation are shown below.

Following the presentation, Mr. Fusaro demonstrated the new *NASA Space Mechanisms Handbook and Reference Guide CD ROM*, which was featured as a highlight of the workshop. The handbook is an authoritative guide for design and testing of space mechanisms and related components. Over 600 pages of guidelines written by 25 experts in the field provide in-depth information on how to design space mechanisms and components, including: deployables, release devices, latches, rotating and pointing mechanisms, dampers, motors, gears, fasteners, valves, etc. The handbook provides details on appropriate environmental and tribological testing methods and practices required to evaluate new mechanisms and components.

Distribution of the *Handbook and Reference Guide* is limited by ITAR (International Traffic in Arms Regulations). It is available only to US companies and citizens. A request form for the CD ROM can be found on the Space Mechanisms Project website at http://www.grc.nasa.gov/WWW/spacemech/.

Spacecraft Drive Systems Technology Workshop

Goals, History & Current Programs

Sponsored by

Mechanical Components Branch

NASA Glenn Research Center

Cleveland, OH

Goals of Workshop

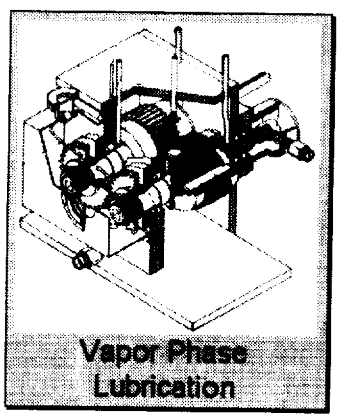
- Premiere the NASA Space Mechanisms Handbook & Reference Guide CD ROM
- Assess the State of the Art of Spacecraft Drive System Technology
  - Is the current technology base adequate for future NASA Space Missions?
  - What are the most critical problem areas that should be addressed to insure future Space Mission success?
- Determine whether regular meetings would be of benefit to the space mechanisms technology community

Previous Space Mechanisms Workshops

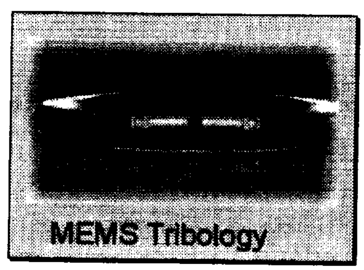
- **September 22 & 23, 1992 in Cleveland, OH**
  - Determine the Space Mechanisms technology challenges for future NASA missions
  - Obtain an industry perspective on current and future problems as well the the community's capabilities to solve them
- **May 17, 1994 in Cleveland, OH**
  - Evaluate the current state-of-the-art and determine the type of information that should be included in a Space Mechanisms Handbook
- **September 26-27, 1994 in Denver, CO**
  - Determine Non-Ozone depleting cleaning methods for spacecraft lubricating systems

Current GRC Space Mechanisms
Technology Programs

- Lubrication
- High Temperature Seals
- Actively Controlled Magnetic Bearings
- Permanent Magnet Magnetic Bearings
- Mechanical Backup Bearings
- Flywheels
- Probabilistic Prediction Methods
- Materials



Vapor Phase Lubrication

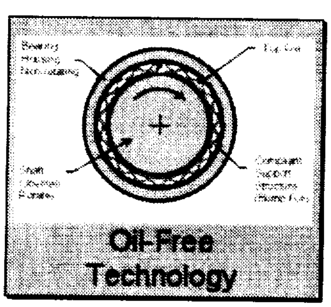


MEMS Tribology

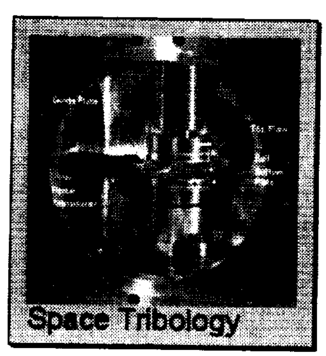
Computational Materials

Tribology and Surface Science Branch (5960)

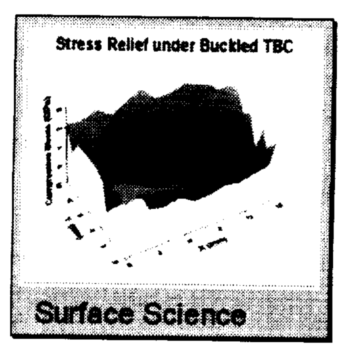
www.grc.NASA.gov/WWW/SurfSci/



Oil-Free Technology

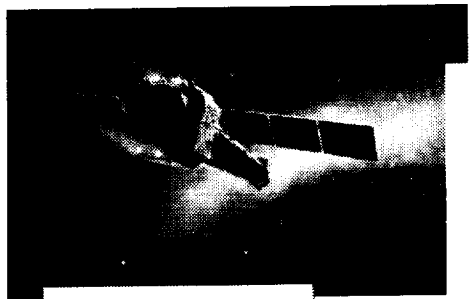


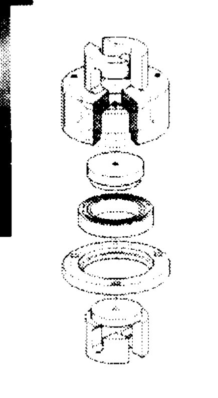
Space Tribology



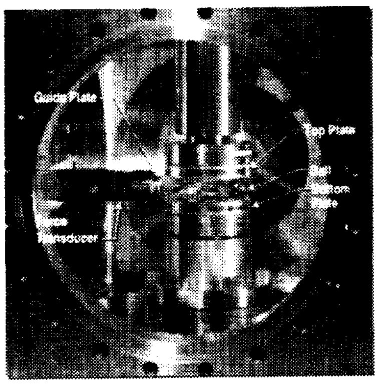
Surface Science

SPACE TRIBOLOGY AND MATERIALS

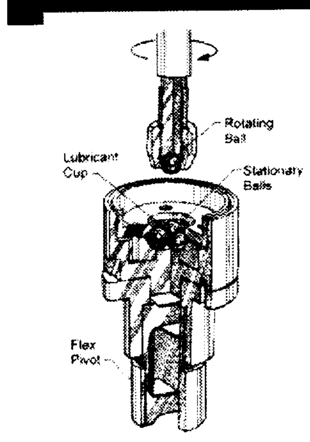




BEARING RIG
Full Scale
Bearing Tests



SPIRAL ORBIT TRIBOMETER
Accelerated Lubricant Life
Testing Under Realistic
Conditions

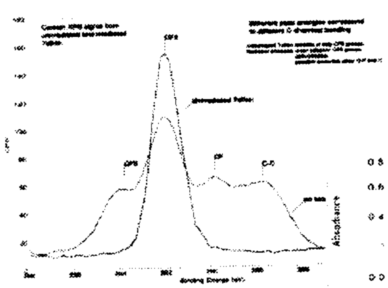


VACUUM 4-BALL
Accelerated Bulk Property
Testing of Lubricants

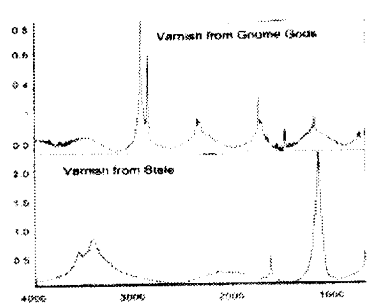
Other Facilities:
•Vapor Pressure of Fluids
•Radiation Damage of Polymers

Surface Science

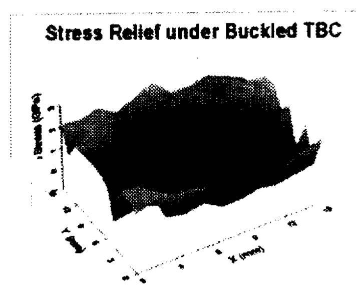
XPS

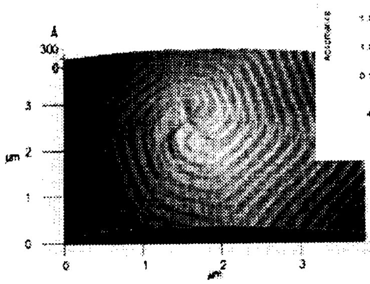


FT-IR

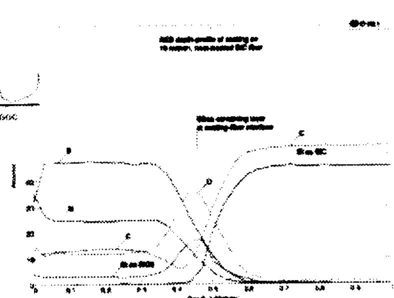


Raman





AFM

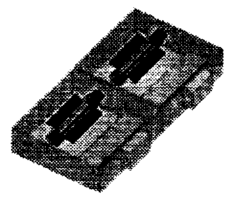


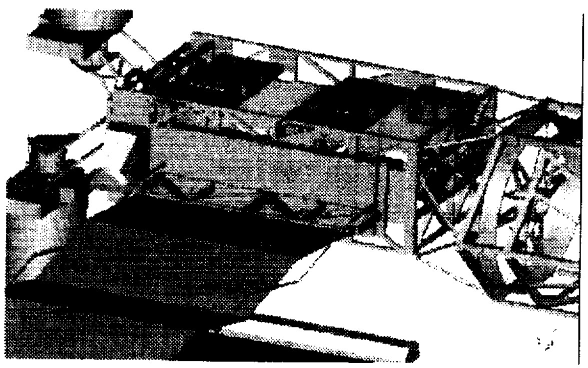
Auger

FESS Conceptual Design

2 FESU ORUs

Each ORU contains 1 Flywheel Module with the associated electronics.





Design Features

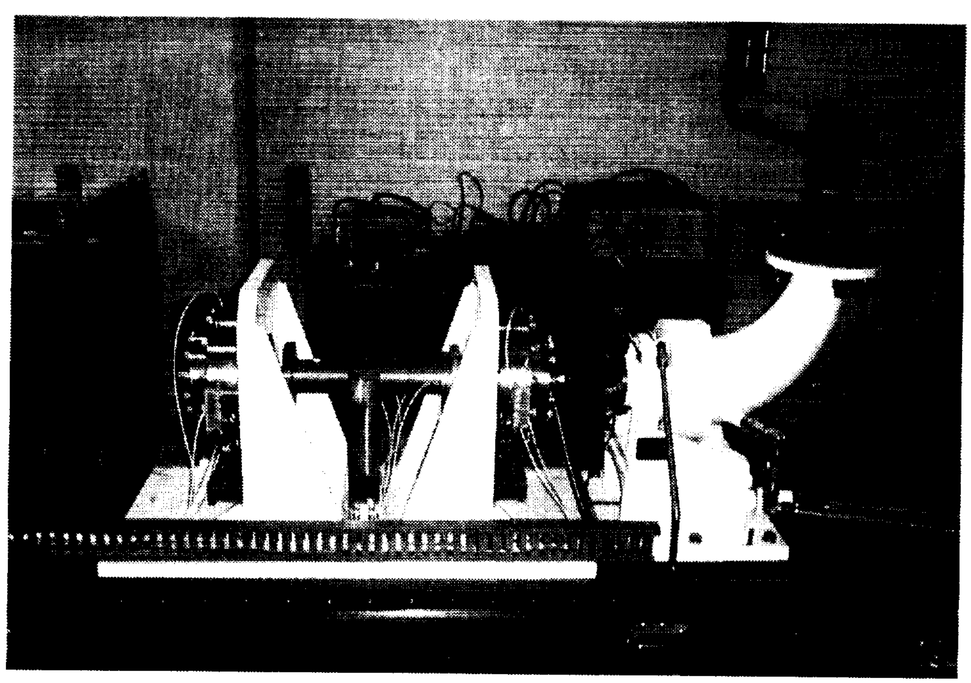
FESS:
Weight - 912 lbs
Energy Storage - 5.525 K W hr
2 Contingency Orbits
Power - 4.14 kW nominal discharge
5.45 kW peak for 7.5 min

FESU:
Volume-33.5"L x 33.9"W x 25.5"H
Weight- 445 lbs

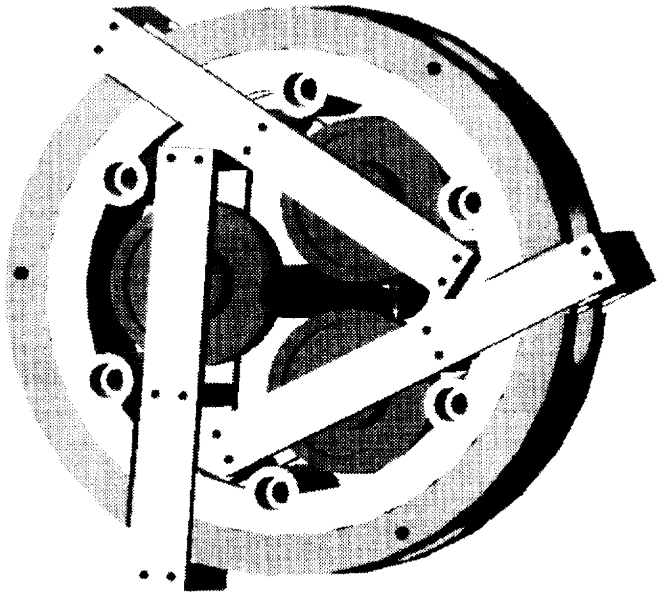
Flywheel Module:
Volume - 13" Dia x 29" L
Weight - 245 lbs
Max Operating Speed - 53,000 RPM
Tip Speed - 920 m/s

Electronics:
Volume - 33"L x 20"W x 15"H
Weight - 42lbs

Fault Tolerant Magnetic Bearing Rig



Three Roller Backup Bearing Design

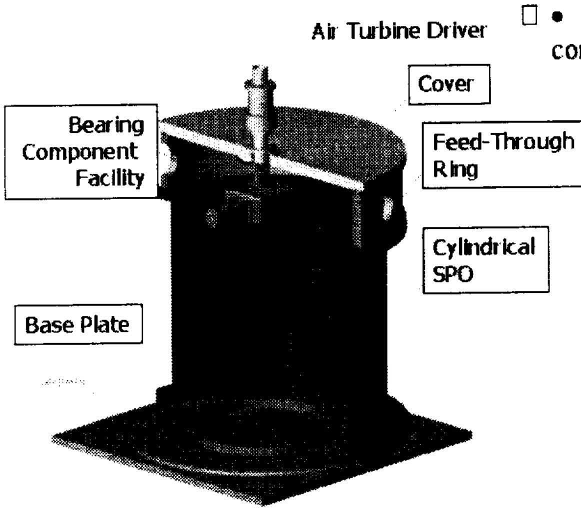


52" Diameter x 55" High Vacuum Chamber

Current vacuum levels limited by pumping system ($1x10^{-2}$ Torr) Hyvac Roughing Pump

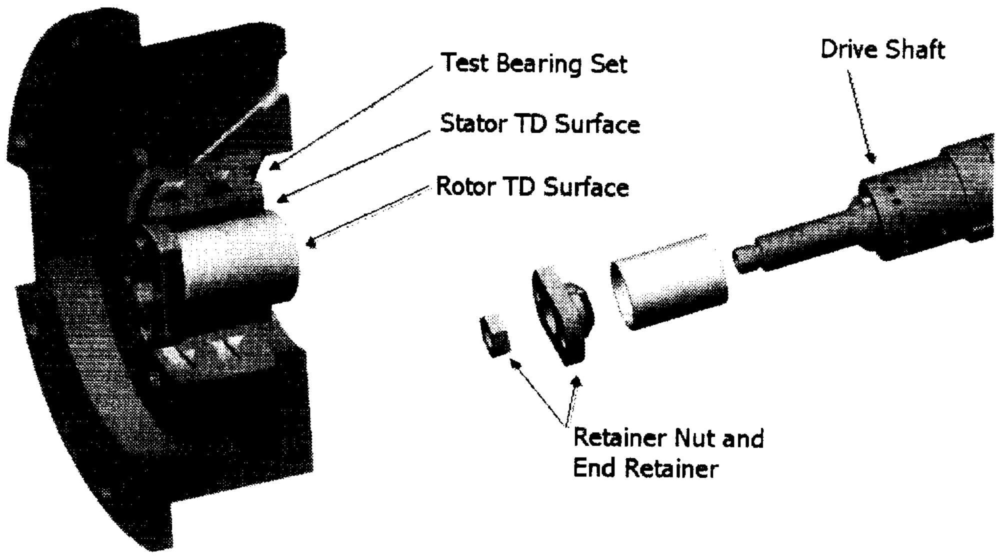
Chamber designed to operate at higher vacuum levels ($1x10^{-5}$ Torr)

- Viton gaskets and seals
- Threaded feed throughs
- Stainless Steel Chamber and components



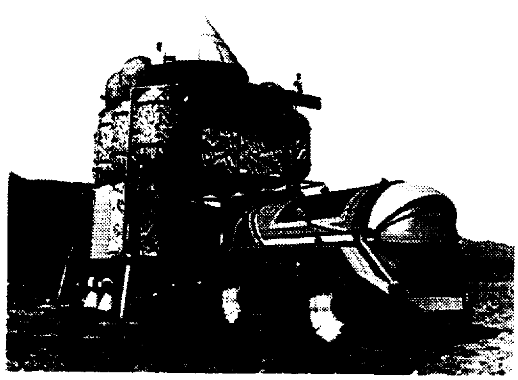
High Speed Bearing Test Section and Drive Shaft End

35mm bore bearings, 25mm Rotor TD Surface, 60,000 RPM and 1000 lb. Radial Load Maximum



Vehicles Needed for Planetary Exploration

- **Robot explorers**
- **Small utility "rovers"**
- **Large pressurized transports**
- **Mining machines**



Requirements for Planetary Vehicle Drives

- Long-life, reliable, maintenance free
- Works in extreme cold
- Tolerant to large temperature differentials
- Minimal friction losses & heat generation
- Light-weight
- Tolerant to abrasive dust
- No outgas

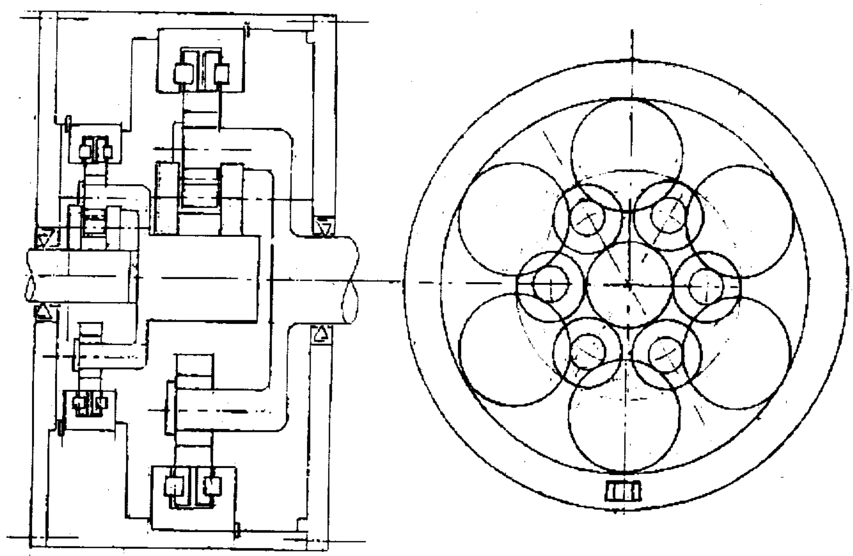
Solid Lubricated Vehicle Drives for Planetary Exploration

Current Status of Planetary Drive Technology

Only "planetary qualified" drive is the harmonic drive

- Cannot operate below ~ -50° C (oil lubricated)
- Efficiency is low (60-80%)
- Flexspline is subject to fatigue failure
- Loads on bearings high
- Solid lubricant film wear rate high on gear teeth

Proposed Traction (Roller) Drive For Martian "Rover"



Solid Lubricated Vehicle Drives for Planetary Exploration

Objective

Provide efficiency & long life in hostile planetary environments by developing a traction drive lubricated by solid lubricants

Approach

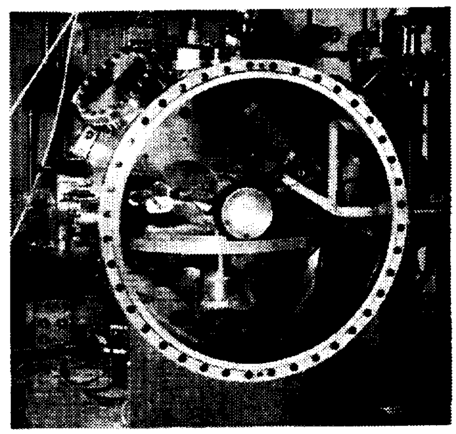
- **Optimize the solid lubricated rollers**
- **Design and build a prototype traction drive**
- **Test in simulated Mars/Moon environments**

Solid Lubricated Vehicle Drives for Planetary Exploration

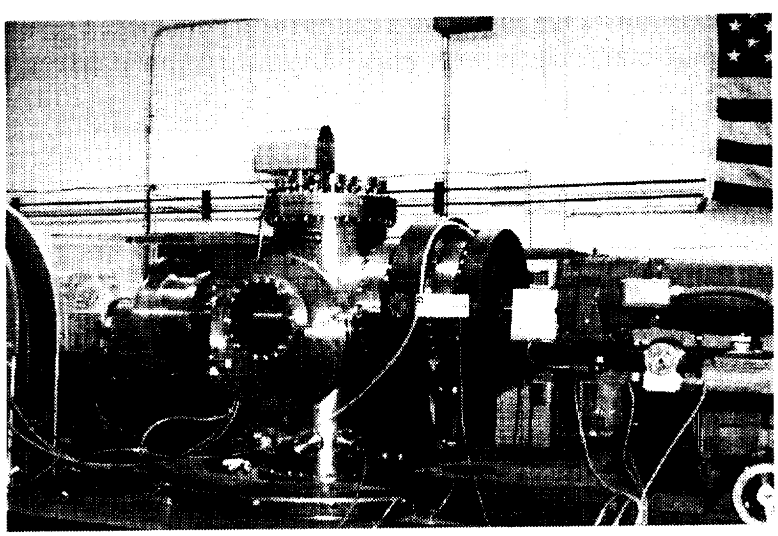
Experimental Facilities to Be Used

- *Pin-on-disk and Block-on-ring rigs for screening tests*
- *Vacuum Roller Contact Rig for roller durability tests*
- *Space Mechanisms Accelerated Test Chamber for prototype tests*

Space mechanisms test chamber (with Mars Pathfinder wheel)



Vacuum Roller on Roller Rig



Rover Robot Vehicle Technology

Dr. William (Red) Whittaker, director of the Field Robotics Center of the Robotics Institute at Carnegie Mellon University, discussed design challenges, applications, robot mechanisms and materials used in robot manufacture. He also presented a short history of robotics technology including rover mechanisms developed for the Russian Lunar program.

Rover vehicles include piloted rovers, such as the Apollo Lunar Rovers, teleoperated robots remotely operated by human controllers and autonomous robots that must make their own decisions to accomplish their missions.

Design challenges include difficult operating environments, such as extreme temperatures, radiation, dust, corrosive chemicals, and vacuum or extremely dry atmospheres. Design constraints include severe weight requirements, low available power to overcome friction, and the demand for ruggedness, reliability and long life. In addition, these mechanisms have limited possibilities for redundancy.

Planetary rovers face additional problems from landing on alien worlds. This introduces hazards including the shock of landing, deployment from a stowed configuration, righting the device after landing, and dealing with slopes and obstacles.

Not all rovers use wheels for locomotion. On very rough terrain, a complicated system of hinges and joints is needed to keep the wheels in contact with the ground. Thus, legged rovers gain advantages in difficult terrain. Such "walkers" may require less power on a low-gravity body. Under the very low gravity of an asteroid, hopping robots become practical.

Current rovers have only one drive speed ratio, which must be optimized for climbing. This makes the rover slow. A variable speed drive system would be more effective for traversing because it could move faster on easy terrain.

Present human piloted rover concepts use old technology, which is slow and inefficient. Large pressurized vehicles will be needed for long distance planetary surface exploration. These must be extremely reliable for life-critical missions. We need real innovations, not just incremental changes to existing technologies to meet mission demands. These innovations may replace gears and traditional mechanisms with such things as hydraulic drives, or manipulators.

Space Drives Challenges

Mr. Stuart Loewenthal of Lockheed Martin Space Systems discussed the challenges and the need for research to enhance design of space drives. He observed that space mechanisms are often implicated when something goes wrong.

Space drives must often operate outside the range of a standard design database, such as that from AGMA (American Gear Manufactures Association). These drives are often made from non-standard materials because of the demands of the environment. Designers have inadequate experience with these materials to support design. Lubrication options are limited due to vacuum and cold temperatures. Despite these restrictions, space drives must provide long life without maintenance.

Failures in space drives are often related to lubricant failure which causes scoring and excess wear, rather than the pitting or bending fatigue typical of terrestrial applications. Demands for future long-life, lightweight drives are likely to be much tougher. This means we must develop special materials and design processes. We need life data to allow optimum sizing of components. However, the time and money to create the database will be limited.

Space mechanisms present the designer with an extreme range of requirements in terms of life, speeds, and lubrication conditions. These range from release devices, which operate only once and at low speeds, where stiction (unwanted adhesion between moving parts) can cause failure, through various devices that operate under mixed, boundary, or even parched EHL (Elastro-Hydrodynamic Lubrication) conditions, and to very high speed, long life components such as gyros, which may need to operate at tens of thousands of rpm and for hundreds of billions of revolutions.

Space mechanisms generally must operate with "one shot" lubrication provided at assembly with no opportunity for replenishment. Concerns about outgassing or contamination restrict lubricant choices. Devices must survive launch loads; work under hard vacuum with minimal torque loss due to friction.

Solar array drives for the space station must last 15 to 20 years without added lubrication. Present practice is to use ion-sputtered gold as a solid lubricant.

Planetary rovers will require ultra reliable drives systems, including motors, bearings, gears and seals. These systems must work in extreme cold as well as over a large temperature range. Friction losses and heat generation must be minimal. The devices must be lightweight and rugged and they must tolerate abrasive dust.

Harmonic drives are popular choices for spacecraft designers because of their compact size and high gear ratio. However, in long-life applications, such as pointing solar arrays, wear can be excessive. Requirements for long life and low weight are pushing the capabilities of harmonic drives.

A public database of materials, processes and capabilities would benefit the space community. The present situation, where every program must develop its own design data, is inefficient and wasteful. The database should include data on performance of stainless steels, aluminum and titanium as gear materials and effects of coatings, surface treatment and lubrication. To validate the database, reliable methods must be developed for accelerated life testing including testing actual components, not just tribology specimens.

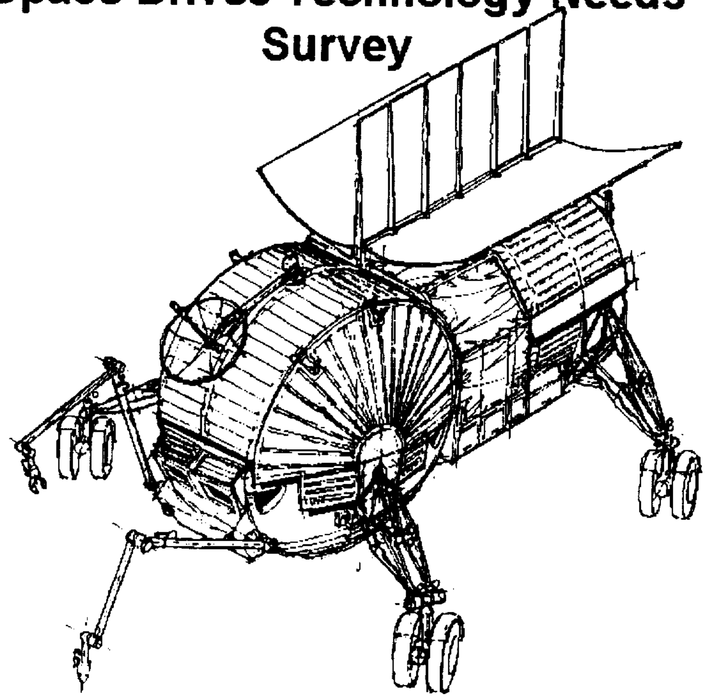
Results From the Survey on Space Drives Research Needs

NASA has identified an ambitious program for space exploration that includes exploration of planets and moons of the Solar System. This program will involve new types of spacecraft, including the manned space station, unmanned space probes, robotic and manned "rover" vehicles and mining machines operating on alien worlds.

We are concerned that some of the technology that will be required for these ambitious space missions is not ready. This problem is especially critical in the area of drive (transmission) systems.

Fred Oswald presented results of a survey in which "Space Mechanisms Experts" were asked: "What will be the most critical needs for space drive systems in the next ten to thirty years?" Results from the survey are summarized below.

Space Drives Technology Needs Survey



Opinions of Space Mechanisms Experts

Space Drives System Needs Survey

Survey Questions:

- **What will be the most critical technology needs for space drive systems in next 10 to 30 years?**
  - **What characteristics are most important?**
  - **What size/power levels are most needed?**
  - **What speed regimes are most important?**
- **What drive concepts should we develop?**
- **What technology problems will we face?**

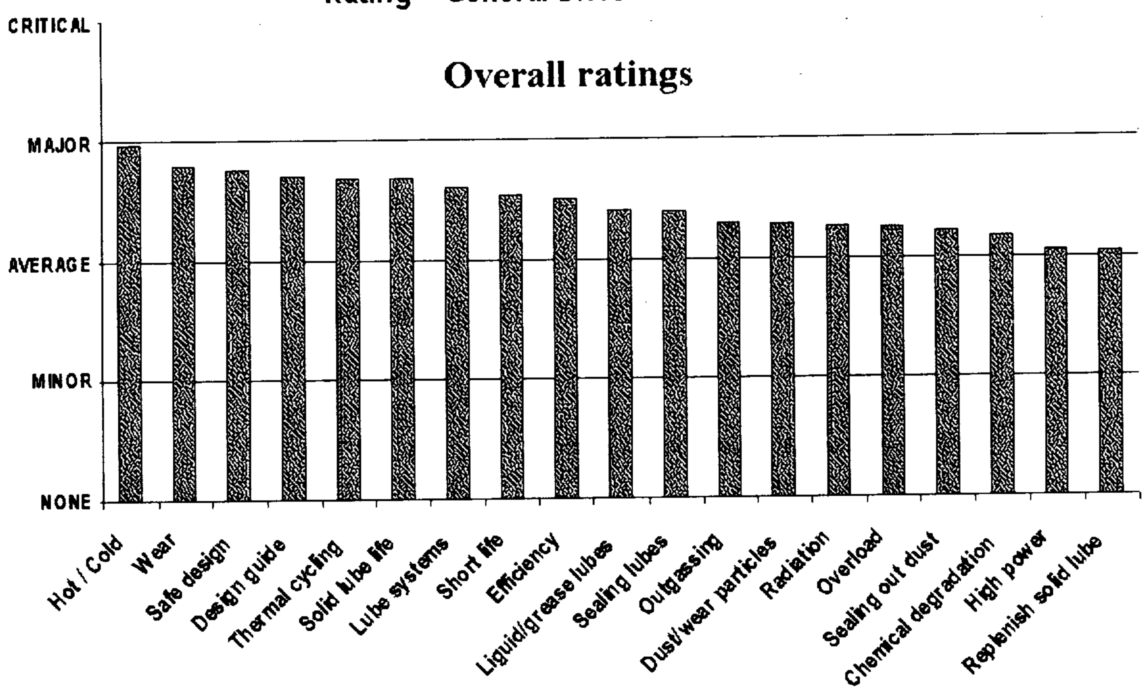
--- 38 surveys returned

Space Drives System Needs Survey

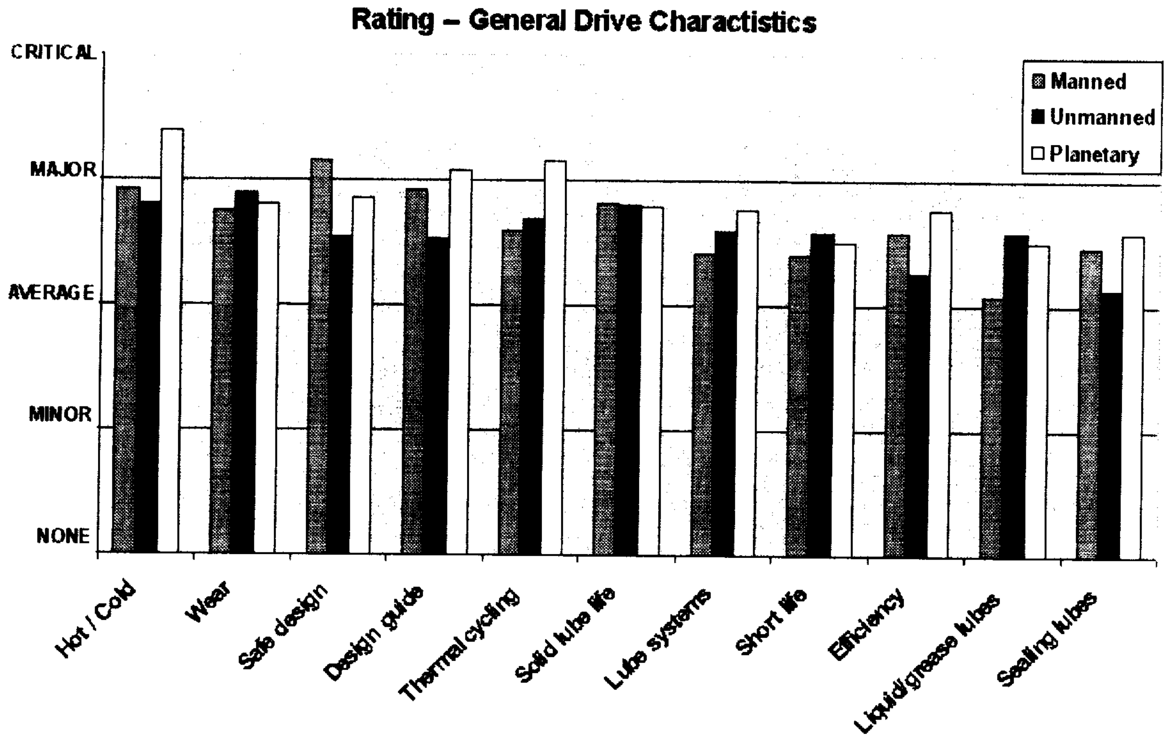
I. General Drive Characteristics		Rating of Needs			
		manned	unmanned	planetary	other
1	High power capacity				
2	Design guidelines				
3	Fail safe/redundant design				
4	Overload capacity				
5	Mechanical efficiency				
6	Wear				
7	Long-life solid lubricants				
8	Replenishing solid lubricants				
9	Developing liquid/grease lube systems				
10	Liquid / grease lubricants				
11	Lubricant outgassing				
12	Robustness to (hot or cold) temperatures				
13	Robustness to thermal cycling				
14	Robustness to chemical degradation				
15	Tolerance to dust/wear particles				
16	Sealing out dust/contaminants				
17	Sealing in lubricants				
18	Tolerance to radiation				
19	Lightweight designs for short life mission				
20	Other(s)				

Space Drive System Needs Survey Results —

Rating -- General Drive Charactistics



Space Drive System Needs Survey Results ---



Space Drive System Needs Survey Results ---

"Other" Areas of Concern:

- Payloads
- Micro Satellites
- Scientific Instruments
- Release Mechanisms
- Cell Bypass Switches
- Manned Rovers
- Powertrain
- Gears
- Launch Vehicles (2)

"Other" Drive Characteristics:

- Brush Wear in Vacuum
- Life Testing
- Pitting Under Boundary Lube
- Linear Motion
- Stiffness in Actuators
- Launch Load Protection
- Reliability
- Supplier Base
- Position Sensors
- Electrical Pwr. Trans. Devices
- Cost (small quantity buys)

Space Drive System Needs Survey
--- General Characteristics Comments

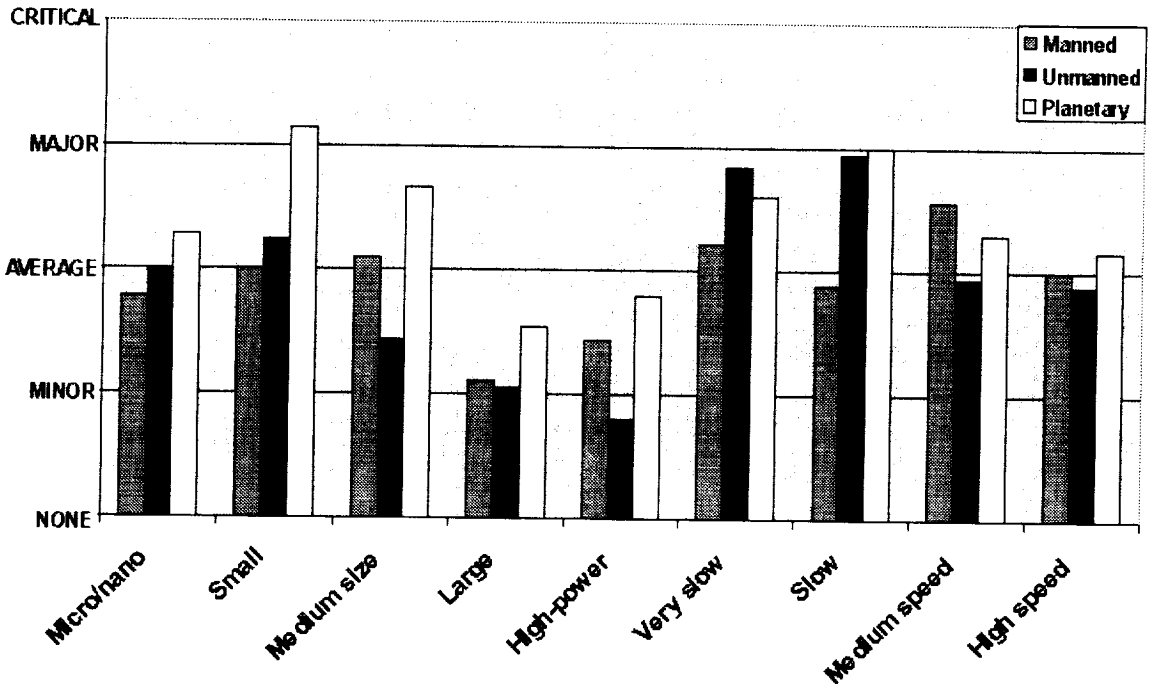
- Light weight and long-lived mechanisms needed.
- Reliable mechanism hardware (and support) from US based suppliers is problem.
- Test studies about effects of radiation on lubricants is lacking.
- Biggest deficiency in the field of space drives is inadequate life testing, due to ---
    - Limited funds,
    - Lack of time to do unaccelerated life test
    - Lack of recognition of difficulty of making mechanism last 5+ years.
- Mechanical bearing for aerospace flywheel.
    - Launch while spinning
    - Precision pointing at high speeds, high loads (gimbaled)
    - Magnetic bearings as primary, backup or fault protection.

Space Drive System Needs Survey

II.	What are technology needs for various size / power levels and rotation speeds?	Rating of Needs			
		manned	unmanned	planetary	other
1	Micro/nano machines				
2	Small robot machines (Pathfinder)				
3	Medium size rovers (Apollo Moon rover)				
4	Large rovers ("Winnebago")				
5	High-power machines (mining equip.)				
6	Very slow/intermittent speed (stiction)				
7	Slow speed (10-200 rpm)				
8	Medium speed (200-2,000 rpm)				
9	High speed (> 2,000 rpm)				

Space Drive System Needs Survey Results ---

TechnologyNeeds Rating



Space Drive System Needs Survey --- Technology Needs Comments

- Nanosat lubrication problems.
- Needs for micro and nano machines still evolving.
- Extreme temperature liquid lubricants.
- Mega-rover needs that far surpass those of the Apollo & Pathfinder rovers
- Small robots for on-board inspection and troubleshooting on Geostationary communications spacecraft/platforms
- Ultra high speed (> 40,000 rpm) for flywheel applications with long life.

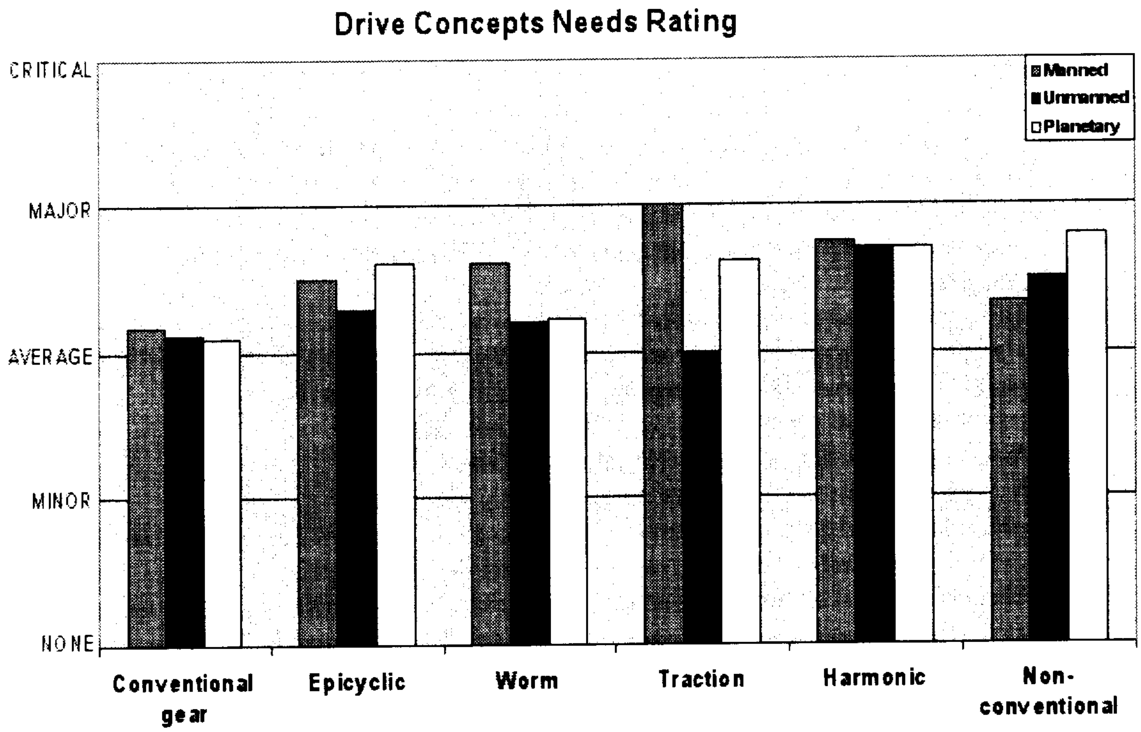
Space Drive System Needs Survey

III.	Where are there needs for development of drive concepts?	Rating of Needs			
		manned	unmanned	planetary	other
1	Conventional single/compound gear meshes				
2	Epicyclic (planetary) systems				
3	Worm/wheel drives				
4	Traction drives				
5	Harmonic drives				
6	Non-conventional				
7	Other				

"Non-conventional" & "Other" items mentioned --

- Leadscrews & ballscrews
- Piezo-electric actuators
- Chain & sprockets
- Centralized drives

Space Drive System Needs Survey Results ---



Space Drive System Needs Survey
--- Drive Concepts Development Comments

- Harmonic drives need better lubricants for long life.
- Gear systems could benefit from light, robust, low cost anti-backlash devices.
- Worm drives are unreliable due to lube problems but alternatives exist so no need to solve the problem.
- Alternate cost effective and lighter geartrains are important. (These must have low ripple and backlash for control applications.)
- Most drive systems need efficient light weight high ratio speed reducers.
- One shot gear and drive lubrication benefits from low contact stresses

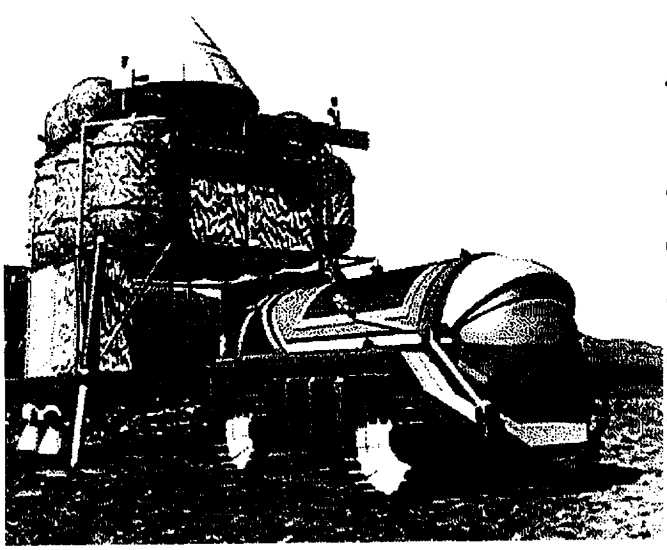
Space Drive System Needs Survey
Technology Problems Anticipated #1

- **Get "Gray Beards" to teach youngsters to design reliability into the product early.**
- **Life/load capacity issues with reduced sizes and longer mission lives.**
- **Precision gear sets for fine pointing applications.**
- **Wide operating temperature ranges will affect drive performance.**
- **Lightweight designs.**
- **Technology not ready for long life, high power, hostile environments.**
- **Micro/nano tribology technology may not advance fast enough to ensure reliability.**
- **Precise motion control (stepper motor) with high torque capacity.**
- **Shortened life due to operation in hostile environments.**
- **Low torque operation over wide temperature range.**
- **Repair / replacement on planetary surfaces or space station.**
- **Long duration reliability in extremes – hot or cold, vacuum of Moon and Mercury.**
- **Reduce cost while improving performance, mass and reliability.**
- **Credible accelerated testing for increasing mission & storage life requirements.**
- **Vendor supply deteriorating as space becomes unprofitable and loses its "cachet".**

Space Drive System Needs Survey
Technology Problems Anticipated #2

- Lubrication loss or breakdown.
- Lubrication/Life/Pitting.
- Maintaining lubrication during very long term missions.
- Nanosat lubrication problems. Extreme temperature liquid lubricants.
- Inadequate lubrication in non-oxygen, dusty environment.
- Sealing liquid lubricants to prevent contamination.
- Liquid lubricant replenishment in a zero G environment.
- Development of "oil free" systems for planetary surfaces.
- Longer lasting dry lubes for cryo / high radiation environments.
- Gear Train Efficiency – reduces cooling needs.
- Efficient method of cooling gears in zero gravity.
- Seals – Keep the lubricant in and abrasive dirt out.
- Life of lubricant in space environment (vacuum, thermal cycling, effect on wear).
- Management of liquid lube system.
- Replenishment of solid lubricants.
- Grease lubricant gear pitting life operating in Regime 1 for long life/high load.

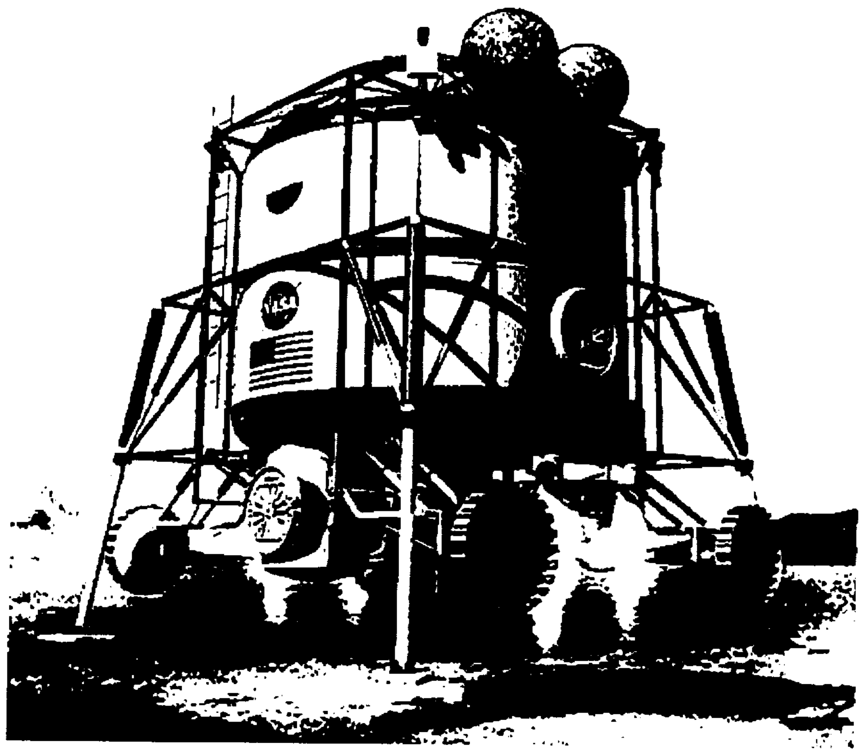
Pressurized Crew Vehicle for Manned Mars Mission



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

- ***16.5 Metric ton rovers for Mars missions***
- ***500Km, 10 day excursions***
- ***Lightweight & Efficient***
- ***Thin, dry atmosphere***
- ***Cold & dusty conditions***

Movable Lander for Manned Mars Mission



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

Working Group Sessions

In the second half of the workshop, participants split into three groups to develop a consensus on the following questions: (1) What are the current space drive resources and issues? (2) What are the future space drive technology needs and issues? and (3) Should we hold regular workshops on space mechanisms and space drives? The three groups considered these questions from the perspective of researchers working in (1) manned spacecraft; (2) unmanned spacecraft; and (3) planetary surface exploration vehicles. Notes from the sessions appear below.

The Manned Spacecraft Session

Moderators: Stuart Loewenthal and Robert Fusaro

1) What are the current space drive resources and issues for manned spacecraft?

- Describe the current state of the art:
    - Current state of the art appears to be adequate for current manned projects
    - Harmonic drives used for many applications
- Currently known space drive technology problems:
    - Trade-off between performance and robustness
    - Space shuttle turbopumps still a problem
    - RL–10 idler pump system a problem

- Unknowns exist for manned spacecraft going to Mars
    - Nuclear propulsion poses mechanisms problems
- Current facilities and people working in space drives:
    - No facilities and very little technology research being conducted in space drive area
- Missions where technology problems will be an impact:
    - Propulsion systems
    - Manned missions to Mars
- Technology deficiencies:
    - How do we replace or service drives in space?
    - How do we qualify and how much qualification is necessary?
        - There is a need to develop accelerated life test techniques and scale factors that people can believe in
        - What are the life-limiting factors?

2) What are the future space drive technology needs and issues for manned spacecraft?

- Future missions are expected and drives will be needed for the following missions:
    - Space Station
        - Need improved bearings, lubricants, and gears
        - Type is dependent on application
    - Manned missions to Mars
        - Need improved bearings, lubricants, and gears
        - Type is dependent on application
    - Shuttle flights to space station
        - Cryogenic propulsion issues
- Technology barriers for future space drive systems:
    - Inadequate qualification testing methodologies
- Significant technology milestones we should strive for:
    - Improved accelerated life-testing techniques
    - Reliable scaling factors
    - Improved design methodologies
- Future space drive research facilities needed:
    - Project centers to develop technology
    - Facility to develop improved robotic joints
    - Facility to develop easily replaceable systems
- Space qualification methods needed for future space drives:
    - Developing accelerated life-testing methodologies
    - Developing scale factors that are accurate
    - Determine synergistic or combined parameter effects on life
    - Reduce the cost of qualification
- Other issues:
    - A need for a vendors' list for approved supply sources
    - A need for NASA to define the specifications for spacecraft more precisely
    - A need for Centers in charge of NASA missions to define the state of the art in technology and ensure that programs are in place to develop enabling technology necessary for success of the mission
    - Fracture properties of exotic materials need to be determined

3) Should we hold regular workshops on space mechanisms and space drives?

- Is a space drives working group needed?
  - The general consensus was such a group would be advantageous
  - A need for a list of experts to obtain information
  - A need for an approved vendors lists
- Other space mechanisms areas that need to be addressed in future workshops:
  - Bearing seals
  - Vibration isolation both active and passive systems
  - High-temperature applications such as those found on the X-vehicles
  - Lubricant management (supply systems)
  - Dry lubricants for gears
  - Heat rejections
  - Cryogenic lubrication
  - Space qualification techniques
  - Magnetic bearings
- How do we communicate?
  - Yearly workshops
  - An extra day at the AMS to deal with new technology
  - Chat rooms on the Internet
  - Teleconferences or video conferences

<u>The Unmanned Spacecraft Session</u>

Moderators: Romer Predmore and Wilfredo Morales

Summary of main conclusions reached by the group:

1. NASA support for mechanisms technology and subsystem mechanism standards should be established using commercial standards to reduce costs.
2. NASA should fund the technology for future space mechanisms, including MEMS devices, under the guidance of industry steering groups.
3. Unless there is government support for space mechanisms research, there will be little need for future workshops.
4. Industry needs to know the future needs of NASA.
5. An immediate need is flywheel energy storage systems, in lieu of batteries, for flat spacecraft.
6. Need much more work in magnetic bearings for use with small momentum wheels and for improvements in "control electronics."
7. NASA should define the performance requirements for advanced space mechanisms.
8. NASA should increase support for MEMS technology and smart materials technology.

Comments: Over 50% of the discussions focused on the need to establish space mechanisms standards in order to reduce costs. A number of the attendees were design engineers and not researchers; therefore, future workshops should be geared towards either research or design. Future workshops should have a single theme or objective.

The Planetary Surface Exploration Vehicles Session

Moderators: Red Whittaker and Fred Oswald

1) What are the current space drive resources and issues?

Technology of today such as on Sojourner Rover and the Mars '03 Rover, (originally called Athena or Fido) uses commercial brush-type motors (manufactured by Maxon) with harmonic or multistage planetary drives. Typical transmission ratio: 80:1 to 250:1
Sojourner Mass = 11 Kg, Power = 10 W. Athena/Fido Mass = 32 to 60 Kg
Power level of typical antenna or solar-array pointing mechanism ~8 W

Russian Lunokhod used radioisotope heater/generator and brush-type motors in sealed enclosure. The Apollo Moon Rovers used brush motors and harmonic drives operating in a sealed enclosure with a 7.5 psi nitrogen atmosphere (for heat transfer). The performance of the Apollo rovers was seriously degraded by dust by the end of their missions (about 3 Earth days).

Small positioning mechanisms may use ultrasonic motors, for example, camera focus mechanism and robot joints. These employ a polymer that changes dimension in an electrostatic field. This produces wave motion in a ring, which acts like a motion transducer. Contacts for more information: Hari Das or Paul Schenker at JPL.

MEMS: Micro Electronic Mechanical Systems (solid-state switch) can replace brushes in motors.

Problems:

- Life of present motors and transmissions is too short for long-duration missions.
- Dust interferes with cooling, contaminates seals, and causes wear.
- Brushes are no good in vacuum. Current technology must use pressurized chamber in vacuum.
- Extreme temperatures (on Moon, range from ~40 K in craters at poles to ~400 K at noon on equator with dark soil.
- Present technology cannot endure heat of day or cold of night on Moon.
- Present technology not adequate for long duration missions, especially when using solid lubrication.

2) What are the future space drive technology needs and issues?

Needs and Problems:

- Long-duration missions will require new technology. Mars environment is "easy" compared to Moon and Mercury. However, 2-year mission means equipment must be extremely reliable.
- Possible mission to Jovian moon Europa may require a submarine.
- Mars reference mission calls for power plants ~2 Km from base. Laying power cable is difficult job for rover vehicles.
- Burrower robots may be needed on Moon (underground habitat for radiation shielding).
- For more information, contact Wilxox at JPL.

Promising Technology:

- Reversed electrostatic field may repel charged dust.

- Variable reluctance motors provide for start and run power requirements.
- Motion measurement encoders are heavy. Hall effect sensors are an alternative.
- Most current actuators do not have torque sensors. They operate in on/off mode.
- NASA should issue RFP for studies to identify technology needs.
- Need studies to examine tracked versus wheeled vehicles (efficiency and reliability issues).

An interesting concept: The lifetime range of a device is related to its size (within limits). Consider range of ant versus deer. However an elephant's range is not much greater than a deer's.

3) Should we hold regular workshops on space mechanisms and space drives?

There were only 12 people in this discussion group (the smallest group). All favored holding regular Space Mechanisms Technology meetings, possibly every year. We should investigate operating a "listserv" discussion group for ongoing discussions.

The 1-day meeting was too short and people did not arrive prepared to make the best use of the limited time available. Prior communication (preparation) would help improve the focus of the discussions.

Possible future topics: motors, commutators, wheels, suspensions, materials, manipulators, and antenna/solar-array pointing.

Workshop Summary

Participants at this workshop considered whether space mechanisms technology, particularly for drive systems, is adequate to support future space exploration for the next 10 to 30 years. They considered critical problem areas in this technology and what research is needed to address the problems. Several critical technology deficiencies were identified and are summarized below.

Space drives must operate reliably at high-power densities, under extreme environmental conditions, usually without maintenance or replenishment of lubricants. This means that nonstandard materials and lubricants must be used to meet the requirements. However, the experience database for these nonstandard materials is much more limited to support design. In order to develop this database, we need better techniques for accelerated life testing and accurate methods for scaling test data to design requirements.

To compound the difficulty of meeting these challenges, we are losing our space mechanisms experience as present-day experts retire and not enough researchers of the future are being adequately trained.

"Rover" and mining vehicles required for manned planetary exploration will impose particularly severe requirements. Some of these vehicles will be life critical whenever they are operated beyond "walk back" range of the base.

Workshops such as the one discussed here help to identify needs and problems and help researchers to share information. In addition to workshops, we should conduct teleconferences and Internet discussion groups.

Editor's note: A new discussion group for space drives has now been established. For information, see http://www.grc.nasa.gov/WWW/5900/5950/Space-drives-list.html or contact the editor at fred.oswald@grc.nasa.gov.

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13. ABSTRACT *(Maximum 200 words)*

The Mechanical Components Branch at NASA Glenn Research Center hosted a workshop to discuss the state of drive systems technology needed for space exploration. The Workshop was held Thursday, November 2, 2000. About 70 space mechanisms experts shared their experiences from working in this field and considered technology development that will be needed to support future space exploration in the next 10 to 30 years.

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