Space Mechanisms Lessons Learned Study
Volume I—Summary

Wilbur Shapiro, Frank Murray, and Roy Howarth
*Mechanical Technology Incorporated*
*Latham, New York*

Robert Fusaro
*Lewis Research Center*
*Cleveland, Ohio*

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FORWARD

There appears to have been a corporate loss of memory in the USA on how to build space mechanisms (mechanically moving components) for long life and reliability. A large number of satellite failures and anomalies have occurred recently (e.g. Galileo, Hubble, etc.). In addition, more demanding requirements have been causing failures or anomalies to occur during the qualification testing of future satellite and space platform mechanisms even before they are launched (GOES-NEXT, CERES, Space Station Beta Joint Gimbal, etc.). For these reasons, it is imperative to determine what worked in the past and what failed so that the best selection of mechanical components can be made as well as to make timely decisions on initiating research to develop any needed technology. The purpose of this study was to capture and retrieve information relating to the performance of mechanical moving equipment operating in space to determine what components have operated successfully and what components have produced anomalies.

Data was obtained through various sources, such as: (1) An extensive literature review that included government contractor reports and technical journals. (2) Communication and visits (when necessary) to the various NASA and DOD centers and their designated contractors. This included contact with project managers of current and prior NASA satellite programs as well as their industry counterparts. (3) Requests for unpublished information was made to NASA and industry. (4) A mail survey which was designed to establish specific mechanism experience and also to solicit opinions of what should be included in a future Space Mechanisms Design Guidelines Handbook.

The majority of the work was done at MTI under contract NAS3-27086. The following acknowledgement section also lists some organizations and individuals who contributed to the work.

ACKNOWLEDGMENTS

The literature review required the assistance of knowledgeable technical personnel. The assistance of Dr. Dantum Rao was helpful. Dr. E.M. Roberts of the European Space Tribology Laboratory (ESTL) provided the European literature review and a listing of experts; his efforts are acknowledged and appreciated. Mr. Bobby McConnell of Tribotech Consultants also provided valuable information from his knowledge of Air Force space mechanisms programs. The authors appreciate those who responded to the Space Mechanism Survey. Special recognition goes to Mr. Richard Fink and David Marks of the Honeywell Electro Components Division, Durham, North Carolina, and to Mr. Bryan Workman of the Honeywell Satellite Systems Operation who organized their many responses. Recognition also goes to Laurence Bement of the National Aeronautics and Space Administration Langley Research Center (NASA-LaRC) for his contribution on Pyrotechnics; to Claudia Woods of NASA Goddard Space Flight Center (NASA-GSFC); to Dennis Egan of Applied Innovation; and to Stuart Lowenthal of Lockheed Missle & Space Company, Inc. We would also like to acknowledge the reviewers of the manuscripts: Dr. Michael Khonsari of the University of Pittsburgh, Mark Siebert of Toledo University and Ralph Jansen of the Ohio Aerospace Institute.
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INTRODUCTION
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Future National Aeronautics and Space Administration (NASA) space missions will require advanced performance standards, increased life, and improved reliability of mechanical systems and their components. Enhancements require learning from past experience and transferring technology to newer generations. Accordingly, NASA has embarked on a program to produce a Space Mechanisms Handbook that will provide guidelines and recommendations to future mechanism designers. As part of that program, a Lessons Learned study was performed to determine prior anomalies and how to avoid them in the future. This report provides the information obtained during the Lessons Learned study.

Three major categories of mechanisms were selected: deployable appendages, rotating systems, and oscillating systems. Subsystems of these major categories are as follows.

Deployable Appendages
- Solar Arrays
- Retention and Release Mechanisms
- Bearings, Lubrication, and Tribology Considerations
- Antennas and Masts
- Actuators, Transport Mechanisms, Switches
- General and Miscellaneous

Rotating Systems
- Momentum Wheels
- Reaction Wheels
- Control Moment Gyroscopes
- Gears
- Motors
- Bearings and Lubrication
- Slip Rings and Roll Rings
- Miscellaneous

Oscillating Systems

Information for the Lessons Learned study was retrieved from a number of sources including:

Available Literature. The literature review proved to be the most significant source of information. In particular, the 28 Annual Proceedings of the Aerospace Mechanism Symposium was an extremely valuable resource. Also, a NASA-Goddard publication on deployable appendages was very informative. In compiling the literature review, a specific format was adhered to. The ingredients of the format are described in Volume II, Literature Review.
The constraints of the literature search limited publications to those that described anomalies and/or lessons learned. Mechanism descriptions contained in these publications were also summarized and documented for subsequent use in generation of the handbook.

**Industrial Survey.** A survey form was created, which is presented in the Survey Results section of this report. Over 600 surveys were mailed with approximately 30 responses. Some significant information was provided, especially by the Satellite Systems Operation and the Electro Components Division of the Honeywell Corporation, who spent considerable time in preparing information. Other responses provided additional reference material.

**Subcontracts.** The European Space Tribology Laboratory (ESTL) contributed a review of the European Literature and provided a listing of European experts. Also Bobby McConnell, of Tribotech Consultants, who has considerable experience with military applications of space mechanisms contributed information.

This report is organized into two volumes. Volume I provides a summary of the lessons learned, the results of a needs analysis, the survey responses, a listing of experts, a description of some available facilities, and a compilation of references. The completed literature reviews comprise Volume II.
SUMMARY OF LESSONS LEARNED
SUMMARY OF LESSONS LEARNED

This section summarizes the lessons learned from the Survey Results and from the Literature Review (Volume II) performed for the three main categories (deployable appendages, rotating systems, and oscillating systems) and their respective sub-systems. Authors' names that appear in brackets, e.g., [Farley], indicate that more detailed information on a topic is included in Volume II under the same category, subsystem, and author/expert name.

Deployable Appendages

Solar Arrays

- Cosmic background explorer [Farley]
  - One damper required replacement because of an air bubble (reason not stated). However, it could be attributed to the selection of the viscous damper fluid. McGhan-Nusil CY7300 silicone fluid is preferred because of stable viscosity and low outgas characteristics.
  - A pin puller shaft fractured and rebounded into an unfired position. Excessive hole drilling in this puller caused the failure. Pin pullers should be x-ray inspected.
  - The array experienced inconsistent behavior of a microswitch; quality assurance needed improvement.

- Earth Radiation Budget Satellite (ERBS) [Mollerick]
  - Excessive bearing friction was experienced due to poor characteristics of molybdenum disulfide (MoS₂) lubricant at cold conditions. Under conditions of cold temperature (-44°F) and the bailing up phenomenon of MoS₂, moisture molecules could create frozen balls in the path of the rolling elements impeding available driving torque. In fact, this is the major contributor believed to have prevented the solar array from initially deploying while the spacecraft was attached to the orbiter remote manipulator system. Application of sputter-coated MoS₂ with proper run-in may have avoided some of these problems. [Fleischauer, Hilton]
  - Spring drives must use a minimum torque ratio of four. The deployment drive systems each had a torque ratio of less than three. However, each drive had redundant torsion springs and analysis indicated ample capacity for successful deployment. In looking at the ERBS solar array deployment, it is conceivable that a combination of cold temperatures, thermal gradients, MoS₂ lubricant, and insufficient torque margins are likely to result in deployment problems.

- Torque increases and fluctuations can be caused by wire harnesses due to cold temperatures and complex wiring paths. Testing is required at simulated environments to resolve torque problems. [ESTL, Hostenkamp]
MILSTAR employed a flexible substrate solar array. A summary of lessons learned during its development are as follows: [Gibb]

- Minimize deployed mass at the deployed end of the array or mast (leave the cover at the base).
- Conduct analyses and test to ensure adequate blanket container preload. Testing should include acoustic and shock testing.
- Maximize spreader bar stiffness in the deployment plane, and perform analysis to ensure acceptably low deflection to avoid panel warping or wrinkling.
- Be aware that MoS$_2$ coatings have a coefficient of friction dependent upon humidity. Variations are on an order of magnitude between ambient and vacuum conditions. Do not apply MoS$_2$ coatings to both surfaces of a mating pair or else a higher coefficient of friction will result than if only one surface is coated.
- To avoid panel sticking, insist on high-cleanliness standards during cell bonding, especially when the process involves cutting film adhesives.
- Do not rely on preload and friction to hold a blanket stack in place during ascent; use a positive mechanical device, such as pins, skewers, or interlocking sections.

Retention and Release Mechanisms

- Pip pins are used on many space mechanisms. Pip pins are most often used when an astronaut will have direct interface with the mechanism. The main reason for incorporating pip pins is convenience and their ability to provide quick release of interfacing parts. [Skyles]
  - To prevent locking balls from vibrating out of their sockets, four balls instead of two should be installed to provide redundancy if one ball falls out of its socket.
  - Swaged tethers could create a tear hazard to an astronauts pressure suit. Tether rings should be solid or have welded ends. Split rings can allow disconnect and are also a tear hazard.
  - Dowel pins for handle attachments could loosen from vibration and thermal effects. The handles should be welded to the pins to avoid loosening.
  - Liquid lubricants or grease could freeze and cause seizure of the pins. Dry film lubricants should be used to lubricate all internal parts of the pip pin.
  - Double-acting pins should be provided that allow release capability when the handle is either pushed or pulled to facilitate operation.
  - A Teflon sleeve should cover the tether swage fitting and cable termination, providing a smooth surface and preventing the possibility of astronauts contacting frayed or broken cable strands.
  - Hitch pins are recommended where the pip pin only has to be removed and not reinstalled.
  - Further development of ball retention is required. The present method is by staking which is subject to error. Inspections have shown incomplete staking that would allow the balls to fall out. Also, the staked material is relatively thin and stress concentrations can be created at the tip of the staked material. Vibrations can cause fracture and subsequent failure by ball loss.
• Problems experienced with pyrotechnic pin pullers include:
  - Blow-by across O-ring seals caused by wearing of the MoS$_2$ coating on the pin that deposited on the O-ring preventing the seal. For pistons, an electro-deposited, nickel/Teflon coating is recommended. Hard-anodized aluminum uncoated housings were recommended, although in an earlier paper it was indicated that steel housings would not distort as much as aluminum and combined with a durable dry coating on the pin improved functional performance. [Bement]
  - For pyrotechnic devices, tests must be carried out to ensure that a device has an acceptable functional margin where the functional margin is a comparison of the energy that can be delivered to the device and the energy required to operate the device. [Bement]
  - For pyrotechnic devices, material impact strength is usually a more critical variable than inertia load capability especially when the temperature drops. When the inertia load of a deployable system is low, a ductile material should be selected, as opposed to a brittle material, for the actuator housing and piston. [Phan]
  - For a pin puller lot acceptance test, at least one puller should be exposed to 125% explosive power in a cold environment. [Phan]
  - If the spacecraft requires a high level of cleanliness, then multiple pyrotechnic seals must be used to prevent gas leakage. A hybrid sealing system consists of Viton O-rings and silicon O-rings in tandem. [Phan]

• A resettable binary latch mechanism was developed utilizing a paraffin actuator as a motor. The polyamide rail failed due to unexpected high inertia loads. Substitution of titanium resulted in galling. CDA 630 aluminum nickel-bronze was finally selected because of its resistance to corrosion and superior wear characteristics. After initial wear-in (approximately 50 cycles), the toggle was burnished from contact with the rail and neither part demonstrated significant wear during subsequent testing to 20,000 cycles. [Maus]
  - For the same binary latch mechanism discussed above, thermal testing revealed interference between the output shaft and its bushing at low temperatures. The bushing, fabricated from polyamide, shrank into the output shaft at -60° C and created friction. Enlarging the bushing bore corrected the problem. Thermal binding must be considered not only for high-temperature operation, but for low temperature as well.
  - Iteratively designing a complex mechanism in computer-aided design (CAD) and using pasteboard mock-ups can be a more efficient process than detailed mathematical analysis of component geometries (components can be visualized throughout their range of motion, interferences can be identified and eliminated, and kinematics and component shapes can be easily optimized by simultaneously seeing the effect of changes in all positions).

• The patented Lockheed Super*Zip spacecraft separation joint was planned for use on the space shuttle to release the Centaur vehicle (120 in. diameter), the inertial upper stage (91 in.) at the same separation plane as the Centaur, and the Galileo spacecraft. Following functional failures of two out of a group of five Lockheed Super*Zip spacecraft separation joints in a shuttle/Centaur thermal development test
series to quantify thermal effects, an evaluation program was initiated on this and
the related inertial upper stage and Galileo systems to assist in preventing a
recurrence of failure. The results of the investigation revealed that thin ligaments
are better than thick ones because they are more difficult to sever under explosive
conditions. Also, a single-cord configuration indicated no trend toward tube rupture
with increased explosive load as did a double-cord configuration. [Bement]

- A survey has been compiled on pyrotechnic devices for a 23-yr period that included
84 serious component or system failures, 12 of which occurred in flight with fully
developed and qualified hardware. Table 1 lists anomalies.

The 1987 failure of two Magellan pin pullers has far greater potential impact than is
initially apparent. This pin puller was the same unit fully qualified for the Viking Lander
spacecraft for the 1976 landing on the surface of Mars. After this experience and with
its pedigree, two units from a duplicate lot of pin pullers failed to function in a failure
mode not recognized in the original design, development, and qualification. First, the
extremely dynamic pressure impulse output of the NSI (as designed) when fired into a
small eccentrically vented cavity was severely attenuated, reducing the energy
available to stroke the piston. Furthermore, the bottom of the cavity was deformed by
the pressure into a groove in the piston, which had to stroke to pull the pin. This
device may have always been marginal when operated by a single-cartridge input.

Table 1. Anomalies of Pyrotechnic Devices

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<th>Failure</th>
<th>Source of Failure</th>
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<td>RSRA</td>
<td>Firing pin assemblies corroded and locked in qualification</td>
<td>Bad design</td>
<td>Redesigned, requalified</td>
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<td>1973</td>
<td>Classified</td>
<td>Pin puller failed during system test (cartridge closure blocking port)</td>
<td>Lack of understanding</td>
<td>Redesigned, requalified</td>
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<tr>
<td>1979</td>
<td>Classified</td>
<td>Pin puller ruptured during system test (inadequate containment margin and variation in metal grain orientation)</td>
<td>Lack of understanding</td>
<td>Redesigned, requalified</td>
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<td>1987</td>
<td>Magellan</td>
<td>Pin puller failed to stroke against flight side load (NSI output restricted, causing reduced output and housing deformation against working piston)</td>
<td>Bad design; misapplication of hardware</td>
<td>Replaced, requalified</td>
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<tr>
<td>1986</td>
<td>Magellan Orbiter</td>
<td>Pin puller failed to function in LAT (NSI produced insufficient pressure caused by coatings of pressurized volume)</td>
<td>Misapplication of hardware; lack of understanding</td>
<td>Changed manufacturer and design</td>
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<td>1986</td>
<td>ASAT</td>
<td>Bolt cutter failed LAT (improper compression margin test requirement)</td>
<td>Incorrect specification</td>
<td>Correct specification</td>
</tr>
</tbody>
</table>
For the source of failures, the shocking statistic is that 35 out of 84 (42%) of the failures were caused by lack of understanding; that is, the personnel working the problem at the time, did not have the technology needed to understand and correct the failure. Unfortunately, 24 were mistakes caused by poor designs and misapplication of hardware, which means that personnel did not apply the known technology. The next 23 failures have to be categorized as carelessness through manufacturer's poor procedures and quality control.

Since pyrotechnics are single-shot devices, past approaches for demonstrating reliability have relied heavily on developing statistical verification without a clear understanding of functional mechanisms and the relative importance of system parameters. That is, once a successful performance was achieved, emphasis was placed on accomplishing large numbers of consecutive successes. (More than 2000 units are needed to establish a 99.99% reliability at a 95% confidence level.) However, the current approach often is to run full-scale systems tests on as few as six assemblies or less with no statistical guarantee of reliability, and without an adequate understanding of how the mechanisms function, which can be a prescription for disaster. [Bement]

- The high-output paraffin actuator provides an alternative device to the mechanism designer requiring significant mechanical work from a small, compact, reliable component. The work can be generated from heat provided by internal electrical resistance elements or from environmental temperature changes. [Tibbits]

- In internally heated configurations, the advantages over conventional electrically powered actuators can be significant (low weight, resetability, full verification before flight, high force, long stroke, gentle stroke, and flexibility in materials of construction). [Tibbits]

- Structural latches for modular assembly of spacecraft and space mechanisms are exposed to a number of problems. Problems and suggestions are as follows. [McCown]
  - Load control is a particular problem with hook systems where the load is usually preset by rigging. Load changes due to thermal or dynamic fluctuations cannot be compensated.
  - The selection methodology described by McCown, is an excellent guideline for designers.
  - For roller screw latches, thread engagement is improved by providing lead-ins.
  - Rolling element latch interfaces reduce particle generation. The addition of Teflon wiper seals control loose particles in the roller screw structural latch and receptacle nut.
  - A run-in and clean-up procedure reduces particle generation from initial actuations. The only reliable method to control the roller screw structural latch preload was to limit motor power.

- At launch, the near-infrared mapping spectrometer of the Galileo spacecraft had two covers in place to protect the instrument from contamination. Two and a half months after launch, initial attempts to eject the covers were unsuccessful. It was subsequently determined that this was due to differential expansion caused by the shield heater being energized. The shield heater was turned off, the covers allowed to cool, and they were successfully ejected. Untested flight sequences frequently
result in unexpected events. Because of concern for contamination caused by spacecraft outgassing, a flight rule was modified prior to launch requiring the shield heater to be energized before cover deployment. The flight rule was in error by not requiring heater shutoff before deployment. The lessons learned are that the cover should have been tested in the flight environment and the consequences of flight rule changes should be carefully evaluated. [JPL SSEF, Schaper]

- During one of the solar array deployment tests in 1989, a pin puller in a release mechanism was actuated, the pin was retracted inside its housing to release the solar array, but then rebounded back out of its housing. The normal function of a pin puller is to retract and stay flush inside the pin puller housing. The malfunction of this pin puller did not stop the deployment of the solar array because of the mechanical redundancy of the release mechanism. The rebound of the pin outside the housing forced us to investigate our pin puller design. The result of this investigation showed that an extra shear pin hole was accidentally drilled at 120° away from the original shear pin hole on the pin puller. From past pyroactuator design experience, it was determined that material impact strength is usually a more critical variable than the ability of the pin puller to withstand the high inertia load of a deployable system, especially if the device is required to operate in a cold environment. Material impact strength drastically drops when the temperature drops. It is recommended that when the inertia load of the deployable system is low, a more ductile material be selected over a brittle material for the actuator housing and piston. It is also recommended that for the pin puller lot acceptance test, that at least one test include subjecting the pin puller to zero inertia load in the shear direction, and in a cold operating temperature, actuate the pin puller with 125% explosive power. [Hinkle]

- Some gas molecules will leak out of a pyrotechnic actuator assembly during the actuation and some over a period of time after actuation, because most pyrotechnic actuators have only a single Viton O-ring. If the spacecraft requires an extremely high level of cleanliness, then a hybrid sealing system must be designed for the actuator assembly. Hybrid sealing systems design consists of a Viton O-ring and a silicon O-ring that are located side by side in the leakage path. [Hinkle]

- Microwelding of high-load contact areas can occur from induced random vibrations that will prevent smooth transition of linear devices. [ESTL, Coquelet]

- Thermal problems are prevalent with actuators and retention and release mechanisms. Differences in coefficients of thermal expansion must be thoroughly explored to avoid jamming and excessive torque. [ESTL, del Campo]

- Vibrations can cause unwanted deployment of components. Additional restraint is sometimes required. [ESTL, Henton-Jones]

- Microswitches on the Magellan were mounted such that they would detect the position of the solar panels (as opposed to the status of the latching mechanism). As a result, they were just a position indicator and not a "panels locked" indicator. Care should be taken in deciding where to mount telemetry transducers to assure that the desired function is actually being measured and not just a related function. [JPL SSEF, Wagoner]
- The mechanical joint between the biaxial drive assembly and its mounting to the spacecraft allowed the ACTS transmit antenna to shift locations during launch. The four bolts did not maintain the proper preload and the joint slipped during launch loading. This has reduced the available design adjustment for the ACTS transmit antenna. All mechanical joints that require precise alignments should not use friction to maintain alignments during any type of loading. All types of alignment joints should be matched drilled with body-bound bolts or be drilled and pinned after assembly. [Survey, Collins]

- A paraffin actuator used to open and close the main sensor cover on the Clementine spacecraft experienced a heater failure during acceptance testing. There were two causes of the problem: excessive temperature and stress from driving the heater at high voltage (36 V), and mechanical stress on the heater element from flowing wax within the actuator during heating. The problem was resolved by remounting the heater and dropping voltage by incorporating a resistor in series with the heater. In the future, a circuit with a zener diode will be installed to keep the operating voltage from varying excessively. A similar approach will be considered for other mechanisms sensitive to variations in supply voltage and especially for other heat-actuated mechanisms. [Survey, Purdy]

- Mechanisms that depend on frictional characteristics to restrain a load during launch vibration may slip and relieve the applied load. Components such as worm gears and lead screws are normally considered to be nonbackdrivable. Certain conditions of vibration can cause backdriving to occur. [Survey, Fink]

- Because of concerns about the nonconductive Tufram coating allowing a charge buildup that might affect instruments for the Polar satellite, a change to a conductive coating (NEDOX) was directed. Although, the coefficient of friction of NEDOX was better than that of Tufram, the NEDOX-coated V-band failed to release during acceptance testing. Previously, an engineering unit with a Tufram-coated V-band was successfully released more than a dozen times. Extreme care should be used when changing even the simplest process or procedure from what had worked previously. Testing of the new coating prior to acceptance test was bypassed due to budget and schedule constraints and the similarity of the two coatings. In the end, neither schedule nor budget was saved and testing had to be repeated with the final V-band design, which consisted of Tufram coating only on the contacting surfaces of the band to minimize surface area for charge buildup. [Survey, Osterberg]

- The x-ray telescope covers for the Alexis spacecraft failed to operate consistently during thermal vacuum testing. On orbit, three of the six covers failed to open on the initial command. The lifting mechanism was not sufficient to completely break the O-ring seal. Avoid covered O-rings if at all possible. Spring-energized Teflon seals are a better solution. If O-ring seals are used, ensure that the complete seal area is actively broken through by high-force actuation. If it is not possible to actively break the seal, kick-off springs opposite the hinge line should be used to supply the initial torque rather than additional hinge line spring force. [Survey, Tibbits]
Bearings, Lubrication, and Tribology Considerations

- Thin-section, four-point contact ball bearings are increasingly employed in spacecraft mechanisms because of the potential advantages they offer. Internal preload, housing design and external axial clamping force on the bearing rings all have a strong influence upon torque, conductance, and stiffness. The thermal conductance of a dry or marginally lubricated bearing depends upon the thermal strain and varies linearly with radial temperature difference between the rings. Additionally, conductance is a function of type and quantity of lubricant. The Coulomb torque exhibits almost a square relation with thermal strain. [Rowntree]

- MoS₂ solid lubricant films were prepared by radio frequency magnetron sputtering on 440C steel, 52100 steel, and silicon substrates. [Hilton]
  - Multilayered films exhibited excellent endurance in sliding wear and thrust bearing tests. Friction coefficients in ultra-high vacuum ranged between 0.05 and 0.08.
  - With metal multilayer films, the optimum structural spacing is in the order of 10 Nm.
  - Minimum metal layer thickness is best.
  - A thin surface overlay of pure MoS₂ seems to facilitate transfer to an uncoated surface.

- Solid lubricant films are used in a variety of mechanisms on various spacecraft and launch vehicles. Relative to liquid lubricants, solid lubricants generally have lower vapor pressures, better boundary lubrication properties and relative insensitivity to radiation effects, and operate in wider temperature ranges. [Hilton]
  - Lead coating has had good success as a solid lubricant in vacuum applications.
  - Optimum performance of lead and other metals is achieved at approximately 1 mm thickness.
  - Deposition of soft metals (Pb, Au, Ag, In) by ion plating provides excellent adhesion. These films have been particularly effective in spacecraft bearings found in solar array drive mechanisms in European satellites and on the Hubble space telescope.
  - A particular disadvantage of lead is that it oxidizes rapidly and must be stored in vacuum dry environments.
  - Gold and silver are used in situations requiring electrical conductivity.
  - Sputter-deposited MoS₂ has a lower coefficient of friction than ion-plated Pb (0.01 versus 0.1), which means that MoS₂ components should develop less torque.
Mechanical Technology Inc.

- General lubrication problems and lessons learned with spacecraft deployable appendages include: [Devine]
  - Seizures of relative motion surfaces caused by excessive friction.
  - Vibration-induced fretting and adhesion due to excessive clearance in caging devices.
  - Unlubricated surfaces exceeding bearing yield strength of substrate on hard-coated materials.
  - Seizures caused by dissimilar materials with high mutual solubility.
  - Maximum utilization of rolling surfaces as opposed to sliding motion should be employed.
  - Lubrication or separation of all moving surfaces either by suitable aerospace grease or dry lubricant coating should be used. No exceptions are allowed, even for lightly loaded friction-compatible surfaces.
  - On hard mating surfaces where hard coatings are used (such as Type III anodizing on aluminum), loads must be kept below the bearing yield strength of the substrate material (e.g., 60 ksi for 6061-T6 aluminum).
  - Smooth and polished surfaces are preferred.
  - Dissimilar material mating surfaces should have mutual solid solubility or at least one of the two should have a heavy dissimilar coating (e.g., nitride, carbide, or oxide).
  - Caging devices should be designed to positively preclude relative motion between clamped surfaces when subjected to shipment or launch vibration.
  - Wet lubrication is generally preferred because friction is low and predictable. The grease with the most heritage is the Braycote 600 series, a synthetic-fluorinated oil-thickened grease with micron-size Teflon powder. The grease has extremely low outgassing (TML <0.1% and CVCM <0.05% for the standard 125°C 24-hr test) and concerns relative to contamination are negligible for virtually all spacecraft applications. The wet lubricant usable temperature range is -80 to 200°C.
  - For extreme low temperatures and cryogenic applications, solid lubricants are preferred. Epoxy and polyamide-bonded films can be successfully employed with proper application and burnishing to remove excess material.

- Table 2 summarizes the technology shortfalls currently affecting Air Force and Strategic Defense Initiative Organization (SDIO) mission requirements for deployable components, together with suggested tribomaterials (or design) solutions to overcome shortfalls. [Fehrenbacher]
Table 2. Tribomaterials for Deployment Mechanisms

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>Mission Requirement</th>
<th>Technology Shortfall</th>
<th>Tribomaterials/ Mechanical Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Array Drive</td>
<td>• Reversible fast stow and deploy (10-sec retraction)</td>
<td>• Reduced torque and torque noise</td>
<td>• Solid lubricant (wear-resistant films)</td>
</tr>
<tr>
<td></td>
<td>• 360° continuous rotation (0.3 to 15°/sec)</td>
<td>• Lightweight (reduced size) bearings/gears</td>
<td>• Traction drives with controlled friction solid lubricant coatings</td>
</tr>
<tr>
<td></td>
<td>• 10- to 15-yr life, high torque with very small ripple</td>
<td>• Long-life lubrication (thermal gradients, decontamination)</td>
<td></td>
</tr>
<tr>
<td>Antennas and Sensor Platforms</td>
<td>• Synchronous and sequential deployment</td>
<td>• Lubricant life and survivability (thermal gradients, decontamination, laser irradiation)</td>
<td>• Synthetic hydrocarbons (low vapor pressure and additives)</td>
</tr>
<tr>
<td></td>
<td>• Pointing accuracy while retracting</td>
<td>• Low friction, friction noise, and jitter</td>
<td>• Solid lubricant films (low friction and wear)</td>
</tr>
<tr>
<td></td>
<td>• Consistent friction over 10- to 15-yr life</td>
<td>• Reliability under quick transition from stowed to deployed</td>
<td>• New polymeric retainers for ball bearings</td>
</tr>
<tr>
<td>Release Mechanisms</td>
<td>• Launch load protection</td>
<td>• Shape memory alloy, fatigue/reliability</td>
<td>• Solid-lubricated mechanical release mechanisms</td>
</tr>
<tr>
<td></td>
<td>• Operational performance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Based upon a detailed study of the performance records of almost 400 satellites between 1958 and 1983, it was established that about 10% of the successfully launched satellites had some type of deployment anomaly, the majority of which were mechanical. [Feherenbacher]

- Many of the problems experienced by satellites were due to thermal or thermal gradient problems that reduced clearances or caused lubricants to fail. [Feherenbacher]

- It was demonstrated, on a test of a spacecraft oscillating scanner that the polyalpholefin (PAO) oil provided excellent lubrication, consistent torque with negligible torque noise, and good wear to 22,000 hr with the test still running. The other oils (chloroaryalkylsiloxane (CAS), originally used in the application, and a perfluoropolyalkylether (PFPE)) exhibited a reduction in torque (loss of preload) and an increase in torque noise, as well as extensive wear after a few thousand hours. [Feherenbacher]

- The best options for solid lubricant films for space applications appear, at present, to be ion-plated lead and ion-sputter deposition of, and/or ion-assisted deposited, MoS$_2$. These lamellar films have demonstrated very low friction operation in sliding and/or high low-load rolling bearings and latch and release mechanisms. They are under development for a variety of ball bearing applications. For solid lubricants for satellite gears, lead films were found to provide good lubrication after a breaking in period that produced a 100 Angstrom elastic film. Best results were obtained for a film thickness of 1 micron. Solid films of MoS$_2$ and TiN in the same application resulted in unacceptably short gear lives, demonstrating that tribomaterials must be tailored to the system design. MoS$_2$ has, in fact, been shown to be an excellent
lubricant for many space applications, although its reaction with atomic oxygen requires further study. Recent sputtered-deposited films have shown a 10 to 100% increase in film life over previous MoS₂-coated bearings. [Feherenbacher]

- Both titanium carbide and titanium nitride have been demonstrated to be effective wear coatings under appropriate conditions. Titanium carbide has been applied to gyroscope ball bearings and has increased operational lifetime by an order of magnitude in this application when used with an uncoated steel raceway and superrefined mineral oil. To date, titanium nitride has been used only on tool steels, but the Aerospace Corporation is currently testing both gimbal and spin bearings with titanium-carbide and titanium-nitride-coated balls. [Feherenbacher]

- The development of new polymeric bearing retainer materials is a critical need to achieve required bearing lifetime. The phenolic materials that are commonly used have been demonstrated to absorb oil in a time-dependent and nonreproducible manner. These retainer materials are unacceptable for the missions under consideration unless an active lubricant supply system is used. [Feherenbacher]

- Avoid the use of wet lubricants where optical devices or sliding electrical contacts are employed. [Rowntree]

- PFPE fluids have produced high torque noise and excessive ball bearing wear. The precise mechanism of degradation is still not established. In Europe, the evidence points to chemical reaction between nascent wear particles and the exposed oxygen in the Z-type molecule. The product is described as a metal polymer, or "brown sugar", which is autophobic and thus repels the oil from the ball/raceway contact region. [Rowntree]

- Ion-plated lead films are extensively used in Europe. In solar array drives alone, more than 2 million operational hours in orbit have been accumulated. [Rowntree]

- An important property of the lead film is its high load-carrying ability. Under Hertzian contact, the as-deposited film flows plastically until a thin film (10 Nm thickness or less) remains and then elastically deforms the substrate. In this condition, the film can survive contact loads approaching the static load capacity of a rolling element bearing. [Rowntree]

- Thin films of gold have also been investigated as a bearing lubricant, but the higher yield strength and ductile adhesional property results in work-hardened debris and thus high torque noise. Silver and indium have been investigated too, but actual usage in space is not reported. [Rowntree]

- Sputtered application of MoS₂ is the preferred and, perhaps, necessary method. Sputtered films of MoS₂ are currently applied to numerous space components such as screw threads, ball bearings, sleeves, and bushes. [Rowntree]

- An investigation at ESTL of MoS₂ films deposited by magnetron RF sputtering in which the rate of evaporation of the MoS₂ target is greatly increased by magnetic field intensification of the plasma, led to significant gains in triboproperties under vacuum. Not only is the friction coefficient remarkably low under pure sliding motion (values of 0.005 to 0.04 are typical), but the wear resistance of the film is greatly improved. [Rowntree]
• Ion-beam application of MoS$_2$ also appears promising, although it has not been used in space mechanisms. A feature of this method is an increase in the density of the film and it is possible that this compaction may help in extending film lifetime. [Rowntree]

• MoS$_2$ works well with ceramics, such as titanium carbide and hot-pressed silicon nitride. [Rowntree]

• An extensive study restricted to air usage in the United Kingdom over 10 years ago, showed that the PTFE/glass fiber/MoS$_2$ combination was preeminent in terms of friction torque and endurance, provided that the maximum Hertzian contact stress was kept below 1200 MPa at room temperature. [Rowntree]

• Friction torque of ball bearings under thrust load and low temperature is difficult to predict. Unexpected increases in friction torque have been experienced. Testing at temperature is recommended to determine torque levels. [ESTL, Kaese]

• Linear rolling elements and cages can creep, which leads to high torque spikes at the end of travel. These high forces were generated as the cages were driven into contact with the bearing end stops, at which point any further movement of the nonstationary races resulted in sliding motion between the races and the sliding elements. In addition to causing higher friction forces, the effect also resulted in more rapid wear of the MoS$_2$ film. To prevent roller and cage creep, and thus eradicate high end forces, a cage speed control device is required to ensure the correct cage to ball speed ratio. [ESTL, Roberts]

• Considerable care must be exercised when mounting close-clearance bearing components into aluminum structures that must operate at cold temperatures. Contraction of the aluminum must be accounted for. [Survey, Lowenthal]

Antennas and Masts

• Tracking and data relay satellite (TDRS) [Luce]
  - The field of view of one of the single-axis antennas was restricted, probably due to a pinched or snagged electrical cable that runs across one of the single-axis antenna gimbal joints. The joint cable operation should have been checked on the ground and the design modified accordingly. Cable circuitry should avoid regions where the cable can get caught or snagged.
  - The single-axis antenna delayed deployment by nearly 3 hr when one of the compartment attachment lugs came into contact with the compartment kick-off spring mechanism. Interference between actuation devices and attachment lugs should be avoided.
  - One of the single-axis antenna drive motors stalled because the biax service loop harness became pinched between the boom and compartment. The motor was reversed to relieve the pinch, and deployment proceeded normally. Reversible motors can help correct deployment problems.
• On the second flight of the INTELSAT V spacecraft, the time required for successful deployment of the north solar array was longer than originally predicted. The south polar array deployed as predicted. The difference in deployment time was found to be due to a significant increase in hinge friction at low temperatures and vacuum. The hinge friction problem was overcome by increasing the bearing clearances to allow for greater temperature variations and giving the hinges special lubrication.

• The Galileo's high-gain antenna, which opens like an umbrella, never reached the fully deployed condition. [Johnson]
  - The failure was caused by galling and excessive friction in the midpoint restraint pins and V-groove socket of the struts, which required mechanical drive torques in excess of motor capacity to free the pins and permit deployment.
  - Contact stress of any mating surfaces should not be great enough to cause plastic deformation and/or destroy applied coatings.
  - Friction in vacuum can substantially exceed friction in atmosphere, especially when coatings are destroyed and galling occurs.
  - Moments applied to ball screws severely degrade their capacity.
  - The use of a dry lubricant, specifically MoS₂, on a mechanism that is going to be operated in an atmosphere should be carefully evaluated. The wear rate of the MoS₂ in air is so much higher than in a vacuum, that any coatings could be worn out by air testing and shipping lubrication, and not provide the desired lubrication when needed. Replacing dry lubricated surfaces just prior to launch, so that virgin lubricant surfaces are available is recommended, if feasible.
  - Shipping vibrations and ground testing can destroy coatings and dry lubricants.
  - Vacuum deployment tests on the ground, should include simulated vibrations prior to deployment.

• During ground testing of the dynamics explorer, an end-of-travel shutoff switch failed to activate during Astromast deployment. The microswitch failure in space could have been catastrophic and points to the necessity for switch redundancy for mission critical components. [Metzger]

• The mechanism was to deploy/restow two large Hubble space telescope deployable appendages in a varying but controlled manner. The initial predicted aperture door mechanism temperatures could be well below -125°F. This proved to be a problem for the grease plating of Braycote 3L-38RP on the angular contact bearings. The solidification temperature of this lubricant is approximately -120°F. The resulting stiffness of the lubricant caused unacceptably high bearing torques even though the mechanism would operate to as low as -160°F. Braycote 3L-38 RP grease works well in angular-contact bearings in a vacuum if the temperature is kept above the grease solidification temperature. The range of motion of the hinges is approximately 90°. For the aperture door mechanism, this motion takes place over 1 min, and for the high-gain antenna hinge, the time is 7 min. [Greenfield]

• During subsystem testing of the high-gain antenna configuration, the tests were plagued by a problem that was finally diagnosed as lost motion. This resulted in variable performance at the stowed position. In a mechanism, it is important to eliminate all backlash to avoid lost motion. [Greenfield]

Summary of Lessons Learned
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- The Gamma Ray Observatory (GRO) had two solar array wings weighing approximately 500 lb each and one high-gain antenna boom assembly weighing approximately 525 lb. The high-gain antenna did not deploy when it was initially commanded. A portion of the antenna release mechanism (close to the antenna dish) was caught by a piece of thermal insulation blanket. The lessons learned are: [Hinkle]
  - Deployment tests should be accomplished with the final configuration including thermal blankets. Spacecraft attachments should be simulated accurately.
  - Interference that might be caused by thermal blankets should be evaluated during the design process.

- Mechanisms must be evaluated for vibration problems and appropriate damping applied. Vibrations can cause unwanted deployment that must be constrained. [ESTL, Abarrategui]

- Stowage time can inhibit deployment mechanisms, especially at soft-contact interfaces that require relative motion at deployment. Rubber contact could cause separation problems by sucking or sticking. MoS₂ coatings can alleviate this problem. [ESTL, Barho]

- Brush contact encoders are prone to a wear problem that renders them unsuitable for use on high-accuracy, high-reliability space mechanisms. [ESTL, Gallagher]

- After positioning GEOS in its final orbit, its eight booms and five mechanisms were deployed. Two axial booms showed anomalies during deployment and one of these, a long axial boom, extended to only about 80 to 90°. To reduce the possibility of friction due to cold flow of guide rings, the tightening torque was reduced and the Teflon guide modified. The release mechanism modification mainly concerned the ball release piston and ball cage area. The hard edge of the titanium sleeve was replaced by a soft aluminum chamfer to prevent indentation of the balls. The ball cage holes that were cylindrical in GEOS-1 are now conical to improve the ball release. [ESTL, Schmidt]

- During the Hubble space telescope antenna pointing system testing, the internal thermostats failed making the internal heaters inoperable. External heaters were bonded to the outside surface of the gimbal housing with externally mounted thermostats, completely bypassing the external circuit. Where possible, the wiring for internal heaters and thermostats should be completely accessible in case the internal components fail, during prototflight tests. [Ruebsamen]

- During acceptance testing of space telescope antenna pointing system gimbals, the external cover of the heater dislodged during thermal cycling test. The cause was incompatibility of the coefficient of thermal expansion between the cover materials with the housing materials and the fact that the cover and housing were gold plated, which prevented a proper epoxy bond between two parts. Three lessons learned were:
  - Heater covers should include a mechanical means of mounting along with the epoxy bond (i.e., screws).
  - The area where the epoxy bond is to occur should be free of gold plating.
  - If external heaters are to be used, an epoxy designed for use as a thermal conductor should be designated and its coefficient of thermal expansion should match that of the major structure. [Survey, Ruebsamen]
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Actuators, Transport Mechanisms, and Switches

- A deployment actuator mechanism was developed for the Topex satellite. Post-vibration testing showed that the dry lubricant film in the journal bearing was flaking causing an increase in torque. The problem was determined to be excessive lubricant film thickness. Applying the lubricant to one bearing surface rather than both and burnishing the film to reduce thickness resolved the problem. [Jones]

- Thermal vacuum testing of the Topex deployment actuator viscous fluid rotary damper revealed a region of undamped travel, immediately after deployment had been initiated, followed by normal operation throughout the remainder of the travel. The result was unacceptably high-impact loads in the damper input shaft as damper operation returned to normal. Potential explanations included air pockets and ineffective thermal compensation. The reason for the anomaly was never confirmed and another damper was installed. Further investigation of rotary dampers is required. [Jones]

- For a mirror transport mechanism, loads were developed during vibration testing that caused a rocking motion of the dihedral platform resulting in a pivoting motion about the latch cone axis. This placed excessive loads on the pivot flexures, causing them to fail. To limit the load, the pivots were enclosed in sleeves that restricted radial movement to acceptable levels. [Stark]

- On April 11, 1991, a command to unfurl the Galileo spacecraft high-gain antenna resulted in a stalled motor about 50 sec into deployment [Johnson], which was considerably short of full antenna deployment. The prevalent theory of cause has been that the undeployed ribs' locating pins were still locked or stuck in their receptacles due to a misalignment taper plus a high-friction condition. Tests revealed that the transportation environment resulted in a classic fretting condition. Since the fretting condition of small oscillatory translational movement coupled with high-frequency cycling was not duplicated in friction testing, a coefficient of friction greater than 1.4 could have resulted. The lesson learned was: [Lewis]
  – Packaging for shipment should not allow relative motion between components.

- Redundant push-off springs should be incorporated for initial release of all spacecraft deployable appendages. [Sharma]

- An anomaly occurred with a plunger-activated, hermetically sealed switch during ground testing of the Upper Atmosphere Research Satellite (UARS). Gravity effects caused the plunger to deflect away from the switch preventing motor cutoff at the desired position. The solution was to redesign the switch activation device so it was not gravity sensitive. The lessons learned are: [Leary]
  – Mechanisms must be designed for both ground test and space operation.
  – Plunger designs of switches could pose problems on ground test due to gravity. Cam actuation may be preferable.

- For harmonic drive support bearings, two oils were tested: NPT-4 (a neopentylester spacecraft oil) and Pennzane SHF 2000 (a synthetic hydrocarbon oil). The effects of antiwear additives tricresyl phosphate (TCP) and naphthenate (PbNb) were also investigated. Pennzane with TCP gave the longest life. The failure mechanism with...
the two oils were different. Bearings tested with oils plus TCP failed due to wear. Bearings tested with oils plus PbNb failed due to a hard, lead-containing carbon film which resulted in high friction. From this it appeared that TCP would be effective in light-load applications where low friction was important, while PbNb would be more suitable for high-load applications where friction was of secondary importance. [Kalogeras]

- An optical actuator required accuracy better than conventional systems. Table 3 summarizes the approaches taken by Lockheed to overcome the limitations of conventional designs. [Lorell]
  - The use of a motor-driven screw or gear mechanism was rejected because of mechanical inaccuracies. Piezoelectric devices require high voltages. The best choice appears to be a voice coil-type actuator that can have high bandwidth capabilities and is both simple and reliable.
  - The force unloading system proposed by Lockheed may be useful in other satellite applications where it is necessary to maintain a continuous power input. Eliminating the need for bearings and lubricants by the use of flex pivots also has merit.

- Dehydration of brake materials and accumulation of wear debris, trapped between the opposing surfaces, can cause a marked reduction in friction of brake materials. Problems have been encountered with the asbestos/phenolic friction elements of the shuttle remote manipulator system. When slip tested under load, the pads showed a greatly diminished friction in vacuum, which is fully recovered on return to atmosphere. Polymers are also unacceptable because they will not provide sufficient friction as a brake material in vacuum. Lessons learned are as follows: [Hawthorne]
  - Some ceramics or cermets can provide stable and moderately high friction as brake materials. This group includes Cr$_2$O$_3$ and Al$_2$O$_3$/SiC.
  - To ensure in-vacuo stable friction, run-in of opposed surfaces is recommended.

**Table 3. Lockheed Solutions to Limitations of Conventional Designs**

<table>
<thead>
<tr>
<th>Problem</th>
<th>Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamic range</td>
<td>Use of an electromagnet actuator in an analog closed-loop using special low-noise sensor electronics</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>Use of electromagnetic actuator and moderate equivalent gear ratio</td>
</tr>
<tr>
<td>Stiction/friction</td>
<td>No bearings or lubricants; exclusively flex pivots</td>
</tr>
<tr>
<td>High power consumption</td>
<td>Four-bar linkage (lever) and force unload system</td>
</tr>
<tr>
<td>Inability to cancel static friction</td>
<td>Force unload system</td>
</tr>
</tbody>
</table>
• During development of robotic arms, the Europeans have found that phenolic/asbestos brake materials present torque anomalies under thermal vacuum conditions. [Priesett]

• A movable stop mechanism activated flaps to change telescope aperture on command. The mechanism consists of a rotary solenoid that drives dual four-bar linkages in synchronism to rotate butterfly flaps into position. During testing, the mechanism jammed in the open position. Galling and scuffing of the surfaces of a fixed stop and the mating stop surface on the actuating arm had occurred. Some lessons learned are as follows: [Tweedt]
  – Ion-plated lead lubrication proved to be satisfactory for a lightly loaded, low-speed, intermittent journal bearing type of application at cryogenic temperature and in a vacuum.
  – Tungsten-carbide coating was effective in preventing galling and cold welding of the contacting surfaces on the fixed stop and the mating surface of the actuator arm when subjected to impact on contact.
  – The importance of exactly replicating the fits, geometry, and assembly parameters of the engineering models in the subsequent production of flight units has been very positively demonstrated.
  – Low temperature can cause reduction in clearance and consequent high torques. Heaters may have to be applied to gear heads and other devices if excessive friction results. [ESTL, Cawsey]

General and Miscellaneous

General anomalies and lessons learned (guidelines) for deployment mechanisms are given below: [Farley]

• Anomalies
  – Nonredundancy of the motion-producing elements.
  – Insufficient torque margin.
  – Snagging.
  – Stiction.
  – Binding of panel hinges.
  – Excessive impact loads from deployment.
  – Poor selection of solid lubricants. Molydisulfide solid lubricants absorb water, which can freeze and jam hinges and V-cone guides.
  – Improper cone angle for cone supports.
  – Excessive bending stiffness of wire harness at low temperatures.
• **Lessons Learned**

  - **Torque Ratio:** \( T_r = \frac{\text{available torque}}{\text{resisting torque}} > 4 \)
  
  - **Torque margin:** \( T_m = \frac{(\text{available torque} - \text{resisting torque})}{\text{resisting torque}} > 3 \)
  
  \[ T_m = T_r - 1. \]

  - Panel hinges should have spherical bearings with axial clearance to avoid binding.

  - Dampers are necessary to reduce kinetic energy at impact.

  - Tioxide-V provides an acceptable hard slippery coating. Avoid molydisulfide solid lubricants.

  - Cone support angle <30° to avoid locking.

  - Joint actuators must have sufficient margin to overcome low-temperature wire harness torque. Capability should be tested at temperature with wire harness.

  - Sensors should be applied to deployment devices to determine initial motion, intermediate position, and latch-lock indication.

  - For articulation motors, sensors should be applied for output shaft position, null reference indication, speed, and current.

• **United States Air Force Mil Standard, MIL-A-83577B,** sets forth general requirements for the design, manufacture, quality control, and testing of moving mechanical assemblies to be used on space launch vehicles. Many of the requirements listed are based on anomalies in spacecraft. Deployables shall (where practicable) be designed so that they are self supporting when placed in any orientation relative to gravity while in either the stowed or deployed configuration. Deployables shall be designed with sufficient motive force to permit full operation during ground testing without depending upon the assistance of gravity to demonstrate deployment.

  - **Retention and Release Devices.** Positive retention provisions shall be provided for deployables in the stowed and in the deployed position. The effects of deflections such as those induced by centrifugal forces or differential thermal growth of any deployable with respect to its space vehicle attachments shall be considered in the design of the attachments. Devices that may be subject to binding due to misalignment, adverse tolerances, or contamination shall not be used. Slip joints shall be avoided (where practicable).

  - **Pin Pullers.** Where pin pullers are used, such as cartridge-actuated or nonexplosive pin pullers, they shall be designed to be in double shear. The design, installation, and checkout procedures for pin pullers shall ensure that loads due to misalignment of the pin are within design limits. A minimum retraction force margin of safety of 100% at worst-case environmental conditions and under worst-case tolerances shall be maintained for all nonexplosive pin pullers.

  - **Bearings.** For deployables, hinges, and linkages, self-aligning bearings shall be used (where practicable) to preclude binding due to misalignments. Bearings shall not be used for ground current return paths or to carry electric current. All ferrous material bearings shall employ (where practicable) a corrosion-resistant steel that is in accordance with QQ-S-763. Rolling element bearings shall (where practicable) be of 440C stainless steel; however, 52100 or M50 steels may be employed providing they are suitably protected from corrosion.
- **Dry Film Lubrication.** Application of dry film lubricants to the surfaces of bearings, V-band clamps, coil springs, leaf springs, clock springs, constant force springs, gears, or other items shall be by an appropriate process. Bonding, peening, sputtering, vacuum deposition, ion plating, or any other process that provides a predictable, uniform, and repeatable lubricant film may be appropriate. Composite materials containing dry film lubricant in their composition may be used in appropriate applications. Where appropriate, dry film lubricants should be burnished to provide a uniform film that reduces the coefficient of friction from the as-applied condition and minimizes the generation of lubricant powder. Corrosion-resistant materials shall be used in bearings employing dry film lubricants. Consideration shall be given to protection of MoS$_2$ dry film lubricants from adverse affects due to exposure to atmospheric humidity. Testing in a humid environment shall (where practicable) either be avoided or minimized.

- **Hard Coatings.** Hard coatings such as titanium carbide, titanium nitride, and chromium may be used to extend life, reduce wear, prevent welding, reduce friction, and prevent corrosion either with or without a liquid dry film lubricant.

**Cryogenic cooling is necessary for infrared detectors.** There is a need for a remotely controlled, motorized cryovalue that is simple, reliable, and compact and can operate over extended periods of time in cryovac conditions. The lessons learned are as follows: [Lorell]

- In general, the mechanical problems that are encountered with cryomechanisms are the result of: a) mismatches in the coefficients of thermal expansion, and b) the friction and wear properties of moving parts.

- Motors should be of the brushless or stepper design because brushes are unreliable in vacuum. They must have adequate power to overcome friction even with unlubricated surfaces. Motor leads to the outside are also thermal paths along which heat can travel.

- There are two sources of heat that can be of concern. One is the thermal energy generated by the equipment inside the shell and the other is thermal energy from the outside traveling along the wires.

- Since the mechanisms are usually located inside the shell where they are inaccessible, it is critical that they function with a high degree of reliability.

**A 10-yr review of the major test observations at ESTL is given, during which time some totally unexpected failure modes have been detected.** Full confidence now exists in many mechanisms and component designs, and much valuable data have been obtained that are available to mechanism designers for improving reliability. Lessons learned are as follows: [Parker]

- Thermal vacuum testing has proved to be essential in providing a detailed assessment of the reliability of complex mechanisms by subjecting them to realistic simulations of the anticipated flight conditions, where lifetimes in excess of 10 yr are now expected.

- Thermal vacuum tests have been proved to be cost-effective in avoiding delays and disturbances to a number of European projects, as several previously unknown failure modes have been detected. There is now complete confidence in many designs following independent, fully documented performance assessment.
Much valuable data have been obtained on many mechanisms and components about their operational parameters, power dissipation, and wear processes. There is frequent evidence of how important it is to implement comprehensive inspection and product assurance systems at all stages of mechanism development and construction, to avoid the human factors of accidents, errors, and poor judgment.

• The solar maximum mission satellite was launched into orbit with experiments to monitor solar activity. To obtain common object observations, experiments must be coaligned within 90 sec of the spacecraft pointing vector. Lessons learned are as follows: [Federline]
  - Using kinematic principles and good design practices, it is possible to produce a stable support platform that is isolated mechanically and thermally from its supporting structure and from experiments mounted on it.
  - Through the use of reference surfaces, gages, and optical measuring techniques, it is possible to coalign experiments to a high degree of accuracy.

• Several panels on the long-duration exposure facility were coated with Everlube 620C, a common solid lubricant. It was completely degraded due to ultraviolet exposure. Phenolic systems are susceptible to ultraviolet degradation, a fact that should be transmitted to design engineers. [Survey, Gresham]

• Almost every deployment device related to a spacecraft on-orbit configuration change is a mission-catastrophic single-point failure if it does not function properly. The following are some ground rules from lessons learned for designing such devices: [Hinkle]
  - All deployed appendage programs must have engineering test units.
  - All flight units and engineering test units must be testable to determine deployment margins.
  - Analyses must be verified by judicious hardware testing programs.
  - There must be adequate life testing early in the program.
  - There must be redundant backup systems in all critical areas.
  - Worst-case analyses and failure modes effects and critical analyses must be performed and verified by actual hardware testing. Conditions that must be considered include worst-case friction, misalignment, and excessive preload.
  - All devices should be designed to be as simple as possible to do an adequate job.
  - Consider the effects of mounting system redundancy and structure-induced input forces not only on the devices but also on the internal components of the devices.
  - Look for all possible hostile environmental effects and design to minimize their impact. Pay particular attention to vacuum, thermal control, and g effects that are not always intuitive to the designer.
  - Select devices that are directly testable and reusable to be qualified by analysis rather than single-use devices that are statistically qualified to a pass/fail criterion.
- Use the largest possible margin of operation in all devices consistent with consideration of undesirable effects on the surrounding hardware. These undesirable effects include large forces developed by end-of-travel latch-up and shock from pyrotechnic device firing.

- Proper installation should be verifiable. Knowledge of preloads, position of parts, status of switches or other electrical interfaces should be known or testable.
Rotating Systems

Momentum Wheels

- Bearing lubricant depletion between the ball race retainer causes cage instability and subsequent pointing errors, increased bearing torque, and wheel vibration. [Feherenbacher]

- The practice of using steel bearings lubricated with mineral-oil-based greases or superrefined mineral oils with porous phenolic cages is unacceptable. Tests by Aerospace Corporation have shown that the phenolic cages continue to absorb oil from the bearing ball contact regions during operation instead of supplying oil, thereby hastening the onset of cage instability. [Feherenbacher]

- An active oiling system can be incorporated to periodically lubricate the bearings and avoid erratic torque behavior. The trade-off is added complexity. [Feherenbacher]

- The characteristic cage instability frequency is an inherent geometric mass property of the cage/bearing system and is essentially invariant to external vibration, bearing speed, or lubrication condition. [Lowenthal]

- A biased cage has a different instability pattern and frequency than the commercial unbiased cage. Both the cage motion pattern and the instability frequencies are reasonably predictable. [Lowenthal]

- Each cage-bearing design has a critical friction coefficient for instability. The ball cage interface is much more critical than the cage land. This was also predicted by computer simulation. [Lowenthal]

- Increased lubricant viscosity enhances the chances and severity of instability. Room temperature grease triggered instability, while room temperature oil and warm grease did not. [Lowenthal]

- Simulation computer codes can predict cage instabilities for steady-speed conditions. They cannot predict stability onset as speed is ramped up. Commercial codes are available from P.K. Gupta and Avcon Corporation. [Lowenthal]

- Bearings shall meet ABEC 7, 7P, or 7T tolerance (or better) in accordance with the AFBMA standards. [USAF MIL Standard, MIL-A-83577B; 1 February 1988]

- Momentum wheel bearings shall operate in the elastohydrodynamic film regime and confirmed by analysis or test. [USAF MIL Standard, MIL-A-83577B; 1 February 1988]

- Magnetic bearings have the potential to provide a superior alternative to ball bearings. [Yabu-uchi]
For a combined Earth scanner and momentum wheel, the bearing lubricant condensation on the rotating scan mirror cannot interfere with the infrared radiation reflection of the mirror. Pennzane X2000 was the preferred lubricant over Bray 815Z because it has a much higher transmission in the region of the horizons sensor's infrared bandpass. With the exception of its lower viscosity index, the Pennzane X2000 was superior to the Bray 815Z. [Bialke-3]

Ball bearing lubrication remains the principal life-limiting problem on momentum and reaction wheels. [Auer]

Means for lubricant replenishment can improve life characteristics. A lubrication reservoir actuated by centrifugal force to relubricate the bearings is described. The base oil is stored as a grease in a ring-type chamber which is centrifuged out through orifices. The rate is limited by the thickener of the grease that forms a microporous filter in the vicinity of the orifices. Overlubrication, as measured by torque increase, does not appear to be a problem for this system. [Auer]

Oil lubrication is favored over grease because of superior torque characteristics and means of replenishment. [Auer]

The minimum amount of initial lubricant required is 2 mg. [Auer]

With the replenishment device, extended life appears promising. The test results and flight operations are promising and not conclusive. Two ground test wheels (3000 and 3800 rpm) had run for 16 yr after full qualification. These wheels had been subjected to temperature cycling and showed minimal changes in torque. The longest operational time in space was the OTS wheel, which had run 11.5 yr at the time this paper was presented. [Auer]

Reaction Wheels

Passive oilers, which are programmed to release lubricant at a predetermined rate, do not apply lubricant as needed. Overlubrication or underlubrication can occur. Data from the digital signal processor indicate that after about 3 yr of operation, the spacecraft again manifests instabilities associated with lubricant depletion. A need exists for an active oiler, commandable from the ground. [McConnell]

Bray 815Z lubricant, which has the positive qualities of low vapor pressure and high viscosity index, is not a suitable lubricant for a reaction wheel. Bray 815Z is a synthetic fluorocarbon which is unable to dissolve antiwear additives. It performs well when the operating speed is sufficient to form an elastohydrodynamic film, but it has poor performance in the boundary lubrication regime. Thus, the Bray lubricant is not acceptable for a reaction wheel that must go through zero speed. [Bialke]

An acceptable lubricant for reaction wheels available from Pennzoil is Pennzane X2000 (a synthetic hydrocarbon) with 5% PbNp as an antiwear additive. It has a very low vapor pressure, good viscosity index, and good boundary lubrication qualities. [Bialke]
• An ironless armature motor is ideal for the reaction wheel drive being both power and weight efficient. [Bialke]

• A Hall generator is the preferred tachometer. It has good accuracy, low complexity, low power consumption, and zero speed measurement. [Bialke]

• Stability of highly accurate pointing devices, such as those on the Hubble space telescope, can be destroyed by reaction wheel assembly induced vibrations. A Sperry damping device alleviated the problem. The central element is a viscous fluid damped coil spring suspension system. Each reaction wheel assembly is suspended on three units. Damping is provided by a low-volatility silicone-based fluid (Dow Corning 200 series) confined by metal bellows to internal cavities. [Hasna]

• Conical Earth sensors on several satellites experienced lubricant failures because the Bray 815Z lubricant is unstable at boundary lubrication conditions. Changing to a chemically stable hydrocarbon lubricant (Pennzane 2000) with extreme pressure additives, such as TCP or PbNp, resolved the problems. [Bialke-2]

• The lifetime of oil-lubricated bearings is very temperature dependent. Higher temperature results in higher evaporation rates and more surface migration. Also, higher temperature lowers the viscosity which reduces the elastohydrodynamic film. [Bialke-2]

• The disturbing torques produced by reaction wheels at near-zero speed are considerably greater than the normal torque noise level, with consequent reduction in attitude control. For sensitive missions, adequate tests are indispensable for the controller design. Bearing cage instability can be catastrophic and is difficult to predict. This occurred on a reaction wheel. ESTL and SNFA arranged a cure by using cages with loose-fit pockets and applying 10 ml of oil. Flight bearings will have nonequispaced pockets of the original diameter. [ESTL, Stapf]

• For reaction wheel support bearings, three oils were tested: SRG-40 (a highly refined mineral oil), Nye 179 (a synthetic PAO oil), and Nye UC-7 (a synthetic polyolester (POE) oil). All of the oils were formulated with TCP, and tests were carried out in different atmospheres. The tests showed that the TCP did not function as an antwear additive in UC-7. Nye 179 was considered the best choice for this application. Its performance in vacuum was far better than that of SRG-40, and its performance in helium was the best of all oils tested. [Kalegoras]

• The use of oxygen as a component of the fill gas of reaction wheels was determined to be unnecessary and generally harmful to the life of the bearing lubricant. [Kalegoras]
Control Moment Gyroscopes

- The major contributor to torque noise is the dc offset in the drive voltages and the transmission gearing. [Cook]

- A small amount of cross coupling between the inner and outer gimbal servo loops causes variations in frequency response as a function of the inner gimbal angle. These variations appear to be acceptable for current applications but future improvements are needed. [Cook]

- A single gimbal can provide greater torque capability for the same angular momentum than a double gimbal. However, a double gimbal has less complex control laws and greater flexibility to support a large variation in vehicle inertia. [Cook]

- The wheel material and dimensions should provide the necessary angular momentum with a safety factor of 4 based on a yield stress at 105% of nominal speed. [Cook]

- A two-stage parallel-path spur gear transmission with installed windup of one gear with respect to the other will eliminate undesirable backlash. [Cook]

- A control moment gyroscope bearing did not receive adequate lubrication from a centrifugal lube nut. The following modifications were made to improve oil supply:
  - Cage oil feed hole was reduced to overlap outer race groove under all conditions.
  - An additional set of feed holes was provided to centrifuge oil into the center of the outer race contact area.
  - The retainer flange was widened and the ID slope changed to accommodate the oil hole angle and increase lube nut overlap.
  - The retainer OD was increased to allow maximum extension into the race groove of oil feed holes. [Survey, Dolan]

Gears

- Worm gears can experience excessive torque under cold vacuum conditions due to lubricant starvation. Soft extreme pressure greases that contain MoS₂ are effective in alleviating the problem (e.g., Braycote 608). [Purdy]

- Careful worm gear run-in is essential to good operation for worm gears. The break-in should be gradual with light loads and abundant lubrication. [Purdy]

- Techniques for replenishing the lubricant as it is wiped off the tooth surfaces are beneficial to worm gear operation. On the Rexnord mechanism, a wiper system was installed to force grease back onto the gear teeth. [Purdy]

- In worm gears, unacceptable lubricant starvation can be caused by allowing the gears to reach a stall condition. [Purdy]

- General design guidelines for worm gears are given in Table 4.
Table 4. General Guidelines for Worm Gear Systems

<table>
<thead>
<tr>
<th>Guideline</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make the hob as nearly identical to the worm as possible. Use slightly</td>
<td>Optimize contact prior to break-in.</td>
</tr>
<tr>
<td>larger center distance for hobbing.</td>
<td></td>
</tr>
<tr>
<td>Make face width a maximum of 50% of worm diameter.</td>
<td>Avoid high-contact load on outer edges of gear teeth.</td>
</tr>
<tr>
<td>Avoid low-pressure angles on low-tooth-count gears.</td>
<td>Avoid undercutting.</td>
</tr>
<tr>
<td>Total count (worm gear) should be a minimum of 40.</td>
<td>Avoid geometric interference.</td>
</tr>
<tr>
<td>Avoid low speeds and stall.</td>
<td>Low speed promotes severe boundary lubrication.</td>
</tr>
<tr>
<td>Grease lubrication may require special techniques to maintain performance.</td>
<td>Oil film benefits from replenishment such as an oil bath.</td>
</tr>
<tr>
<td>Use fine surface finishes.</td>
<td>Improves lube and wear.</td>
</tr>
<tr>
<td>Set the gear setup so that initial contact pattern is on the entering</td>
<td>Provide oil reservoir on the entering side. Pattern will</td>
</tr>
<tr>
<td>side of the gear.</td>
<td>grow to cover entire width over life.</td>
</tr>
<tr>
<td>Break in gradually with loads and abundant lubrication.</td>
<td>Break-in greatly increases life.</td>
</tr>
</tbody>
</table>

- In a dual-wound dc brush motor gearhead, a shaft failure occurred by a fracture in the cross section from the gear face to the bearing spigot. The failure was attributed to excessive stress concentration and was ameliorated by increasing the blend radius from 0.125 to 0.250 mm and thus reducing the stress concentration factor from 4 to 1.5. The lesson is to examine the design for stress concentrations carefully and ensure adequate safety margin. [Henson]

- In a dual-wound dc brush motor gearhead, bearing failures were experienced. Bearing loads should be carefully examined and a double bearing applied, if necessary. A Tuftride process applied to the bearing spigots reduces wear debris and avoids bearing contamination. The Tuftride process should be applied after the bearing spigot is finished ground. The growth of the Tuftride process is insignificant, and if applied prior to grinding, it could be removed by wear. [Henson]

- All gears used in moving mechanical assemblies shall be in accordance with the standards of the American Gear Manufacturers Association (AGMA). Hunting-tooth gear ratios shall be used, where the application is appropriate, to distribute wear. For better protection of the gear teeth, the through hardness of surface hardness (or both) may be increased, and the surface finish of the teeth improved through grinding, honing, lapping, and prerun-in. The through hardness may be increased by material or heat treatment changes. The surface hardness may be increased by nitriding, carburizing, induction hardening, or anodizing. Undercutting of spur gear pinions should be avoided. [MIL Standard, MIL-A-83577B; 1 February 1988]

- An harmonic drive flex spline galled severely at the bearing/flexcup interface. The anomaly occurred due to poor material selection. Materials must be carefully selected to avoid galling of sliding surfaces. Also, lubrication helps to prevent galling. [Survey, Farley]
Motors

- Brush-type motors should be avoided. Carbon brushes wear excessively in vacuum. Wear debris contaminates the bearings, increasing drag and reducing life. Accumulated debris shorts the commutator, increasing current and resulting in motor failure. Some organizations take necessary precautions in material selection and coatings that permit brush motors to perform satisfactorily (see Table 5). The use of these motors, however, require substantiation by experience and/or test. [Sharma]

Table 5. Actuators Using Brush Motors

<table>
<thead>
<tr>
<th>Description</th>
<th>Application</th>
<th>Customer</th>
<th>Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-torque gear motor</td>
<td>150 ft-lb torque driver</td>
<td>NASA-Goddard</td>
<td>Solar Maximum Repair</td>
</tr>
<tr>
<td>Latch gear motor</td>
<td>Tool latching</td>
<td>NASA-Goddard</td>
<td>Solar Maximum Repair</td>
</tr>
<tr>
<td>Gear motor</td>
<td>Caging mechanism</td>
<td>Martin Marietta</td>
<td>FTS</td>
</tr>
<tr>
<td>Linear actuator (1000 lb)</td>
<td>Unknown</td>
<td>Grumman</td>
<td>Unknown</td>
</tr>
<tr>
<td>Linear actuator (15 lb)</td>
<td>OSSE experiment</td>
<td>Ball Aerospace</td>
<td>Gamma Ray Observatory</td>
</tr>
<tr>
<td>Rotary actuator</td>
<td>Umbilical disconnect mechanism</td>
<td>Lockheed</td>
<td>Classified</td>
</tr>
<tr>
<td>Rotary actuator</td>
<td>Rocket nozzle extension actuator</td>
<td>Allied Signal</td>
<td>Atlas Centaur II</td>
</tr>
<tr>
<td>dc common drive unit</td>
<td>Solar array deployment</td>
<td>Fokker</td>
<td>Eureka</td>
</tr>
<tr>
<td>dc gear motor</td>
<td>Solar array deployment</td>
<td>Astro</td>
<td>Olympus (L-SAT)</td>
</tr>
<tr>
<td>Gear motors (various sizes)</td>
<td>Various drive function</td>
<td>Martin Marietta</td>
<td>Classified</td>
</tr>
<tr>
<td>Gear motor</td>
<td>Unknown</td>
<td>Martin Marietta</td>
<td>TOS</td>
</tr>
<tr>
<td>Gear motor</td>
<td>Solar boom deployment</td>
<td>ISRO (India)</td>
<td>India Communication Satellite</td>
</tr>
<tr>
<td>High-torque actuator</td>
<td>Antenna deployment</td>
<td>GE Astro</td>
<td>Upper Atmosphere Research Satellite</td>
</tr>
<tr>
<td>Redundant drive motor</td>
<td>Astromast deployment</td>
<td>Ford</td>
<td>GOES</td>
</tr>
<tr>
<td>Worm gear drive unit</td>
<td>Classified</td>
<td>Harris</td>
<td>Classified</td>
</tr>
<tr>
<td>Center drive unit</td>
<td>Classified</td>
<td>Harris</td>
<td>Classified</td>
</tr>
<tr>
<td>Payload spin motor (integral hp)</td>
<td>Deploy spinner satellites</td>
<td>Martin Marietta</td>
<td>Titan Launch Vehicle</td>
</tr>
</tbody>
</table>
• Brushless dc, permanent-magnet dc, and brushless stepper motors are the preferred motors. [Sharma]

• Stepper motors can have positioning errors due to:
  - The encoder
  - The drive electronics
  - The attitude control electronics
  - A power supply interruption
  - A single-event upset in the electronics
  - A mechanical failure of the unit. [Sharma]

• The torque margin for any motor > 3, where $T_M = T_a/T_r - 1$
  \[ T_a = \text{available torque} \]
  \[ T_r = \text{resistance torque} \]
  \[ T_M = \text{torque margin.} \] [Sharma]

• The design torque margins should be verified during flight testing. [Sharma]

• In rotary actuators, a hard-stop collision can cause the rotor to continue to turn, which elastically winds up the harmonic drive. The spring energy of the harmonic drive can catapult the motor backward three steps as it unloads. The motor then picks up the pulse signals as if it were starting from standstill and drives into the hard stop repeating the same series of events over and over. A hard stop must be avoided by proper application of end-of-travel limit switches. [Sharma-2]

• Motor drives for rotary actuators should be a dc torque motor or stepper motor. The dc motor should be of the brushless permanent-magnet type with position and velocity sensors. [Sharma-2]

• The output shafts of rotary actuators should be supported by a pair of back-to-back duplex bearings (for high-moment resistance) preloaded for a desired stiffness and life span. [Sharma-2]

• In a brush motor gearhead, brush debris caused problems and reinforces the view that brushless motors should be applied if possible. The brush material was Boeing Compound 046-45 because of good wear resistance in vacuum. It consists primarily of MoS$_2$, which requires purging for operation in normal atmosphere. Post-test examination revealed brush debris that had blown around the gaseous purge applied during air operation. During the initial phase of the ambient life test, the winding current trace became noisy and the shaft speed reduced. It was concluded that the temporary anomalous performance was caused by a brush fragment. [Henson]

• Motor winding redundancy is recommended in the event of winding or connection failure. A clever scheme is described by Henson. [Henson]

• Stepper motor stability is very dependent on friction and damping and it is important to ensure that adequate friction and damping are present over the range of operating conditions. [Kackley]

• Superimposing rotordynamic behavior and separatrices on the phase plane technique is a valuable tool for analyzing stepper motor stability. [Kackley]
Simulation analyses is valuable to determine problems and solutions prior to building and testing expensive hardware. [Kackley]

High bearing torque was encountered on the despins drive assembly of two flight models of the HELIOS solar science satellite. Improving the perpendicularity of the lower bearing inner race seat from 0.8 to 0.3 arc-min dropped bearing drag at -50°C about 40%. [Phinney]

Bearing distortions can increase bearing torque. On the HELIOS despins drive assembly, a favorable indexed rotation of the end plate reduced torque significantly. The end plate and aluminum housing were distorted. [Phinney]

Small, fractional horsepower motors are likely to experience cold-temperature performance problems if Pennzane or Rheolube bearing lubricant is used. The lubricants become very stiff at cold temperatures and start-up torque becomes appreciable. A lubricant-channeling phenomenon was observed, which interfered with cold motor start-up and running capability. Braycote Micronic 601 bearing lubricant did not interfere with motor performance. Small rotary components may be sensitive to lubricant effects not seen in larger hardware. Special testing should be planned to evaluate cold-temperature lubricant start-up as well as running torque in small components. [Survey, Marks]

Bearings and Lubrication

- Retainer instability is a major cause of bearing failure in control moment gyroscopes, momentum wheels, and reaction wheels. [Boesiger]

- There is a critical friction level associated with each retainer design, beyond which the retainer is unstable. [Boesiger]

- Ball pocket friction is more critical to stability than retainer land friction for the bearings investigated by Boesiger. [Boesiger]

- Optimization of the retainer design was accomplished by computer simulations coupled with experimentation. Computer codes were useful tools and qualitatively compared with experiment. [Boesiger]

- Operating ball bearings lubricated with Z25 (a perfluoroether) in a vacuum results in an interaction between the lubricant and the races. This resulted in race wear and oil degradation. [Baxter]

- When ball bearings lubricated with YVAC 40/11 (a perfluoroether oil recommended for instrument bearings) are operated in a vacuum, there is no oil degradation and no wear. However, the higher viscosity of the YVAC 40/11 leads to undesirable running torque. [Baxter]

- Modification of the bearing surfaces with inert coatings, that results in decoupling of the lubricant from the bearing surfaces offers the best course to ensure maximum lubricant life. [Baxter]
Most mechanical problems with momentum/reaction wheels, control moment gyroscopes, and gyroscopes are lubrication problems. Table 6 provides a sample of experience. [Fleischauer]

There are two primary types of lubrication problems:

- Supply or loss of lubricant
- Chemical reaction (oxidation, polymerization) of lubricant. [Fleischauer]

Synthetic oils can increase life by a factor of 10. [Fleischauer]

Sputter-deposited solid lubricant thin films provide low friction and long life. [Fleischauer]

Hard coatings and ceramic parts are used for low torque noise. [Fleischauer]

Lubricant additives, such as TCP, provide protection of contacting surfaces to reduce wear and minimize torque. [Fleischauer]

The relative wear life of PAO lubricants is significantly greater than PFPE lubricants. [Fleischauer]

Lubricant replenishment is a major problem with spacecraft bearings. A centrifugal bearing cartridge design, invented at the Draper Laboratories, provides a method for a continuous and controlled supply of lubricant without incurring excessive torque. [Singer]

Table 6. Partial Listing of Momentum/Reaction Wheel, Control Moment Gyroscope, and Gyroscope Experience

<table>
<thead>
<tr>
<th>Program</th>
<th>Wheel Type</th>
<th>Problem</th>
<th>Cause</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navstar/GPS</td>
<td>Reaction wheel; four per satellite</td>
<td>On-orbit and test failures; high torque</td>
<td>Lubricant depletion</td>
<td>New lubrication qualification</td>
</tr>
<tr>
<td>GPS IIR</td>
<td>Reaction wheel</td>
<td>High-speed cage instability</td>
<td>Force, mass resonance</td>
<td>Force, mass; biased cages</td>
</tr>
<tr>
<td>DMSP</td>
<td>Reaction wheel</td>
<td>Bearings/lubricant could not be delivered</td>
<td>Lubricant degradation</td>
<td>Extensive bearing run-in and screening</td>
</tr>
<tr>
<td>DSP</td>
<td>Large momentum wheel</td>
<td>Torque/temperature anomalies</td>
<td>Lubricant starvation</td>
<td>Redundant wheels</td>
</tr>
<tr>
<td>MILSTAR</td>
<td>Rate gyroscopes</td>
<td>Drive rate/torque instability</td>
<td>Lubricant starvation</td>
<td>Improved lubrication, cage processing</td>
</tr>
<tr>
<td>CDP</td>
<td>Large control moment gyroscopes; &gt; one per satellite</td>
<td>Extensive torque</td>
<td>Lube loss, cage instability</td>
<td>Active oiler system, new oil</td>
</tr>
<tr>
<td>DSCS III</td>
<td>Reaction wheel</td>
<td>Torque noise, vibration</td>
<td>Unknown</td>
<td>Redundant wheels</td>
</tr>
</tbody>
</table>
• Retainerless instrument bearings avoid cage instability and are advantageous if ball impact is not a problem. [Singer]

• Screening tests provide an accurate and expeditious approach to predict bearing cartridge performance. [Singer]

• Accuracy, mobility, and lifetime requirements require tribological interaction early in the design phase. A significant number of spacecraft anomalies are attributable to tribology problems as outlined in Volume II, page 329, Table 1. [Fleischauer]

• Problems in rotating assemblies are often caused by ineffective lubricant supply, caused by inadequate initial amount, loss via transport processes, normal consumption without resupply, and chemical degradation. [Fleischauer]

• Perfluorinated lubricants cannot dissolve antiwear additives, and thus are not suitable for boundary-lubricated applications (reaction wheels, gimbals). [Fleischauer]

• PAO lubricants significantly outlast a silicone oil for oscillatory motion. It is expected that these synthetic oils can be applied to high-speed applications to provide added protection against retainer instability and wear. [Fleischauer]

• Titanium-carbide-coated balls have been used in gyroscope bearings with uncoated steel raceways and superrefined mineral oil to produce operational lifetimes a factor of ten or more longer than for uncoated balls. The commercial process for coating bearing parts with TiC is available in the United States but has only been used for instrument bearings of the type used in gyroscopes. Titanium-nitride coatings are used for tool steels to provide much longer service lives and considerable research and development is underway to use TiN for bearings and gears. Tests are currently under way to test the performance of both gimbal and spin bearings with TiC- and TiN-coated balls. [Fleischauer]

• Analysis of lubricants from laboratory tests in control moment gyroscope bearings show depletion of oil from grease samples taken from control moment gyroscope spin bearing cage surfaces and no depletion from samples of bulk grease. Analysis of metal parts show little evidence of wear although some metal is found in degraded lubricant. Analytical simulations and measurements of bearing motions suggest cage instability may be involved in retainer wear and ultimate bearing torque increases. [Fleischauer]

• PAO and multiple-alkylated cyclic compounds (Pennzane) are excellent candidates for use in spin bearings of reaction/momentum wheels, in solar array drives, and in rate gyroscopes. The PAO lubricant did well in both hard vacuum and in atmosphere of 380-torr helium gas. [Fleischauer]

• The formulation of Pennzane with TCP in solution outperformed the other systems tested, however, considerable wear was noted. [Fleischauer]

2-32 Summary of Lessons Learned
• Pennzane plus Naphthalene had less torque life than with TCP additive, but there was no evidence of wear. The increased torque failure was caused by the accumulation of excessive protective additive film containing metallic lead and carbonaceous material. The conclusion is that varying the amount of Napthenate could lead to superior friction and wear performance. Future tests are planned. [Fleischauer]

• A run-in period is recommended for lubricated ball bearings to transfer lubricant from the ball pockets of the sacrificial retainer to the balls and then to the raceways. Approximately $1.3 \times 10^6$ cycles of run-in were accomplished. [Fleischauer-3]

• An optical chopper assembly had power beyond specifications. The bearing power loss is very sensitive to the amount of lubricant present and, from observations during testing, this was the probable cause of the anomaly. [Allen]

• For low-speed operation ($<3000$ rpm) a fixed lubricant oil quantity in a shielded bearing is adequate for a 10-yr life. Bendix applies shielded contact bearings: R4A, R6, R8, and R10. Lubricants include Winsor lube (MIL-L-6085A) plus 5% TCP. [Allied Signal Aerospace (Bendix)]

• For high-speed operation ($>3000$ rpm), a make-up mechanism must be provided to overcome the oil loss due to centrifugal force. Angular-contact bearings (104H, 106H, 107H, and 305H) are applied. Bendix uses proprietary design phenolic retainers and an active continuous lubrication system. KG-80 (MIL-L-83176A) super-refined mineral oil is utilized. [Allied Signal Aerospace (Bendix)]

• Grease lubrication for momentum/reaction wheels is not recommended because of high running torque, torque variations, uncertain lubricant supply, and retainer instability. [Allied Signal Aerospace (Bendix)]

• To produce a boundary lubricating film using a liquid lubricant, a run-in must be performed. [Vest]

• For high-load boundary-lubricated contacts, a bonded solid film lubricant, such as MoS$_2$, is recommended. [Vest]

• For slow-speed ball bearing rotation, a Teflon or MoS$_2$ filled grease, or a transfer film lubricating polymeric cage is recommended. [Vest]

• Sliding motion applications are mostly boundary lubricated. A high load-carrying grease with an extreme pressure gradient additive must be used. The grease produces a high load-carrying solid film, such as Teflon, MoS$_2$, graphite, or TCP between the rubbing surfaces. [Vest]

• Despin bearings lubricated with ion-plated lead were capable of meeting the GIOTTO mission life with an insignificant noise spectrum. [Todd]

• Tests of the complete energized despin mechanism on GIOTTO showed that the stepper motor harmonics excited a strong undamped torsional resonance of the antenna at certain speeds. [Todd]
After approximately three months of life testing, the lubricant in the Galileo slip ring bearing (KG80 oil) had a thick, black, gooey appearance and the bearing friction torque was higher than expected. Even careful cleaning of spacecraft components can leave residues that may eventually react with adjacent materials. Cleaning processes must be followed by an outgassing vacuum-bake treatment. This is particularly important for porous materials that may have absorbed various fluids, including the cleaning medium itself. [JPL SSEF, Langmaier]

Phenolic retainers must be carefully and thoroughly dried to remove any absorbed moisture before they are impregnated with oil. Otherwise, the retainer will not saturate and can absorb and remove oil from the bearing it is intended to lubricate. Thus, the retainer becomes a liability rather than an asset. [Bertrand]

Current telemetry can detect spin motor current, which is proportional to the drag torque, and an increase in bearing temperature, which is also indicative of the increase in drag torque. These measurements provide an indication of the need to supply fresh oil to the system. The authors propose to use Coray 100 (an uninhibited napthenic-base machine and engine oil with a viscosity of about 110 cs at 40°C) to resupply the Andock C grease that lubricates the control moment gyroscope bearings. The system is essentially a pressurized reservoir with a solenoid activated by the loss of lubricant sensor. [Smith] In the reviewer's opinion, in a weightless environment there are questions about how a drop of oil will behave. Even at a distance of 0.004 in., the drop may not transfer smoothly. It may touch and then be slung off the moving surfaces to create a number of finer droplets that will float around the bearing housing. Any lubrication scheme should be evaluated in a weightless environment. [Murray]

X-rays can be used to provide images of balls in a bearing that are not directly visible. Using the x-ray technique, it is possible to measure the contact angle in assembled bearings. [Fowler]

Advanced elastohydrodynamic computer simulation techniques can provide benefit in design of space lubrication systems. [Benzing]

Failure modes of despins mechanical assemblies operation include the following:
- Insufficient bearing lubricant film thickness
- Lubricant incompatibility with system materials
- Inadequate lubricant quantity
- Improper lubricant transfer
- Lubricant creep
- Lubricant dewetting
- Lubricant degradation
- Bearing and cage instability
- Torque variations
- Slip ring and brush wear
- Lubricant volatility
- Cage wear. [Benzing]

Bearings operating in the boundary lubrication regime (i.e., contact asperities) shall be avoided where practicable. If bearings must be operated in the boundary lubrication regime, a boundary lubricant with good antiwear characteristics shall be used. Perfluorinated polyether and silicone lubricants should be avoided in this
Mechanical Technology Inc.

regime except where light loads and limited travel are expected. Where bearing lubricant reservoirs are used, the reservoir shall be attached, where practicable, to an area of relatively high temperature to enhance molecular and surface flow into the bearing. Barrier films or shielding or both may be used to separate the bearing from reservoirs to minimize surface migration such as that caused by loss of lubricant due to wicking action of the reservoir. Incorporation of the above techniques dictates that the lubricant transfer mechanism be primarily by molecular flow. The preferred approach to lubrication of bearings involves placing the reservoirs in intimate contact with the bearing races and adding a larger amount of lubricant than would be ordinarily required to provide acceptable lubricant films. The above method of lubrication is preferred providing that any increase in churning torques can be tolerated. [MIL Standard, MIL-A-83577B; 1 February 1988]

- Bearing lubrication tests and supporting analyses shall be used to show that the chosen lubricant transport mechanisms, such as surface migration, vaporization, and wick action provide effective lubricant films over the expected operating temperatures, thermal gradients, and internal environments. If providing adequate life of bearings depends on their operating in an elastohydrodynamic lubrication regime and not in the boundary lubrication regime, and it cannot be clearly shown by analysis that the bearing operating range as well is well within the regime, then a test method (such as contact resistant measurements) shall be used to establish that an elastohydrodynamic film is being generated. In general, the lubrication system variables that should be substantiated by component development tests include (as appropriate) amount of lubricant, retainer design, reservoir design, and the reservoir proximity to the areas requiring lubrication. When liquid lubrication is used, the design shall ensure that migration of the lubricant through the seals is not excessive or detrimental to the space vehicle. [MIL Standard MIL-A-83577B; 1 February 1988]

**Slip Rings and Roll Rings**

- Roll rings are effective rotary joint electrical transfer devices and avoid the deficiencies of slip rings and flex capsules. Flex capsules are limited with respect to rotation and fatigue life. Slip rings wear due to sliding electrical contacts, generate debris, and require lubrication. [Batista]

- Roll rings have had considerable development for both high- and low-power applications. They are reliable, low-noise, drag-torque devices and should receive primary consideration for rotary joint electrical transfer applications. [Batista]

- To accomplish noise reduction, plating processes, plating purity, and cleaning processes must be carefully controlled. [Batista]

- High-purity plating and elimination of metallic oxides from surfaces by stringent reduction of low-nobility metals in the gold-plating process enhances noise reduction. [Batista]

- Software that models geometric tolerances and maximizes rolling efficiency is very helpful to roll ring design. [Batista]

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Summary of Lessons Learned

2-35
• Flexure fatigue of the roll rings must be considered and the rings designed to accommodate the specified life cycling. Fatigue tests carried out on beryllium-copper roll rings made from bar stock showed that the endurance limit was approximately 20% lower than published data. The published data were generated from test samples that had grains oriented in the most advantageous direction. Thus, the design of the roll ring should be based on a lower endurance limit with adequate safety margin. [Smith]

• Contamination of the flexures and ring surfaces can cause high noise. A principal source of the noise is copper and lead oxides on the surface. Contamination can come from plating, migration of substrate materials through the plating, or migration from adjacent components. Great care must be taken to ensure that contamination is not introduced during plating and is not allowed to take place after plating. [Smith]

• Corona effects can be prevented by avoiding line of sight between conductors of different potential and by using appropriate insulation. [Smith]

• A high correlation was found between the presence of silicones in the system and resultant electrical noise. The primary source was silicone grease used to lubricate other components. Silicone sources should be eliminated around roll rings. [Smith]

• Primary sources of outside contamination include: organic films, silicone, and metal oxides. Migration of metallic oxides can come from solder used to attach the lead wires. In the Holloman roll ring design, solder was separated from critical surfaces by plastic rings with good results. [Smith]

• Particularly important in a signal roll ring application is the isolation of adjacent circuits. [Smith]

• For high power transfer, a multiple-flexure design in which the flexures are separated by rolling idlers is required. [Smith]

• Slip ring assemblies were constructed of gold- or silver-plated rings and wire wipers lubricated with the same fluid lubricants used in the bearings of the despin mechanical assemblies. However, extreme care is required to prevent excessive oxidation of the MoS2 lubricant and simultaneous tarnish formation that results in unacceptable electrical noise and even measurable torque increases. Many such problems with electrical noise can be traced to the fabrication and assembly practices during construction of the slip ring mechanisms, but even after incorporation into satellites it is still necessary to protect the brushes from atmospheric exposure. [Fleischauer]

• Anomalous values of contact resistance was found in both pyrotechnic and power/signal slip ring assemblies. Contamination of slip rings can occur if they are exposed to atmosphere for any length of time. The material chosen was Ag/C/MoS2 (12% MoS2). Subsequent high resistance was due to surface contamination (possibly Ag2O or Ag2S). [Atlas]
For slip ring assemblies, provide adequate and proper lubrication of the rings and brushes when self-lubricating contacts are not employed. A liquid lubricant is necessary if significant rotation is involved. Ball Aerospace Systems Division's (BASD) most widely used lubricant consists of a highly refined mineral oil with extreme pressure additive. Recently, a synthetic oil with improved characteristics has come into use. With the mineral oil, reservoirs are placed along the brush access slots in the housing. Vapor pressure of the new oil is so low that surface films are sufficient for multiyear missions and reservoirs are not required. [Phinney]

Measure brush forces and correct, if required. Brush force must be set carefully. BASD rings have used 3 to 5 gm of force and lubricants that produce a friction coefficient of 0.3 to 0.5. [Phinney]

Brush wear particles remain under the brush pad and provide an additional lubricating medium that prevents further wear. [Phinney]

The precaution of side-by-side brushes is unnecessary because of the 5-yr demonstrated life with single-groove bearings. [Phinney]

For self-lubricating brushes: [Phinney]
- Coat the brush springs with thin films of polyurethane.
- To minimize vibration problems on brush assemblies of this type, maintain brush height <0.090 in.
- The Ag/MoS₂ brush on silver is outstanding in vacuum but it is not good in air. To eliminate electrical noise, slip rings with this brush material should only be operated in dry nitrogen or vacuum.
- Remove all humidity before starting.
- For space applications, power brushes are operated at current densities in the 100- to 150-A/in.² range and contact pressures of 6 psi. Signal brushes commonly have pad face areas in the 0.007 in.² range (0.060 x 0.12 in.) or less and brush force is set about 20 gm.
- Friction coefficients are in the 0.25 to 0.50 range.
- Conduct hard vacuum run-in tests, followed by disassembly, run-in wear debris removal, reassembly, and checkout.
- Evaluate slip ring performance during drive acceptance tests, which should always include thermal vacuum operation.
- Maintain coordination with suppliers. They have developed significant experience and knowledge. Sources include: Electro-Minatures Corp, Moonachie, New Jersey; KDI Electro-Tec, Blacksburg, Virginia; and Poly-Scientific Division, Litton Industries, Inc., Blacksburg, Virginia.
- Prepare definitive specifications.
- Conduct detailed review of suppliers design, materials selection, and processes.
- Inspect critical manufacturing and test operations at the supplier's facility.
Some experiences have indicated the need to improve the dynamic noise performance of dry film lubricated, silver bearing slip ring/brush combinations. [Matteo]

To initiate noise, some form of dielectric contamination must exist at the slip ring/brush interface. [Matteo]

A reduction in brush spring force to significantly less than the design minimum force must occur to render the slip ring assembly susceptible to contamination. [Matteo]

The fewer the number of brush/ring sets in contact with each signal circuit, the more statistically susceptible the circuit is to contamination-induced resistance variations. [Matteo]

Critical sensor signals should be carried by two parallel slip rings, thus, placing four brushes in parallel. [Matteo]

Synchronization of sensor sampling times and drive pulses must be maintained at all times. [Matteo]

Slip ring assemblies of the dry lubricant type must be purged with clean, dry nitrogen at all times (except when precluded by other tests) up to as close to launch time as possible. [Matteo]

Margin above normal brush force (approximately 80%) should be provided to account for in-process or in-service degradation. [Matteo]

The individual brushes of a brush pair should be electrically separated to enable in-process measurement of individual brush/ring contact resistances during testing. [Matteo]

Whenever possible, critical signals should be amplified before passing across the slip rings. [Matteo]

Long storage times can result in slip ring contamination. They must be examined and cleaned prior to installation. Also, investigations should be conducted to provide nonpollutant materials. [ESTL, Atlas]

During flight assembly, an open shield and a shield shorted to a conductor were discovered on a flight slip ring assembly. X-rays of the unit revealed that the assembly had been improperly reworked at the vendor. Inspectors should look for obvious signs of rework, such as a different color of epoxy, and the paperwork should be checked if the rework was recorded. The data sheet should have a line for each measurement and require that the actual meter reading be recorded. The specification should have then been listed and a check mark placed in either a pass or fail column. A quick scan would then tell if any failures were present and still allow the detailed information to be recorded. The test equipment, calibration, and temperature should also be required on the data sheet. [Survey, Osterberg]
• After accelerating to 30 rpm, the Teflon toroid ball separators on the GGS slip rings shredded. The failure was traced to exceeding the pressure-velocity limits of the toroid material. Toroids should be used with only lightly loaded bearings due to the stress on the nonconforming outer diameter of the toroid to the adjacent ball, which was three times higher than the pocket stress for GGS. Toroids allow balls to bunch up, making it difficult to predict dynamic performance. Bearing drag torques are less predictable with toroids. Accelerated testing of bearings is not recommended because even at subelastohydrodynamic speeds, the wear mechanisms can be very nonlinear. Pressure-velocity curves should be determined and used to check all new retainer designs. These curves need to be established for the various materials used and the method of analysis made consistent for all programs. [Survey, Osterberg]

Miscellaneous

Potentiometers

• A potentiometer for a position sensor experienced excessive electrical noise, unacceptable wear of beryllium copper contacts, and beryllium-copper contact breakage. When lubricated with Bray 815Z, the lubricant beaded and contained wear debris. Wiper contacts of Paliney-7 (a precious metal alloy primarily comprised of Palladium), silver, gold, and platinum proved effective. To assure adequate contact, the contact force was increased to 204 cN. The material combinations must be compatible for rubbing contact and have low coefficient of friction, and the mating surfaces must have sufficient preload to assure contact. [Iskenderian]

• Hub connections should not loosen during vibrations. In this instance, each steel hub was first mechanically fastened to the shaft with two set screw joints (one cone point, one cup point) at 90° to each other, then bonded with a bead of epoxy at the shaft hub interface. The set screws themselves were blocked from backing out by a drop of epoxy. [Iskenderian]

• The potentiometers should not be contaminated by shipping packages. Individual nylon bags were employed. [Iskenderian]

Cryogenic Grating Drive Mechanism

• To avoid undesirable temperature gradients and barreling of the bearing, flexible copper thermal strapping (shunts) were added to both rotating and stationary components. [Dubitschek]

• To ensure precise accuracy control of bearing preload over the temperature range, a flexible diaphragm of similar thermal characteristics was incorporated. [Dubitschek]
Payload Spin Assembly

- The dc drive motor assemblies failed insulation testing because of brush wear debris and insulation cracking. The problem was resolved by applying a coating of chemglaze to the windings. Anomaly reinforces use of brushless motors. [Robinson]

- The spin bearing drag torque, especially at -23°, was too high. The problem was due to a mismatch in the coefficient of thermal expansions of aluminum housings and steel bearing races. This was resolved by interference fitting the steel races into the aluminum housings and then final grinding the steel raceways in place. Thermal mismatch of bearing components and housing can cause serious torque and cage problems. The potential problem should be recognized and analyzed prior to build. [Robinson]

- During run-up for a room-temperature operational test on the flight payload spin assembly, the unit shut down after achieving an approximate speed of 30 rpm. All of the power FETS were blown due to a runaway oscillating condition. No problems were experienced during testing of the engineering model. S-level FETS were used in the flight unit, while low-quality FETS were used in the engineering unit. Investigation revealed that the S-level FETS were too fast for the snubber circuits and created instability, leading to a major failure. The low-quality engineering FETS were slow enough for the snubber circuits to handle. The lesson learned is that any changes made to a successful engineering model design should be analyzed before incorporation into qualification/flight hardware. [Survey, Robinson]

Multichannel Chopper System

- Special floating mounts had to be developed for the slit plate and chopper disk to maintain their dimensional accuracy and alignment. [Krueger]

- To maintain dimensional tolerances under varying environmental conditions and in the presence of thermal gradients, the slit plate and chopper disk were made from INVAR 36, a low expansion metal. [Krueger]

- To achieve the desired accuracy and minimize possible distortion from internal machining-induced stresses, electrical discharge machining was used for the final machining of the slit plate and the chopper disk and for machining the apertures for these components. [Krueger]

- For a close sliding fit of two shafts with limited motion, the dry lubrication approach was unsatisfactory and increased the friction between the two parts to an unacceptable level. A very small amount of Krytox oil applied to the inner shaft was the solution. [Krueger]
Vapor Compressor

- Oil lubrication is not feasible for reciprocating machines in space because of zero gravity. Grease-packed rolling elements are generally used. Cam interfaces are critical life-limiting elements because of the large radius of curvature of the cam's surface compared with the roller radius. Cams made of nitrided steel or coated with tungsten carbide or titanium carbide deteriorated rapidly. Excellent results were obtained with through-hardened steels for cam and roller and also with boronized cam surfaces. [ESTL, Berner]

- The original design of the ISTP despin platform employed 8-in. thin-section bearings, a one-piece phenolic retainer, a hollow steel shaft, and an aluminum scalloped housing with a band of titanium around the bearings. The bearings ran at 10 rpm. The one-piece phenolic cage warped causing high torques. Teflon toroids were installed and a full titanium scalloped housing was incorporated. Lobing in the bearing due to mounting caused ball speed variations, high retainer loads, and badly damaged toroids. Finally, a four-piece segmented phenolic retainer was installed and life tests did not result in torque anomalies. [Survey, Woods]
Oscillating Systems

- General information on anomalies and lessons learned for gimbal systems from NASA-Goddard is as follows: [Sharma]
  - Oil replenishment for small oscillatory motions as experienced by gimbal bearings is difficult. Torque magnitudes increase significantly due to oil breakdown or bearing starvation.
  - In a test conducted at Hughes Aircraft Company, Bray 815Z had half the initial torque of Apiezon C (with an extreme pressure additive) in a 4° gimbal bearing test. However, after $7 \times 10^4$ cycles, the Bray lubricant turned to brown sugar and the bearing torque quickly increased by a factor of 10. The Apiezon Z continued without torque increase to the end of the test ($8 \times 10^6$ cycles).
  - Lessons learned are: 1) to prevent destructive chemistry; surfaces in contact must be passivated in some manner; and 2) ceramic hard coatings, such as TiN or TiC, will eliminate catalytic action; replacing stainless steel 440C balls with ceramic SiN$_4$ balls eliminates lubricant breakdown; and, to prevent oil starvation, it is good practice to use a porous ball retainer, which functions like a reservoir of oil and dilutes breakdown products.

- For typical gimbal mechanisms, ball bearings are forced to oscillate over very small arcs (dither) and then turn to a new position and continue to dither. The gimbal system combines the severity of boundary lubrication with fretting motion of contacting surfaces. Gimbals are critical elements of most pointing mechanisms, antennas, sensors (telescopes) and weapons platforms, and of control moment gyroscopes. Usually, performance levels are met when systems are first tested, but with time, lubricant degradation, bearing wear (or both) degrade performance levels so that mission requirements no longer can be satisfied. [Fleischauer]

- Gimbals and electrical contacts have consistently been a source of anomalies and failures. Gimbal bearings that operate in an oscillatory (dithering) mode and rarely make a full revolution are troublesome. [Fleischauer]

- Ultra-low friction-durable films of MoS$_2$ are deposited by various ion-sputter deposition processes. They can be used for some sliding applications, very low load bearings, or for latching and release mechanisms. There is very encouraging evidence that ion-assisted, sputter-deposited MoS$_2$ films can provide ultra-low friction operation even in air applications. [Fleischauer]

- For oscillating gimbal applications, sputter-coated MoS$_2$ films were recommended. Benign ball retainers (those that do not transfer films) were tested with good results. [Fleischauer]

- During the thermal vacuum test phase of the GOES-7 spacecraft, the primary scan mirror system exhibited unacceptably high drive friction. The observed friction was found to correlate with small misalignments of the mirror structure and unavoidable loads induced by the vehicle spin. The friction became very high at the end of the oscillation. During the spacecraft spin tests, the torque was found to be sensitive to spin speed and load. The solution to these problems was to reduce the moment loads by using larger race curvature to reduce alignment sensitivity. Also, the frame limit was shifted 5° whenever the torque became too high, so the balls could roll over the torque bumps at the end of travel. [Bohner]
• CAS and PFPE oils were seriously degraded under oscillating load and vacuum testing and produced excessive bearing wear and torque noise for <2500 hr of operation. A PAO lubricant with a TCP wear additive did not cause bearing failure and had run 11,000 hr with no indication of a problem. Its success has been (attributed by the authors) to the TCP additive. This type oil should be used for oscillating applications. [Carre]

• When properly made and installed, lightly preloaded duplex bearings having phenolic laminate separators and lubricated with thin films of BASD 36234 liquid lubricant can withstand more than 16 million low-angle oscillating cycles without any signs of degradation and without significant torque variation. [Phinney]

• Blocking can occur in oscillating duplex bearings even at extremely narrow angles of motion. Blocking is a condition where some of the bearing balls jam into ends of the separator pockets as a result of creeping away from their centered position. [Phinney]

• Table 7 shows the effects of various factors on blocking. [Lowenthal]

• Races should be slip fits, if possible, to assure proper performance and prevent blocking. [Phinney]

• Soft (spring) preloading is better than hard preloading if bearing torque is critical. [Phinney]

• Bearings must be scrupulously clean. [Phinney]

### Table 7. Factors Tending to Increase Blocking

<table>
<thead>
<tr>
<th>Factor Increased</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conformity (tighter)</td>
<td>Increases spin; higher spin torque and drag</td>
</tr>
<tr>
<td>Contact angle</td>
<td>Increases spin; higher spin torque and drag</td>
</tr>
<tr>
<td>One-piece cage</td>
<td>Restricts ball speed spacing; increases cage windup</td>
</tr>
<tr>
<td>Misalignment</td>
<td>Increases ball speed variation; increases cage windup</td>
</tr>
<tr>
<td>Friction coefficient</td>
<td>Increases traction forces; increases anomalous torque</td>
</tr>
<tr>
<td>Contact angle variation</td>
<td>Increases ball speed variation</td>
</tr>
<tr>
<td>Ball diameter tolerance</td>
<td>Increases ball speed variation</td>
</tr>
<tr>
<td>Thrust versus radial bearing</td>
<td>Thrust bearing has all balls loaded; no opportunity for ball spacing to readjust</td>
</tr>
</tbody>
</table>
- Torque spikes are the result of buildup of debris at the ends of the ball travel. The debris was primarily aluminum particles with a small amount of titanium debris and dry lubricant from the inner race retaining nut threads. [Phinney]

- Using aluminum tools during assembly can produce aluminum debris that contaminates the bearings; use titanium tools instead. [Phinney]

- Race conformity and separator type can have a dramatic effect on bearing torque. Slightly opening the race conformity and switching to alternating ball toroid separators reduced the excessive torque problem to an acceptable level. Particular attention must be paid to gimbal bearings to avoid blocking. Blocking torque phenomena for gimbal bearings is very much dependent on friction levels between the ball and race as well as the retainer ball pocket. The bearing should be well aligned, the race conformity should be increased as much as possible without incurring a contact stress problem, and the ball retainers should have either generous pocket clearance, slots or alternating ball toroids. [Survey, Lowenthal]

- Bearing computer codes are useful in determining appropriate race conformity. [Lowenthal]

- Excessive thermal gradients across the races can have a significant effect on internal preload and contact stress and can cause torque problems in gimbal bearings. Bulk temperature effects are much less severe. If tight control over preload is necessary, heaters are recommended to maintain proper temperature. Bearing computer codes are useful in establishing an acceptable operating temperature envelope. [Lowenthal]

- Large, thin-sectioned bearings in stiff mounts are particularly vulnerable to torque excursions from rolled over debris and degraded lubricant. Prolonged dither gimbal cycles should be minimized and periodic, have a longer stroke, and maintenance cycles should be included to maximize bearing life. [Lowenthal]

- Conformity ratio has a dramatic effect on torque levels. A buildup of compacted debris in the contact zone reduces the ball/race conformity ratio and can cause a torque increase of a factor of five above normal torque levels. [Gill]

- Liquid lubricant torque levels are less than cage lubricants or solid lubricants. [Gill]

- Of many lubrication systems tested, Pennzane SHF 2000 lubricant was the best for all conditions of operation. [Gill]

- Torque levels dramatically increase when direction changes. [Gill]

- Variable angle of oscillations are preferred, particularly for solid lubricants. [Gill]

- For oscillating scanner bearings, three oils were tested: G.E. Versilube F-50 (a CAS oil); Brayco 815Z (PFPE oil); and Nye 188B (a synthetic hydrocarbon oil, PAO). The PAO oil outperformed the other oils by a wide margin. The primary reason for this was the presence of the antiwear additive, TCP, in the PAO oil. The other two oils suffered rapid degradation. [Kalegoras]
For the angular-contact ball bearings in the shutter and filter wheel mechanisms of the Michelson Doppler Imager (MDI), lubrication with Bray 815Z oil met and exceeded the design life goals. [Akin]

For the thin-section ball bearings in the tuning motors of the MDI, lubrication with Bray 815Z oil did not meet the design life goals, but lubrication with Braycote 600 grease did meet the goals. [Akin]

Using bearings for small rocking motion applications has its problems. Even with a porous retainer, there is no fresh supply of oil to replenish the contacting surfaces when the motions are small oscillatory. Torque can skyrocket as either the oil breaks down or the bearing starves. In a test conducted at Hughes, Bray 815Z had half the initial torque of Apiezon C (with an extreme pressure additive) in a 4° gimbal bearing test. But after $7 \times 10^4$ cycles, the Bray turned to brown sugar and the bearing torque quickly increased by a factor of 10. [Hinkle]

- To prevent destructive chemistry, the surfaces in contact need to be passivated in some manner. Ceramic hard coatings, such as TiN or TiC, will eliminate catalytic reaction. Conventional nitride hard coatings are also effective. In the case of ball bearings, replacing the stainless steel 440C balls with ceramic SiN$_3$ balls eliminates breakdown. To prevent starvation, it is always good practice to use a porous ball retainer that functions like a reservoir of oil and dilutes any breakdown products.

Each of the beta gimbals on space station Freedom have four 18-in. diameter ball bearings with a specified 30-yr life. The original bearings failed after one week. The cause of failure was incompatible bearing materials and lubricant. Using the SEM/AES/XPS Tribometer, a substantial number of accelerated tribological tests were run in simulated low Earth orbit environment on a variety of bearing materials and solid lubricated composites. Based on these tests, improved materials were recommended and subsequent testing for an equivalent 35-yr life was successfully completed. Simple material tests should be run before selecting materials and building full-scale hardware. With suitable equipment, it is also possible to accelerate the testing while controlling the critical parameters. [Survey, Naerheim]

Many gimbal systems have travel limited by physical features and protection against contact of these features in the form of stops, both mechanical and electrical. With the very high forces available due to large gear ratios, significant damage can be done if the motor is driven past the normal stopping range. Equipment should be designed with a foolproof means of stopping the motor drive when approaching the limit of travel to prevent damage to the equipment or operator injury. Even though the position can be easily monitored, it is likely that during initial checkout the unit will be driven beyond its normal range of travel. [Survey, Sutter]
• Maximum torque was exceeded during gimbal checkout of the Hubble space telescope. The problem was harness interference. Where possible, preflight testing of the gimbal over its whole gimbal travel must be performed to determine if the wire harness or any other obstruction, such as thermal blankets, will prevent gimbal travel. The wiring harness must be designed to eliminate service loops where they are not necessary to prevent harness obstruction. [Survey, Ruebsamen]

• A gimbal torque anomaly occurred during space telescope antenna pointing system testing for the Hubble telescope. The cause was a tight curvature ratio of the balls to the race. The curvature ratios were changed to 53% on the inner race and 54% on the outer race. Also the rigid phenolic cage was replaced by a set of Teflon toroids. [Survey, Ruebsamen]

• A gimbal Kapton strip heater burned out during testing of the high-gain antenna pointing system. The failure was due to excessive input power coupled with epoxy vaporization. The epoxy was changed from a standard structural epoxy to a thermally conductive material. Also, bonding voids were eliminated when bonding the heaters to the shaft. Lessons learned were:
  - Minimize power density below 9 W/in.².
  - Eliminate voids when bonding heaters to the shaft.
  - The epoxy must be a highly filled, thermally conductive material and must be able to handle high power densities. [Survey, Ruebsamen]
NEEDS ANALYSIS
NEEDS ANALYSIS

A review of the information compiled for the Lessons Learned study reveals that bearing and lubrication problems are the most prevalent and, thus, improved technologies are most needed in these areas. This was further substantiated by a survey conducted by Fusaro, where the number one need was for liquid lubricants. There are other areas of importance. The principal needs derived from the study are given below.

Deployable Appendages

- Solid lubricant hard coatings, that will not produce wear debris are desirable to improve actuator reliability. Relative to liquid or grease lubricants, solid lubricants generally have lower vapor pressures, better boundary lubrication properties and relative insensitivity to radiation effects, and operate in wider temperature ranges. Investigation of ion-plated lead coatings, which have enjoyed good success in Europe should be undertaken, as well as ion-sputtered MoS2. In European solar array drives alone, more than 2 million operational hours have been accumulated with ion-plated lead films. An important property of the lead film is its high load-carrying ability. Under Hertzian contact, the as-deposited film flows plastically until a thin film (10 Nm or less thickness) remains and then elastically deforms the substrate. In this condition, the film can survive contact loads approaching the static load capacity of a rolling element bearing. Burnishing of epoxy and polyamide films to remove excess material may be acceptable and should receive further attention.

- Thermal problems (binding) are prevalent with actuators and retention and release mechanisms. Differences in coefficients of thermal expansion must be thoroughly explored to avoid jamming and excessive torque. Most problems occur at low temperatures. Considerable care must be exercised when mounting close clearance bearing components into aluminum structures that must operate at cold temperatures. More detailed finite-element analyses to establish clearances and tolerances is needed.

- The functional margin of pyrotechnic devices must be determined by test to assure actuation. The functional margin is a comparison of the energy that can be delivered to the device and the energy required to operate the device. Consultation with Bement at NASA-Langley is recommended.

- Increased use of the latest CAD software is needed. Iteratively designing a complex mechanism in CAD and using pasteboard mockups can be a more efficient process than detailed mathematical analysis of component geometries.

- Improved quality control of microswitches is required.

- Harnesses and cables have caused torque problems because of snagging and stiffness at low temperatures. These problems should be further addressed through analytical and empirical methods.
Rotating Systems

- The development of new polymeric bearing retainer materials is critical to achieve bearing lifetime. The phenolic materials that are commonly used have been demonstrated to absorb oil in a time-dependent and nonreproducible manner. These materials are unacceptable for the missions under consideration unless an active lubricant supply system is used. Retainerless bearings should be further studied and developed.

- Bearing lubricant depletion between the ball race retainer causes cage instability and subsequent pointing errors, increased bearing torque and wheel vibration. Phenolic cages continuously absorb oil from the contact regions instead of supplying oil, thereby hastening the onset of cage instability. A concentrated effort to develop active oil systems that periodically or continuously lubricate the bearings should be undertaken [Singer, Auer].

- Lubricant degradation is a common failure mode and is not amenable to accelerated testing. Continued development of vacuum tribometers such as those at NASA-Lewis is needed (see "Facilities" section), and extensive experimentation conducted to better understand and combat lubricant degradation.

- Both titanium carbide and titanium nitride have demonstrated to be effective wear coatings under appropriate conditions. Titanium carbide has been applied to gyroscope ball bearings and has increased operational lifetime by an order of magnitude in this application when used with an uncoated steel raceway and superrefined mineral oil. To date, titanium nitride has been used only on tool steels, but the Aerospace Corporation is currently testing both gimbal and spin bearings with Titanium-carbide and titanium-nitride-coated balls. These investigations should continue and effectiveness quantified.

- In a weightless environment, there are questions about how a drop of oil will behave. Even at a distance of 0.004 in., the drop may not transfer smoothly. It may touch and be slung off the moving surfaces to create a number of finer droplets that will float around the bearing housing. Lubrication phenomenon should be examined in a weightless environment by, for example, shuttle experiments.

- Bearing simulation computer codes can predict cage instabilities for steady-speed conditions, bearing performance parameters, elastohydrodynamic lubricant thickness, etc. More extensive use and continued development of computer codes is recommended and should include nonsymmetric cages, lubricant starvation, thermal effects, retainerless bearings, and acceleration and deceleration.

- Roll rings have demonstrated excellent performance; continued development is recommended.

- Small, fractional horsepower motors have experienced cold-temperature performance problems, primarily due to high lubricant viscosity. Development should be planned to evaluate and improve cold-temperature lubricant start-up as well as running torque in small components.

- Development of screening tests for various components can improve reliability in an expeditious and accurate manner. Screening tests are presently being used, with good success, for bearing cartridges, and extension to other components is recommended.
Oscillating Systems

- Gimbal bearings, which operate in an oscillatory (dithering) mode and rarely make a full revolution, are the primary problem area.

- For oscillating gimbal applications, solid dry lubricants, such as sputter-coated MoS$_2$, with benign ball retainers (those that do not transfer films) are recommended. Continued development of solid lubricants for gimbal races, with objectives of low torque and no debris formation is suggested.

- Race conformity and separator type can have a dramatic effect on bearing torque. Blocking phenomenon should be avoided. Computer code development for oscillating bearings, that can determine effects of race conformity, predict blocking, and establish consequences of debris formation on driving torque would be a useful design tool and is recommended.
SURVEY RESULTS
MTI and NASA developed a survey form and solicited various industries for information. The information requested is indicated on the sample form shown in Figure 1.

Over 600 survey forms were transmitted and approximately 30 replies were received. The replies varied in quality from scribbles to detailed amounts of lessons learned. Honeywell Electro Components and the Honeywell Satellite Systems Operation were particularly responsive. The significant responses follow.
### SPACE MECHANISMS SURVEY FORM

<table>
<thead>
<tr>
<th>Name</th>
<th>Address</th>
<th>Phone/FAX Number</th>
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</table>

**Areas of space mechanisms expertise** (check all those that apply)

- Rotating Mechanisms
  - Momentum Wheels
  - Motors
  - Despin Assemblies
  - Solar Array Drives
  - CMGs
  - Gyroscopes
  - Other __________________

- Scanning Mechanisms
  - Antennas
  - Telescopes
  - Sensors
  - Weapons
  - Instruments
  - Other __________________

- Deployment Mechanisms
  - Hinges
  - Joints
  - Latches
  - Releases
  - Actuators
  - Other __________________

Would you be willing to provide input into a space mechanisms guidelines handbook?

- Yes
- No

Names, addresses, phone numbers, and areas of expertise of mechanisms experts that you know who could provide input into the lessons learned study or handbook. Include yourself, if appropriate.

Identify reports that should be documented in the computerized database

Recommend any suggestions or topics for the Space Mechanisms Handbook

---

*Figure 1. Space Mechanisms Survey Form*
**SPACE MECHANISMS SURVEY FORM**

Provide a listing and description of Experimental Facilities, including capabilities and usage. Pictorial representation is desirable. (Use extra sheets, if necessary.)

---

*Figure 1. Continued*
### SPACE MECHANISMS SIGNIFICANT EVENT (Anomaly or Failure)

<table>
<thead>
<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEY WORDS</th>
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**Description of Problem Mechanism.** Provide pictorial representation and written description. Concentrate on features causing difficulties.

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<th>SUBMITTED BY</th>
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</table>

*Figure 1. Continued*
### SPACE MECHANISMS SIGNIFICANT EVENT (Anomaly or Failure)

<table>
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<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEY WORDS</th>
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<tbody>
<tr>
<td>EVENT DESCRIPTION (What happened and Impact)</td>
<td></td>
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</table>

**LESSONS LEARNED**

**SUBMITTED BY**

**DATE**

**ADDRESS**

*Figure 1. Continued*
### EXAMPLE OF SPACE MECHANISM SIGNIFICANT EVENT

<table>
<thead>
<tr>
<th>SUBJECT (Accompaniment of Event Occurrence)</th>
<th>INDICES/KEYWORDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage of Galileo Flight Antenna From Testing</td>
<td>Galileo Development Management Testing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EVENT DESCRIPTION (What Happened and Impact)</th>
<th>YEAR OF EVENT OCCURRENCE: 1983</th>
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<tbody>
<tr>
<td>The Galileo spacecraft Development Test Model (DTM) included the spare flight antenna subsystem (SXA-1). Informal characterization testing used to validate the analytical model included extensive modal vibration testing. Several organizations were involved in both developing and conducting the tests. At the conclusion of three tests (modal, acoustic, and pyro shock), three problems were identified: 1) the surface mesh, restraining cords, certain fittings, and sunshade were damaged. 2) the number of vibration cycles permitted by Space Transportation System (STS) safety criteria had been exceeded, and 3) the antenna failed to deploy properly due to a cord snag. The first problem, which reduced RF output by 3.4 dB at X-band, was probably caused by fatigue-type wear during modal testing. The second problem was the result of a calculation error during the test and would have precluded the use of the antenna for STS launch without some sort of refurbishment and requalification. The third problem, potentially mission catastrophic, was the third observed occurrence of a snag, indicating underlying design problems. The Project decided the SXA-1 antenna nonflight qualified due to gain loss, noncompliance with STS criteria, and questionable deployment reliability.*</td>
<td></td>
</tr>
</tbody>
</table>

### LESSONS LEARNED

1. The consequences and risk of damage to flight or developmental hardware imposed by test levels and test environment must be evaluated by the Project Office and the supporting technical division(s) with a formally commensurate with the consequences.
2. To clearly understand the results of environmental tests, especially those that include exploratory or characterization aspects, detailed physical and functional inspections should be performed between "separate tests" to isolate any problems attributable to each particular test.
3. The responsibility for the care and handling of any flight hardware should be unambiguously assigned throughout its preflight operational lifetime. Transfer of this responsibility should be unambiguous and formal.
4. Kinematically indeterminate structures, not capable of detailed analysis, should be tested with prototype hardware rather than flight hardware.

---

* The project decided the SXA-1 antenna nonflight qualified due to gain loss, noncompliance with STS criteria, and questionable deployment reliability.
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity / Area of Event Occurrence and Year)
Anomolous Motor Performance due to Bearing Lubricant Assembly/Contingency Subsystem for Communications 1993

INDICES / KEYWORDS
Space Station ACS
Stepper Motor
Lubricant Viscosity
Rheolube Grease (Pennzane)

EVENT DESCRIPTION

The Assembly/Contingency Subsystem (ACS) is a two-axis pointing gimbal designed by Honeywell for Space Station communications. During cold temperature development testing of the ACS, the system did not perform as expected. Subsequently, the drive components were removed for evaluation. The ACS uses a size 11 stepper motor, which is also designed by Honeywell, to provide motion control.

As a part of the failure evaluation, the stepper motors were removed, and special tests were performed at cold temperature (-25 degrees F.) Anomalous operation was discovered which had not appeared during acceptance testing. The stepper motor, which was designed to develop 2.5 ounce-inches of torque at 480 pulses per second, would not run at rates higher than 100 pulses per second. This was surprising, because motor acceptance testing of drag torque had been done at constant speeds and was generally found to be acceptable. The drag at cold did show an unusual gradient of decreasing drag with increasing speed, which was attributed to lubricant channelling.

Failure evaluation included a battery of tests which concentrated on cold start-up and showed that the full performance range could only be obtained if the motor received a brief, low speed run-in first. This had not been observed on other similarly designed and tested Honeywell stepper motors which had used Braycote bearing lubricant (rather than Rheolube.)

Evaluation concluded that the Rheolube grease in the small motor bearings became very stiff at cold temperature to the extent that the start-up torque was an appreciable and unexpectedly high portion of the available motor torque. A 20 second, low speed run-in reduced the grease's drag effect. The anomaly was not detected during acceptance testing, because the motor was constantly running. And, testing was not looking for start-up anomalies.

Finally, Honeywell disassembled the stepper motors and relubricated the bearings with Braycote. Successful performance resulted at cold temperature without any run-in period for the bearings. The motor performance met design requirements at cold and continued to perform at all other temperatures. A recommendation to use Braycote Micronic 601 was made.

LESSONS LEARNED

(1) Small, fractional horsepower motors are likely to experience cold temperature performance problems if Rheolube bearing grease is used. A lubricant effect similar to channelling was observed using Rheolube, which interfered with cold motor start-up and running capability. Braycote bearing lubricant did not interfere with motor performance.

(2) Small rotary components may be sensitive to lubricant effects not seen in larger hardware. Special testing should be planned to evaluate cold temperature lubricant start-up as well as running torque in small components.

(Please See Stepper Motor Figure Attached)

SUBMITTED BY
David B. Marks
Sr. Project Engineer

DATE
Revised:
February 23, 1994

ADDRESS
Honeywell Electro Components
Durham, North Carolina
(919) 955-4312
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)
Rotational Creeping of Actuators During Launch
Solar Max Repair Mission
1981

INDICES / KEYWORDS
Caging Mechanisms
Latch Mechanisms
Brakes, Lead Screws, Worm Gears

EVENT DESCRIPTION

Honeywell designed and fabricated the common drive units first used on the Solar Max repair mission. They were used for latching, rotating, and tilting functions on the repair cradle. The unit houses redundant motors and friction brakes driving through gearing and a differential to a common output shaft.

One of the requirements was to hold the rated torque load during launch vibration. A verification test was performed during unit qualification and the shaft was found to rotate very slowly with applied torque. Preliminary analysis showed that the normal force of the brake springs would not significantly reduce during vibration, so the test results were unexpected. At low torque levels and/or low vibration levels, the brake would hold. Vibration perpendicular to the rotational axis was a significant contributor to the amount of "slip" or "creep."

The cause was determined to be vibration peaks of a sufficient level to cause movement of the brake armature in the radial direction, thus supplying the energy to overcome the friction coefficient. The brake could then rotate. Since the vibration peaks were of short duration, the brake was operational most of the time. It was thus capable of restraining a load without total loss of brake holding torque. The shaft rotation was found to be about 10 degrees during launch, and was consistent from unit to unit. Fortunately, the system could tolerate this movement, so no corrective action was required.

Since the original discovery of this condition, Honeywell has observed similar characteristics in actuators using lead screws and worm gears.

LESSONS LEARNED

(1) Mechanisms which depend on frictional characteristics to restrain a load during launch vibration may slip and relieve the applied load.

(2) Components such as worm gears and lead screws are normally considered to be non-backdriveable. Certain conditions of vibration can cause backdriving to occur.

SUBMITTED BY
Richard Fink
Lead Engineer

DATE
January 21, 1994

ADDRESS
Honeywell Electro Components
Durham, North Carolina
(919) 956-4264
Mechanical Technology Inc.

Survey Results
## SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

<table>
<thead>
<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEYWORDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PSA (Payload Spin Assembly)</td>
<td>PSA, Electronics, FETS</td>
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</table>

### EVENT DESCRIPTION (What Happened and Impact)

During runup for a room-temperature operational test on the flight PSA the unit shut down after achieving an approximate speed of 30 rpm. Current traces from SEAs showed normal traces until the event then dropped to zero. All of the power FETS were blown due to a runaway oscillating condition. No problems were experienced during testing of the engineering model. S-level FETS were used in the flight unit, while lower-quality FETS were used in the engineering unit. Investigation revealed that the S-level FETS were too fast for the snubber circuits and created instability, leading to major failure. The lower-quality engineering FETS were slow enough for the snubber circuits to handle.

### LESSONS LEARNED

Any changes made to a successful engineering model design should be analyzed before incorporation into qualification/flight hardware.

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<tr>
<th>SUBMITTED BY</th>
<th>DATE</th>
<th>ADDRESS</th>
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<tbody>
<tr>
<td>Wilf Robinson</td>
<td></td>
<td>Honeywell Inc., Satellite Systems Operation, 19019 N. 55th Ave, Glendale, AZ 85308-9650</td>
</tr>
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</table>
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEYWORDS</th>
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<tbody>
<tr>
<td>GGS Slip ring Wire Corrosion</td>
<td>GGS, Slip Rings, Wires</td>
</tr>
</tbody>
</table>

## EVENT DESCRIPTION (What Happened and Impact)

During flight assembly, an open shield and a shield shorted to a conductor were discovered on a flight slip ring assembly. A search of the test data showed only that a continuity test had been performed. It was unclear if the shields were tested individually or only the conductors. The procedure stated only to test all of the rings for continuity per the drawing. It also was not clear if any of the readings had changed after the unit left the vendor because no data was recorded (only pass/fail). X-rays of the unit revealed that the assembly had been improperly reworked at the vendor. The flight spare slip ring unit was substituted and assembly proceeded.

## LESSONS LEARNED

Inspectors should look for obvious signs of rework, like a different color of epoxy, and the paperwork should be checked to see if the rework was recorded.

The data sheet should have had a line for each measurement and required that the actual meter reading be recorded. The specification should have then been listed and a check mark placed in either a pass or fail column. A quick scan would then tell if any failures were present and allow the detailed information to be recorded. The test equipment, calibration, and temperature should also be required on the data sheet.

## Submitted by

Dave Osterberg

## Date


## Address

Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650

9STRMV1
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tr>
<th>SUBJEC(T (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEYWORDS</th>
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</thead>
<tbody>
<tr>
<td>GGS Accelerated Life Test Failure</td>
<td>GGS Life-Test, Bearings, Toroids</td>
</tr>
</tbody>
</table>

EVENT DESCRIPTION (What Happened and Impact)

After an initial 10 rpm checkout phase, the GGS slip ring life test was accelerated from 10 rpm (flight speed) to 30 rpm in order to gather all of the three-year mission life data in one year. The bearing design utilized Teflon toroids as ball separators. Shortly after increasing to 30 rpm, the toroids shredded, causing a bearing failure. The failure was traced to exceeding the pressure-velocity (PV) limits of the toroid material.

LESSONS LEARNED

Toroids should be used with only lightly loaded bearings due to the stress on the nonconforming outer diameter of the toroid to the adjacent ball, which was three times higher than the pocket stress for GGS. Toroids allow balls to bunch-up, making it difficult to predict dynamic performance. Bearing drag torques are less predictable with toroids.

Accelerated testing of bearings is not recommended because even at sub-EHD speeds the wear mechanisms can be very nonlinear.

PV curves should be determined and used to check all new retainer designs. These curves need to be established for the various materials used and the method of analysis made consistent for all programs.

SUBMITTED BY
Dave Osterberg

DATE

ADDRESS
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9550
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEYWORDS</th>
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## EVENT DESCRIPTION (What Happened and Impact)

Because of concerns about the nonconductive Tufram coating allowing a charge buildup that might affect instruments for the POLAR Satellite, a change to a conductive coating (NEDOX) was directed. Even though the coefficient of friction of NEDOX was reportedly better than that of Tufram, the NEDOX-coated V-band failed to release during acceptance testing. Previously, an engineering unit with a Tufram-coated V-band was successfully released under various conditions greater than a dozen times.

## LESSONS LEARNED

Extreme care should be used when changing even the simplest process or procedure from what has worked previously. Testing of the new coating prior to acceptance test was bypassed due to schedule and budget constraints and the similarity of the two coatings. In the end, neither schedule nor budget was saved, and testing had to be repeated with the final V-band design, which consisted of Tufram coating only on the contacting surfaces of the band to minimize surface area for charge buildup. While you should strive for constant improvement, always test any changes early.

### SUBMITTED BY
Dave Osterberg

### DATE

### ADDRESS
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

## SUBJECT (Activity/Area of Event Occurrence and Year)
GGS Duplex Bearing Torque Variations Due to Lobing – 1991

## INDICES/KEYWORDS
GGS, Bearings, Thin Section

## EVENT DESCRIPTION (What Happened and Impact)

The duplex bearing used on the GGS program is a 9.25 in. OD thin section bearing that operates at 10 rpm. The bearing was designed with rings having nonuniform cross sections. The duplex bearing assembly was bolted to the shaft via six mounting tabs designed into the one-piece inner ring. One of the two outer rings was scalloped for weight considerations.

Due to the flexibility of the rings inherent in thin-section bearings and the manner in which the bearing was bolted to the shaft (i.e., shaft contacts inner ring at ID of tabs only), deformations in the form of lobing occurred in the rings when the bearing was preloaded. The magnitude of the lobing increased with increase in preload. Some lobing in the inner ring occurred during processing due to the nonuniform cross section.

Impact to bearing performance occurs in the form of torque variations, increased ball loading, and ball sliding due to possible regions of ball unloading. Ball sliding increases wear, thereby shortening life.

## LESSONS LEARNED

Unmounted preload should be minimized, as well as mounting fits at the shaft-to-bearing interface to reduce operational preload to a minimum.

Bearings should be designed with constant cross sections. System mating parts should be designed to interface a bearing assembly that has a constant cross section.

## SUBMITTED BY
Dave Osterberg

## DATE

## ADDRESS

Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)  |
PSA Pyrotechnic Pin Puller Failure During Life Test – 1989

INDICES/KEYWORDS
PSA, Pyrotechnics, Pin Puller

EVENT DESCRIPTION (What Happened and Impact)
During one of the SA deployment tests in 1989, a pin puller in a release mechanism was actuated. The pin was retracted inside its housing to release the SA, but then rebounded back out the housing. The normal function of a pin puller is to retract and stay flush inside the pin puller housing. The malfunction of this pin puller did not stop deployment of the SA because of the mechanical redundancy of the release mechanism. The rebound of the pin outside the housing forced us to investigate our pin-puller design. The result of this investigation showed that an extra shear pin hole was accidentally drilled at 120° away from the original shear pin hole on the pin puller, reducing the buckling strength of the pin; therefore, when the pin puller was actuated, the pin was retracted and came to an instantaneous stop inside the housing at the end of travel. The impact force caused the pin to break in buckling and the top portion of the pin to protrude back to the outside of the pin-puller housing. The extra shear pin hole was not detected at the component inspection level because the pin (piston) drawing only required measuring the hole location and hole diameter rather than counting the number of shear pin holes. The extra shear pin hole was not detected at the pin-puller-assembly level inspection by using X-ray either. Up to that time, pyro-actuated devices were only required to be X-rayed on one side view of the actuator assembly. The extra shear pin hole was not shown in the particular X-ray view.

LESSONS LEARNED
After this incident, we recommend that all pyro-actuated device assemblies have two X-ray pictures taken – one on the side view and one turned 90°.

Pyrotechnic pin pullers have many actuation times; therefore, they normally are subjected to very high impact forces (impulse forces). From past design experience in pyro actuators, we learned that the material impact strength is usually a more critical variable than the ability of the pin puller to withstand the high inertia load of a deployable system, especially if the device is required to operate in a cold environment. Material impact strength drastically dips when the temperature dips. It is recommended that when the inertia load of the deployable system is low, a more ductile material be selected over a brittle material for the actuator housing and piston. It is also recommended that for the pin puller lot acceptance test, at least one test be to subject the pin puller to zero inertia load in the shear direction and, in a cold operating temperature, actuate the pin puller with 125% explosive powder material. The zero external shear load allows the pin (piston) to retract at a higher velocity, which, in turn, yields a higher impact force. The material impact strength is also lower at the lower temperature; this is the worst-case test for impact strength.

SUBMITTED BY  | DATE  | ADDRESS
W. Robinson  |  | Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650

Survey Results 4-17
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

<table>
<thead>
<tr>
<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
<th>INDICES/KEYWORDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage of Galileo Scan Actuator Sub Assembly During Heat Treat – 1981</td>
<td>Galileo, Titanium, Heat Treat</td>
</tr>
</tbody>
</table>

## EVENT DESCRIPTION (What Happened and Impact)

The housing for the Galileo scan actuator is a complex mechanical part machined from titanium bar stock 6 in. in diameter. After all machining is complete (except for a final skin cut on critical surfaces), this material goes through a heat-treat process to stabilize it. The part is then machined to final dimensions and typically does not require any surface treatment. The finished housing had a value of several thousand dollars.

On this program the housing was machined by a well-qualified machine shop. The part was then sent out for heat treat. The heat treat house was not carefully selected and the oven did not have over-temperature shut down circuitry; through some fault of the operator or equipment, the temperature got into a run-away condition. The housing was damaged beyond salvage with a resultant severe impact on the build schedule and cost to the Galileo program.

## LESSONS LEARNED

Heat-treat suppliers should be carefully selected and their equipment evaluated to ensure protection against conditions that could irreparably damage parts during their processing. In particular, all ovens used on expensive parts should have over-temperature protection and treat time limiting that is reliable and redundant.

Operations subsequent to creating significant value on a part should be carefully monitored and selected to minimize the likelihood of damage to a part that would impact a program significantly.

## SUBMITTED BY

Clair Sutter

## DATE

March 21, 1994

## ADDRESS

Honeywell Inc.
Satellite Systems Operation
19019 N. 55th Ave
Glendale, AZ 85308-9550

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Survey Results
**SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)**

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<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
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</thead>
<tbody>
<tr>
<td>Protection for Limited Travel Gimbal Systems – 1993</td>
<td>Gimbal, Travel Limits, Limit Switches</td>
</tr>
</tbody>
</table>

**EVENT DESCRIPTION (What Happened and Impact)**

Many gimbal systems have travel limited by physical features and protection against contact of these features in the form of stops, both mechanical and electrical. With the very high forces available due to large gear ratios, significant damage can be done if the motor is driven past the normal stopping range.

On the assembly contingency subsystem for Space Station Freedom, initial testing of the gimbal was being done without an indication of gimbal position available to the operator except visual monitoring of gimbal travel. In spite of careful monitoring there were several times when the hard stops were contacted at full speed, either due to operator error or equipment malfunction. Fortunately for this program, the hard stops were designed to withstand this impact and no damage was done.

**LESSONS LEARNED**

Equipment should be designed with a foolproof means of stopping the motor drive when approaching the limit of travel to prevent damage to the equipment or operator injury. Even though the position can be easily monitored, it is likely that during initial checkout the unit will be driven beyond its normal range of travel.

**SUBMITTED BY**
Clair Sutter

**DATE**
March 21, 1994

**ADDRESS**
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9550
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)
Impact of Stop Work or Customer invoked Schedule Extension – 1980

INDICES/KEYWORDS
Galileo, Stop Work Order

EVENT DESCRIPTION (What Happened and Impact)
The Galileo program was initially started on a very fast track to fit an upcoming launch window. When problems occurred with the upper stage of the launch system the schedule was revised and much of the work was stopped for a period of one to two years. This extension caused and/or allowed considerable design refinement, both with the customer and the supplier, and a resultant cost growth of more than 100%. It is not obvious at this point that the original design would not have accomplished the mission, but certainly with the additional time the design was considerably improved.

LESSONS LEARNED
Careful consideration of all of the ramifications and impacts of schedule changes is required to prevent significant cost growth on complex space programs. Even though the intention is to use the same design, the tendency of designers is to continually improve a design and justify the additional cost with improved performance of reliability or other desirable characteristic.

SUBMITTED BY
Clair Sutter

DATE
March 21, 1994

ADDRESS
Honeywell Inc.
Satellite Systems Operation
19019 N. 55th Ave
Glendale, AZ 85308-9650
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tbody>
<tr>
<td>Customer Furnished Parts for the Galileo Program – 1980</td>
<td>Galileo, Customer Furnished Parts</td>
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</tbody>
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## EVENT DESCRIPTION (What Happened and Impact)

In order to provide more consistent radiation data, quality, and testing, and to save costs by a common procurement of electronic parts and hardware, JPL directed the use of customer-furnished parts for the Galileo program. Ostensibly, this would provide larger lot buys and timely delivery of parts by providing suppliers with a common requirement even though the usage would be widespread among the suppliers.

In practice, this approach extended the lead time and created additional costs not originally expected. One problem was the need to use flat-pack microcircuits (standardized by the customer) instead of the dual in-line packages with which Honeywell has extensive experience; this required new skills to be learned by the assemblers. Another problem was the logistics of parts providing requirements to the customer and then developing a system to track the part's status and obtain timely delivery.

## LESSONS LEARNED

When the tried and proven procedures in an organization are deviated from, the costs of revising the procedures are very likely to outweigh the savings achieved by the purported improvements.

---

**SUBMITTED BY**
Clair Sutter

**DATE**
March 21, 1994

**ADDRESS**
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
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### EVENT DESCRIPTION (What Happened and Impact)

During STAPS proto-flight testing the internal thermostats failed. The customer-required wiring was such that the thermostats could not be by-passed by external thermostats and still use the existing internal heaters without complete disassembly of the unit. In order to minimize schedule impact external heaters were bonded to the outside surface of the gimbal housing with externally mounted thermostats. Then internal heater circuit was completely by-passed. The external heater had a metal cover bonded to the housing to protect it.

### LESSONS LEARNED

Where possible, the wiring for internal heaters and thermostats should be completely accessible in case the internal components fail during protoflight test. Extensive screening of the thermostats should be performed prior to installation to prevent reoccurrence of this event.

### SUBMITTED BY

Dale Ruebsamen

### DATE

April 12, 1994

### ADDRESS

Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
**SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)**

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<tbody>
<tr>
<td>Heater Cover failure during Hubble Space Telescope Antenna Pointing System (STAPS) component testing – 1987</td>
<td>Hubble Space Telescope, STAPS, Heater Failure</td>
</tr>
</tbody>
</table>

**EVENT DESCRIPTION (What Happened and Impact)**

During acceptance testing of refurbished STAPS gimbals the external cover of the heater dislodged during thermal cycling test. Due to this failure, all of the previously tested units were completely disassembled and the internal heaters and thermostats reworked and retested. This was a major schedule impact to the program.

**LESSONS LEARNED**

The cause of the event was an incompatibility of the thermal coefficient of expansion between the cover materials with the housing materials and the fact that the cover and housing were gold plated, which prevented a proper epoxy bond between the two parts. Three lessons were learned:

- Heater covers should include a mechanical means of mounting along with the epoxy bond (i.e., screws)
- The area where the epoxy bond is to occur should be free of gold plating
- If external heaters are to be used, an epoxy designed for use as a thermal conductor should be designated and its CTE should match that of the major structure

**SUBMITTED BY**

Dale Ruebsamen

**DATE**

April 12, 1994

**ADDRESS**

Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
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**EVENT DESCRIPTION (What Happened and Impact)**

During on-orbit checkout of the Hubble Space Telescope (HST) gimbal sets, the onboard computer indicated that the torque command to one of the two gimbal sets exceeded full torque for an unexpected period of time. This happened only on one of the two gimbal sets at extreme gimbal angles. Using a stick model and reviewing pre-flight photographs of the HST, it was determined that a service loop in the gimbal harness was not properly tied to the boom during satellite integration, which interfered with the antenna latch trundles.

The onboard software was modified to prevent the gimbals from going into the area where the trundles could impact the harness; this has limited the total capabilities of the system data transfer, but the impact has been minimized.

**LESSONS LEARNED**

Where possible, pre-flight testing of the gimbal over its whole gimbal travel must be performed to determine if the wire harness or any other obstruction, such as thermal blankets, will prevent gimbal travel.

The wiring harness must be designed to eliminate service loops where they are not necessary in order to prevent the possibility of the harness becoming an obstruction.

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<td>Dale Ruebsamen</td>
<td>April 12, 1994</td>
<td>Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650</td>
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95TRM01
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

## SUBJECT
- Activity/Area of Event Occurrence and Year: Gimbal Torque Anomaly during STAPS Acceptance Testing – 1985

## INDICES/KEYWORDS
- Hubble Space Telescope,
- Component Testing,
- Bearings

## EVENT DESCRIPTION
During protolight testing of the scan gimbal set a torque anomaly occurred. The anomaly can be best described as an increase in the gimbal drag torque as the gimbal approached the end of travel in one direction. This made the drag torque trace look like a trumpet instead of a rectangular shape as expected (constant drag torque in both directions). The cause was narrowed down to two possibilities: the flex-capsule or the bearings. Extensive testing eliminated the flex-capsule. The cause was a tight curvature ratio of the balls to the race of 51.7% with rigid phenolic cages. In low-speed application of the gimbals, the tight ratio caused the balls to climb the race toward the lands. When the balls climbed the race, each at a different amount, their contact angles dictated that they move at different velocities. This caused some balls to push on the cage, while others dragged on it. Two actions were taken to eliminate this problem. First, the curvature ratios were changed to 53% on the inner race and 54% on the outer race. This decreased the ball’s tendency to climb the race. Second, the rigid phenolic cage was replaced by a set of Teflon toroids, eliminating loads due to the ball climbing into the cage. This caused the drag torque of the bearings to decrease to half of the previous bearing design, and the load capacity of the bearings to decrease to half of the previous bearings. This was still within the limits of the required load capacities.

A complete accelerated life test was performed on the new gimbal bearing configuration to prove the concept. All of the gimbal sets were refurbished with new bearings and completely retested to the protolight levels using the new bearing design.

## LESSONS LEARNED
For low-speed applications the curvature ratio of the bearings must be taken into consideration. This includes the load capacity, type of cage, and speed.

Analysis is not a good substitute for gimbal bearing testing.

## SUBMITTED BY
Dale Ruebsamen

## DATE
April 12, 1994

## ADDRESS
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Ave
Glendale, AZ 85308-9650
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tr>
<td>Gimbal Heater Failure during System level Acceptance Test for TOPEX HGAS. (High Gain Antenna Pointing System) – 1985</td>
<td>TOPEX-HGAS, Heater Failure</td>
</tr>
</tbody>
</table>

## EVENT DESCRIPTION (What Happened and Impact)

During the system-level acceptance of the TOPEX-HGAS one of the gimbal heater circuits indicated an open circuit. After review of all of the test equipment it was determined that the heater was burned out. The gimbal was disassembled and confirmed this conclusion. The heater was a kapton-strip-type heater. During investigation of this failure it was determined that there were two problems that contributed. First, due to an environmental change from the baseline design, the heater power was doubled, which doubled the power density from 9 to 18 W/in.². Second, the epoxy used to bond the heaters to the shaft would vaporize if the local temperature exceeded 125 °C. The thermal model predicted local temperatures in excess of 150 °C at that location. Vaporization of the epoxy caused hot spots in the heater, which would accelerate the heater failure. Also, any voids in the epoxy due to assembly under the heater would decrease the thermal conductance from the heater to the shaft and create hot spots in the heater.

To eliminate this problem the epoxy was changed from a standard structural epoxy to a thermally conductive one. Also, the process of bonding the heaters to the shaft was changed to eliminate voids between the heater and the shaft. Extensive testing was performed to verify that these measures solved the problem.

## LESSONS LEARNED

The power density should be minimized, preferably below 9 W/in.².

The process of bonding the heaters to the shaft needs to be closely controlled to eliminate, as much as possible, the voids between the heater and the shaft.

The epoxy used must be a highly filled, thermally conductive material and must be able to handle high power densities.

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**SPACE MECHANISMS SIGNIFICANT EVENT**

<table>
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<tr>
<th>SUBJECT</th>
<th>DATE: 1987</th>
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</thead>
<tbody>
<tr>
<td>Space Telescope High Gain Antenna Bearing Torque Anomaly during Ground Tests</td>
<td></td>
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</tbody>
</table>

**DESCRIPTION OF PROBLEM**

Hard preloaded, angular contact duplex gimbal bearings experienced high torque at end of stroke during life tests. Bearings were life tested through a fixed stroke of approximately 95 degrees. Bearing conformities were approximately 52% and the retainer was a one-piece phenolic.

**EVENT DESCRIPTION**

The bearing were experienced a phenomena known as blocking in which ball speed variations caused significant cage pinching and resulting high torque. This phenomena was aggravated by the fixed gimbal stroke and tight race conformity.

To fix the problem he race conformity was opened up to approximately 54% which virtually eliminated the torque anomaly. Also the ball retainer was switch to alternating teflon toroids which provide a smaller benefit from allowing the balls more freedom for excursions.

The details of the work can be found in the reference given below.


**LESSONS LEARNED**

Particular attention must be paid to gimbal bearings to avoid this blocking phenomena. The bearing should be well aligned, the race conformity should be increased as much as possible without incurring a contact stress problem and the ball retainers should have either generous pocket clearance, slots or alternating ball toroids should be specified.

**SUBMITTED BY**

Stuart Loewenthal

<table>
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<tr>
<th>Date</th>
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</table>
| 5/15/94 | Lockheed Missiles & Space Company  
Org 74-12 Bldg: 150  
1111 Lockheed Way  
Sunnyvale, CA 94089-3504 |
### SPACE MECHANISMS SIGNIFICANT EVENT

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<tr>
<th>SUBJECT</th>
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<tbody>
<tr>
<td>Torque Anomaly for Bearings in hard Space suit Ground Tests</td>
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</table>

#### DESCRIPTION OF PROBLEM

Hard preloaded, angular contact duplex gimbal bearings in the joints of an experimental aluminum space suit experienced high torque during life tests. These bearings were located in 5 different joints including shoulder, elbow, wrist, hip and knee. The races of these bearings were integral with the space suit joint and a very thin perfluoro polyether oil was used for lubrication. Torque got quite high during astronaut underwater weightless training, impeding joint motion and increasing the astronauts work load.

#### EVENT DESCRIPTION

This anomaly is similar to that of the antenna gimbal bearings in that blocking was at the root of the problem. The poor quality of the bearing races and the water washout of oil in the bearing during underwater tests clearly aggravated the problem.

A search for a oil that could resist water washout and still have low viscous losses was futile. To fix the problem, it was necessary to re manufacture all of the joints with a double seal, one for space and the other to keep water from reaching the bearings during tank tests. This greatly reduced the torque.

The details of the work can be found in the reference given below.


#### LESSONS LEARNED

Blocking torque phenomena for gimbal bearings is very much dependent on friction levels between the ball and race as well as the retainer ball pocket. Also there is no substitute for realistic bearing life testing.

#### SUBMITTED BY

<table>
<thead>
<tr>
<th>Stuart Loewenthal</th>
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<td>Sunnyvale, CA 94089-3504</td>
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</tbody>
</table>
SPACE MECHANISMS SIGNIFICANT EVENT

SUBJECT
On-Orbit Torque Problem with Positioner Bearings

DATE: 1993

DESCRIPTION OF PROBLEM
Thin sectioned bearings approximately 7 inch in diameter, hard mounted in a stiff beryllium housing experienced high on-orbit torque after three years operation at about 25 million cycles. The bearings were lubricated with a perfluorinated polyether oil at light contact stress levels (120 KSI maximum Hertz stress). The bearings operated for prolonged periods of time (up to days) at ± 0.75 degrees at a rate of 1 Hz.

EVENT DESCRIPTION
Prolonged cycling over a given spot on the bearing race with a short gimbal stroke squeezed needed oil out of the contact and inhibited replenishment. The mode of operation accelerated oil degradation and retainer wear.

The duty cycle was reprogrammed to greatly reduce operation in this dither mode. Also periodic long slew "maintenance" cycles were incorporated to help rewet the contacts and redistribute degraded lubricant and retainer wear products.

LESSONS LEARNED
Large, thin sectioned bearings in stiff mounts are particularly vulnerable to torque excursions from rolled over debris and degraded lubricant. Prolong dither gimbal cycles should be minimized and periodic, longer stroke, maintenance cycles should be included to maximize bearing life.

SUBMITTED BY
Stuart Loewenthal

Date 5/15/94

Address
Lockheed Missiles & Space Company
Org 74-12 Bldg: 150
1111 Lockheed Way
Sunnyvale, CA 94089-3504
# SPACE MECHANISMS SIGNIFICANT EVENT

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<tr>
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<tbody>
<tr>
<td>Cold Temperature Jamming with Spherical Bearing</td>
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</table>

## DESCRIPTION OF PROBLEM
A spherical bearing as part of the hinge of a solar array panel experienced lock up torque during ground tests at below -40°F. The ball in the bearing was coated with a bonded MoS2 film. The bearing was screwed and epoxied into an aluminum clevis housing.

## EVENT DESCRIPTION
This anomaly was the result of the spherical bearing being epoxied into place. Normally there was sufficient clearance in the threads between the steel bearing outer race and the aluminum housing to accommodate the contraction of the aluminum at cold temperature. However, when the bearing was epoxied into place, the epoxy filled the threaded area allowing the aluminum clamping loads to pass into the bearing. Eliminating the epoxy and thread by staking the bearings into place eliminated the problem.

## LESSONS LEARNED
Considerable care must be exercised when mounting close clearance bearing components into aluminum structure that must operate at cold temperatures.

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| Stuart Loewenthal | 5/15/94 | Lockheed Missiles & Space Company  
Org 74-12  Bldg: 150  
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## SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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<tbody>
<tr>
<td>Transmit Antenna Adjustment Limits via Bi-Axial Drive Assembly</td>
<td>ACTS Attachment Design</td>
</tr>
</tbody>
</table>

### Description of Problem Mechanism

Provide pictorial representation and written description. Concentrate on features causing difficulties.

The Transmit Antenna on the Advanced Communications Technology Satellite (ACTS) has the capability to traverse in both elevation (North-South) and azimuth (East-West) directions for adjusting the alignment between the Transmit and Receive Antennas. The adjustment was to be accomplished by using a Bi-Axial Drive Assembly mounted between the Transmit Antenna and the spacecraft. The Bi-Axial Drive Assembly consists of two axial drive mechanisms mounted orthogonally. Each drive mechanism contains a stepper motor capable of rotating a minimum of 0.30 degrees and a maximum of 0.35 degrees in either direction, in steps of 0.0075 degrees ± .0015.

The structural joint between the Bi-Axial Drive Assembly and the Transmit Antenna was designed to accommodate final adjustments for final positioning or alignment of the Transmit Antenna. The joint was held by friction with shims via four bolts through large holes to allow adjusting or shifting the Transmit Antenna for final RF alignments.

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<tr>
<td>John L. Collins</td>
<td>4/03/94</td>
<td>NASA LeRC</td>
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<td>Attachment Design</td>
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</table>

#### EVENT DESCRIPTION (What happened and Impact)

The mechanical joint between the Bi-Axial Drive Assembly and its mounting to the spacecraft allowed the Transmit Antenna to shift locations during launch aboard STS-51. The four bolts did not maintain the proper preload and the joint slipped during launch loading. This has reduced the available design adjustment for the ACTS Transmit Antenna.

#### LESSONS LEARNED

All mechanical attachment-type joints that require precise alignments will not use friction to maintain alignments during any type of loading. All types of alignment joints should be match drilled with body-bound bolts or be drilled and pinned after assembly.

### Submitted by

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SPACE MECHANISM SIGNIFICANT EVENT

Problem Description

BETA GIMBAL BEARING ON SPACE STATION FREEDOM (1992)

The Beta Gimbal Bearing Modules connect the Solar Array Panel Assemblies to the Space Station Freedom (SSF) through the Alpha Gimbal Modules. The purpose of these joints is to keep the solar panels that provide the power for the SSF facing the sun as the SSF moves through space. Each of the Beta Gimbal Modules have four 18 in diameter ball bearings. These bearings, like the SSF, have a design life goal of 30 years. However, the original bearings failed after one week into a planned two-year test at NASA-LeRC. The failure was determined to be caused by using incompatible bearing materials and lubricant. This problem would have a detrimental impact on the SSF Electric Power System cost and program schedule if not quickly resolved.

The Rockwell Science Center was requested to find solutions to the problem. Using the SEM/AES/XPS Tribometer, a substantial number of accelerated tribological tests were run in simulated low earth orbit environment on a variety of bearing materials and solid lubricating composites to determine the performance level and consistency over time. Based on these tests improved materials were recommended and new bearings manufactured in a very short time. During subsequent testing at NASA-LeRC the new bearings have operated within specifications for more than 35 years equivalent on orbit SSF time.

Lessons Learned

Many problems with associated costs and slipped schedules can be avoided by running simple, but representative tests before selecting materials and building full scale hardware. With suitable equipment it is also possible to accelerate the testing while controlling the critical parameters.

Yngve Naerheim
May 5, 1994
Rockwell Science Center
1049 Camino Dos Rios
Thousand Oaks, CA 91360

Survey Results 4-33
**SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)**

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<td>Clementine Program</td>
<td>Paraffin Actuator</td>
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<tr>
<td>Paraffin actuator heater failure 9/93 in ground testing</td>
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</table>

**Description of Problem Mechanism. Provide pictorial representation and written description. Concentrate on features causing difficulties.**

A paraffin actuator used to open and close the main sensor cover on the Clementine spacecraft experienced a heater failure during its acceptance testing. There were two causes of the problem: 1) excessive temperature and stress from driving the heater at high voltage (36V) and 2) mechanical stress on the heater element from flowing wax within the actuator during heating.

This was an extremely challenging heater design in that the actuator had to function from 24 volts @ 5.75 watts to 36 volts @ 13 watts, a ratio of 2.25:1 on power supplied. Additionally the mechanism had to work with this voltage range from -10°C to +50°C. It turns out that 36 volts is very close to the operating limits of the heater, although this is not a problem in and of itself. When the high operating voltage was combined with the wax flow issues it resulted in heater design that was marginal.

The wax flows upward as it is melting when it is in a gravity field because the melted wax is lighter than the semi solid wax that has not finished melting. This flow puts significant mechanical stress on the heater which is very hot and therefore weak at this point in the cycle. The heater is rolled in a cylinder of 350° around its circumference leaving a narrow gap parallel to the cylinder's axis to accommodate this wax flow. The stresses can be alleviated somewhat by positioning the gap so that it is at the top of the cylinder for all tests in gravity which better accommodates the wax flow.

We resolved the problem by mounting the actuator with the heater positioned with its gap up for ground testing. We also dropped the voltage range to 22 to 33 volts by incorporating a resistor in series with the heater. These changes resulted in a successful design and a successful flight. In the future however, we will use a much narrower voltage supply range for any paraffin actuators. A reasonably simple circuit using a zener diode can keep the operating voltage for the actuators from varying excessively. The addition of this circuit would greatly reduce the severity of the requirements for the heater while adding very little complexity to the host satellite. The lessons that we learned about reducing the voltage range for paraffin actuators have lead us to consider this approach for other mechanisms sensitive to variations in supply voltage, and especially for other heat actuated mechanisms.

**SUBMITTED BY**

Bill Purdy

**DATE**

5/6/94

**ADDRESS**

Naval Research Laboratory
Code 8221
4555 Overlook Avenue
Washington, DC 20546
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)  INDICES/KEYWORDS
ISTP Despin Platform
Honeywell, Phoenix AZ
Large Diameter Thin Section Bearings
Teflon Toroids
Segmented Retainers

Description of Problem Mechanism. Provide pictorial representation and written description. Concentrate on features causing difficulties.

Original Design: ~8" thin section bearings, one-piece phenolic retainer, hollow steel shaft, aluminum scalloped housing with band of titanium around bearings. Bearings run at 10 RPM.

Problem 1: Could not keep one-piece phenolic cage concentric. Warping caused high torques.

Attempted Solution: Teflon toroids. Also changed to full titanium scalloped housing.

Result: Lobing in bearing due to mounting caused ball speed variations which highly loaded toroids.

- Toroids badly damaged/wedged. Teflon and other metallic debris from unknown source accelerated toroid damage.
- High torques

Final Solution: Four piece segmented phenolic retainer. Currently in lifetest with no torque anomalies to date.

SUBMITTED BY
Claudia Woods

DATE
1/7/94

ADDRESS
NASA/GSFC
Code 723.4
Greenbelt, MD 20771
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

<table>
<thead>
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<th>SUBJECT (Activity/Area of Event Occurrence and Year)</th>
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<td>Solid Film Lubricants</td>
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<td>Long Duration Experimental Facility</td>
<td>LDEF</td>
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<td>Photochemical Degredation</td>
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</tbody>
</table>

Description of Problem Mechanism. Provide pictorial representation and written description. Concentrate on features causing difficulties.

Several panels on the LDEF were coated with Everlube® 620C, a common solid film lubricant. When LDEF returned, the panels which had previously been coated with the solid film lubricant were bare. This observation was covered in a report and presented at a conference at Marshall Space Flight Center in October 1993.

Lesson Learned
The important point is that this product was doomed to failure before the experiment was initiated. Everlube 620C utilizes an organic phenolic based binder system. On earth, phenolic systems are subject to U.V. degradation due to the low energy involved in the \( \pi \rightarrow \pi^* \) transition associated with polymeric aromatic systems. Thus, in Low Earth Orbit where U.V. radiation is more intense, the quantum yield of this negative reaction would be expected to increase leading to rapid product degradation. Design engineers must be cognizant of these processes. These considerations would also apply to other coating systems as well as solid film lubricants.

SUBMITTED BY
Robert M. Gresham

DATE
April 11, 1994

ADDRESS
2501 Kent Avenue
West Lafayette, IN 47906
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)
Various failures of space mechanisms in space 1968 thru 1975

INDICES/KEYWORDS
Thermal Vac Testing, Simplicity, Lubrication

EVENT DESCRIPTION (What happened and impact)
During the subject time period there were in-space failures of various mechanisms. Based on failure analysis, and in some cases inspection both in-space and after return to earth, it was found that the following causes often contributed to the failures:

- Tolerances/clearances, often too tight for space mechanisms in space
- Materials often unsatisfactory for use under space conditions
- Lubricants often unsatisfactory in space

LESSONS LEARNED
1. Test under space, thermal/vacuum, conditions if possible, and or perform thermal cycling analysis.
2. If normal earth design practices for tolerances/clearances are not required, I.E. possible one time function, do not use them. Loosen up.
3. Use simple sleeve bearings with dry lubrication if at all possible. Avoid oils and greases if possible.
4. The main lesson learned was KISS Keep It Simple Stupid.

SUBMITTED BY
Alex B. Hunter

DATE
2/16/94

ADDRESS
The Boeing Company
499 Boeing Blvd.
Huntsville, AL 35824
# SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

**SUBJECT (Activity/Area of Event Occurrence and Year)**
CMG BEARING FAILURE 1974

**INDICES/KEYWORDS**
Control Moment Gyro

**EVENT DESCRIPTION (What happened and impact)**
Control Moment Gyro (CMG) bearings were lubricated by a centrifugal lube nut (rotating nut with reservoir containing oil). The lube nut dripped oil into an overlapping flange cut into the bearing cage. The cage had oil feed holes machined through it at three positions at angle of 30° that were to provide an avenue for the oil to centrifugally migrate into the contact area of the outer race. The cage oil feed hole angle was too steep. Instead of lubricating the ball track oil was delivered onto the land of the outer race. Because of wetability some oil made its way into the bearing outer race groove; however, the quantity of oil replenishment was insufficient to sustain adequate lubrication of the bearing. After approximately 160 hours the bearing failed.

**LESSONS LEARNED**
1. Some oil wet or wicked its way into the bearing outer race groove.
2. The quantity of oil replenishment was insufficient to sustain adequate lubrication of a minimally lubricated bearing.

The following list gives features of retainer redesign used to correct problem:
1. Changed angle of cage oil feed hole from 30° to 19° to overlap outer race groove under all conditions.
2. Add another set of feed holes to centrifuge oil into center of outer race contact area.
3. Widen retainer flange and change I.D. slope to accommodate oil hole angle change and further overlap lube nut.
4. Increase retainer O.D. to allow maximum extension into race groove of oil holes in 1 and 2 above.

**SUBMITTED BY**
Fred Dolan

**DATE**
April 7, 1994

**ADDRESS**
MSFC
EH11
Huntsville, AL 35812
SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)  INDICES/KEYWORDS
CMG BEARING FAILURE 1974  BEARINGS; CMG

Description of Problem Mechanism. Provide pictorial representation and written description. Concentrate on features causing difficulties.

Figures 2 and 3 on attached sheet show bearing cage before suggested corrections were made. Note steep angle of drilled oil hole. Figures 1 and 4 show corrections, in particular one can see the change angle for oil hole. Also widened retainer flange and change I.D. slope to accommodate oil hole angle change and further overlap the lube nut.

Survey Results 4-39
### SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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**Description of Problem Mechanism.** Provide pictorial representation and written description. Concentrate on features causing difficulties.

**FIG. 1**

**NOMINAL CASE 180° HOLE**

**FIG. 2**

**WORST CASE 30° HOLE**

**ORIGINAL RETAINER**

---

**SUBMITTED BY**

**DATE**

**ADDRESS**
### SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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**Description of Problem Mechanism.** Provide pictorial representation and written description. Concentrate on features causing difficulties.

![Diagram](image)

**FIG. 3**

![Diagram](image)

**FIG. 4**

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**SUBMITTED BY**

**DATE**

**ADDRESS**
Description of Problem Mechanism. Provide pictorial representation and written description. Concentrate on features causing difficulties.

Description:

Six X-ray telescopes on the ALEXIS spacecraft each had a hinged cover, 6 in. diameter. Vacuum was required inside the telescopes prior to launch and therefore a good cover seal was required. A Viton O-ring face seal was used on the cover and the cover was held closed by a paraffin powered latch. The initial motion of the cover was generated by release of the latch and then the cover was moved to the full open position by a small torsion spring on the hingeline.

During thermal/vacuum testing the covers would not consistently open due to stiction of the O-rings (cold flow into micro-scratches in surface of sealing face). An analysis of the latch showed that the active lifting function was not sufficient to break the seal all the way around the cover. The solution adopted was to increase the spring force on the hingeline and lubricate the surface of the cover with space qualified grease. Proper function was confirmed through additional testing.

On orbit, 3 covers failed to open on command but repeated operation of the actuators eventually allowed them to open.

Lessons Learned:

- Avoid O-ring seals if at all possible. Spring-energized Teflon seals are a better solution.
- If O-ring seals are used, ensure that the complete seal area is actively "broken" through high force actuation.
- If it is not possible to actively break the seal, kick-off springs opposite the hinge line should be used to supply the initial opening torque, rather than additional hingeline spring force.
LISTING OF EXPERTS
LISTING OF EXPERTS

Deployable Appendages

Gibb, John
Lockheed Missiles & Space Co., Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Retention and Release Mechanisms

Bement, Laurence J.
NASA-Langley Research Center
Hampton, Virginia 23681-0001
(804) 864-7084

Hinkle, K.
NASA-Goddard Space Flight Center
Engineering Directorate
Greenbelt, Maryland 20771

Maus, Daryl
Starsys Research Corp.
5757 Central Avenue, Suite E
Boulder, Colorado 80301
(303) 444-6707

McCown, William
Rexnord Aerospace Mechanisms
2530 Skypark Drive
Torrance, California 90505

Phan, M.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Schaper, P.W.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-2140

Schimmel, Morry L.
Schimmel Company
St. Louis, Missouri
Retention and Release Mechanisms (continued)

Sevilla, D.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-3644

Skyles, Lane P.
Lockheed Engineering & Sciences Company
1150 Gemini Avenue
Houston, Texas 77058
(713) 333-6456

Tibbitts, Scott
Maus Technologies
Boulder, Colorado

Wagoner, B.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-3644

Bearings, Lubrication, and Tribology Considerations

Bauer, Reinhold
The Aerospace Corporation
2350 East El Segundo Boulevard
Los Angeles, California 90009-2957

Didziulis, Stephen V.
The Aerospace Corporation
2350 East El Segundo Boulevard
Los Angeles, California 90009-2957

Divine, E.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Dugger, Michael T.
Sandia National Laboratories
Albuquerque, New Mexico 87185-5800

Fehrenbacher, L.
Technology Assessment and Transfer, Inc.
Annapolis, Maryland

Fleischauer, P.D.
The Aerospace Corporation
2350 East El Segundo Boulevard
Los Angeles, California 90009-2957
Bearings, Lubrication, and Tribology Considerations (continued)

Hilton, M.D.
The Aerospace Corporation
2350 East El Segundo Boulevard
Los Angeles, California 90009-2957
(310) 336-0440

Keem, John M.
Ovonic Synthetic Materials Corporation
Troy, Michigan 48084

Rowntree, Robert A.
European Space Tribology Laboratory
UKAEA, Risley, Warrington, England

Rowntree, Robert A.
National Center of Tribology
Northern Research Laboratories
UKAE, Risley, Warrington, United Kingdom

Scholhamer, James
Ovonic Synthetic Materials Corporation
Troy, Michigan 48084

Todd, M.J.
National Center of Tribology
Northern Research Laboratories
UKAE, Risley, Warrington, United Kingdom

Antennas and Masts

Greenfield, Herbert T.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Hinkle, K.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Johnson, Michael R.
Jet Propulsion Laboratory/California Institute of Technology
4800 Oak Grove Drive
Pasadena, California 91109-8099

Metzger, J.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
Actuators, Transport Mechanisms, and Switches

Aubrun, J.N.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Farley, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Hawthorne, H.M.
Tribology and Mechanics Laboratory
NRCC
Vancouver, Canada

Jones, Stephen R.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Leary, W.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Lewis, D.F.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099

Lorell, K.R.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

O'Donnel, T.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099

Perez, E.O.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Poulsen, R.N.
Hughes Aircraft Company
P.O. Box 902
El Segundo, California 90245

Priesett, Klaus
Dornier GmbH
Friedrichshafen, Germany
Actuators, Transport Mechanisms, and Switches (continued)

Sharma, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Stark, Kenneth W.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Tweedt, R.E.
Hughes Aircraft Company
P.O. Box 902
El Segundo, California 90245

Tyler, A.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Wilson, Meredith
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Zacharie, D.F.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

General and Miscellaneous

Anonymous
United States Air Force Space Division, SD/ALM
P.O. Box 92960
Los Angeles, California 90009-2960

Aubrun, J.N.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Devine, E.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Farley, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Federline, Robert E.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
General and Miscellaneous (continued)

Frank, D.J.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Lorrell, K.R.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Parker, K.
European Space Tribology Laboratory
Risley, Warrington, United Kingdom

Zacharie, D.F.
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304
Rotating Systems

Momentum Wheels

Akishita, S.
Mitsubishi Electric Corporation
Amagasaki, Japan

Anonymous
United States Air Force Space Division, SD/ALM
P.O. Box 92960
Los Angeles, California 90009-2960

Auer, W.
TELDIX GmbH
Heidelberg, Germany

Bialke, B.
ITHACO, Inc.
735 W. Clinton Street
Ithaca, New York 14851-6437
(607) 272-7640

Boesinger, E.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Donley, A.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Fehrenbacher, L.L.
Technology Assessment and Transfer
Annapolis, Maryland

Inoue, M.
Mitsubishi Electric Corporation
Amagasaki, Japan

Lowenthal, S.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Murakami, C.
National Aerospace Laboratory
Tokyo, Japan
Momentum Wheels (continued)

Okamoto, O.
National Aerospace Laboratory
Tokyo, Japan

Warner, Mark H.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Yabu-uchi, K.
Mitsubishi Electric Corporation
Amagasaki, Japan

Reaction Wheels

Bialke, B.
ITHACO, Inc.
735 W. Clinton Street
Ithaca, New York 14851-6437
(607) 272-7640/(800) 847-2080/Fax: (607) 272-0804

Hasna, Martin D.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Control Moment Gyroscopes

Blondin, Joseph
Allied Signal Aerospace Company
Guidance Systems Division
Teterboro, New Jersey 07608

Cook, Lewis
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812

Golley, Paul
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812

Gurrisi, Charles
Allied Signal Aerospace Company
Guidance Systems Division
Teterboro, New Jersey 07608
Control Moment Gyroscopes (continued)

Kolvek, John
Allied Signal Aerospace Company
Guidance Systems Division
Teterboro, New Jersey 07608

Krome, Henning
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812

Gears

McCown, William
Rexnord Aerospace Mechanisms
2530 Skypark Drive
Torrance, California 90505

Motors

Devine, E.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Farley, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Henson, Barnie W.
European Space Agency
Noordwijk, Holland

Kackley, Russell
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

McCully, Sean
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Sharma, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Tyler, A.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
Bearings and Lubrication

Allen, Terry
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Anonymous
Allied Signal Aerospace Company (Bendix)
Guidance Systems Division
Teterboro, New Jersey 07608

Baxter, Bryan H.
British Aerospace plc.
Stevenage, England

Benzing, R.J.
Air Force Materials Laboratory
Wright-Patterson AFB, Ohio 65433

Bertrand, P.A.
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Boesiger, Edward A.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Fleischauer, P.D.
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Fowler, Peter H.
TRW Space and Technology Group
Redondo Beach, California 90278

Gelette, Erik
The Charles Stark Draper Laboratory
Cambridge, Massachusetts

Hall, Barry P.
British Aerospace plc.
Stevenage, England
Bearings and Lubrication (continued)

Hilton, Michael
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Hooper, Fred L.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Kingsbury, Dr. Edward
The Bearing Consultants
1063 Turnpike Street
Stoughton, Massachusetts 02072

Langmaier, J.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-2031

Manders, Frank
Ball Aerospace Systems Division
960 6th Street
Boulder, Colorado 80302

Parker, K.
European Space Tribology Laboratory
Risley Nuclear Power Development Laboratory
UKAEA, Risley, Cheshire, England

Phinney, Damon D.
960 6th Street
Boulder, Colorado 80302
(303) 442-7824

Rowntree, R.A.
National Tribology Center (ESTC)
United Kingdom

Singer, Herbert
The Charles Stark Draper Laboratory
Cambridge, Massachusetts

Smith, Dennis W.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650
Bearings and Lubrication (continued)

Strang, J.R.
Air Force Materials Laboratory
Wright-Patterson AFB, Ohio 65433

Todd, M.J.
National Tribology Center (ESTC)
United Kingdom

Vest, C.E.
Applied Physics Laboratory
Pennsylvania

Warner, Mark H.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Slip Rings and Roll Rings

Atlas, G.
Societe Europeenne de Propulsion (SEP)
Vernon, France

Batista, J.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Langmaier, J.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-2031

Matteo, Donald N.
General Electric Company
Space Systems Operations
Valley Forge, Pennsylvania

Phinney, Damon D.
Ball Aerospace Systems Division
960 6th Street
Boulder, Colorado 80302

Smith, Dennis W.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650
Slip Rings and Roll Rings (continued)

Smith, Dennis W.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Thomin, G.
Centre National d'Etudes Spatiales (CNES)
Toulouse, France

Vise, J.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Young, K.
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Miscellaneous

Dubitschek, Michael J.
Ball Corporation, Aerospace Systems Group
Electro-Optics/Cryogenics Division
Boulder, Colorado

Isekenderian, Theodore C.
Jet Propulsion Laboratory/California Institute of Technology
Guidance and Control Section
4800 Oak Grove Drive
Pasadena, California 91109-8099

Krueger, Arlin J.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771

Pech, Greg
Martin Marietta
Denver, Colorado

Robinson, Wilf
Honeywell Inc.
Satellite Systems Operation
19019 N. 59th Avenue
Glendale, Arizona 85308-9650

Weilbach, August O.
Helvart Associates
Fullerton, California
Oscillating Systems

Oscillating Mechanisms

Akin, David
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Bohner, John J.
Hughes Aircraft Company
Space and Communications Group
Los Angeles, California

Carre, David
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Conley, Peter L.
Hughes Aircraft Company
Space and Communications Group
Los Angeles, California

Didziulis, Stephen
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Farley, R.
NASA-Goddard Space Flight Center
Mail Code 731
Greenbelt, Maryland 20771

Fleischauer, Paul
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Gill, Steven
European Space Tribology Laboratory
AEA Technology
Risley, Warrington, United Kingdom

Hilton, Michael
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009
Oscillating Mechanisms (continued)

Hinricks, J.T.
Ball Aerospace Systems Division
960 6th Street
Boulder, Colorado 80302

Horber, Ralph
H. Magnetics Corporation

Kalogeras, Chris
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Khonsari, Michael
Mechanical Engineering Dept.
University of Pittsburgh
Pittsburgh, PA 15261
(412) 624-9790

Loewenthal, Stuart H.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086

Phinney, D.D.
Ball Aerospace Systems Division
960 6th Street
Boulder, Colorado 80302

Pollard, C.L.
Ball Aerospace Systems Division
960 6th Street
Boulder, Colorado 80302

Sharma, R.
NASA-Goddard Space Flight Center
Mail Code 731
Greenbelt, Maryland 20771

Wolfson, Jake
Lockheed Palo Alto Research Laboratory
3251 Hanover Street
Palo Alto, California 94304

Woods, C.
NASA-Goddard Space Flight Center
Mail Code 731
Greenbelt, Maryland 20771
Survey Responses

Rotating Mechanisms

Brown, Lee
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Christiansen, Scott
Starsys Research Corp.
5757 Central Avenue, Suite E
Boulder, Colorado 80301
(303) 494-6707

Christy, R.
(310) 457-2261

Dekramer, C.
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Devine, E.
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Dolan, Fred
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812
(205) 544-2512

Ellis, Robert
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 956-4261

Farley, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
(301) 286-2252

Fink, Richard
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 4264
Rotating Mechanisms (continued)

Gallaher, Jack
NASA-Goddard Space Flight Center
Greenbelt, Maryland  20771
(301) 286-9567

Golley, Paul
NASA-Marshall Space Flight Center
Huntsville, Alabama  35812
(205) 544-3434

Herald, Michelle K.
Space Systems/Loral
3825 Fabian Way, M/S G44
Palo Alto, California  94303-4604
(415) 852-5175

Hodges, Charles
Honeywell Corporation
921 Holloway Street
Durham, North Carolina  27702
(919) 956-4290

Jones, William R.
NASA-Lewis Research Center
21000 Brookpark Road, MS 23-2
Cleveland, OH  44135
(216) 433-6051

Lake, Mark
NASA-Langley Research Center
MS 199
Hampton, Virginia  23681-0001

Loewenthal, Stuart
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 743-2491

Mikulas, Prof. Martin Jr.
University of Colorado
MS 429
Boulder, Colorado  80303

Peterson, Prof. Lee
University of Colorado
MS 429
Boulder, Colorado  80303
Rotating Mechanisms (continued)

Raymond, Bruce  
Honeywell Corporation  
921 Holloway Street  
Durham, North Carolina 27702  
(919) 956-4206

Sevilla, D.  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, California 91109-8099  
(818) 354-2136

Wai, Leilani C.  
P.O. Box 2755  
Sunnyvale, California 94087-0755

Scanning Mechanisms

Allen, Bibb B.  
Harris Corporation  
P.O. Box 37  
Melbourne, Florida 32902

Bar-Cohen, Dr. Y.  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, California 91109-8099  
(818) 354-2610

Bearman, Dr. Greg  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, California 91109-8099  
(818) 354-3285

Christy, R.  
(310) 457-2261

Devine, E.  
Swales and Associates  
5050 Power Mill Road  
Beltsville, Maryland 20705  
(301) 595-5500

Henry, Dr. Paul  
Jet Propulsion Laboratory  
4800 Oak Grove Drive  
Pasadena, California 91109-8099  
(818) 354-3106
Scanning Mechanisms (continued)

Herald, Michelle K.
Space Systems/Loral
3825 Fabian Way, M/S G44
Palo Alto, California 94303-4604
(415) 852-5175

Jones, William R.
NASA-Lewis Research Center
21000 Brookpark Road, MS 23-2
Cleveland, OH 44135
(216) 433-6051

Lilienthal, G.W.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-9082

Loewenthal, Stuart
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California 94086
(408) 743-2491

Wai, Leilani C.
P.O. Box 2755
Sunnyvale, California 94087-0755

Deployable Mechanisms

Allen, Bibb B.
Harris Corporation
P.O. Box 37
Melbourne, Florida 32902

Bar-Cohen, Dr. Y.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-2610

Bearman, Dr. Greg
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-3285
Deployable Mechanisms (continued)

Bement, Laurence J.
NASA-Langley Research Center
Mail Stop 433
Hampton, Virginia 22681-0001
(804) 864-7084

Brown, Lee
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Christiansen, Scott
Starsys Research Corp.
5757 Central Avenue, Suite E
Boulder, Colorado 80301
(303) 494-6707

Christy, R.
(310) 457-2261

Dekramer, C.
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Devine, E.
Swales and Associates
5050 Power Mill Road
Beltsville, Maryland 20705
(301) 595-5500

Dolan, Fred
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812
(205) 544-2512

Ellis, Robert
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 956-4261

Farley, R.
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
(301) 286-2252
Deployable Mechanisms (continued)

Fink, Richard
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 956-4264

Gallaher, Jack
NASA-Goddard Space Flight Center
Greenbelt, Maryland 20771
(301) 286-9567

Gogely, James
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009

Golley, Paul
NASA-Marshall Space Flight Center
Huntsville, Alabama 35812
(205) 544-3434

Henry, Dr. Paul
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-3106

Herald, Michelle K.
Space Systems/Loral
3825 Fabian Way, M/S G44
Palo Alto, California 94303-4604
(415) 852-5175

Hodges, Charles
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 956-4290

Hunter, Alex
The Boeing Company
Space and Lunar Deployment Mechanisms
Huntsville, Alabama 35812
(205) 461-2085

Lake, Mark
NASA-Langley Research Center
MS 199
Hampton, Virginia 23681-0001
Deployable Mechanisms (continued)

Lilienthal, G.W.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-9082

Manning, Hugh E.
The Boeing Company
Materials and Processes
Huntsville, Alabama 35812
(205) 461-5858

Menichelli, Vince
TRW, Norton Air Force Base
P.O. Box 1310
San Bernardino, California 92402

Mikulas, Prof. Martin Jr.
University of Colorado
MS 429
Boulder, Colorado

Peterson, Prof. Lee
University of Colorado
MS 429
Boulder, Colorado 80303

Raymond, Bruce
Honeywell Corporation
921 Holloway Street
Durham, North Carolina 27702
(919) 956-4206

Schimmer, Morry L.
8127 Amherst Avenue
St. Louis, Missouri 63130

Sevilla, D.
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, California 91109-8099
(818) 354-2136

Wai, Leilani C.
P.O. Box 2755
Sunnyvale, California 94087-0755

Wittschen, Barry
NASA-Johnson Space Flight Center
Houston, Texas 77058
Miscellaneous

Boesiger, Edward
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 743-2377

Dursch, H.
Boeing Defense and Space Group
Seattle, Washington
(206) 773-0627

Gresham, Robert M.
E/M Corporation
2801 Kent Avenue
West Lafayette, Indiana  47906-0400
(317) 497-6340

Hopple, George
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 746-2502

Hustad, Gary
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 743-7455

Loewenthal, Stuart
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 743-2491

Putnam, David
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94086
(408) 743-2987
ESTL Space Mechanisms

Altshuler, Y.
Israeli Aircraft Industries
Electronics Division
Yehud, Industrial Zone 56 000
Israel
Phone: 3-5314439

Andersson
Saab Ericsson Space AB
S-58188 Linkoping
Sweden
Phone: 13-286400

Atlas, G.
SEP
Forest De Vernon - BP 802
27207 Vernon, France
Phone: 32-21-72-00

Bekaert, G.
Sabca
Departement Etudes Aerospatiales
1470 Chaussee de Haecht
B-1130 Brussels, Belgium
Phone: 2-216-80-10

Banerjee, S.K.
Vikram Sarabhai Space Centre
Indian Space Research Organisation
Trivandrum 695 022, India
Phone: 0471-562621

Barho, R.
Dornier GmbH
RST 123, Postfach 1420
D-7990 Friedrichshafen, Germany
Phone: 7545-80

Bentall, Dr. R.H.
ESA/ESTEC
Keplerlaan 1
220 AG Noordwijk ZH, The Netherlands
Phone: 1719-86555

Bialke, W.E.
ITHACO, Inc.
735 West Clinton Street, P.O. Box 6437
Ithaca, New York 14851
(607) 272-7640
ESTL Space Mechanisms (continued)

**Birner, R.**  
MBB, Unternehmensbereich Raumfahrt  
Postfach 801169  
8000 Munchen 80 (Munich), Germany  
Phone: 089-607-22643

**Bohner, J.J.**  
Hughes Space and Communications Group  
P.O. Box 92919, S12/V361  
Los Angeles, California 90009  
(213) 648-2393

**Bollinger, W.**  
Carl Zeiss  
P.O. Box 1369/1380  
D-7082 Oberkochen, Germany  
Phone: 07364-20-3354

**Borrien, A.**  
CNES  
18 Av. Edouard Belen, F-31055 Toulouse Cedex, France  
Phone: 61-27-3131

**Briscoe, H.M.**  
Tykes Barn  
Goose Street  
Southwick, Wiltshire, United Kingdom  
Phone: 0225-753100

**Caslini, D.**  
Fiat Avio  
112, Corso Ferrucci  
1-10138 Torino (Turin), Italy  
Phone: 11-33 02 12

**Clemmet, J.F.**  
British Aerospace (Space Systems) Ltd.  
Argyle Way  
Stevenage, Herts, United Kingdom SG1 2AS  
Phone: 0438-313456

**Comparetto, V.**  
L.A.M. Rinaldo Piaggio SpA  
I-17024 Finale Ligure, Italy  
Phone: 19-692741
ESTL Space Mechanisms (continued)

Corcorcuto, I.S.
Fiat Avio
Corso Ferrucci, 112
1-10138 Torino, Italy
Phone: 11-3302-644

Cracknell, D.
GEC Marconi Research Centre
West Hanningfield Road
Great Baddow
Chelmsford, Essex, United Kingdom
Phone: 0245-473331

del Campo, F.
Sener
Avda Zugazarte 56
E-48930 Las Arenas-Vizcaya, Spain
Phone: 4-481-7500

Edeline, E.
SEP
Division Propulsion A Liquides et Espace
Forêt de Vernon, BP802
F27207 Vernon, France
Phone: 32 21 54 50

Escobar, J.
CASA
Avenida Aragon, 404
E-28022 Madrid, Spain
Phone: 1-586 3700

Etzler, C-Chr.
Dornier GmbH
RST 123, Postfach 1420
D-7990 Friedrichshafen, Germany
Phone: 7545-80

Eyles, C.J.
School of Physics and Space Research
Chancellor's Court
The University of Birmingham
P.O. Box 363
Birmingham, United Kingdom  B15 2TT
Phone: 021-414-4565
ESTL Space Mechanisms (continued)

Fabbrizzi, F.
Officine Galileo
via Einstein, 35
I-50013 Campi Bisenzio
Firenze (Florence), Italy
Phone: 055 8950380

Felkai, R.
Erno Raumfahrttechnik GMBH
Huenefeldstrasse 1-5
P.O. Box 105909
D 2800 Bremen 1, Germany
Phone: 0421 539 4378

Fleischauer, Dr. P.D.
The Aerospace Corporation
P.O. Box 92957
2350 East El Segundo Boulevard
Los Angeles, California 90009-2957
(213) 336-6098

Flew, A.
Norcroft Dynamics, Ltd.
Fellows House
High Street
Pewsey, Wiltshire, United Kingdom SN9 5AF
Phone: 0672-62169

Gallagher, K.
Marconi Space Systems Ltd.
Anchorage Road
Portsmouth, Hants, United Kingdom PO3 5PU
Phone: 0705-664966

Gomm, M.A.
Devtev, Ltd.
20 Viscount Avenue
Airways Industrial Estate
Cloghran
Dublin 17, Eire
Phone: 1-426668

Graftas, O.
Raufoss A/S
P.O. Box 2
N-2831 Raufoss, Norway
Phone: 4761 52 281
ESTL Space Mechanisms (continued)

Greener, B.
Met Office 19
Remote Sensing Instrumentation
Room 8, Building Y 70
Royal Aircraft Establishment
Farnborough, Hants, United Kingdom GU14 6TD
Phone: 0252-515523

Hartwig, H.
Max-Planck-Institut fur Aeronomie
Postfach 20, D3411 Katlenburg
Lindau, Germany
Phone: 05556 4011

Hawthorn, Dr. H.M.
National Research Council
Tribology and Mechanics Laboratory
Division of Mechanical Engineering
3650 Westbrook Mall
Vancouver, BC
Canada V6S 2L2
Phone: 604-663-2603

Henton-Jones, W.A.
Sira Research and Development Division
Sooth Hill
Chislehurst, Kent, United Kingdom BR7 5EH
Phone: 081-467-2636

Hostenkamp, R.G.
Dornier GMBH
Postfach 1360
7990 Friedrichshafen, Germany
Phone: 7545-80

Humphries, M.
British Aerospace (Space Systems) Ltd.
Earth Observation and Science Division
FPC 321
P.O. Box 5
Filton, Bristol, United Kingdom BS12 7QW
Phone: 0272-693831

Huomo, H.
Technical Research Centre of Finland
VTT Instrument Laboratory
P.O. Box 107
SF-02151 ESPOO, Finland
Phone: 0-4561
ESTL Space Mechanisms (continued)

Kemper, Ir. C.A.L.
Stork Product Engineering PV
70 Oostenburgervoorstraat
1010 MR Amsterdam
P.O. Box 379
1000 AJ, The Netherlands
Phone: 20 6262011

Koller, F.
ORS
Operngasse 20b
A-1040 Wien (Vienna), Austria
Phone: 222-58814-240

Kong Chang, Soo
Spar Aerospace, Ltd.
1700 Ormont Drive
Weston, Ontario
Canada M9L 2W7
Phone: 416-745-4680

Kose, Dr. S.
Oerlikon-Contraves AG
580 Schaffhauserstrasse
CH-8052 Zurich, Switzerland
Phone: 01-829-4534

Lavadoux, M.
Sagem
Avenue du Gros Chene
PB 51
F-95612 Cergy-Pontoise
CeDEX, France
Phone: 1-34-30-52-74

Leefe, S.E.
BHR Group
Cranfield, Bedford, United Kingdom MK43 0AJ
Phone: 0234-750422

Leveille, A.R.
The Aerospace Corporation
2350 East El Segundo Boulevard
P.O. Box 92957
Los Angeles, California 90009
ESTL Space Mechanisms (continued)

Loewenthal, S.
Lockheed Missiles & Space Company, Inc.
1111 Lockheed Way
Sunnyvale, California  94089-3504
(408) 743-2491

Long, J.S.
Serc Rutherford Appleton Laboratory
Chilton
Didcot, Oxen, United Kingdom  OX11 0QX
Phone: 0235-21900

Magani, P.G.
Tecnopazio Spa
via Delle Mercantesse, 3
20021 Branzate di Bollate
Milan, Italy
Phone: 023560950

Marchetto, C.
GE Astra Space
P.O. Box 800
Princeton, New Jersey  08543-0800
(609) 490-3392

Maus, D.
Starsys Research Corporation
5757  Central Avenue, Suite E
Boulder, Colorado  80301
Phone: (303) 444-6707

Morris, N.
Rutherford Appleton Laboratories
Space and Astrophysics Department
Chilton
Didcot, Oxfordshire, United Kingdom  OX11 0QX
Phone: 0235-445210

Mueller, G.
Matra Marconi Space
31 Rue Des Cosmonautes
Z.I. du Palays
31077 Toulouse
CeDex, France
Phone: 6224 75 86
ESTL Space Mechanisms (continued)

Nieuwenhuizen, M.
Fokker Space and Systems PV
P.O. Box 12222
1100 AE Amsterdam-Zuidoost, The Netherlands
Phone: 20-605 9111

Patin, J.F.
Aerspatiale Space and Strategic Systems Division
Establishment De Cannes
100 Boulevard Du Midi, BP 99
F-06322 Cannes la Bocca, CeDex, France
Phone: 92-92-74-07

Patrick, T.J.
Mullard Space Science Laboratory
Holmburg St. Mary
Dorking, Surrey, United Kingdom RH5 6NT
Phone: 0483-274111

Privat, M.
CNES
18 Avenue Edouard Belin
F-31055 Toulouse, CeDex, France
Phone: 61 27 3131

Rockly, G.
TELDIX GmBh
Postfach 10 56 08
D-6900 Heidelberg, Germany
Phone: 06221-5120

Roth, M.
MBB Space Systems Group
P.O. Box 801169
D-8000 Munich 80, Germany
Phone: (089)-60006302

Schwarzinger, D.C.
ORS
The Austrian Aerospace Company
Operngasse 20B
A-1040, Wien, Austria
Phone: 0222-58814

Shmulevitz, M.
Israel Aircraft Industries
Electronics Division/MBT
Yehud, Industrial zone 56 000
Israel
Phone: 3-4024
ESTL Space Mechanisms (continued)

Smith, B.
British Aerospace (Space Systems) Ltd.
Argyle Way
Stevenage, Herts, United Kingdom SG1 2AS
Phone: 0438-313456

Smith, D.
Honeywell Inc.
P.O. Box 52199
Phoenix, Arizona 85072-2199
(602) 561-3237

Sneiderman, G.
NASA-Goddard Space Flight Center
Greenbelt Road
Greenbelt, Maryland 20221
(301) 286-2000

Tasker, J.
Moore Reed Ltd.
Walsworth Ind. Estate
Andover, Hampshire, United Kingdom
Phone: 0264-324155

Turner, R.F.
Rutherford Appleton Laboratory
British National Space Centre
Chilton
Didcot, Oxfordshire, United Kingdom OX11 0QX
Phone: 0235-21900

Whiteman, P.
Marconi Space Systems Ltd.
Anchorage Road
Portsmouth, Hampshire, United Kingdom PO3 5PU
Phone: 0705-664966

Zwanenburg, R.
Fokker Space and Systems BV
P.O. Box 12222
100 AE Amsterdam-Zuidoost, The Netherlands
Phone: 20-605 9111
FACILITIES

This section presents descriptions of testing facilities available at the following installations:

- Boeing Company
- European Space Tribology Laboratory
- Honeywell Electromagnetic Controls
- Lockheed Missiles & Space Company, Inc.
- Miniature Precision Bearings
- NASA Johnson Space Flight Center
- NASA Langley Research Center
- NASA Lewis Research Center
- NASA Marshall Space Flight Center
- Pyrotechnic Test Facility
- Rockwell Science Center
- Space Systems/Loral
- University of Maryland
- Viking/Metrom Laboratories.
Boeing Company

A large thermal vacuum chamber is located at the Boeing Company. Specifications include:

- One sun thermal input capability
- Space vacuum
- Space temperature
- Mechanical pass-throughs
- Large working area.

Specification sheet available upon request.
European Space Tribology Laboratory

ESTL was the first laboratory outside the main European Space Agency (ESA) establishments to become fully compliant with ESA's standards for test houses (ESA PSS-01-203), contamination and cleanliness control (ESA PSS-021-201), thermal vacuum tests for screening space materials (ESA PSS-01-702), and also ISO9001.

There are some 25 vacuum chambers, 4 physical vapor deposition chambers for lubricant application, and 3 tribometers.

ESTL's facilities are designed for versatility and flexibility. A wide range of mechanisms and components can be accommodated. Laboratory systems can be adapted and modified to suit customers' requirements.

Clean Room

ESTL has a total laboratory floor area of 550 m²; approximately 300 m² of this area is better than Class 10,000 (U.S. Federal Standard 109E), with Class 100 areas maintained for component inspection, and mechanism and bearing assembly.

Vacuum Chambers

ESTL has 11 chambers from 150 to 1000 mm in diameter (up to 0.95 m³ in working volume), with an achievable vacuum pressure down to $10^{-9}$ mbar, and typical temperature range of $-150°C$ to $+150°C$ (see Figure 2).

Emphasis is laid on vacuum chamber cleanliness and pump reliability. Turbomolecular pumps are used for initial pumping; the lowest pressures are achieved with ion pumps or cryogenic pumps. With such systems, there is no risk of chamber contamination. Long-term performance (more than eight years with ion pumps) can be guaranteed.

Each large chamber is equipped with two or more thermal-radiation shrouds and electric heaters. With these, a wide range of thermal conditions (including rapid changes of temperature) can be achieved.

Dedicated facilities include those for testing the torque disturbance and qualification of solar array drives, measuring directional accuracy of antenna pointing mechanisms, gearbox performance evaluations (from 1- to 500-Nm output torque), scanner simulation, and motor/gearhead evaluation.

Experimental rigs that have been used in the above chambers include those to study separable electrical and fluid connectors, slip rings, motor commutation, oscillatory bearing behavior, gears (four-square arrangement) and thermal conductance measurements of Hertzian contacts.
Figure 2. ESTL Vacuum Chamber
Specific Test Facilities

Vacuum Cryogenic Test Rig. Baseplate temperatures down to 4.2 K can be achieved within a 6000-cm³ (6-liter) working volume (will accept mechanisms to 20 cm in diameter) and at pressures below 10⁻⁸ mbar. Rolling element bearing evaluations can be performed with in situ cryocompatible torque and force transducers. Pin-on-disk friction and wear evaluations are also possible in this facility.

Pin-on-Disk Tribometers. Loads to 150 N and speeds to 500 rpm can be achieved. These were designed by ESTL and used to evaluate the basic tribological properties of materials and dry lubricants. Specific applications cover both vacuum and air environments.

Ball Bearing Test Facilities. Fourteen vacuum chambers (nominal size 150 mm diameter) are available to measure bearing torque behavior (dc and noise level) continuously under thermal vacuum conditions. Radial thermal conductance of ball bearings can also be measured. The test chambers are also used for PVD bearing lubrication characterization. Vacuum-compatible piezo and RVDT transducers are used to measure transmitted torques directly. Typically speeds are to 1500 rpm, bearing preload as required. An air bearing rig is available for cage stability studies (speeds to 5000 rpm).

Gearbox Test Facility. This facility is used for invacuo testing of high-torque gearboxes (up to 500 Nm output torque) for space usage (e.g., robotic actuators).

Boundary Lubrication Accelerated Screening Tester (BLAST). The tester is used to perform accelerated screening of the boundary lubrication (and degradation) behavior of liquid lubricants, bearing materials, and surface treatments. Loads to 500 N and speeds to 3000 rpm can be achieved (see Figure 3).

Figure 3. Boundary Lubrication Accelerated Screening Tester
High-Temperature Reciprocating Tribometer. The following conditions can be achieved: up to 800°C; stroke length: 1 to 15 mm; load range: 20 to 250 N; stroke frequency: -2 strokes/sec. Friction and wear can be measured. The gaseous environment can be controlled to -15 ppm of water vapor and oxygen.

Instrumentation

The instrumentation used to support the mechanism/component tests includes:

- Ion gages or various types for pressure measurement
- Mass spectrometers for residual gas analysis
- Vacuum-compatible torque transducers (RVDT and piezo)
- Fast Fourier transform (FFT) frequency analyzers
- Digital frequency analyzers
- Digital storage oscilloscopes
- X-ray fluorescence for thin film thickness determination
- Temperature sensors (thermistors, thermocouples, solid-state devices)
- Theodolite
- Vacuum-compatible tilt sensors
- Linear and rotary encoders.

Data Logging

Data logging facilities vary from standard pen and UV recorders, programmable DVMs, etc., to stand-alone 386/486-based data loggers, with logging rates up to 50,000 readings/sec. Appropriate data handling, analysis, and graphical display can be performed.

Related Facilities

AEA Technology's extensive facilities are readily available to ESTL. They include:

- CAD design and finite-element thermal and mechanical stress modeling
- Materials examination chemical analysis: infrared spectrometry, x-ray diffraction
- Metallography: sample preparation
- Surface examination and analysis: scanning electron microscopy (SEM), SIMS, Auger, x-ray photoelectron spectroscopy (XPS)
- Surface coating thickness: x-ray fluorescence
- Workshops and NAMAS accredited calibration and measurement facility
- Nondestructive testing and crack detection
- Surface metrology and examination equipment Talysurf 6 (linear and rotary), Talyrond 3-D surface profilometer, macro/micro/ultra-low hardness testers
- CRAY supercomputer.
Honeywell Electromagnetic Controls

Test Capabilities

Honeywell Electromagnetic Controls' (HEC's) fully equipped and well-staffed testing department performs a wide variety of electromechanical, electromagnetic, and electronic tests. The 3200-ft² facility is routinely used to conduct standard functional, environmental, and life tests. Additionally, HEC custom designs and fabricates consoles and fixtures to test dynamic and functional characteristics. All technicians are ESD trained in parts handling. Measuring equipment is calibrated regularly in accordance with the Bureau of Standards requirements. Major equipment includes:

- Thermal chambers (temperature range from -73 to +125°C)
- Thermal vacuum chambers (cryogenic and diffusion: vacuum to $1 \times 10^6$ torr)
- Thermal vibration chambers
- Vibration equipment (sine and random vibration capability)
- Thermal humidity chamber
- Computerized automatic test equipment.

Functional Test Capabilities. Equipment for functional capabilities tests include computerized automatic test equipment, which uses a laser interferometer to track movement to 0.000001 in./step; a Spectral Dynamics SD380 signal analyzer, which checks harmonic content or distortion of a signal and plots distortion against frequency; and shaft torque sensors, which have a load range of 10 oz-in. to over 2000 in.-lb to check output torque of motors.

Augmenting the functional test laboratory equipment are direct-drive rate tables for testing drag torque and detent torque, various phase angle voltmeters that determine the phase relationship of ac voltage at various frequencies, digital oscilloscopes for troubleshooting and monitoring rotor calibration, and a Digasine AA gage for checking rotational accuracy to within 0.1 min.

Environmental Test Capabilities. The environmental test lab (Figure 4) utilizes eight thermal chambers (Figure 5) that perform a variety of tests, including thermal cycling and thermal shock in a temperature range of -73 to +125°C. Three of the eight thermal chambers are also vacuum chambers capable of producing $1 \times 10^6$ torr of vacuum. Vibration capability (sine and random) for subassemblies and end item products is generated by four vibrators, three of which are thermal, and range in size from 2 ft³ to approximately 50 ft³ (Figure 6). Mechanical shock and thermal humidity tests are also performed.

Life Test Capabilities. Life tests encompass a number of tests performed in the thermal chambers (temperature range from -73 to +125°C), including burn-in tests whereby a unit is powered and left in the temperature-controlled chamber for 96 hr, and cycling unit tests, whereby the temperature is varied along with powering and unpowering the unit. This test is often done for 300 hr. Thermal humidity tests are also performed.
Figure 4. Honeywell Environmental Test Facility

Figure 5. Honeywell Environmental Thermal Chamber
Figure 6. Honeywell Shaker Table Facility and Control Room
Lockheed Missiles and Space Company, Inc. (LMSC)

LMSC Testing Facilities

Bearing Test Laboratory. Fully equipped bearing test laboratory contains:

- Four computerized bearing life testers capable of testing bearings from 0.25 to 14 in. in diameter under any duty cycle at vacuums to $10^{-7}$ torr
- Bearing assembly and diagnostics equipment contained in Class 5000 clean room
- Special bearing equipment for setting bearing preload, measuring bearing angular runout, bearing torque signature with precision rate table, and measuring bearing defect frequencies
- Bearing retainer friction test rig for measuring ball pocket friction of instrument bearings at ball speeds from 5 to 25,000 rpm and loads as low as 1 gm.

Mechanisms Laboratory. The mechanisms laboratory contains:

- Specialized mechanisms deployment test setups with computer data acquisition systems
- Mechanisms assembly clean room
- Variety of thermal enclosures and thermal/vacuum chambers
- Variety of large and small general-purpose environmental test equipment including: thermal/vacuum, pyroshock, random vibration, etc. equipment.

Failure Analysis Laboratory. The failure analysis laboratory contains:

- Surface analysis capabilities including: SEM, EDS, XPS, XRD, FTIR, GCMS.
Miniature Precision Bearings

- Ball bearing and rotating assembly torque testing per MIL-STD-206 and a wide range of speed and load combinations
- Dry-film lubrication testing of axially loaded bearings from 1 to 50,000 rpm in an Argon atmosphere from room temperature to 1000°F; instrumented with a force transducer
- Special testing for ball quality including thin, layered film coating adhesion on balls
- Milliwatt power consumption testing
- Extensive clean room and laboratory facilities focused on processing and testing of ball bearings.
NASA-Johnson Space Flight Center

Structures Test Lab (STL)

This facility is utilized for material property testing of metallic and nonmetallic materials at ambient, thermal, and/or vacuum conditions. Industrial load test frames and test systems can test specimens with tensile loading as well as comprehensive loading. The STL has a wide variety of test systems available for structural testing, including servohydraulic test systems, electromechanical test systems, a computer-controlled load system, and various miscellaneous equipment.

Thermal Facilities

The RHTF and SRHTF use electrically powered radiant heater arrays that utilize graphite-resistance elements and water-cooled reflectors for reliable and efficient operation. The radiant heaters are operated in test chambers that contain vacuum pumps to allow simulation of temperature and pressure conditions. Cryogenic cooling panels are employed to allow preconditioning of TPS material samples to simulate on-orbit cold soak. The RHTF has a 10-ft diameter vacuum chamber (R-1) that can accommodate test articles as large as 6 x 8 ft and can simulate temperature gradients through use of multizone temperature control. The SRHTF can accommodate test panels up to 2 x 2 ft and can simulate uniform temperature conditions. The heater in the SRHTF was transferred to the RHTF and was used with the R-1 vacuum chamber for radiant heat test programs during the past year. The SRH will be deactivated when an 8-ft diameter chamber (R-2) becomes operational.

Vibration and Acoustic Test Facility (VATF)

The vibration and acoustic laboratories (contained in the VATF of Building 49) are capable of performing the wide range of tests needed to evaluate all aspects of acoustic, vibration, structural dynamic, and shock problems. This facility has the capability for development, qualification, and acceptance testing, not only of aerospace vehicles and equipment, but also nonaerospace equipment that is to be subjected to high-intensity acoustic noise, vibration, and shock environments. The VATF test team works in cooperation with visiting users during every phase of a test program to optimize test support and assure accomplishment of test objectives. This facility provided extensive dynamic structural test support for shuttle orbiter certification. State-of-the-art techniques are incorporated in all facility laboratories; the facility has unsurpassed low-frequency acoustic test capabilities, and provides unparalleled features for accomplishing acoustic testing, mechanically induced vibration testing, and empirical modal analysis within one building. Laboratory arrangements and test support systems are equally suited for readily and efficiently dynamic testing of small components or large assemblies.
Materials Technology Laboratories (MTL)

The MTL provides the NASA-Johnson Space Flight Center with the capability for supporting experimental investigations and evaluations of materials for current and advanced programs. The following tasks are typical of those conducted with laboratory support:

- Failure investigations of both metallic and nonmetallic materials
- Chemical analyses of contaminants and material samples.
- Evaluation of mechanical properties of materials
- Nondestructive testing of materials
- Evaluation of the compatibility of materials with the space environment
- Preparation and evaluation of special elastomeric compounds
- Preparation of TPS tiles and test articles.

Facilities available in the laboratory include:

- Scanning electron microscopes
- Fourier transform infrared spectrometer.
- Ultraviolet-visible spectrometer
- Vacuum microbalances
- Nondestructive test equipment
- Materials evaluation equipment
- Instron mechanical test device
- Gas chromatographs
- X-ray fluorescence and diffraction, metallograph, atomic oxygen testing apparatus
- Tile coating furnace
- Rubber mill used for the preparation of special formulations
- Metallurgical specimen preparation facility.

Lubrication and Wear

A new experimental apparatus is being developed for the lubrication and wear of materials. The experimental setup consists of a shoe-on-drum arrangement, which allows a maximum of five material couples to be evaluated simultaneously under sliding wear conditions. The material specimens can also be exposed to a flowing atomic oxygen discharge and UV radiation in order to provide for the accelerated testing of spacecraft materials. Coefficient of friction and surface chemistry and morphology data may be collected using this system.
NASA-Langley Research Center

Pyrotechnic Test Facility

The pyrotechnic test facility (Building 1159) contains the Langley Research Center aerospace environmental and functional simulation equipment used for the handling and testing of small-scale potentially hazardous materials, including explosive and pyrotechnic materials, devices, and systems (see Figure 7). The facility contains three 12- by 18-ft test cells, which are used for assembly and checkout, environmental testing, and test firing, respectively (see Figure 8). A 30- by 60-ft general-purpose, high-bay, open work area is used for system testing and contains control systems for test capabilities for small items, including remotely operated vibration (2000 lbf); mechanical shock (30,000 g for 0.2 ms); constant acceleration (200 g); thermal (-320 to +600°F); thermal vacuum (-320 to +200°F at vacuums to 1 x 10⁻⁷ mm Hg); electrostatic discharge (25,000 V with 500 pf capacitor); electrical and mechanical firing systems; and high-speed measurements (40-kHz response analog) of acceleration; force; pressure; temperature; and explosive performance monitoring systems. Adjacent facilities, containing larger test cells, provide an expanded capability of testing pounds of high-explosive materials (see Figure 9).

Figure 7. Pyrotechnic Test Facility at NASA-Langley
Figure 8. Pyrotechnic Test Cells at NASA-Langley

Figure 9. Pyrotechnic Test Cells Outside NASA-Langley
Potentially Hazardous Materials Test Area

Langley Research Center has the capability to test materials and systems that are potentially hazardous to both personnel and equipment. Specially designed facilities on a land area, measuring 1000 by 1400 ft, are located in a remote area of the center to allow dissipation of noise and venting, as well as capturing fragments and debris produced by pressurized systems and explosive devices. The facilities were originally created to assemble and test rocket motors and explosive devices. The facilities are surrounded by fences to control traffic. Earth berms around the large test facility and storage sites provide protection, meeting all military requirements for all but mass-detonating explosives, such as bombs. Testing is accomplished remotely, providing high-speed electronic and photographic recording of a variety of parameters, such as force, pressure, temperature, velocity, ignition, and energy. The following facilities are in this test area.

Pyrotechnic Storage. Buildings 1158 and 1158A provide for receiving, packaging and unpackaging, and storage of pyrotechnic and explosive devices. These facilities are completely surrounded by an earth berm.

Control Room (Building 1160) and Test Cells (Building 1161). The control room provides automatic programming and monitoring of remote tests conducted in the three test cells. Two cells measure 15 by 19 ft and the third is 20 by 19 ft; all three have vertical clearances to 18 ft with overhead cranes to 15 ft. The cells have full-access, up doors, as well as roll-back ceilings. A fragment-containing net covers the entire width of the building. Capabilities include 250,000 lb of thrust and testing 5 lb of high explosives. Emergency containment of up to 6000 lb of double-base rocket motor propellant is provided by thick, reinforced concrete covered by earth, as well as earth berms on two sides.
NASA-Lewis Research Center

Surface Science Branch Facilities

Surface Characterization

- **SEMEDS:** Scanning Electron Microscopy/Energy Dispersive Spectroscopy
  - Maximum magnification of 100,000 x
  - Ultimate resolution of 3 Nm with CeB₆ filament
  - Chamber/specimen imaging with infrared chamberscope
  - Secondary and backscatter electron detectors
  - X-ray microanalysis for elemental imaging including C, N, and O

- **XPS:** X-Ray Photoelectron Spectroscopy
  - Monochromatic Al Kα x-ray source and twin Al/Mg source
  - Five channeltron hemispherical analyzer
  - Small spot analysis area (150 µm)
  - Depth profiling at 10 Å per minute
  - In situ heating and cooling stage (liquid nitrogen: 1000°C)
  - In situ thin-film deposition and quartz crystal thickness monitor

- **AFM/STM:** Atomic Force Microscopy/Scanning Tunneling Microscopy
  - Digital imaging of 0.2-mm features down to atomic dimensions
  - Imaging of conductors and nonconductors
  - Force modulation measurements (nanohardness)
  - Lateral force measurements (nanotribology) simultaneous with topology

- **SAM:** Scanning Auger Microscopy
  - Schottky field emission electron gun
  - Lateral resolution of <15 Nm (SEM)/<30 Nm (AES)
  - Minimum sample heating/charging at low beam current of 0.5 nA
  - High energy resolution analyzer (resolve Si, Si-oxide, Si-nitride)
  - Angle resolved AES to distinguish surface from bulk
  - Multiple detectors for rapid elemental maps
  - Sample handling includes in situ fracture, heating to 1000°C, gas dosing, and residual gas analysis

- **μFTIR:** Fourier Transform Infrared (with Microscope)
  - Molecular structure identification of 15-µm size particles
  - Identification of monolayer chemistry with grazing angle optics

Chemical Analysis

- **HPLC:** high-pressure liquid chromatography
- **SCF extraction:** supercritical fluid extraction
- **DTA/TGA:** differential thermal analysis/thermogravimetric analysis
Liquid Lube/Tribology

- Four-Ball Vacuum Tribometer
  - Vacuum range: ambient (air, inert) -10^7 torr
  - Speed: 10 to 500 rpm
  - Load: 50 to 1032 N
  - Temperature: room
  - Specimens: 3/8-in. diameter bearing balls
  - Motion: sliding (most accelerated testing)

- Ball-on-Plate Vacuum Tribometer
  - Vacuum range: ambient (air, inert) -10^9 torr
  - Speed: 1 to 100 rpm
  - Load: 440 N
  - Temperature: room
  - Specimens: 1/2-in. diameter bearing balls, 2 flat 2-in. diameter plates
  - Motion: rolling/sliding

- GOES-Bearing Vacuum Tribometer
  - Vacuum range: ambient (air, inert) -10^9 torr
  - Speed: continuous 1 to 1200 rpm or dither
  - Load: 220 N
  - Temperature: room
  - Specimens: 1219 size angular contact bearing
  - Motion: rolling (actual mechanism)

- High-Temperature Pin-on-Disk Tribometer
  - Atmosphere: dry air or dry nitrogen
  - Speed 10 to 100 rpm
  - Load: 5 to 20 N
  - Temperature: room to 700°C
  - Specimens: 3/8-in. balls, 2-1/2-in. disk
  - Motion: sliding

- Ball-on-Disk Tribometer
  - Atmosphere: dry air or dry nitrogen
  - Speed: 1 to 100 rpm
  - Load: 1 to 10 N
  - Temperature: room
  - Specimens: 1/4- to 3/8-in. balls, 1-in. disk
  - Motion: rolling

- Parched Elastohydrodynamic Bearing Apparatus
  - Atmosphere: ambient or dry air
  - Speed: 1000 to 7000 rpm
  - Load: 200 to 1000 N
  - Temperature: room
  - Specimens: type 7808 angular-contact ball bearings
  - Motion: rolling
Solid Lube/Tribology

• Controlled Atmosphere Tribometer
  - Pin-on-disk configuration
  - 25 to 1000°C
  - Air inert or reducing (H₂) environment
  - 100- to 5-kg load
  - 10 rpm to 4000 rpm, unidirectional sliding
  - Induction heating

• High-Temperature Pin-on-Disk Ceramics Tribometer
  - Pin-on-disk, block-on-ring configuration
  - 25 to 1200°C
  - Air or inert purge atmosphere
  - 50 g to 100 kg load
  - 10 rpm to 8000 rpm unidirectional sliding
  - Oscillatory sliding 0.1 to 15 Hz (±1° to ±60° amplitude)
  - Resistance furnace suitable for ceramics heating

• High-Temperature Solid-Lubricated Ball Bearing Rig
  - Tests axially loaded ball bearings
  - 25 to 650°C
  - Speeds to 10,000 rpm

• High-Temperature Bushing Tester
  - Plain sleeve or spherical bushing configuration
  - 25 to 1000°C, induction heated
  - Up to 500-kg load
  - Slow speed oscillatory sliding

• High-Temperature Foil Bearing/Brush Seal Tuft Tester
  - Foil bearing/brush seal tuft testing configuration
  - High-speed (up to 15,000 rpm) shaft speed
  - Temperatures to 700°C

• High-Frequency Cameron-Plint TE-77 Tester
  - Pin-on-plate geometry
  - 1 to 50 Hz reciprocating sliding
  - 25 to 600°C
  - Controlled purge atmosphere
  - 1- to 25-kg load

• High-Temperature Double-Rub Shoe Ring
  - Block-on-ring geometry
  - Speed to 1500 rpm
  - 25 to 900°C
  - 1- to 100-kg load
  - Controlled purge atmosphere
Thin Film Deposition

- Thin Film Deposition with Auger Analysis
  - Sputter deposition of conductors (0 < thickness ≤ 10 µm)
  - Sample heating to 1000°C
  - In situ scanning auger microscopy analysis
  - Auger depth profiling

- RF-DC Magnetron Sputtering System
  - Three 6.5-in. diameter source material targets capable of co-sputtering
  - Three sputtering gas sources available simultaneously
  - capable of reactive sputtering
  - Base pressure less than 5 × 10⁻⁷ torr with LN₂ trap

- Hollow Cylindrical Cathode Sputtering System
  - Provides uniform fiber coatings
  - Small cylindrical target
  - Coats 6-in. lengths of fiber

- Cryogenic to High-Temperature Pin-on-Flat Tribometer
  - Pin-on-flat configuration
  - -120 to 1000°C (electron beam or resistance heating, XPS or AES analysis, and residual gas analysis)
  - Ultra-high vacuum (10⁻¹⁰ torr)
  - Environment: oxidizing, reducing, inert, or air
  - 0.1- to 10-N load
  - 0.1 to 80 mm/min, reciprocating sliding
  - As low as 1-µN adhesion force measurement
  - Ion sputter cleaning

- Controlled Atmosphere Pin-on-Disk Tribometer
  - Pin-on-disk configuration
  - Ultra-high vacuum (10⁻⁹ torr), oxidizing, reducing, inert, or air environment
  - 0.5- to 10-N load
  - 10 to 120 rpm, unidirectional sliding
  - Endurance life measurement of solid-lubricating films
  - Residual gas analysis, quadrupole

- High Vacuum Tribotester
  - Pin-on-disk geometry
  - Slow-speed oscillatory sliding
  - Ambient temperature testing
  - Up to 0.5-kg load
  - Controlled purge atmosphere
Structural Characterization

- Hot Hardness Tester
  - Vicker's testing at ambient to 1600°C under vacuum
  - Integral microscope for observation and measurement at temperature

- Profilometer
  - Vertical resolution down to $1 \AA$
  - Vertical range up to $130 \mu m$ maximum
  - Scan lengths from 50 $\mu m$ to 50 mm
  - Specimen weight up to 1 lb

- Form Talysurf Profilmeter
  - Vertical resolution down to 10 mm
  - Vertical range up to 4 mm
  - Scan lengths from 0.5 mm to 120 mm
  - Specimen weight to over 40 lb on transverse stage
  - Diamond pyramid or sapphire ball stylus

- Desktop Fiber Push-Out Apparatus
  - Continuous load/displacement measurements
  - Video and acoustic emission monitoring
  - Cylindrical, flat-bottomed indenters provide optimum fiber loading
  - Compact, easy to operate

- Elevated Fiber Push-Out Apparatus
  - Measures fiber/matrix interfacial shear strength up to 1100°C
  - Continuous fiber loading
  - Real-time video monitoring
  - $10^6$ torr vacuum
STRUCTURAL DYNAMICS BRANCH

Title: Space Mechanisms Bearing Facility (under construction)
Location: Building 5 - Room CW-14
Description: This facility can test rolling-element bearings under simulated spacecraft conditions.
Features:
  o Long-term testing of multiple bearings.
  o Bearing size, speed, load to be determined.
  o Measurement of torque, ripple, temperature.
  o Vacuum to 10^-8 torr.
  o Variable configuration lubrication system.
Contact: Douglas A. Rohn 433-3325

Schematic of test rig.
STRUCTURAL DYNAMICS BRANCH

Title: Space Mechanism Accelerated Test Rig

Location: Building 5 - Room CW-14

Description: This rig can test a complete spacecraft mechanism (or any part thereof) under simulated vacuum and lunar surface (dust) conditions.

Features:

- Mechanism chamber size to fit 24" outside diameter by 24" long.
- Vacuum to $10^{-7}$ torr.
- Low temperatures using LN$_2$.
- High temperatures to be determined.

Contact: Douglas A. Rohn 433-3325

Overall view of rig.
STRUCTURAL DYNAMICS BRANCH

Title: Space Simulated Roller Contact Performance Rig

Location: Building 5 - Room CW-14

Description: This rig can evaluate roller traction contact friction and wear performance under vacuum, atmospheric, lubricated, and/or non-lubricated conditions.

Features:
- Metallic, polymeric, and coated roller specimens.
- Surface speed to 180 fpm.
- Normal load to 200 lbf.
- Contact stresses (geometry and material dependent) can be as high as 400,000 psi for steel specimens.
- Torque transmission to 200 in-lbf.
- Axial thrust capacity to 200 lbf.
- Misalignment angles to ±1.7°.
- Vacuum to 10⁻⁷ torr.

Contact: Douglas A. Rohn 433-3325

Overall view of facility.
STRUCTURAL DYNAMICS BRANCH

Title: Microgravity Manipulator Prototype

Location: Building 5 - Room CW-14

Description: This robot system can evaluate control strategies and joint designs for smooth-motion and reaction-compensated manipulation.

Features:
- VME bus-based control computer.
- Mac II operator interface.
- 6-degree-of-freedom force torque base reaction. Sensor loads:
  - vertical: up to 250 lbf.
  - horizontal: up to 100 lbf.
  - torque: 1650 in-lbf
- 4-degree-of-freedom manipulator arm; with 2-degree-of-freedom, no-backlash, traction-driven, differential actuator joints.
- Robot joint data acquisition of speed, motor torque and angle.

Contact: Douglas A. Rohn -33-3325

Researcher taking data on robot in background.
THE PRELIMINARY EVALUATION OF LIQUID LUBRICANTS FOR SPACE APPLICATIONS BY VACUUM TRIBOMETRY

NASA Lewis Research Center
Cleveland, Ohio

L.S. Helmick
Cedarville College
Cedarville, Ohio

and

M. Masuko
Tokyo Institute of Technology
Tokyo, Japan

Abstract

Four different vacuum tribometers for the evaluation of liquid lubricants for space applications are described. These range from simple ball-on-flat sliders with maximum in-situ control and surface characterization to an instrument bearing apparatus having no in-situ characterization. Thus, the former provide an abundance of surface chemical information but is not particularly simulative of most triboelements. On the other hand, the instrument bearing apparatus is completely simulative, but only allows post-mortem surface chemical information. Two other devices, a four-ball apparatus and a ball-on-plate tribometer, provide varying degrees of surface chemical information and tribo-simulation. Examples of data from each device are presented.

Introduction

The development of new satellite, spacecraft, and space station components will place increased burdens on the tribological systems for the many mechanical moving assemblies (Ref. 1). These assemblies include: momentum/reaction wheels, solar array drives, pointing mechanisms, filter wheels, de-spin mechanisms, slip rings, gears, etc. (Ref. 2). Improved lubrication systems are not only required because of increased mission lifetimes but also to insure greater reliability. In the past,
other components (e.g., batteries, electronics, thermal and optical systems) caused premature spacecraft failure (Ref. 3). It is now apparent, that advances in these areas have now exposed tribology as the primary roadblock in achieving mission requirements.

Liquid lubricants (or greases) are often used in space mechanisms for a variety of reasons. These include: no wear in the elastohydrodynamic (EHL) regime, low mechanical noise, ease of replenishment, relatively insensitive to environment, and ability to scavenge wear debris. A number of different chemical base stocks have been used. These include: mineral oils, esters, polyalphaolefins, perfluoro-polyethers (PFPE) and more recently, synthetic hydrocarbons (Ref. 4) and silahydrocarbons (Ref. 5).

Based on the speed, load, temperature, type of motion and type of contact, these lubricants are required to operate in either the EHL, mixed, or boundary lubrication regimes. For a more detailed discussion of these regimes, see Reference 6. Spacecraft designers are in constant need of tribological data for various material/lubricant combinations. These data include: lubricant degradation and outgassing characteristics, friction, torque, and wear characteristics.

Short term characteristics can easily be measured using conventional techniques. However, long term performance of liquid lubricated components poses some difficult problems. Mission lifetimes are typically five to thirty years. This obviously precludes real time testing in most cases. Usually, some form of accelerated test is required. Tests can be accelerated by increasing temperature, load, speed, and duty cycle.

For unlubricated or solid lubricated components, these accelerating methods are usually valid. However, liquid lubricated systems are much more difficult to accelerate. If one is trying to simulate the boundary or mixed film regimes, speed increases may well drive the contact into EHL regime resulting in surface separation. Obviously, this situation is not simulative. In some cases, speed increases are combined with temperature increases. Increasing temperature decreases viscosity and, if carefully controlled, can negate the film forming speed effect. However, high temperatures can initiate chemical reactions and also increase volatility. Stepper motor tests are often accelerated by increasing the duty cycle by removing dead time. This may also cause partial EHL film formation.

Vacuum Tribometers

There are four tribometers available at the NASA Lewis Research Center for evaluation of liquid lubricants under vacuum conditions. These are: (1) UHV rubbing apparatus, (2) four-ball apparatus, (3) ball-on-plate apparatus and (4) instrument bearing apparatus.
These devices range from a simple slider with maximum in-situ control and characterization of the flat rubbed surface to a complete rolling contact ball bearing with no in-situ characterization. Since friction and wear is affected by and also alters surface chemistry, in-situ control and characterization are obviously advantageous. However, there are trade-offs in that control and characterization usually require flat geometries that are not simulative of real components. Thus, the greatest degree of control and characterization requires triboelements unrealistically simple and realistic simulation precludes effective in-situ surface analysis. Therefore, our suite of tribometers spans these trade-offs from the simple planar slider with x-ray photoelectron spectroscopy (XPS) providing in-situ analysis but poor simulation to the instrument bearing apparatus providing no in-situ analysis but complete tribo-simulation.

UHV Rubbing Apparatus

The UHV rubbing apparatus is depicted in Figure 1. The device consists of a 6 mm diameter bearing ball which is placed in pure sliding contact with a flat disk. The disk is positioned below the ball and remains stationary during the test. The ball is held in a chuck which is attached to a long rod through a flex pivot assembly. The rod is attached to an XYZ manipulator which is motorized in the Y axis. The entire apparatus is mounted on a 6 inch flange which attaches directly to the preparation chamber of an XPS spectrometer. The virtue of this arrangement is that the flat which is to be rubbed may be subjected to surface analysis and surface treatment (ion bombardment cleaning or in-situ lubricant deposition) without exposure to air either before or after rubbing. Loading is effected by a spring attached to the flex pivot assembly which is extended when the ball contacts the disk surface. Specifications for this tribometer appear in Table 1.

Four-Ball Apparatus

The overall apparatus is shown in Figure 2. The specimen configuration is the same as the conventional four-ball apparatus, except for the use of 9.5 mm (3/8 in.) diameter precision bearing balls (grade 10). The apparatus is mounted in a vacuum chamber. The chamber is evacuated using a turbomolecular pump (140 l/s) and a mechanical backing pump to achieve a vacuum of approximately $10^{-4}$ to $10^{-6}$Pa. The chamber is equipped with a hot filament ionization gage for chamber pressure and mass spectrometer (residual gas analyzer).

The rotating upper ball is mounted on a spindle which is connected to a ferrofluidic rotary feedthrough. The lower three stationary balls are fixed in a ball holder (lubricant cup) which is mounted on the stage. The stage can be moved upward from outside the chamber with a pneumatic cylinder through a linear motion feedthrough sealed with a welded metallic bellows.
The shaft of the linear motion feedthrough is supported under the “flex pivot” inside the chamber with a linear ball bearing. The lower end of the shaft of the feedthrough is mounted on a plate outside the chamber which is supported with four linear ball bearings. A load cell is mounted between the plate and the pneumatic cylinder to measure the applied load.

The “flex-pivot” shown in Figure 2, which is stiff toward axial thrust but elastic for angular displacement around its center axis is used to mount the stage, where the lubricant cup is fixed, on the top of the shaft of the linear motion feedthrough. Torque is obtained by measuring the angular displacement of the cup holding the three balls. A set of Hall-effect position sensors and a magnet are used to measure the angular displacement. The capability of this tribometer is summarized in Table 1.

Ball-on-Plate Apparatus

This apparatus is a planar simulation of the rolling contact in a ball bearing. The ball-on-plate geometry is shown schematically in Figure 3. The device consists of a ball set rolling between a stationary bottom plate and a spinning top plate. The apparatus is contained in a turbomolecularly pumped cubical vacuum chamber (typical pressure, \(10^{-6}\) Pa). The top plate is driven by an external motor through a ferrofluidic feedthrough. Load is applied upward on the bottom plate with a deadweight through a lever system located below the apparatus. Typically, for 12.5 mm diameter ball specimens, a total of three balls are used. These are grade 10 precision bearing balls.

These balls are placed between the plates with a positioning device which locates them 120° apart azimuthally and at the same radial distance from the center of the plates. After loading and the start of rotation, the balls will spiral out to the disk periphery. Their spiral path is eventually stopped by a bumper (shown in Figure 3). Each ball in turn is nudged back to its original track once each orbit. This causes a repositioning scrub mark on the bottom plate track, made as the rolling balls are pushed back to their original radius by the bumper. The bumper assembly contains a transducer to determine the force on the bumper. The length of the scrub and the bumper force indicates the degree of boundary lubrication. A cold cathode ionization pressure gauge and a quadrupole mass spectrometer are used to detect species released into the ambient during the rolling and bumping process. The plate to plate electrical resistance determines any separation between ball and plate caused by insulating lubricant films.

The balls are lubricated by a dip coating process by submerging in a dilute solution of the lubricants. Upon removal from this solution, the solvent evaporates, leaving a thin residue of lubricant. The plates are not lubricated but lubricant is transferred during the rolling process. More details about the kinematics of this device appear in Reference 7. Other specifications appear in Table 1.
Instrument Bearing Apparatus

The final vacuum tribometer is shown in Figure 4. As in the other tribometers, the apparatus is contained in a cubical vacuum chamber and driven by an external motor through a ferrofluidic feedthrough. In this case, the motor is a micro-stepper which is computer controlled to effect either continuous rotation or precise dither motion. Loading is effected by a precision screw mechanism below the apparatus. Provision has been made for either hard or soft loading.

The test component is an instrument angular contact bearing. This bearing has the following specifications: O.D. 30.16 mm, bore 19.05, 18-3.175 mm balls and a porous polyimide retainer. Bearing torque is measured with a flex pivot assembly which is instrumented with micro-strain gages. The vacuum cube is also instrumented with a mass spectrometer. The test bearing is also electrically isolated so that contact resistance can be measured. Other specifications are tabulated in Table 1.

Examples of Test Data

UHV Rubbing Apparatus

This apparatus is generally used to generate tribological surfaces for fundamental surface chemistry studies. Typically a flat surface is cleaned and characterized by X-ray photoelectron spectroscopy (XPS). Then it is placed on a collimator and a thin (~40 Å) lubricant film is deposited by evaporation. An in-situ rubbing experiment can then take place. An example is shown in Figure 5 from Reference 8.

Figure 5 is a micrograph of a rubbed area on a 440 C disk lubricated with a perfluoropolyether (PFPE). The area was generated by loading a 440 C bearing ball against the flat translating it linearly in reciprocating motion with a velocity of 0.3 mm/s. A lateral translation of 50 μm at the end of each stroke produced a rectangular patch 5 mm X 8 mm. XPS analysis of this rubbed area indicated that, even under this mild sliding, single pass conditions, surface fluoride was formed. This indicated that the PFPE had been degraded at room temperature. Its chemical signature was similar to that observed during static high temperature experiments. Therefore, this device is very useful in studying the effects of surface pretreatments, such as ion implantation, on the tribological process.

Four-Ball Apparatus

Because of the high loads and pure sliding conditions employed in this device, a great amount of energy is dissipated in the contact regions. This accentuates chemical reactions and therefore results in a highly accelerated test. Steady state wear rates are generated with this device which yield qualitative rankings of the boundary lubrication performance of liquid lubricant basestocks and formulations.
Figure 6 contains a comparison of wear rates for three aerospace lubricants in air and vacuum (Ref. 9). Test conditions were: 25°C, 200N load, and a 100 rpm rotational speed. The three lubricants were (1) an unbranched PFPE (Z-25), (2) a branched PFPE (143 AB) and (3) a formulated synthetic hydrocarbon (2001). Results in air and vacuum clearly discriminate between the more reactive unbranched PFPE (Z-25) compared to the less reactive branched fluid (143 AB). This trend correlated with other vacuum four-ball results (Ref. 10) and vacuum sliding experiments (Ref. 11). In addition, the better performance of formulated hydrocarbons compared to unformulated PFPE fluids correlated with oscillating gimbal tests (ref. 12) and boundary lubricant screening tests (ref. 13).

**Ball-on-Plate Apparatus**

Figure 7a shows bumper force and mass spectrometer data obtained with a PFPE boundary lubricant at room temperature, 6 rpm and $10^8$Pa. In this test the bumper force reached a maximum of 28N and lasted 1.2 seconds. The ball load was 140N, for a sliding friction coefficient of 0.2. Figure 7b shows the corresponding mass spectrometer data for evolution of mass 69 (CF$_3$) lubricant fragments: background, no rotation, level I; rotation, no bump, level II; and during a series of bumps, level III.

**Instrument Bearing Apparatus**

Performance data for an MFB 1219 size bearing operating in a retainerless mode and lubricated with a synthetic hydrocarbon (Nye 2001) are shown is Figure 8. Figure 8 illustrates the effect of speed on torque and contact resistance at room temperature, a hard load of 44.5 N and a vacuum level of approximately $10^{-4}$Pa. A gradual increase in torque with increasing speed is observed. Contact resistance as a function of speed shows the transition from the boundary regime to mixed and finally to full EHL.

**References**

<table>
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<th>Four-Ball</th>
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<th>Instrument Bearing</th>
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<td>Initial Mean Hertz Stress, GPa</td>
<td>0.43</td>
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<td>45-450</td>
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<td>Speed Range, rpm</td>
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<td>10-500</td>
<td>1-100</td>
<td>1-1200 (1Hz dither)</td>
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<td>Environmental Pressure, Pa</td>
<td>10&lt;sup&gt;7&lt;/sup&gt; room</td>
<td>10&lt;sup&gt;-6&lt;/sup&gt; room to 50°C</td>
<td>10&lt;sup&gt;-6&lt;/sup&gt; room to 50°C</td>
<td>10&lt;sup&gt;-6&lt;/sup&gt; room to 50°C</td>
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<tr>
<td>Temperature</td>
<td>room to 50°C</td>
<td>room to 50°C</td>
<td>12.7 mm diameter bearing balls</td>
<td>angular contact instrument bearing (1219 size)</td>
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<tr>
<td>Specimens (440C Steel)</td>
<td>6 mm diameter bearing ball</td>
<td>9.5 mm diameter bearing balls</td>
<td>50.8 mm diameter disks</td>
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Figure 1.—UHV tribometer.

Motorized Y-axis micrometer

X-axis micrometer

Z-axis

Bellows

Strain gauge

Load

Flex pivot

Contact indicator

Sample

Bearing ball

Electrical feed-through

δ° flange
Figure 2.—Four-ball apparatus.
Figure 3.—Ball-on-plate geometry.

Figure 4.—Instrument bearing test rig.
Figure 5.—Optical micrograph of soft 440C steel surface after rubbing with a 440C bearing ball. Lubricant: 50Å Fomblin Z-25.

Lubricant: 50Å Fomblin Z-25.

Figure 6.—Wear rates for three commercial aerospace lubricants in air and vacuum (25°C, 200N load, 100 RPM).

Figure 7.—(a) Intensity of mass 69 (CF₃) from residual gas analyser as a function of time. (b) Bumper force as a function of time (lubricant, Krytox 16256; load, 140N; vacuum, 10⁻⁶Pa; speed, 6 RPM).
Figure 8.—Bearing torque and contact resistance as a function of speed (44.5N hard load).
NASA-Marshall Space Flight Center

The majority of equipment in our labs is for general tribological testing. This equipment can be used to evaluate various types of lubricants such as oils, greases, dry film, and deposited thin film. Below is a list of our equipment:

- Block-on-ring friction and wear testing machine
- Four ball wear testers for measurement of extreme pressure properties of lubricating fluids
- Falex multipurpose friction and wear tester
- Cryogenic traction tester
- Rolling contact fatigue tester
- Pin and Vee-block wear tester
- Vacuum manifold with 12 independent stations with feed-throughs for electrical power and thermocouples. Some stations have water feed-throughs and there are several blanked off ports available for other feed-throughs.
Rockwell Science Center

SEM/AES/XPS Tribometer

This facility consists of a 12.7-mm (0.5-in.) diameter cylinder that rolls against a 50.8-mm (2-in.) diameter crowned disk, corresponding to the ball and raceway of a rolling element bearing, respectively. The rotational speed of the two samples is controlled by two continuous variable-speed electric motors capable of up to 23,000 rpm and 5,000 rpm, respectively. Thus, the slip/roll ratio is controllable over the whole range from pure sliding to pure rolling. The ball retainer function is simulated by pressing a pin of retainer material against the cylinder. Pure sliding can be studied by keeping the cylinder spindle stationary while rotating the disc spindle or vice versa.

The contact stress between the two rotating samples is continuously adjustable in real time up to about 4000 MPa mean Hertz stress or higher depending on contact geometry and elastic modulus of the materials. The pin/cylinder contact stress is adjustable independent of the cylinder/disk loading. Both forces are monitored by separate load cells, as is the traction force between the disk and cylinder.

Experiments can be performed either in ultra-high vacuum or up to one atmosphere of oxygen, hydrogen, and a variety of other gases. The disk and cylinder samples can be internally cooled to liquid nitrogen temperature. Design provisions have been made to accommodate high-temperature testing using laser heating. The temperature is monitored at the cylinder/disk contact separation point with an infrared thermometer with a focal point smaller than the Hertz contact ellipse. The total wear is monitored with a capacitance displacement probe. A 500-kHz acoustic emission detector monitors sample contact and film breakdown.

The facility is equipped with an 8-channel computer data acquisition system that displays in real time on a color monitor and stores on a hard disk drive the disk/cylinder and pin/cylinder normal forces and the disk/cylinder friction force, the motor speeds, the wear, and the temperature. The data retrieval, reduction, calculations, and graphing have been automated using a dedicated 486/33 computer.

The test chamber is equipped with an SEM, a scanning Auger electron spectrooscope (AES) and a small-area multichannel x-ray photoelectron spectrooscope (XPS) operated via an Apollo 3500 computer and PHI surface analysis software to examine the topography and chemically analyze the wear track as the test is running. The chemical composition of the test environment is monitored by a VG triple-filter quadropole mass spectrometer via a 386/20 computer using VG software. Chemical composition depth profiling of the wear track can be done using the ion sputter gun. The facility is also equipped with a high-speed video camera operated as a strobe to obtain real-time freeze-frame images of the wear track using a dedicated 486/66 computer image analysis system.
Space Systems/Loral

- Vibration tables (5)
- Thermal vacuum chamber (30 ft φ)
- Compact RF range
- Near-field range
- Small T/V chambers (~20)
University of Maryland

The University of Maryland's space environment simulation is limited. There is a small vacuum chamber on campus. The proximity of the University to Goddard Space Flight Center is an asset.

The University of Maryland offers one of the four neutral buoyancy facilities in the country. The Neutral Buoyancy Research Facility houses a 50-ft diameter, 25-ft deep neutral buoyancy tank. This is used to simulate the weightlessness of space while performing various operations.
Viking/Metrom Laboratories

- Vibration facilities
- Environmental (numerous)
REFERENCES
REFERENCES

There are numerous publications on space mechanisms available through various societies and publishing firms. The preponderance of material is contained in the 28 volumes of the Aerospace Mechanisms Symposia (AMS) sponsored by NASA. Following is a listing of all the AMS papers sorted by topic.

Some additional references were supplied via the survey responses. These are included also. A strong list of Pyrotechnic publications was provided by Bement. The publications listed below by Fusaro provides an informative prospective of space mechanism technology.


Index of Papers Sorted by Topic

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This Index categorizes the papers into the following topics:

- **ACT**: Actuators/Motors (could have drives, gearing, bearing info)
- **AIR**: Aircraft-related mechanisms (includes wind tunnel info)
- **ANT**: Antennas (could have gimbal, hinge, deployment device info)
- **BOOM**: Booms/Deployable structures/Erectable structures (could have deployment device, hinge, latch info)
- **BFG**: Bearings (could have tribology info)
- **DAMP**: Dampers/Brakes (could have deployment device info)
- **DEPLOY**: Deployment devices/Hinges/Linkages (could have boom, latch, release info)
- **DRIV**: Drives/Gearing/Speed Reducers (could have actuator, bearing info)
- **EVA**: EVA equipment/Astronaut equipment
- **GMB**: Gimbals/Pointing/Servomechanisms (could have actuator, drive, bearing info)
- **INST**: Scanner/Chopper/Mirror/Instrument mechanisms (could have actuator, bearing, drive, gimbal, release info)
- **LATCH**: Latches/Clamps/Docking (could have hinge, linkage info)
- **REL**: Release mechanisms (could have latch info)
- **ROBOT**: Robotics (could have actuator, drive, bearing info)
- **SA**: Solar-array related mechanisms (could have actuator, drive, bearing, gimbal, latch, deployment device info)
- **SAMP**: Soil and particle collection mechanisms (could have actuator, boom info)
- **SEP**: Separation/Ejection/Satellite Despin (could have release info)
- **STE**: Ground and Test Equipment
- **TRAN**: Utility (power, data, fluid) transfer/Umibilicals
- **TREB**: Tribology (could have bearing info)
- **WHEEL**: Momentum/Reaction wheels (could have actuator, bearing info)
- **MSC**: Miscellaneous

The papers listed in bold type were the Hertzl Award winners for each symposium.
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# Space Mechanisms Lessons Learned Study

## Volume I—Summary

### Title and Subtitle
Space Mechanisms Lessons Learned Study

### Authors
Wilbur Shapiro, Frank Murray, Roy Howarth, and Robert Fusaro

### Performing Organization Name(s) and Address(es)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

### SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
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### Abstract (Maximum 200 words)
Hundreds of satellites have been launched to date. Some have operated extremely well and others have not. In order to learn from past operating experiences, a study was conducted to determine the conditions under which space mechanisms (mechanically moving components) have previously worked or failed. The study consisted of (1) an extensive literature review that included both government contractor reports and technical journals, (2) communication and visits (when necessary) to the various NASA and DOD centers and their designated contractors (this included contact with project managers of current and prior NASA satellite programs as well as their industry counterparts), (3) requests for unpublished information to NASA and industry and (4) a mail survey designed to acquire specific mechanism experience. The information obtained has been organized into two volumes. Volume I provides a summary of the lessons learned, the results of a needs analysis, responses to the mail survey, a listing of experts, a description of some available facilities and a compilation of references. Volume II contains a compilation of the literature review synopsis.