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Space Mechanisms Lessons Learned Study

Volume I—Summary

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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 (eg. 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: (l) 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 (3) Requests for unpublished information was made to NASA and industry.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.

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INTRODUCTION

INTRODUCTION

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 subsystems. 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 (MoS_2) lubricant at cold conditions. Under conditions of cold temperature (-44°F) and the balling up phenomenon of MoS_2, 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 MoS_2 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, MoS_2 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 electrodeposited, 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

Date	Project	Failure	Source of Failure	Resolution
1976	RSRA	Firing pin assemblies corroded and locked in qualification	Bad design	Redesigned, requalified
1973	Classified	Pin puller failed during system test (cartridge closure blocking port)	Lack of understanding	Redesigned, requalified
1979	Classified	Pin puller ruptured during system test (inadequate containment margin and variation in metal grain orientation)	Lack of understanding	Redesigned, requalified
1987	Magellan	Pin puller failed to stroke against flight side load (NSI output restricted, causing reduced output and housing deformation against working piston)	Bad design; misapplication of hardware	Replaced, requalified
1986	Magellan Orbiter	Pin puller failed to function in LAT (NSI produced insufficient pressure caused by coatings of pressurized volume)	Misapplication of hardware; lack of understanding	Changed manufacturer and design
1986	ASAT	Bolt cutter failed LAT (improper compression margin test requirement)	Incorrect specification	Correct specification

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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]

- MoS_2 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 MoS_2 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 MoS_2 has a lower coefficient of friction than ion-plated Pb (0.01 versus 0.1), which means that MoS_2 components should develop less torque.

- 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

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

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- 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 MoS_2-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 MoS_2 is the preferred and, perhaps, necessary method. Sputtered films of MoS_2 are currently applied to numerous space components such as screw threads, ball bearings, sleeves, and bushes. [Rowntree]
- An investigation at ESTL of MoS_2 films deposited by magnetron RF sputtering in which the rate of evaporation of the MoS_2 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 MoS_2, on a mechanism that is going to be operated in an atmosphere should be carefully evaluated. The wear rate of the MoS_2 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]

- 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. MoS_2 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 protoflight 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]

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. [Kalegoras]

- 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_2O_3 and Al_2O_3/SiC.
  - To ensure in-vacuo stable friction, run-in of opposed surfaces is recommended.

Table 3. Lockheed Solutions to Limitations of Conventional Designs

Problem	Solution
Dynamic range	Use of an electromagnet actuator in an analog closed-loop using special low-noise sensor electronics
Bandwidth	Use of electromagnetic actuator and moderate equivalent gear ratio
Stiction/friction	No bearings or lubricants; exclusively flex pivots
High power consumption	Four-bar linkage (lever) and force unload system
Inability to cancel static friction	Force unload system

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- 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 = available torque/resisting torque > 4
    Torque margin: T_m = (available torque - resisting torque)/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.
  - Tioxode-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 cryovalve 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 form 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 antiwear 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 MoS_2 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

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

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- 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 nitridng, 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

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

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- 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 = available torque
  T_r = resistance torque
  T_M = 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 despin 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 despin 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

Program	Wheel Type	Problem	Cause	Action
Navstar/ GPS	Reaction wheel; four per satellite	On-orbit and test failures; high torque	Lubricant depletion	New lubrication qualification
GPS IIR	Reaction wheel	High-speed cage instability	Force, mass resonance	Force, mass; biased cages
DMSP	Reaction wheel	Bearings/lubricant could not be delivered	Lubricant degradation	Extensive bearing run-in and screening
DSP	Large momentum wheel	Torque/temperature anomalies	Lubricant starvation	Redundant wheels
MILSTAR	Rate gyroscopes	Drive rate/torque instability	Lubricant starvation	Improved lubrication, cage processing
CDP	Large control moment gyroscopes; > one per satellite	Extensive torque	Lube loss, cage instability	Active oiler system, new oil
DSCS III	Reaction wheel	Torque noise, vibration	Unknown	Redundant wheels

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- 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]

- 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 1.3×10^6 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 despin 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. Perflourinated polyether and silicone lubricants should be avoided in this 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]

- 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 MoS_2 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 $Ag/C/MoS_2$ (12% MoS_2). Subsequent high resistance was due to surface contamination (possibly Ag_2O or Ag_2S). [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/MoS_2 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 7×10^4 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 (8×10^6 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

Factor Increased	Effect
Conformity (tighter)	Increases spin; higher spin torque and drag
Contact angle	Increases spin; higher spin torque and drag
One-piece cage	Restricts ball speed spacing; increases cage windup
Misalignment	Increases ball speed variation; increases cage windup
Friction coefficient	Increases traction forces; increases anomalous torque
Contact angle variation	Increases ball speed variation
Ball diameter tolerance	Increases ball speed variation
Thrust versus radial bearing	Thrust bearing has all balls loaded; no opportunity for ball spacing to readjust

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- Torque spikes are the result of buildup of debris at the ends of the ball travel. The debris was primarily aluminum particles with 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 7×10^4 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, Ruebsame]

- 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 area. 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 MoS_2. 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.

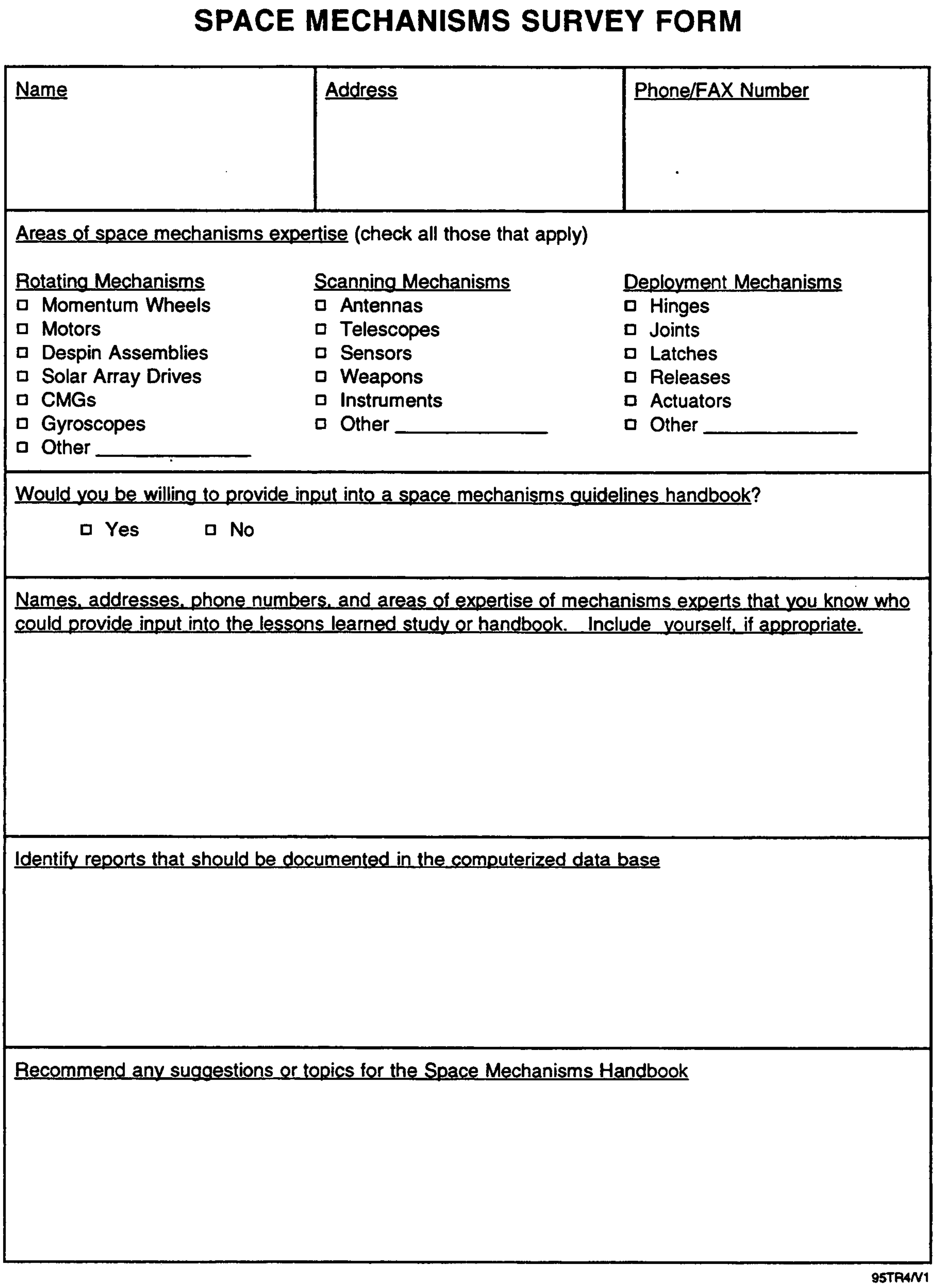
- For oscillating gimbal applications, solid dry lubricants, such as sputter-coated MoS_2, with benign ball retainers (those that do not transfer films) are recommended. Continued development of solid lubricants for gimbal races, with objectives of low torque and no debris formation is suggested.

- 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

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

Name	Address	Phone/FAX Number

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 data base

Recommend any suggestions or topics for the Space Mechanisms Handbook

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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.)

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Figure 1. Continued

SPACE MECHANISMS SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)

INDICES/KEY WORDS

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

SUBMITTED BY

DATE

ADDRESS

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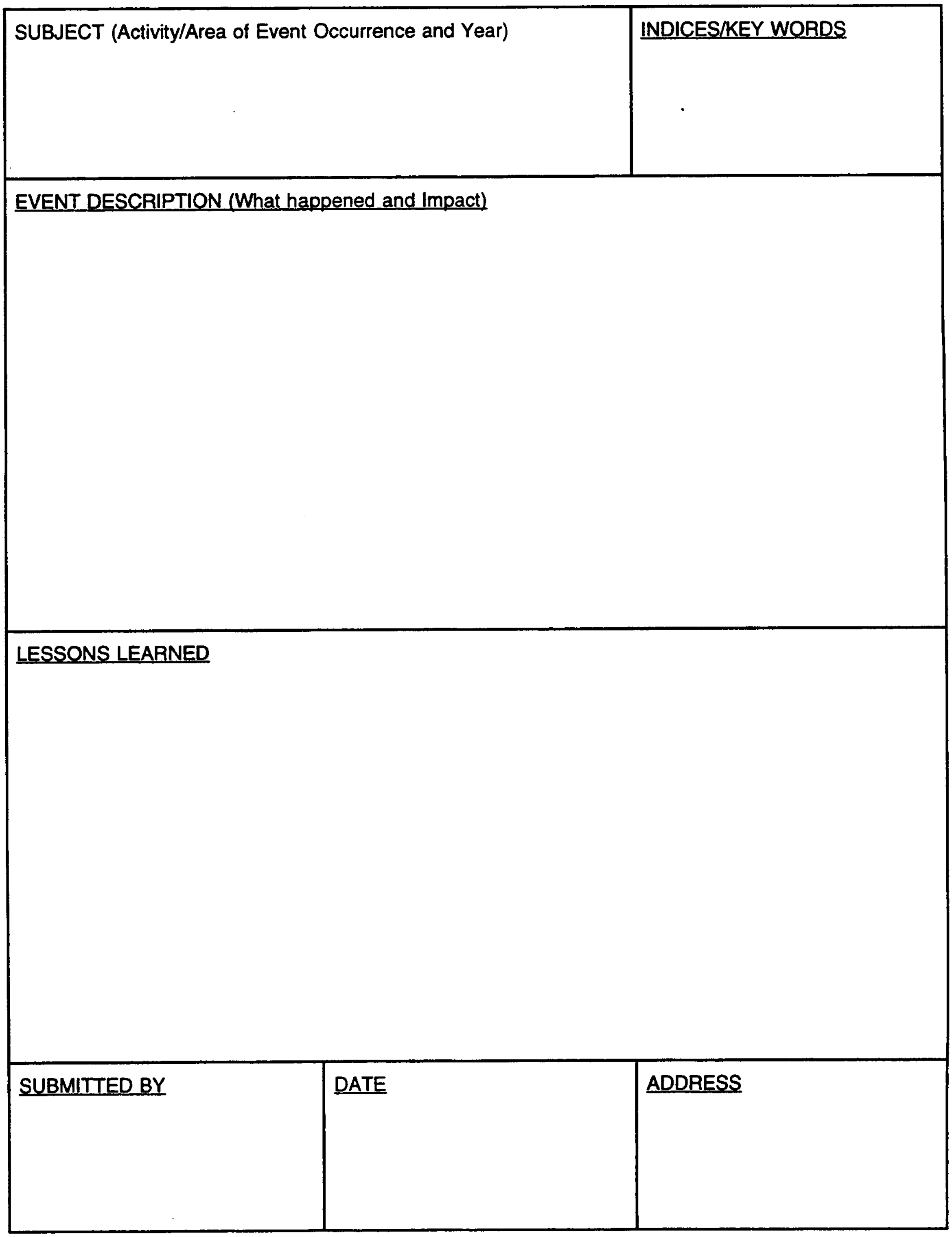
Figure 1. Continued



SPACE MECHANISMS SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)

INDICES/KEY WORDS

EVENT DESCRIPTION (What happened and Impact)

LESSONS LEARNED

SUBMITTED BY

DATE

ADDRESS

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Figure 1. Continued

EXAMPLE OF SPACE MECHANISM SIGNIFICANT EVENT

SUBJECT (Activity/Area of Event Occurrence) Damage of Galileo Flight Antenna From Testing	INDICES/KEYWORDS Galileo Development Management Testing
EVENT DESCRIPTION (What Happened and Impact)	YEAR OF EVENT OCCURRENCE: 1983

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 property 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 declared the SXA-1 antenna nonflight qualified due to gain loss, noncompliance with STS criteria, and questionable deployment reliability.*

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 formality 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.

SUBMITTED BY L. Dumas/G. Coyle	DATE 4/26/85	SSEF APPROVAL K. S. Watkins	DATE 12/10/85 REVISED 10/13/87

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SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity / Area of Event Occurence and Year)	INDICES / KEYWORDS
Anomolous Motor Performance due to Bearing Lubricant *Assembly/Contingency Subsystem for Communications* 1993	*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.) Anomolous 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 surprizing, 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	DATE	ADDRESS
David B. Marks Sr. Project Engineer	Revised: February 23, 1994	Honeywell Electro Components Durham, North Carolina (919) 956-4312

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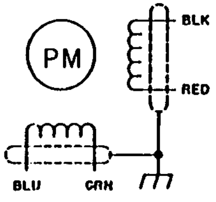
REVISIONS				
LTR	ZONE	DESCRIPTION	DATE	APPROVED
A		DIM ".392±.020 AND .530+.000 -.015" WAS ".342±.020 AND .480 +.000-.015" RESP. AT VIEW A: RMVD DIM "20°±5°" & "Ø.100 (CHAMFER)". ADDED CALLOUT ".003±.002 RADIUS OR CHAMFER". C.O.30086 TLT 02-25-93	03-03-93	T.W.S. D.B.M.

STEPPER MOTOR, SIZE 11	P/N 2961088-1
WEIGHT (OUNCES) (MAXIMUM)	5.3
ROTOR INERTIA GM-CM^2	5.0
VOLTAGE DC/PHASE	110
CURRENT AMPS	0.20
INPUT WATTS (MAXIMUM)	22
STALL TORQUE OZ.-IN.	2.8
DETENT TORQUE OZ.-IN. (MAX./MIN.)	0.50/0.10
DC RESISTANCE PER PHASE, OHMS	115 ± 11.5
ROTATION	REVERSIBLE
WINDING	NONREDUNDANT
STEP ANGLE, DEGREES	45
RUNNING TORQUE AT 110VDC AND 480 PULSES/SEC.,OZ.-IN.	0.9
MAX. WINDING TEMPERTURE °C	185

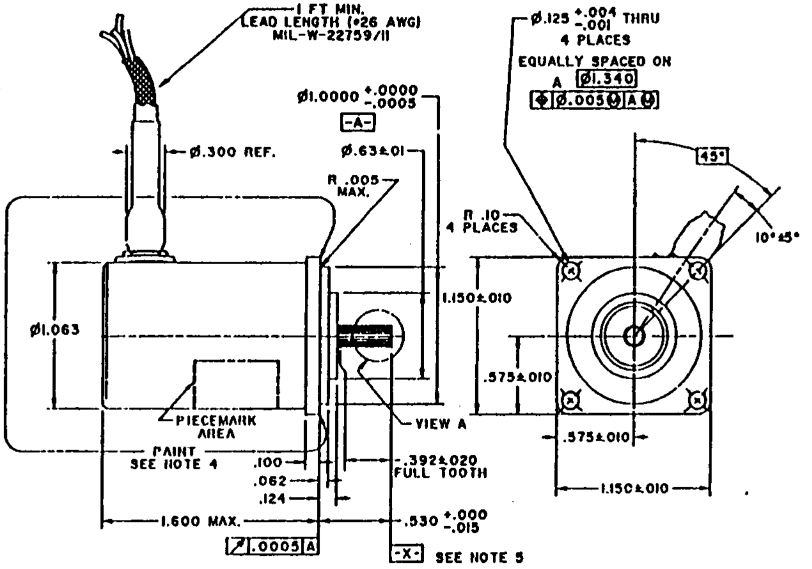
NOTE: UNLESS OTHERWISE INDICATED, VALUES LISTED ARE NOMINAL AT AMBIENT CONDITIONS.



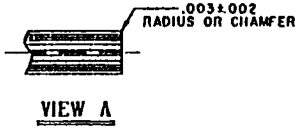
SCHEMATIC

NOTES:

1. ALL VALUES ARE GIVEN AT AMBIENT TEMPERATURE OF 25°C
2. THIS PULSE OPERATED SERVO MOTOR PROVIDES AN ANALOG SHAFT OUTPUT, THE STATOR FIELDS BEING ALTERNATELY EXCITED BY A SERIES OF DIGITAL PULSES.
3. DIRECTION OF ROTATION: TIE TO POWER SOURCE. FOR CCW ROTATION LOOKING AT SHAFT END, EXCITE LEADS SINGULARY IN SEQUENCE SHOWN. FOR CW ROTATION REVERSE POLARITY SHOWN.
4. PAINTED IN AREA INDICATED WITH IIT RESEARCH INSTITUTE Z93. PAINT OMITTED FROM Ø.125 HOLES AND CABLE.
5. ALL GEAR TOOTH SURFACES ARE ION-PLATED WITH TITANIUM NITRIDE. PLATING PERMITTED ON SURFACE -X-.



PINION DATA:	
NUMBER OF TEETH	12
DIAMETRAL PITCH	96
PRESSURE ANGLE	20 DEGREE
OPERATING PITCH DIA.	.125
AGMA QUAL. NO. (AGMA 390.03)	Q12
REFERENCE O.D.	.1565 +.0000 -.0010



VIEW A

ROTATION TABLE					
MOTOR STEP SEQUENCE	LEAD COLOR AND POLARITY				ROTATION VIEWED FROM SHAFT END
	RED	BLK	GRN	BLU	
1 (0°)	-	+			INDEX
2 (90°)			-	+	CCW
3 (180°)	+	-			CCW
4 (270°)			+	-	CCW
5 (360°)	-	+			CCW

DRAWN BY T.L.Tunstall	DATE 03-23-92
DESIGNED BY T.W.S.	DATE 03-23-92
CHECKED BY T.W.S.	DATE 03-26-92
APPROVED BY: D.B.M.	DATE 02-11-93

Honeywell
HONEYWELL INC.
SPACE AND AVIATION SYSTEMS
ELECTRO COMPONENTS
DURHAM, NORTH CAROLINA

TITLE
PERFORMANCE AND OUTLINE
MOTOR. STEPPER SIZE 11

SIZE	CODE IDENT NO	DRAWING NO.	REV
C	90012	2941088	A
SCALE 2:1		SHEET 1 OF 1	

COMPUTER GENERATED

2941088 1

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SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity / Area of Event Occurence and Year)	INDICES / KEYWORDS
Rotational Creeping of Actuators During Launch *Solar Max Repair Mission* 1981	*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 luanch, 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.

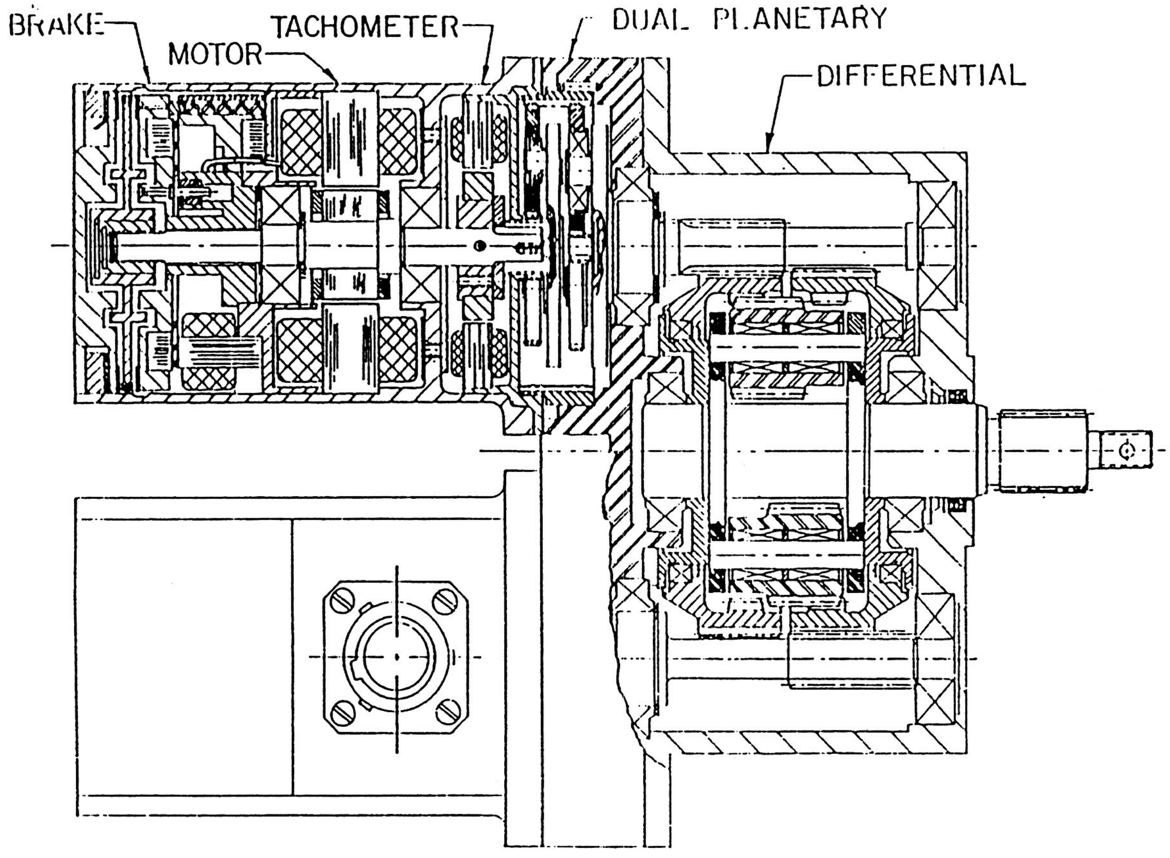
LESSONS LEARNED

(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-backdrivable. Certain conditions of vibration can cause backdriving to occur.

SUBMITTED BY	DATE	ADDRESS
Richard Fink Lead Engineer	January 21, 1994	Honeywell Electro Components Durham, North Carolina (919) 956-4264

95TR4/V1



COMMON DRIVE UNIT

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) PSA (Payload Spin Assembly)	INDICES/KEYWORDS PSA, Electronics, FETS

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 reveled 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.

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

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) GGS Slip ring Wire Corrosion	INDICES/KEYWORDS GGS, Slip Rings, Wires

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 paper work 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 still 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

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) GGS Accelerated Life Test Failure	INDICES/KEYWORDS GGS Life-Test, Bearings, Toroids

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.

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95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)
GGS V-Band Release – 1993

INDICES/KEYWORDS
GGS, V-Band Testing, TUF-RAM, NEDOX

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
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95TR4/V1

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 occured 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

95TR4/V1

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 tow X-ray pictures taken – one on the side view and one turned 90°.

Pyrotechnic pin pullers have ms 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 W. Robinson	DATE	ADDRESS Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)	INDICES/KEYWORDS
Damage of Galileo Scan Actuator Sub Assembly During Heat Treat – 1981	Galileo, Titanium, Heat Treat

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	DATE	ADDRESS
Clair Sutter	March 21, 1994	Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Protection for Limited Travel Gimbal Systems – 1993	INDICES/KEYWORDS Gimbal, Travel Limits, Limit Switches

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 85308-9650

95TR4/V1

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. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Customer Furnished Parts for the Galileo Program – 1980	INDICES/KEYWORDS Galileo, Customer Furnished Parts

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 prcported improvements.

SUBMITTED BY Clair Sutter	DATE March 21, 1994	ADDRESS Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Heater Thermostat failure during Hubble Space Telescope Antenna Pointing System (STAPS) component testing – 1982	INDICES/KEYWORDS Hubble Space Telescope, Component Testing, Thermostat Failure

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

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Heater Cover failure during Hubble Space Telescope Antenna Pointing System (STAPS) component testing – 1987	INDICES/KEYWORDS Hubble Space Telescope, STAPS, Heater Failure

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

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Gimbal Motor Stall Indication On Orbit for the Hubble Space Telescope – 1991	INDICES/KEYWORDS Hubble Space Telescope, Gimbal Motor Stall, Harness interference

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.

SUBMITTED BY Dale Ruebsamen	DATE April 12, 1994	ADDRESS Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Gimbal Torque Anamality during STAPS Acceptance Testing – 1985	INDICES/KEYWORDS Hubble Space Telescope, Component Testing, Bearings

EVENT DESCRIPTION (What Happened and Impact)

During protoflight testing of the spare 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 rations 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 protoflight 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

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Gimbal Heater Failure during System level Acceptance Test for TOPEX HGAS. (High Gain Antenna Pointing System) – 1985	INDICES/KEYWORDS TOPEX-HGAS, Heater Failure

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.

SUBMITTED BY Dale Ruebsamen	DATE April 12, 1994	ADDRESS Honeywell Inc. Satellite Systems Operation 19019 N. 59th Ave Glendale, AZ 85308-9650

95TR4/V1

SPACE MECHANISMS SIGNIFICANT EVENT

SUBJECT DATE: 1987
Space Telescope High Gain Antenna Bearing Torque Anomaly during Ground Tests

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.

Ref: Loewenthal, S. H.: Two Gimbal Bearing Case Studies: Some Lessons Learned , NASA CP-2506, Proceedings of the 22th Aerospace Mechanisms Symposium, NASA Langley Research Center, May 1988.

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	Date	Address
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95TR4/V1

SPACE MECHANISMS SIGNIFICANT EVENT

SUBJECT DATE: 1989

Torque Anomaly for Bearings in hard Space suit Ground Tests

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.

Ref: Loewenthal, S. H., Vic Vykukal, Robert MacKendrick and Philip Culbertson Jr.: AX-5 Space Suit Bearing Torque Investigation , NASA CP-3062, Proceedings of the 24th Aerospace Mechanisms Symposium, NASA Kennedy Space Flight Center, April 18-20 1990.

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	Date	Address
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95TR4/V1

SPACE MECHANISMS SIGNIFICANT EVENT

SUBJECT DATE: 1993

On-Orbit Torque Problem with Positioner Bearings

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 prolong 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	Date	Address
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95TR4/V1

SPACE MECHANISMS SIGNIFICANT EVENT

SUBJECT
Cold Temperature Jamming with Spherical Bearing

DATE: 1992

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 MoS_2 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, ~~the~~ 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.

SUBMITTED BY	Date	Address
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95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)	INDICES/KEYWORDS
Transmit Antenna Adjustment Limits via Bi-Axial Drive Assembly	ACTS Attachment Design

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 accomodate 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.

SUBMITTED BY	DATE	ADDRESS
John L. Collins	4/03/94	NASA LeRC

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Transmit Antenna Adjustment Limits via Bi-Axial Drive Assembly	INDICES/KEYWORDS ACTS Attachment Design

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	DATE	ADDRESS
John L. Collins	4/03/94	NASA LeRC

SPACE MECHANISM SIGNIFICANT EVENT

Problem Description

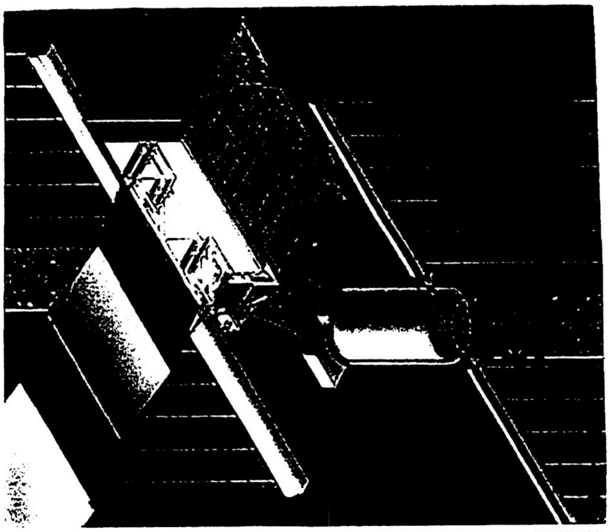
BETA GIMBAL BEARING ON SPACE STATION FREEDOM (1992)

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 soutions 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.



95TR4/V1

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May 5, 1994

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SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)	INDICES/KEYWORDS
Clementine Program Paraffin actuator heater failure 9/93 in ground testing	Paraffin Actuator

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 therefor 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.

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95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) ISTP Despin Platform Honeywell, Phoenix AZ	INDICES/KEYWORDS 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.

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95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) LDEF Results Long Duration Experimental Facility	INDICES/KEYWORDS Solid Film Lubricants LDEF Photochemical Degredation

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.

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95TR4/V1

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.

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a-2.

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year)	INDICES/KEYWORDS
CMG BEARING FAILURE 1974	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 a 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 to 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.

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95TR4/V1

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.

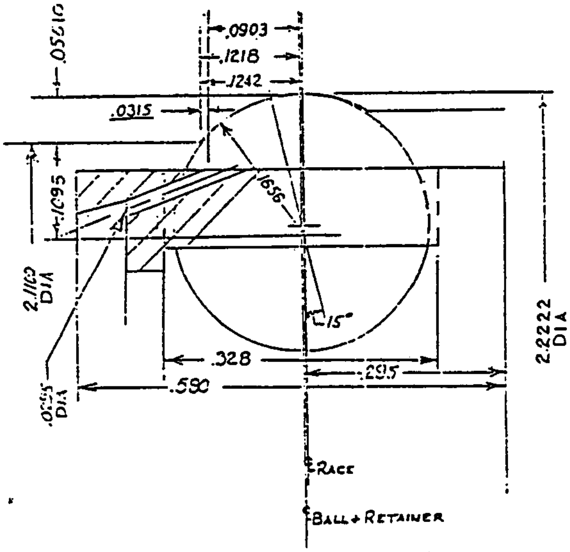
SUBMITTED BY	DATE	ADDRESS

95TR4/V1

SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

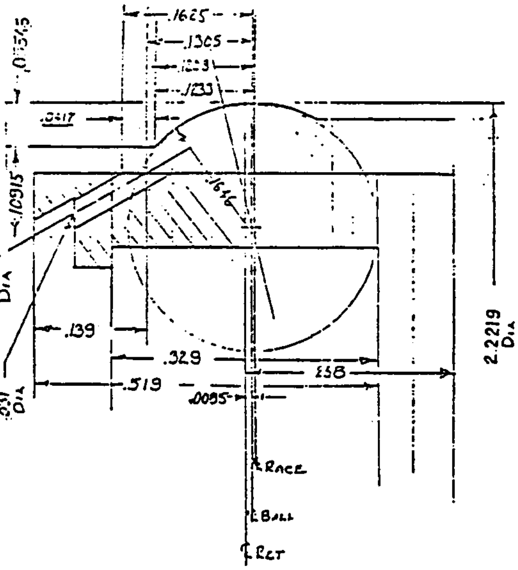
SUBJECT (Activity/Area of Event Occurrence and Year)	INDICES/KEYWORDS
CMG BEARING FAILURE 1974	BEARINGS, CMG

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



NOMINAL CASE 19.0° HOLE

FIG. 1



WORST CASE 30 HOLE
ORIGINAL RETAINER

FIG. 2

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SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

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

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

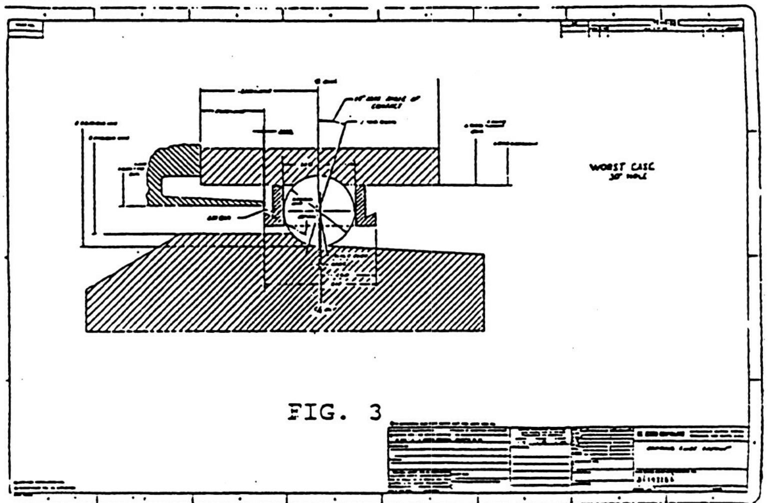

FIG. 3

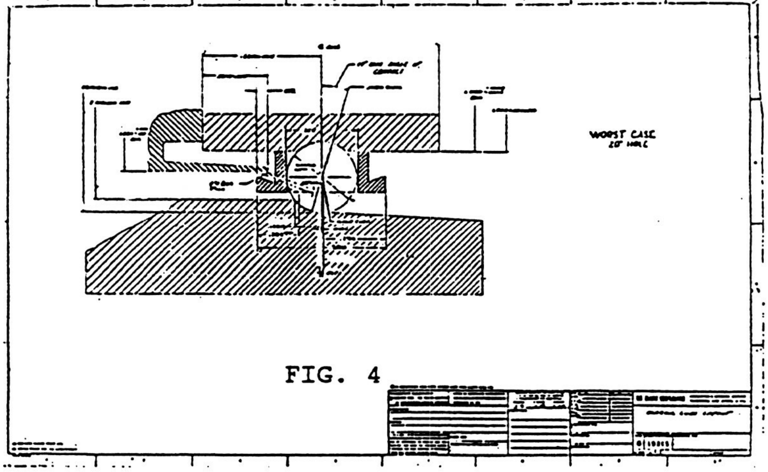

FIG. 4

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SPACE MECHANISM SIGNIFICANT EVENT (Anomaly or Failure)

SUBJECT (Activity/Area of Event Occurrence and Year) Cover Actuation	INDICES/KEYWORDS Covers. Hinges. Springs

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.

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95TR4/V1

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FACILITIES

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 requuest.

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 m^2; approximately 300 m^2 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 m^3 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.

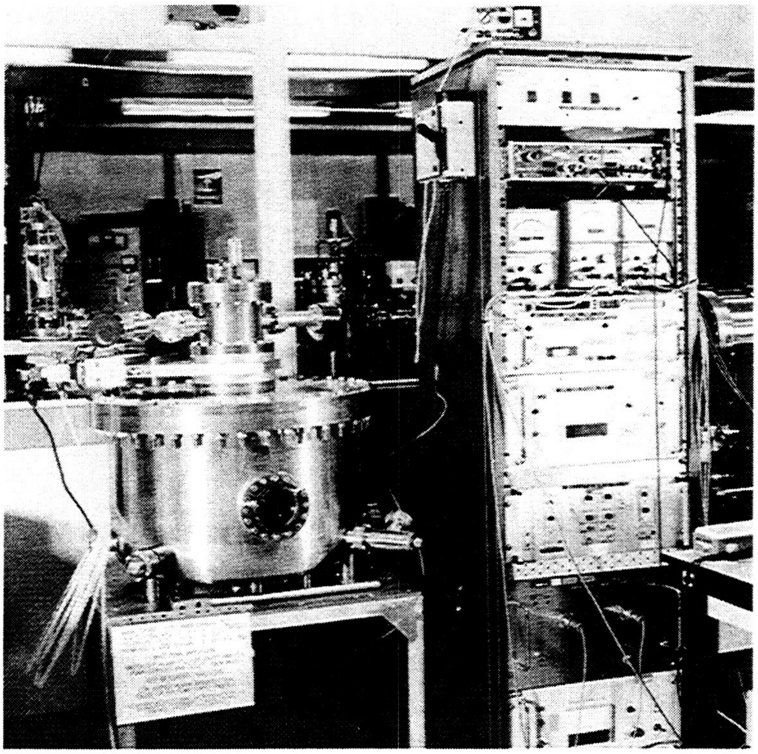
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Figure 2. ESTL Vacuum Chamber

Specific Test Facilities

Vacuum Cryogenic Test Rig. Baseplate temperatures down to 4.2 K can be achieved within a 6000-cm^3 (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).

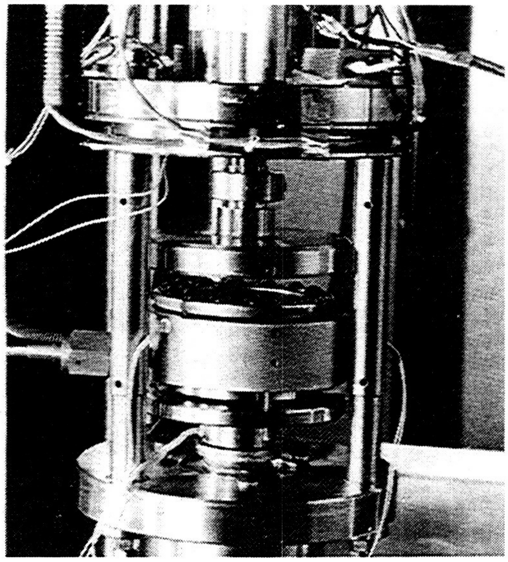

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Figure 3. Boundary Lubrication Accelerated Screening Tester

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
- 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-ft^2 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 1×10^{-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 1×10^{-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 ft^3 to approximately 50 ft^3 (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.

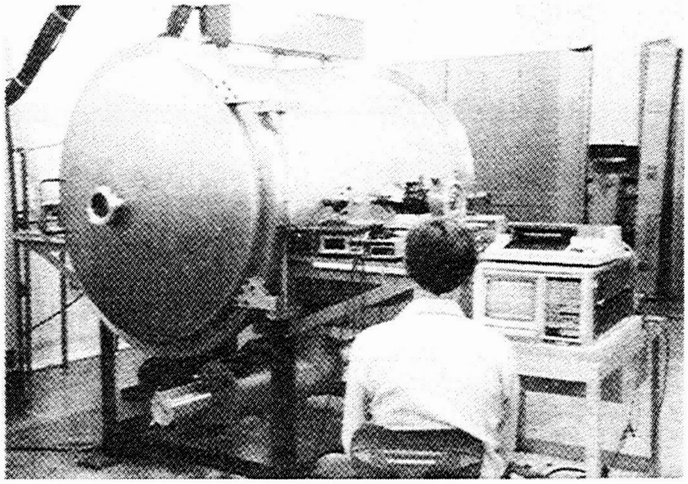

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Figure 4. Honeywell Environmental Test Facility

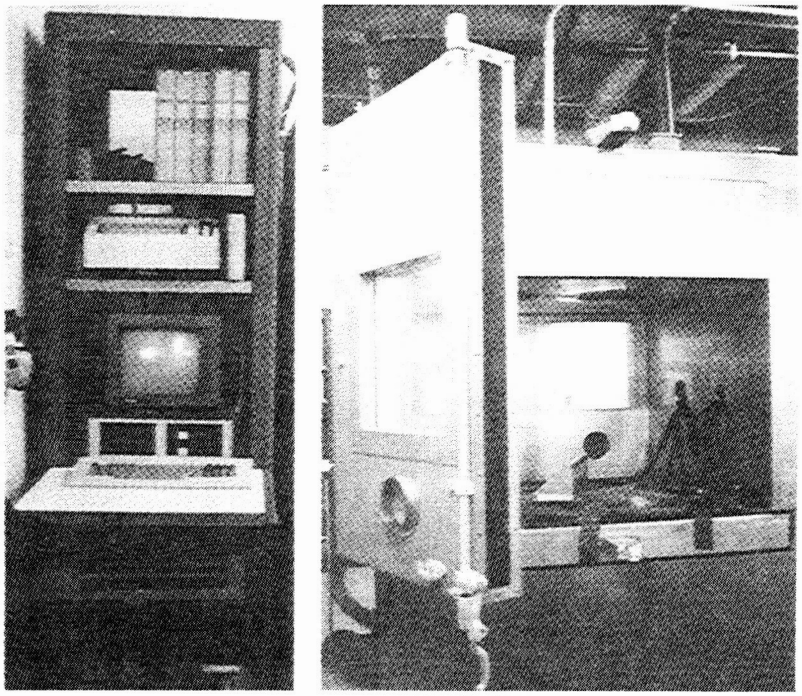

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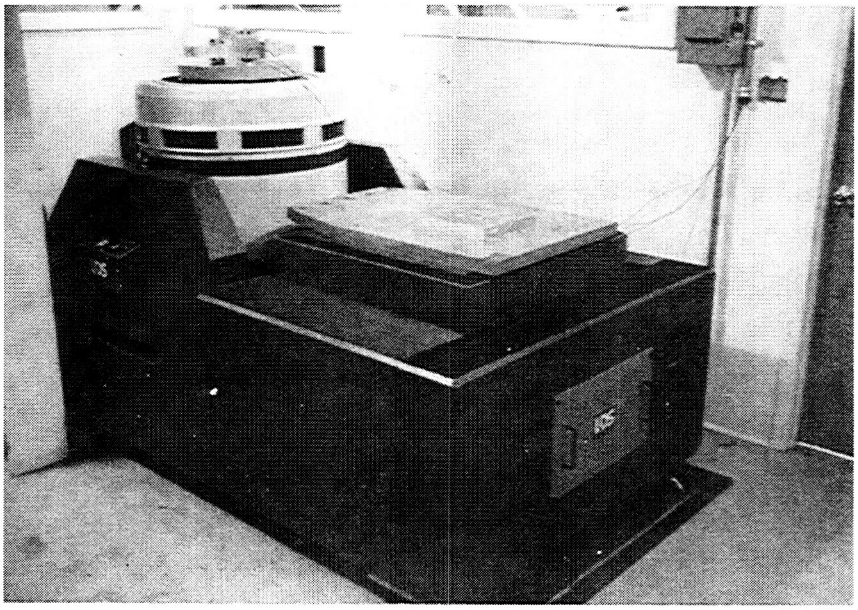
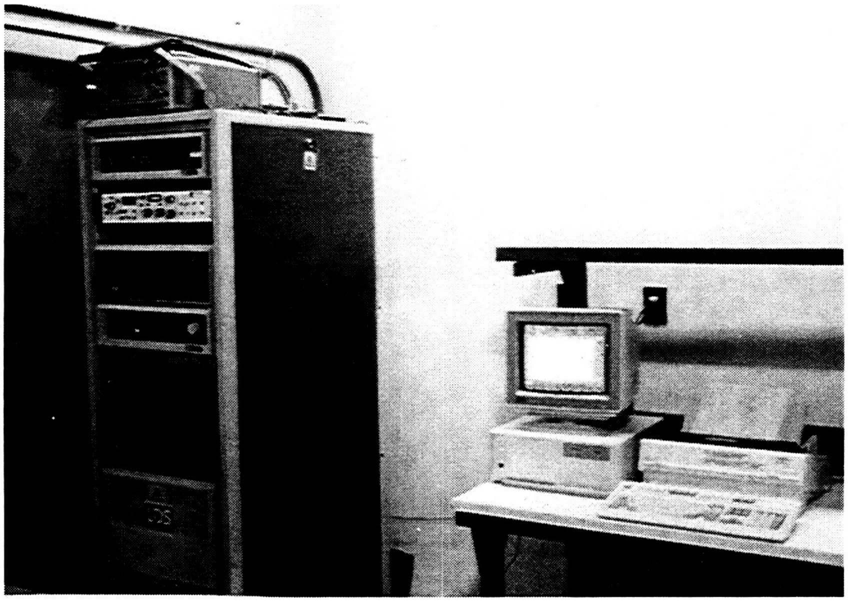
Figure 5. Honeywell Environmental Thermal Chamber



V94-170

a) Shaker Table



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b) Shaker Table Control Room

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 chromotographs
- 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 1×10^{-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).

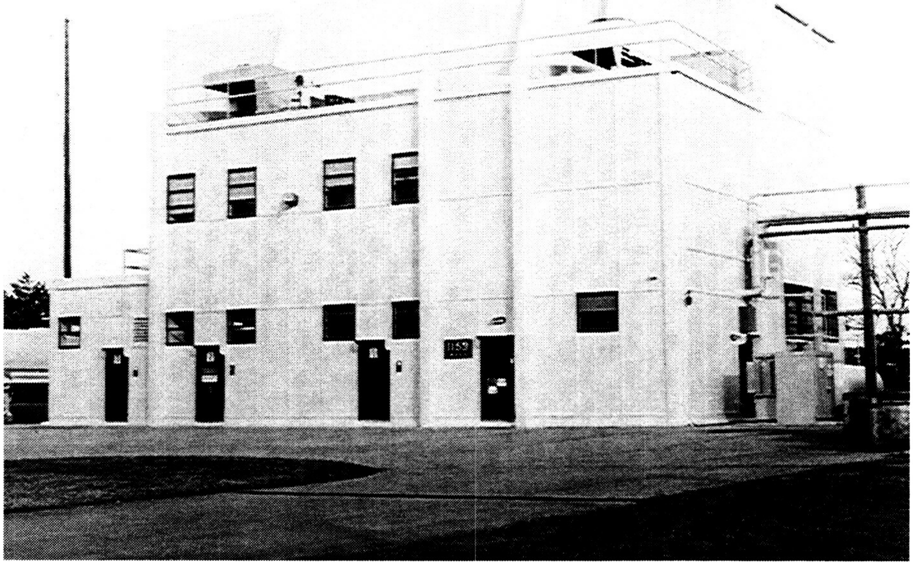

Figure 7. Pyrotechnic Test Facility at NASA-Langley

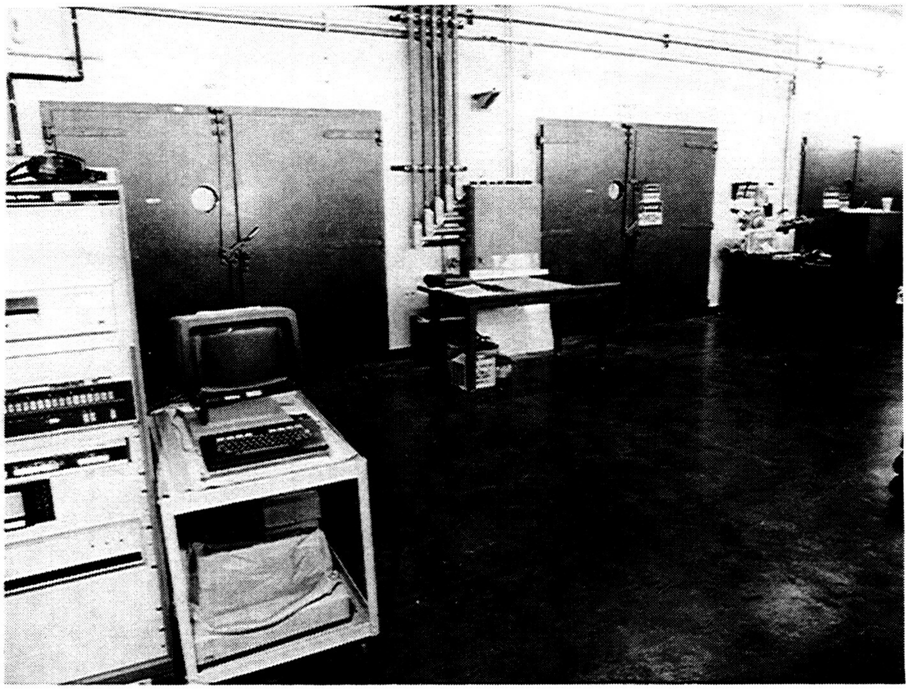
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Figure 8. Pyrotechnic Test Cells at NASA-Langley


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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 CeB_6 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 A1 Kα x-ray source and twin Al/Mg source
  - Five channeltron hemispherical analyzer
  - Small spot analysis area (150 μm)
  - Depth profiling at 10 A 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 (H_2) 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

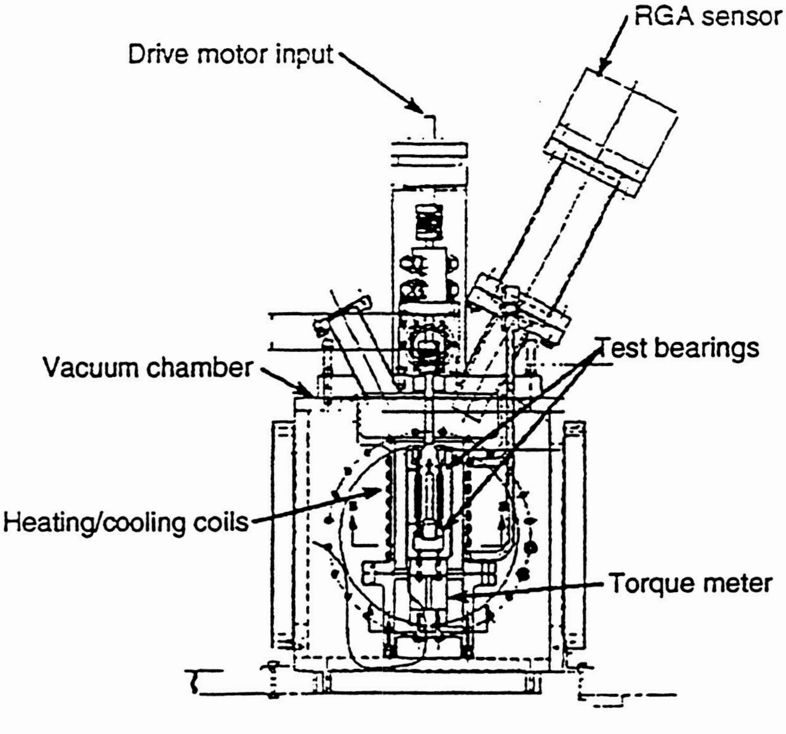
- Thin Film Deposition with Auger Analysis
  - Sputter deposition of conductors ($0 < \text{thickness} \leq 10\ \mu m$)
  - Sample heating to 1000°C
  - In situ scanning auger microscopy analysis
  - Auger depth profiling
- RF-DC Magnetron Sputtering System
  - Three 6.5-in. diameter source material targets capable of co-sputtering
  - Three sputtering gas sources available simultaneously
  - capable of reactive sputtering
  - Base pressure less than 5×10^{-7} torr with LN_2 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, unidirection 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 Å
  - Vertical range up to ~130 µm maximum
  - Scan lengths from 50 µm 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.

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STRUCTURAL DYNAMICS BRANCH

Title: Space Mechanism Accelerated Test Rig

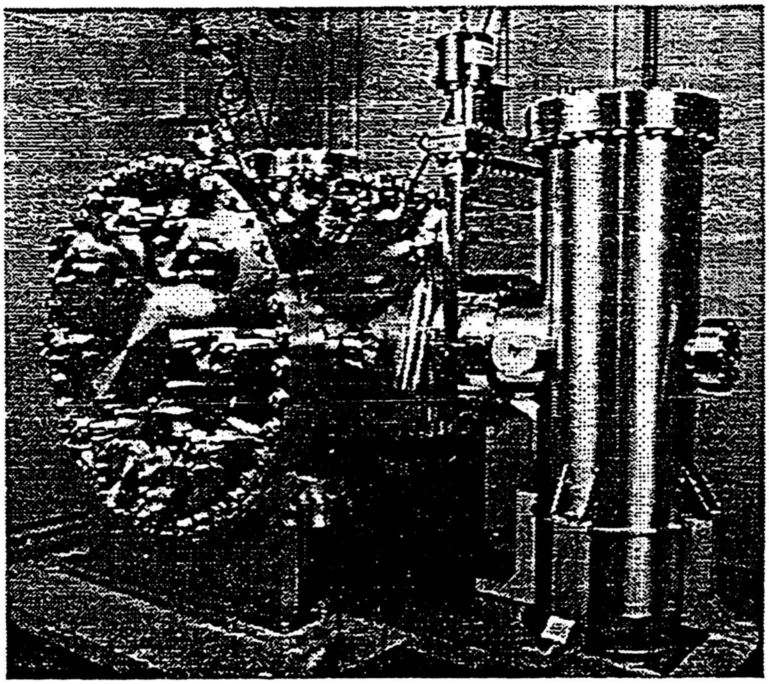
Location: Building 5 - Room CW-14

Description: This rig can test a complete spacecraft mechanism (or any part thereof) under simulated vacuum and lunar surface (dust) conditions.

Features:

- o Mechanism chamber size to fit 24" outside diameter by 24" long.
- o Vacuum to 10^{-7} torr.
- o Low temperatures using LN_2.
- o 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

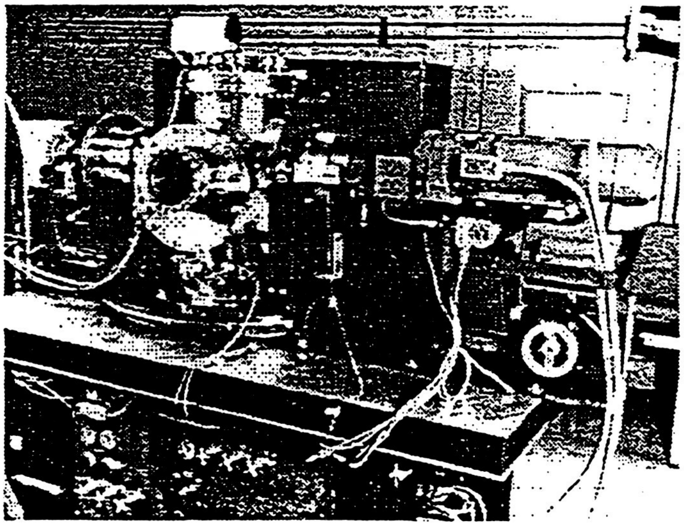
Location: Building 5 - Room CW-14

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.

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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:

- o VME bus-based control computer.
- o Mac II operator interface.
- o 6-degree-of-freedom force torque base reaction. Sensor loads:
  - vertical: up to 250 lbf.
  - horizontal : up to 100 lbf.
  - torque: 1650 in-lbf
- o 4-degree-of-freedom manipulator arm; with 2-degree-of-freedom, no-backlash, traction-driven, differential actuator joints.
- o Robot joint data acquisition of speed, motor torque and angle.

Contact: Douglas A. Rohn 433-3325

Researcher taking data on robot in background.

95TR4/V1

THE PRELIMINARY EVALUATION OF LIQUID LUBRICANTS FOR SPACE APPLICATIONS BY VACUUM TRIBOMETRY

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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 roadback 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, perfluoropolyethers (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 ioization 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 detech 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^{-6}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 MPB 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

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2. Fusaro, R.L. and Khonsari, M.M.: "Liquid Lubrication for Space Applications," NASA TM-105198, 1992.
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9. Masuko, M.; Jansen R.; Ebihara, B.; and Pepper, S.V.: "A Vacuum Four-Ball Tribometer to Evaluate Liquid Lubricatns for Space Applications," NASA TM-106264, 1993.
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12. Conley, P.L. and Bohner, J. J.: "Experience with Synthetic Fluorinated Fluid Lubricants," Twenty-fourth Aerospace Mechanism Symposium, NASA CP-3062, pp. 213-230, Apr. 18-20, 1990.
13. Hilton, M.R. and Fleischauer, P.D.: "Lubricants for High-vacuum Applications,: Aerospace Report No. TR-0091 (6945-03)-6, Mar. 1993.

Table 1. Specifications of Vacuum Tribometers

Apparatus	UHV Rubbing	Four-Ball	Ball-on-Plate	Instrument Bearing
Initial Mean Hertz Stress, GPa	0.43	2-4	1-2	1-1.5
Motion	pure sliding/ reciprocating	pure sliding	rolling/ sliding/ pivoting	rolling/ sliding/ dither
Atmosphere	air, N_2, or vacuum	air, N_2, or vacuum	air, N_2, or vacuum	air, N_2, or vacuum
Load Range, N	~1N	50-1000	45-450	25-200
Speed Range. rpm	0.02-0.2 (linear speed)	10-500	1-100	1-1200 (1Hz dither)
Environmental Pressure, Pa	10^{-7}	10^{-6}	10^{-6}	10^{-6}
Temperature	room	room to 50°C	room to 50°C	room to 50°C
Specimens (440C Steel)	6 mm diameter bearing ball	9.5 mm diameter bearing balls	12.7 mm diameter bearing balls 50.8 mm diameter disks	angular contact instrument bearing (1219 size)

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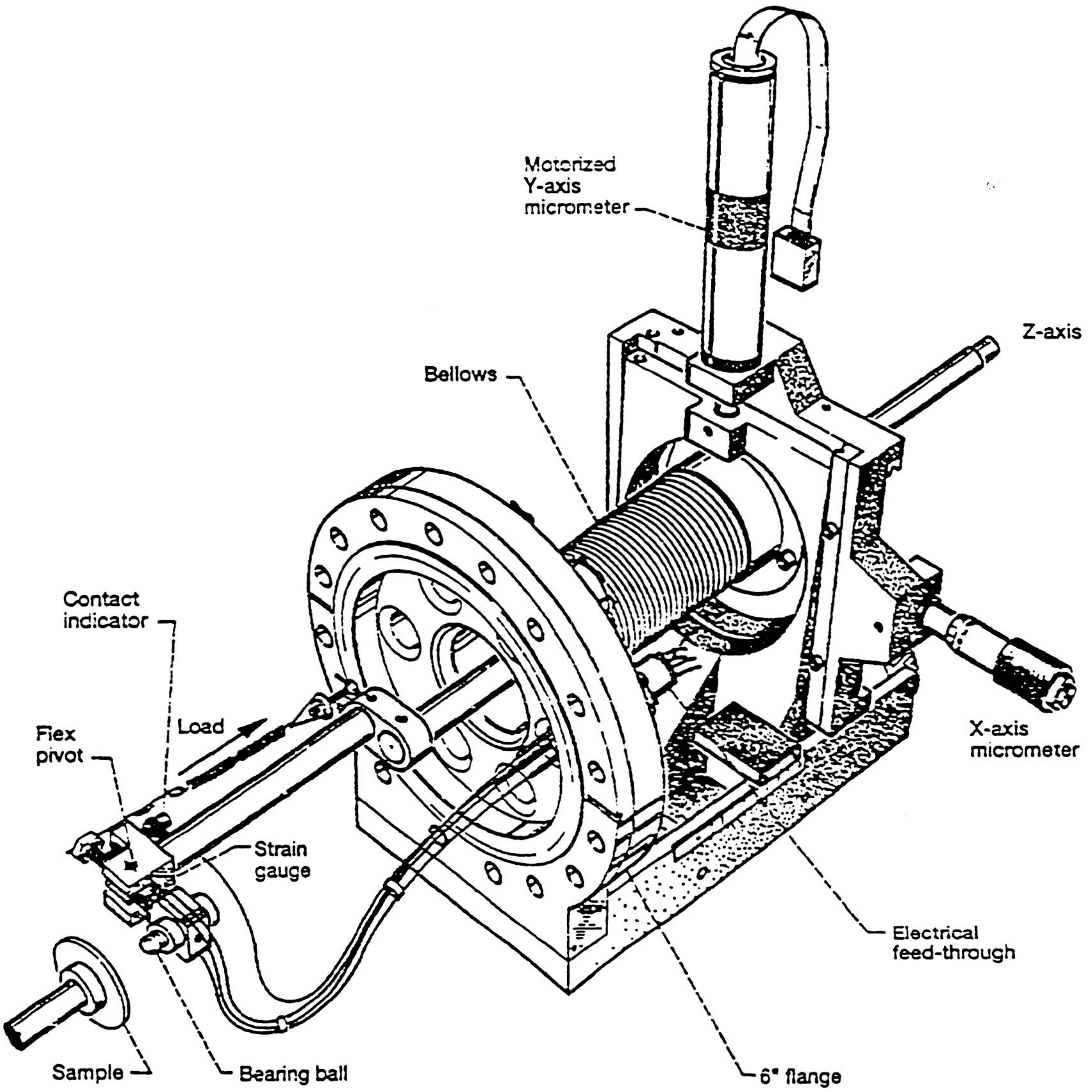

Figure 1.—UHV tribometer.

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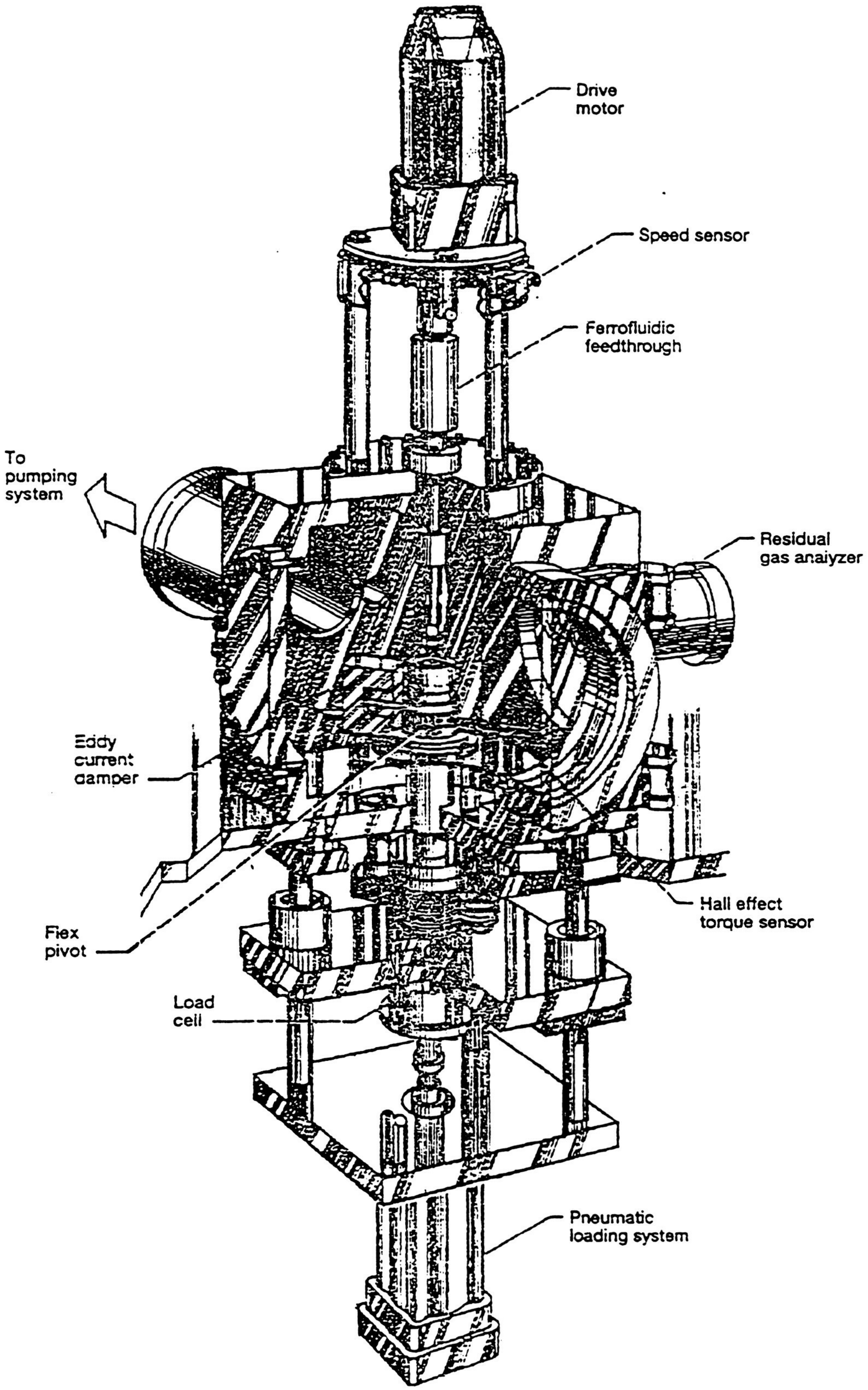

Figure 2.—Four-ball apparatus.

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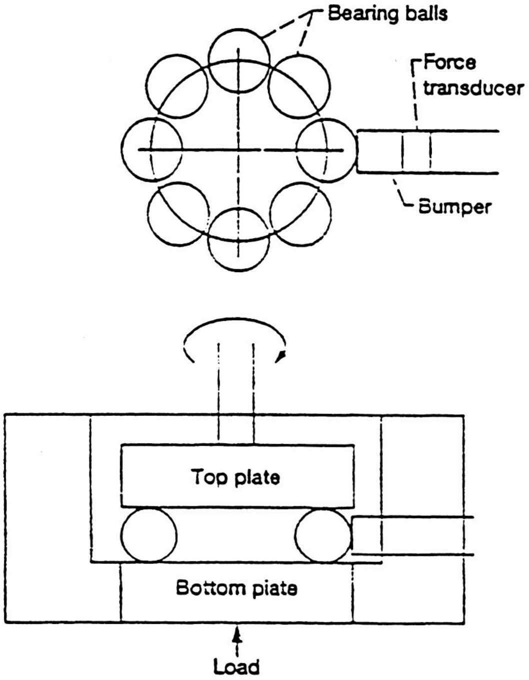

Figure 3.—Ball-on-plate geometry.

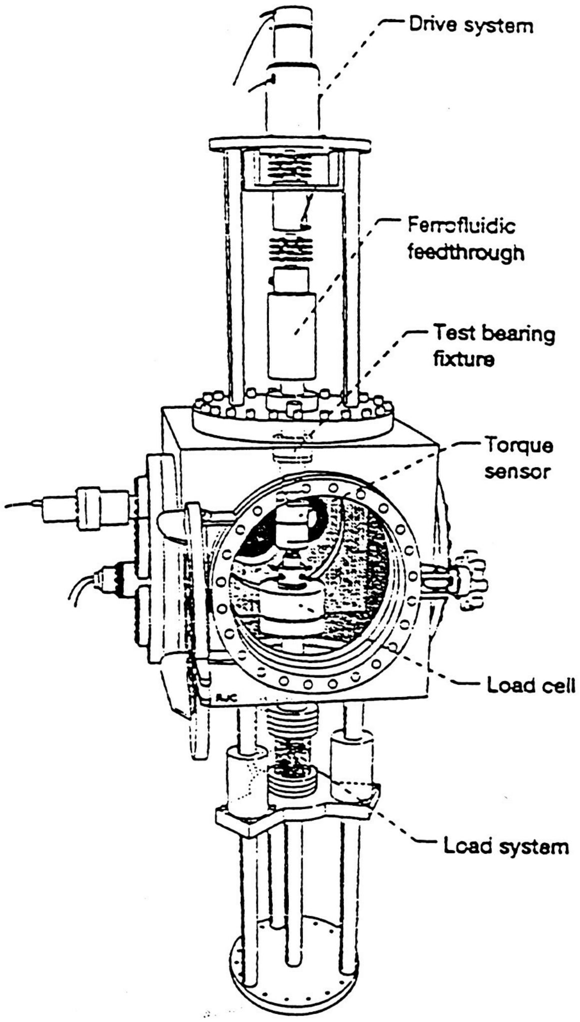

Figure 4.—Instrument bearing test rig.

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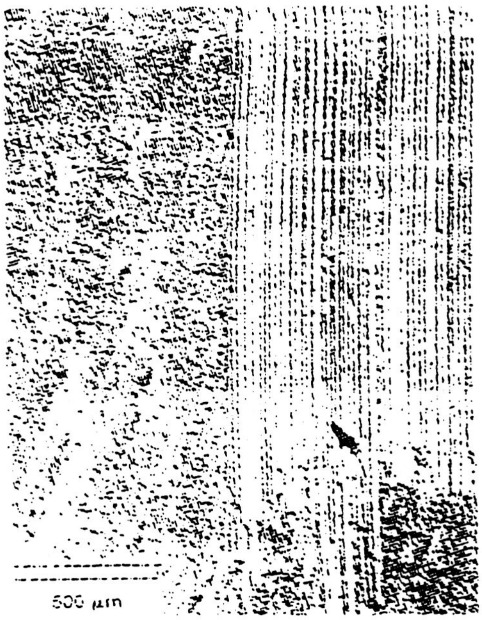

Figure 5.—Optical micrograph of soft 440C steel surface after rubbing with a 440C bearing ball. Lubricant: 50Å Fomblin Z-25.

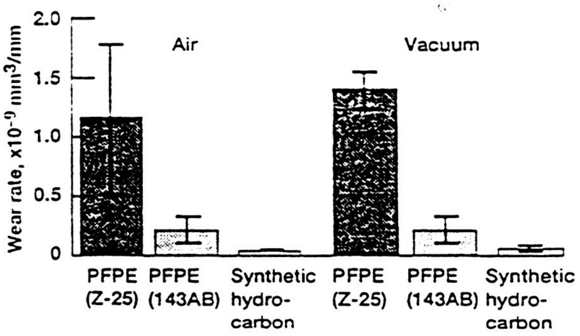

Figure 6.—Wear rates for three commercial aerospace lubricants in air and vacuum (25 °C, 200N load, 100 RPM).

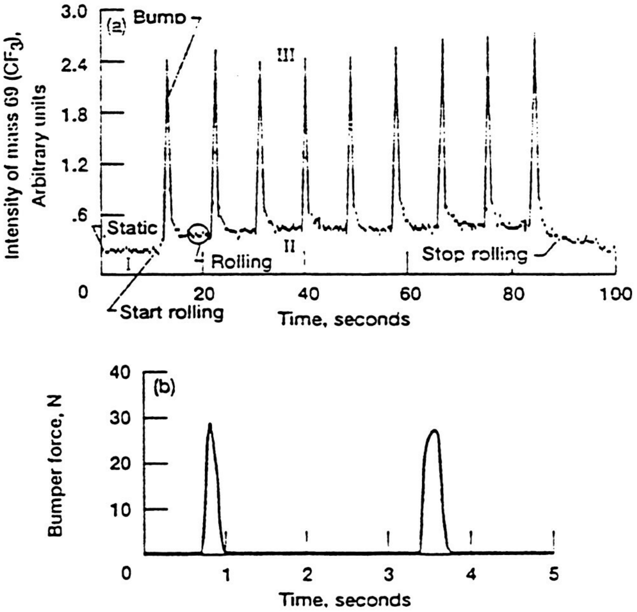

Figure 7.—(a) Intensity of mass 69 (CF_3) from residual gas analyser as a function of time. (b) Bumper force as a function of time (lubricant, Krytox 16256; load, 140N; vacuum, 10^{-6}Pa; speed, 6 RPM).

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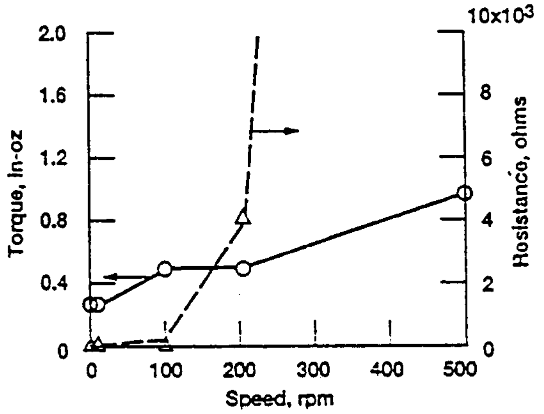

Figure 8.—Bearing torque and contact resistance as a function of speed (44.5N hard load).

95TR4/V1

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 spectroscope (AES) and a small-area multichannel x-ray photoelectron spectroscope (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.

1. Fusaro, R.L. "Tribology Needs for Future Space and Aeronautical Systems." NASA Lewis Research Center, NASA Technical Memorandum 104525, December 1991.
2. Fusaro, R.L. "Government/Industry Response to Questionnaire on Space Mechanisms/Tribology Technology Needs." NASA Lewis Research Center, NASA Technical Memorandum 104358, May 1991.
3. Fusaro, R.L. "Lubrication of Space Systems – Challenges and Potential Solutions." NASA Lewis Research Center, NASA Technical Memorandum 105560, April 1992.
4. Fusaro, R.L. and M.M. Khonsari. "Liquid Lubrication for Space Applications." NASA Lewis Research Center, NASA Technical Memorandum 105198, July 1992.

Index of Papers Sorted by Topic

Aerospace Mechanism Symposia Proceedings
(Volumes 1 through 28)

NASA Langley Research Center	22nd Aerospace Mechanisms Symposium	May 4-6, 1988 NASA CP-2506	N88-23892
NASA Marshall Space Flight Ctr	23rd Aerospace Mechanisms Symposium	May 3-5, 1989 NASA CP-3032	N89-23892
NASA Kennedy Space Center	24th Aerospace Mechanisms Symposium	April 18-20, 1990 NASA CP-3062	N90-22079
Jet Propulsion Laboratory	25th Aerospace Mechanisms Symposium	May 8-10, 1991 NASA CP-3113	N91-24603
NASA Goddard Space Flight Ctr	26th Aerospace Mechanisms Symposium	May 13-15, 1992 NASA CP-3147	N92-25067
NASA Ames Research Center	27th Aerospace Mechanisms Symposium	May 12-14, 1993 NASA CP-3205	(Not yet assigned)
NASA Lewis Research Center	28th Aerospace Mechanisms Symposium	May 18-20, 1994 NASA CP-3260	(Not yet assigned)

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)
BRG	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
GIMB	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
TRANS	Utility (power,data,fluid) transfer/Umbilicals
TRIBO	Tribology (could have bearing info)
WHEEL	Momentum/Reaction wheels (could have actuator, bearing info)
MISC	Miscellaneous

The papers listed in bold type were the Hertzl Award winners for each symposium.

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10	18	'76	JPL	Solar Array Drive System	F. D. Berkopec, J. C. Sturman and R. W. Stanhouse	185	ACT	SA	
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17	5	'83	JPL	Linear Boom Actuator Designed for the Galileo Spacecraft	E. F. Koch	81	ACT		
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18	9	'84	GSFC	Design and Development of Two-Failure Tolerant Mechanisms for the Spaceborne Imaging Radar (Sir-B) Antenna	S. J. Presas	131	ACT	DRIVE	DAMP
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18	18	'84	GSFC	Smart Motor Technology	D. Packard and D. Schmitt	301	ACT		
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21	22	'87	JSC	GIOTTO's Antenna De-Spin Mechanism: Its Lubrication and Thermal Vacuum Performance	M. J. Todd and K. Parker	295	ACT	BRG	TRIBO
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24	5	'90	KSC	A Soft Actuation System for Segmented Reflector Articulation and Isolation	M. L. Agronin and L. Jandura	57	ACT	ANT	
24	14	'90	KSC	Driving and Latching of the Starlab Pointing Mirror Doors	H. R. Beaven Jr and R. R. Avina	187	ACT	LATCH	
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19	7	'85	ARC	Design and Development of a Constant Speed Solar Array Drive	H. M. Jones and N. Roger	103	SA	ACT	
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13	2	'79	JSC	Design and Development of a Motion Compensator for the RSRA Main Rotor Control	P. Jeffrey and R. Huber	15	AIR		
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14	18	'80	LRC	F100 Exhaust Nozzle Area Control Mechanism	J. R. Kozlin	211	AIR	GMB	
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19	23	'85	ARC	Circulation Control Lift Generation Experiment: Hardware Development	T. L. Panontin	363	AIR		
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26	24	'92	GSFC	12-Foot Pressure Wind Tunnel Restoration Project Model Support Systems	G. E. Sasaki	367	STE	AIR	
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10	13	'76	JPL	HELIOS Experiment 5 Antenna Mechanism	E. J. W. Muller	133	ANT		
12	4	'78	ARC	Deployable 0.015-Inch-Diameter Wire Antenna	L. DeBiasi	35	ANT	DRIVE	
12	20	'78	ARC	Deployable Antenna Reflector	W. B. Palmer	223	ANT		
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19	2	'85	ARC	Hoop/Column Deployment Mechanism Overview	B. B. Allen and D. H. Butler	23	ANT	DEPLOY	
22	1	'88	LRC	15-Meter Diameter Hoop/Column Antenna Surface Control Actuator System	E. L. Ahl Jr. and J. B. Miller	1	ANT	GMB	
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8	21	'73	LRC	Viking Lander Antenna Deployment Mechanism	K. H. Hopper and D. S. Monitor	257	DEPLOY	ANT	
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24	5	'90	KSC	A Soft Actuation System for Segmented Reflector Articulation and Isolation	M. L. Agronin and L. Jandura	57	ACT	ANT	
13	12	'79	JSC	Reliability Breakthrough: An Antenna Deployment/Positioning Mechanism with Electrical and Mechanical Redundancy	M. C. Olson, L. W. Briggs and J. B. Pentecost	137	GIMB	ACT	ANT
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4	9	'69	USC	Spacecraft Booms: Present and Future	G. G. Herzl	55	BOOM		
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16	13	'82	KSC	Estimation of Bearing Contact Angle In-Situ by X-Ray Kinematography	P. H. Fowler and F. Manders	189	BRG		
17	22	'83	JPL	Compact Magnetic Bearing for Gimballed Momentum Wheel	K. Yabu-uchi, M. Inoue and S. Akishita	333	BRG	WHEEL	
19	9	'85	ARC	Properties of Thin-Section Four-Point-Contact Ball Bearings in Space	R. A. Rowntree	141	BRG		
20	9	'86	LeRC	Rolling Element Bearings in Space	J. W. Kannel and K. F. Dufrane	121	BRG		
21	23	'87	JSC	Anatomy of a Bearing Torque Problem	D. D. Phinney	315	BRG		
21	24	'87	JSC	Space Station Alpha Joint Bearing	M. R. Everman, P. A. Jones and P. A. Spencer	329	BRG		
22	16	'88	LRC	Experience with Duplex Bearings in Narrow Angle Oscillating Applications	D. D. Phinney, C. L. Pollard and J. T. Hinricks	211	BRG	GMB	
22	17	'88	LRC	On the Torque and Wear Behavior of Selected Thin-Film, MOS2-Lubricated Gimbal Bearings	J. J. Bohner and P. L. Conley	227	BRG		
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22	19	'88	LRC	Two Gimbal Bearing Case Studies: Some Lessons Learned	S. H. Loewenthal	253	BRG	GMB	
23	22	'89	MSFC	The In-Vacuo Torque Performance of Dry-Lubricated Ball Bearings at Cryogenic Temperatures	S. G. Gould and E. W. Roberts	319	BRG	TRIBO	
24	18	'90	KSC	Positive Lubrication System	D. W. Smith and F. L. Hooper	243	BRG		
24	19	'90	KSC	Active Control of Bearing Preload Using Piezoelectric Translators	T. W. Nye	259	BRG		
24	20	'90	KSC	Test Results and Flight Experience of Ball Bearing Momentum and Reaction Wheels	W. Auer	273	BRG	WHEEL	
24	21	'90	KSC	On the Design and Development of a Miniature Ceramic Gimbal Bearing	R. A. Hanson, B. O'Dwyer, K. M. Gordon and E. W. Jarvis	289	BRG		
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25	12	'91	JPL	Spin Bearing Retainer Design Optimization	E. A. Boesiger and M. H. Warner	161	BRG	TRIBO	
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28	21	'94	LeRC	Development of Long-Life, Low-Noise Linear Bearings for Atmospheric Interferometry	E. W. Roberts, R. B. Watters, S. Gill, R. Birner, G. Lange & W. Posselt	245	BRG	TRIBO	
28	23	'94	LeRC	Design of a High-Speed Reliable Ball Bearing	H. B. Singer & E. Gelotte	279	BRG		
3	6	'68	JPL	Development Philosophy for Snap Mechanisms	O. P. Steel III	45	MISC	BRG	

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21	22	'87	JSC	GIOTTO's Antenna De-Spin Mechanism: Its Lubrication and Thermal Vacuum Performance	M. J. Todd and K. Parker	295	ACT	BRG	TRIBO
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28	4	'94	LeRC	International Space Station Alpha's Bearing, Motor, Roll Ring Module Developmental Testing and Results	D. L. O'Brien	51	TRANS	BRG	
28	19	'94	LeRC	Pointing and Tracking Space Mechanism for Laser Communication	A. Brunschvig & M. de Boisanger	211	GIMB	BRG	
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6	3	'71	ARC	Sphere Launcher	W. B. Reed	13	SEP	DAMP	
7	6	'72	JSC	Mechanical Component Screening for Scanner	J. L. Olson and W. J. Quinn	59	INST	DAMP	BRG
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17	1	'83	JPL	Tethered Satellite Control Mechanism	G. M. Kyrias	1	DEPLOY	BOOM	
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18	6	'84	GSFC	Evolution from a Hinge Actuator Mechanism to an Antenna Deployment Mechanism for Use on the European Large Communications Satellite (L-Sat/Olympus)	M. D. De'Ath	79	DEPLOY		
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23	1	'89	MSFC	The Evolution of Space Mechanisms Technology in the European Space Agency R & D Program	D. Wyn-Roberts	1	GMB	DEPLOY	TRIBO
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23	20	'89	MSFC	Practical Experiences with Worm Gearing for Spacecraft Power Transmission Applications	W. Purdy and W. McCown	291	DRIVE		
24	3	'90	KSC	SPOT4 Space Magnetic Recorder Mechanisms	A. Borrien, E. Vialatoux, J. L. Lhermet and A. Didier	25	DRIVE		
25	17	'91	JPL	Harmonic Drive Gear Error: Characterization and Compensation for Precision Pointing and Tracking	T. W. Nye and R. P. Kraml	237	DRIVE		
3	3	'68	JPL	High-Response Electromechanical Control Actuator	G. D. Goldshine and G. T. Lacy	19	ACT	DRIVE	
4	14	'69	USC	Mariner Mars 1969 Scan Actuator	G. S. Perkins	103	ACT	DRIVE	
8	28	'73	LRC	Viking Orbiter 1975 Articulation Control Actuators	G. S. Perkins	335	ACT	DRIVE	
11	15	'77	GSFC	GEOS 20-m Cable Boom Mechanism	G. K. Schmidt and K. Suttner	147	DEPLOY	DRIVE	
12	4	'78	ARC	Deployable 0.015-Inch-Diameter Wire Antenna	L. DeBiasi	35	ANT	DRIVE	
14	10	'80	LRC	Mechanisms of UK Radiometers Flown on Nimbus 5 and 6 with Particular Reference to Bearings, Pivots and Lubrication	H. Hadley	101	BRG	DRIVE	
15	3	'81	MSFC	**Payload Retention Latches for the Shuttle Orbiter**	**R. D. Renken and R. P. Maxwell**	31	LATCH	DRIVE	
15	23	'81	MSFC	Fully Redundant Power Hinge for Landsat-D Appendages	F. E. Mamrol and D. N. Matteo	341	DEPLOY	DRIVE	
17	4	'83	JPL	Broadbased Actuator Concept for Spaceflight Application	J. C. Hammond	55	ACT	DRIVE	
18	9	'84	GSFC	Design and Development of Two-Failure Tolerant Mechanisms for the Spaceborne Imaging Radar (Sir-B) Antenna	S. J. Presas	131	ACT	DRIVE	DAMP
20	12	'86	LeRC	Dual Wound DC Brush Motor Gearhead	B. W. Henson	165	ACT	DRIVE	
20	15	'86	LeRC	Evaluation of a High Torque Backlash-Free Roller Actuator	B. M. Steinetz and D. A. Rohn	205	ACT	DRIVE	
21	9	'87	JSC	Traction-Drive, Seven-Degree-of-Freedom Telerobot Arm: A Concept for Manipulation in Space	D. P. Kuban and D. M. Williams	111	ROBOT	DRIVE	
22	7	'88	LRC	On the Danger of Redundancies in some Aerospace Mechanisms	M. Chew	87	DEPLOY	DRIVE	
22	22	'88	LRC	Robotic Joint Experiments under Ultravacuum	A. Borrien and L. Petitjean	307	ROBOT	DRIVE	
25	14	'91	JPL	Development of Solid-Lubricated Ball-Screws for Use in Space	M. Chiba, T. Gyougi, M. Nishimura and K. Seki	195	TRIBO	DRIVE	
27	10	'93	ARC	Metal Band Drives in Spacecraft Mechanisms	D. Maus	137	ACT	DRIVE	
4	1	'69	USC	Soil Sampler Development for Unmanned Probes	W. H. Bachle	3	SAMP	BOOM	DRIVE
4	20	'69	USC	Dragline Sample-Acquisition Mechanism	H. M. Alexander	149	SAMP	ACT	DRIVE
8	7	'73	LRC	Development and Test of a Long-Life, High Reliability Solar Array Drive Actuator	D. L. Kirkpatrick	69	SA	ACT	DRIVE
9	18	'74	KSC	Modern Mechanisms Make Manless Martian Missile Mobile - Spin-Off Spells Stariclimbing Self-Sufficiency for Earthbound Handicapped	G. N. Sandor, D. R. Hassel and P. F. Marino	247	EVA	ACT	DRIVE

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27	11	'93	ARC	**Pointing Mechanisms for the Shuttle Radar Laboratory**	G. W. Lillenthal, A. M. Olivera and L. R. Shiraishi	147	GMB	ACT	DRIVE
4	4	'69	USC	Dynamics of Human Self-Rotation	T. R. Kane	27	EVA		
5	23	'70	GSFC	Development of Payload Subsystem-Primate Mission-Biosatellite Program	J. F. Hall Jr.	177	EVA		
7	16	'72	JSC	Lunar Cart	G. C. Miller	169	EVA		
7	17	'72	JSC	Liquid Pump for Astronaut Cooling	M. A. Carson	181	EVA		
7	23	'72	JSC	Manipulator Technology for the Space Shuttle	E. G. Burroughs	267	EVA		
8	25	'73	LRC	Gravity Exercise System	W. E. Brandt and A. L. Clark	311	EVA		
9	18	'74	KSC	Modern Mechanisms Make Manless Martian Missile Mobile - Spin-Off Spells Stairclimbing Self-Sufficiency for Earthbound Handicapped	G. N. Sandor, D. R. Hassel and P. F. Marino	247	EVA	ACT	DRIVE
9	19	'74	KSC	Loadcell Supports for a Dynamic Force Place	C. W. Keller, L. M. Musil and J. L. Hagy	265	EVA	STE	
9	21	'74	KSC	Unique Challenge: Emergency Egress and Life Support Equipment at KSC	H. M. Wadell Jr.	295	EVA		
12	1	'78	ARC	Development of a Bedrest Muscle Stress Apparatus	R. Booher, L. Hooper and D. N. Setzer	3	EVA		
12	10	'78	ARC	Design Features of Selected Mechanisms Developed for Use in Spacelab	I. W. Inden	101	EVA		
14	3	'80	LRC	Orbiter Door Closure Tools	W. R. Acres	19	EVA		
14	4	'80	LRC	Orbiter Emergency Crew Escape System	W. W. Lofland	33	EVA		
15	4	'81	MSFC	Space Shuttle Slidewire Emergency Egress System	G. B. Jeffcoat and E. S. Stephan	47	EVA		
18	14	'84	GSFC	Spacelab 4 - Primate Experiment Support Hardware	P. R. Fusco and R. J. Peyran	215	EVA		
21	4	'87	JSC	AKM Capture Device	W. D. Harwell	55	EVA		
23	12	'89	MSFC	Astronaut Tool Development: An Orbital Replaceable Unit - Portable Handhold	J. W. Redmon Jr.	181	EVA		
25	1	'91	JPL	CETA Truck and EVA Restraint System	D. C. Beals and W. R. Merson	1	EVA		
26	21	'92	GSFC	Design, Development, and Fabrication of Extravehicular Activity Tools for the Transfer Orbit Stage	L. M. Albritton, J. R. Redmon and T. R. Tyler	315	EVA		
27	21	'93	ARC	Portable Linear Sled (PLS) for Biomedical Research	W. Vallotton, J. Temple, D. Matsuhior and T. Wynn	315	EVA		
28	14	'94	LeRC	Pip Pin Reliability and Design	L. P. Skyles	153	EVA		
1	8	'66	USC	Drag Make-up Sensor for Low-Altitude Satellites	W. R. Davis	91	GMB		
2	8	'67	USC	Surveyor Television Mechanism	J. B. Gudikunst	59	GMB	TRIBO	
4	17	'69	USC	Thermal Heliotrope: A Passive Sun-Tracker	R. C. Byxbee and D. R. Lott	127	GMB		
5	24	'70	GSFC	Mariner Mars 1971 Gimbal Actuator	G. S. Perkins	185	GMB	ACT	TRIBO
6	12	'71	ARC	NASA-ARC 36-Inch Airborne Infrared Telescope	R. E. Mobley and R. M. Cameron	81	GMB		

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7	8	'72	JSC	Zero-Gravity Tissue-Culture Laboratory	J. E. Cook, P. Montgomery Jr. and J. S. Paul	81	GMB		
8	22	'73	LRC	Optical Module for the Integrated Real-Time Contamination Monitor	E. H. Wrench	271	GMB		
10	11	'76	JPL	High-Resolution, Adjustable, Lockable Laser Mirror Mount	C. H. Chadwick	116	GMB		
11	16	'77	GSFC	Low Cost High Temperature Sun Tracking Solar Energy Collector	G. S. Perkins	157	GMB		
12	21	'78	ARC	NASA-ARC 91.5-CM Airborne Infrared Telescope	R. E. Mobley and T. M. Brown	233	GMB		
13	3	'79	JSC	**Two-Axis Pointing System for An Orbiting Astronomical Instrument**	**R. F. Turner and J. G. Firth**	27	GMB		
13	12	'79	JSC	Reliability Breakthrough: An Antenna Deployment/Positioning Mechanism with Electrical and Mechanical Redundancy	M. C. Olson, L. W. Briggs and J. B. Pentecost	137	GMB	ACT	ANT
13	22	'79	JSC	IUS Thrust Vector Control (TVC) Servo System	G. E. Conner	271	GMB		
14	13	'80	LRC	Precision Bearing Gimbal System for the Teal Ruby Program	C. H. Lowry	143	GMB		
14	15	'80	LRC	Ku Band Deployed Assembly and Gimbal	T. E. Deal	163	GMB		
14	26	'80	LRC	Design and Application of an Antenna Positioner Mechanism for Intelsat-V Series Communication Satellite	B. Szeto	311	GMB		
14	27	'80	LRC	Mechanisms of the SAMS Experiment Flown on Nimbus 7 with Particular Reference to the 2 Axis Scanning Mirror	H. Hadley	323	GMB		
15	16	'81	MSFC	Systeme D'Orientation Fine D'Antenne (An Antenna Fine Pointing Mechanism)	B. Hubert and P. Brunet	235	GMB		
15	17	'81	MSFC	Antenna Pointing Mechanism for Large Reflector Antennas	H. Heimerdinger	253	GMB	ANT	
15	18	'81	MSFC	Drive Unit for the Instrument Pointing System	R. Bimer and M. Roth	263	GMB	TRANS	
16	11	'82	KSC	Development of a High Stability Pointing Mechanism for Wide Application	A. J. D. Brunnen and R. H. Bentall	159	GMB		
17	18	'83	JPL	Design and Development of a Mounting and Jettison Assembly for the Shuttle Orbiter Advanced Gimbal System	E. S. Korzeniowski	267	GMB	SEP	
17	21	'83	JPL	Design of the Galileo Remote Science Pointing Actuators	F. W. Osborn	315	GMB	TRANS	
18	12	'84	GSFC	Design and Development of a Solar Tracking Unit	I. W. Jones and J. B. Miller	187	GMB		
18	13	'84	GSFC	Antenna Tracking Mechanism for Geostationary Satellites	C. M. Francis	203	GMB		
20	14	'86	LeRC	RF Switch Positioner for Communications Satellite Network	A. G. Storaasli, H. P. Griesser and R. W. Grant	195	GMB		
20	22	'86	LeRC	Weight and Power Savings Shaft Encoder Interfacing Techniques for Aerospace Applications	D. H. Breslow	303	GMB		
21	14	'87	JSC	Pointed Telescope Subassembly for the UARS High Resolution Doppler Imager	R. D. Renken	195	GMB		
23	1	'89	MSFC	The Evolution of Space Mechanisms Technology in the European Space Agency R & D Program	D. Wyn-Roberts	1	GMB	DEPLOY	TRIBO
23	18	'89	MSFC	Design of a 60 GHz Beam Waveguide Antenna Positioner	K. S. Emerick	267	GMB	ANT	
23	21	'89	MSFC	A Two-axis LASER Boresight System for a Shuttle Experiment	J. F. DeLorme	309	GMB		

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25	7	'91	JPL	Pointing/Roll Mechanism for the Ultraviolet Coronagraph Spectrometer	M. Ostaszewski and L. J. Guy	93	GMB		
25	8	'91	JPL	**SIRTF/IRS Cryogenic Grating Drive Mechanism (Arc Second Positioning at 4**	**M. J. Kublitschek**	107	GMB		
26	8	'92	GSFC	Modular Antenna Pointing System for the Explorer Platform Satellite	J. Andrus and E. Korzeniowski	111	GMB		
27	11	'93	ARC	**Pointing Mechanisms for the Shuttle Radar Laboratory**	**G. W. Lilienthal, A. M. Olivera and L. R. Shiraishi**	147	GMB	ACT	DRIVE
27	24	'93	ARC	SP-100 Control Drive Assembly Development	T. E. Gleason, A. R. Gilchrist and G. Schuster	367	GMB		
28	10	'94	LeRC	Leveraging Metal Matrix Composites to Reduce Costs in Space Mechanisms	T. Nye, R. Claridge & J. Walker	129	GMB		
28	13	'94	LeRC	Design, Characterization, and Control of the NASA Three-Degree-of-Freedom Reaction Compensation Platform	C. Birkhimer, W. Newmann, B. B. Choi & C. Lawrence	147	GMB	ACT	DAMP
28	15	'94	LeRC	Intelligent Control of a Multi-Degree-of-Freedom Reaction Compensating Platform System using Fuzzy Logic	B. B. Choi, C. Lawrence & Yueh-Jaw Lin	159	GMB		
28	17	'94	LeRC	Two Axis Antenna Positioning Mechanism	M. Herald & L. C. Wai	183	GMB		
28	19	'94	LeRC	Pointing and Tracking Space Mechanism for Laser Communication	A. Brunschvig & M. de Boisanger	211	GMB	BRG	
28	27	'94	LeRC	Lessons Learned from Selecting and Testing Spaceflight Potentiometers	T. Iskenderian	339	GMB		
8	10	'73	LRC	New Approach to Long-Life-Noncontacting Electromechanical Devices	E. J. Devine	109	ACT	GMB	
13	13	'79	JSC	Development of Drive Mechanism for Communication Satellites	A. C. Schneider and T. D. McLay	151	ACT	GMB	
14	18	'80	LRC	F100 Exhaust Nozzle Area Control Mechanism	J. R. Kozlin	211	AIR	GMB	
19	8	'85	ARC	Application of Traction Drives as Servo Mechanisms	S. H. Loewenthal, D. A. Rohn and B. M. Steinetz	119	DRIVE	GMB	
22	1	'88	LRC	15-Meter Diameter Hoop/Column Antenna Surface Control Actuator System	E. L. Ahl Jr. and J. B. Miller	1	ANT	GMB	
22	16	'88	LRC	Experience with Duplex Bearings in Narrow Angle Oscillating Applications	D. D. Phinney, C. L. Pollard and J. T. Hinricks	211	BRG	GMB	
22	19	'88	LRC	Two Gimbal Bearing Case Studies: Some Lessons Learned	S. H. Loewenthal	253	BRG	GMB	
23	4	'89	MSFC	Design, Fabrication, and Test of a 4750 Newton-Meter-Second Double Gimbal Control Moment Gyroscope	L. Cook, P. Golley, H. Krome, J. Blondin, C. Gurrisi and J. Kolvek	59	WHEEL	GMB	
24	1	'90	KSC	Cycle of Life Machine for AX-5 Space Suit	D. S. Schenberger	1	STE	GMB	
26	17	'92	GSFC	Mechanisms of the Space Active Vibration Isolation (SAVI)	F. Schmitt	245	STE	GMB	

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1	13	'66	USC	Mariner IV Science Platform Structure and Actuator Design, Development, and Performance	G. Coyle and E. Floyd	145	INST	LATCH	
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3	13	'68	JPL	Mechanical Design of the Spin-Scan Cloud Camera	D. T. Upton	117	INST	ACT	
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5	14	'70	GSFC	Scanning Mirror System for the Apollo Telescope Mount Ultraviolet Spectroheliometer	C. O. Highman	113	INST	BRG	
6	13	'71	ARC	Goddard Helical Tape Recorder	F. T. Martin and D. K. McCarthy	89	INST		
6	14	'71	ARC	Shutter Mechanism for Spacecraft Spectrophotometer	A. Weilbach	95	INST		
7	6	'72	JSC	Mechanical Component Screening for Scanner	J. L. Olson and W. J. Quinn	59	INST	DAMP	BRG
7	22	'72	JSC	Scanning Mirror for Infrared Sensors	R. H. Anderson and S. B. Bernstein	251	INST		
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10	20	'76	JPL	Viking GC/MS Mechanisms Design and Performance	C. P. Chase and O. Weilbach	208	INST		
11	2	'77	GSFC	Scanning and Focusing Mechanisms of Metosat Radiometer	J. Jouan	13	INST		
11	12	'77	GSFC	Torque-While-Turnaround Scan Mirror Assembly	C. J. Starkus	111	INST		
11	20	'77	GSFC	Focus Drive Mechanism for the IUE Scientific Instrument	E. J. Divine and T. B. Dennis Jr.	207	INST		
13	15	'79	JSC	Magnetic Spring in Oscillating Mirror Linear Scanner for Satellite Camera	G. Thomin and C. Fouche	183	INST		
14	24	'80	LRC	Design of an Atmospheric Sounding Radiometer for the Goes Meteorological Satellite System	R. G. Jensen	289	INST		
14	25	'80	LRC	Polarimeter for the High Resolution Ultraviolet Spectrometer/Polarimeter	J. A. Calvert	303	INST		
15	5	'81	MSFC	Multi-Channel Chopper System for a Total Ozone Mapping Spectrometer	A. J. Krueger and A. O. Weilbach	63	INST	TRIBO	
15	6	'81	MSFC	Systems Approach to Mechanisms for a White Light Coronagraph/X-Ray XUV Telescope	R. Mastronardi and R. E. Cabral	77	INST		
15	15	'81	MSFC	Design and Development of an Optical Scanning Mechanism (OSMA) with Minimum Momentum Transfer	L. B. F. Sainz, E. Herrera, J. M. Bajo and H. J. Mallard	219	INST	BRG	
17	6	'83	JPL	Polarizer Mechanism for the Space Telescope Faint Object	M. D. Thulson	97	INST		
17	9	'83	JPL	Evaluation of Scanning Earth Sensor Mechanism on Engineering Test Satellite IV	M. Ikeuchi, Y. Wakabayashi, Y. Ohkami, T. Kida, T. Ishigaki and M. Matsumoto	143	INST	BRG	

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20	6	'86	LeRC	A Mirror Transport Mechanism for Use at Cryogenic Temperatures	K. W. Stark and M. Wilson	73	INST		
20	7	'86	LeRC	Shutter Mechanism for Calibration of the Cryogenic Diffused Infrared Background Experiment (DIRBE) Instrument	A. Tyler	97	INST		
25	10	'91	JPL	A Synchronous Chopper Mechanism for Use at Cryogenic Temperature	C. Hakun, A. Tyler and C. de Kramer	135	INST		
25	11	'91	JPL	Cryogenic Mechanisms for Scanning and Interchange of the FABRY-PEROT Interferometers in the ISO Long Wavelength Spectrometer	G. R. Davis, I. Furniss, T. J. Patrick, R. C. Sidey and W. A. Towlson	151	INST		
27	6	'93	ARC	Design and Testing of the LITE Variable Field Stop Mechanism	R. A. Dillman	83	INST		
27	12	'93	ARC	Optical Chopper Assembly for the Mars Observer	T. Allen	165	INST		
27	15	'93	ARC	Three High-Duty-Cycle, Space-Qualified Mechanisms	D. Akin, J. Wolfson and R. Horber	219	INST		
28	16	'94	LeRC	High Precision Moving Magnet Chopper for Variable Operation Conditions	W. Aicher & M. Schmid	167	INST		
2	5	'67	USC	Lunar Orbiter Photo-Subsystem Mechanisms	G. Bradley	33	DRIVE	INST	
2	17	'67	USC	Double-Acting, Rotary-Solenoid-Actuated Shutter	A. G. Ford	131	ACT	INST	
6	1	'71	ARC	Evaluation of Mechanisms Returned from Surveyor 3	J. R. Jones, W. J. Quinn and K. C. Bingemann Jr.	1	TRIBO	INST	
1	7	'66	USC	Gemini/Agenda Docking Mechanism	P. H. Meyer	81	LATCH		
4	21	'69	USC	Apollo Command Module Side-Access Hatch System	L. J. Walkover, R. J. Hart and E. W. Zosky	157	LATCH		
5	1	'70	GSFC	Apollo Docking System	K. A. Bloom and G. E. Campbell	3	LATCH		
5	6	'70	GSFC	Docking-Mechanism Attenuator with Electromechanical Damper	V. S. Syromyatnikov	43	LATCH	DAMP	
6	7	'71	ARC	Neuter Docking-Mechanism Study	J. C. Jones	43	LATCH		
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7	3	'72	JSC	Docking System of Androgynous and Peripheral Type	V. S. Syromyatnikov	27	LATCH		
7	5	'72	JSC	Dynamic Analysis of Apollo-Salyut/Soyuz Docking	J. A. Schliesing	47	LATCH		
7	18	'72	JSC	Apollo 14 Docking Anomaly	R. D. Langley	191	LATCH		
7	19	'72	JSC	Dynamic Testing of Docking System Hardware	W. D. Dorland	203	LATCH		
10	3	'76	JPL	Apollo-Soyuz Test Project Docking System	W. L. Swan Jr.	26	LATCH		
10	10	'76	JPL	Design of Mechanisms to Lock/Latch Systems under Rotational or Translational Motion	R. P. Billimoria	104	LATCH		
11	4	'77	GSFC	Fly-Away Restraint Pin Mechanism for the Army's Patriot Missile System	F. W. Knight	35	LATCH		
11	11	'77	GSFC	Docking and Retrieval Mechanism	J. R. Tewell and R. A. Spencer	101	LATCH		
12	9	'78	ARC	Hatch Latch Mechanism for Spacelab Scientific Airlock	G. R. ter Haar Jr.	89	LATCH		

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14	7	'80	LRC	Actuated Latch Pin and its Development	P. J. Lawlor	69	LATCH	REL	
15	3	'81	MSFC	**Payload Retention Latches for the Shuttle Orbiter**	**R. D. Renken and R. P. Maxwell**	31	LATCH	DRIVE	
15	22	'81	MSFC	Latch Mechanism for the Space Telescope	H. F. Schmidt	331	LATCH		
15	25	'81	MSFC	Clamp Mechanism for Deployable Three-Ton Payloads	R. Birner and H. Ral	375	LATCH		
16	2	'82	KSC	Flight Support System Mechanism	W. A. Leavy	23	LATCH		
16	4	'82	KSC	Centerline Latch Tool for Contingency Orbiter Door Closure	R. C. Trevino	63	LATCH		
16	7	'82	KSC	Ball Trunnion Capture Latch	D. V. Adams and B. Alchorn	99	LATCH		
17	17	'83	JPL	Latch Fittings for the Scientific Instruments on the Space Telescope	J. D. Dozier and E. Kaelber	253	LATCH		
17	23	'83	JPL	Hinge Latch Mechanism	J. C. Walker	343	LATCH		
19	4	'85	ARC	Modular Docking Mechanism for In-Orbit Assembly and Spacecraft Servicing	F. Gampe, K. Priesett and R. H. Bentall	59	LATCH		
19	10	'85	ARC	Design and Development of a Spacecraft Appendage Tie Down Mechanism	W. D. Nygren and K. Head	167	LATCH		
20	5	'86	LeRC	Design and Analysis of a Keel Latch for Use on the Hubble Space Telescope	J. Calvert and M. Stinson	55	LATCH		
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21	19	'87	JSC	Space Station Based Options for Orbiter Docking/Berthing	D. J. Hoover	261	LATCH		
21	20	'87	JSC	An Electromechanical Attenuator/Actuator for Space Station Docking	L. Stokes, D. Glenn and M. B. Carroll	275	LATCH		
22	3	'88	LRC	Structural Latches for Modular Assembly of Spacecraft and Space Mechanisms	W. McCown and N. Bennett	29	LATCH		
22	23	'88	LRC	Space Station Full-Scale Docking/Berthing Mechanisms Development	G. C. Burns, H. A. Price and D. B. Buchanon	325	LATCH		
24	11	'90	KSC	The Resupply Interface Mechanisms RMS Compatibility Test	S. W. Jackson and F. G. Gallo	143	LATCH	ROBOT	
24	12	'90	KSC	Relatchable Launch Restraint Mechanism for Deployable Booms	R. M. Warden	157	LATCH	BOOM	
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25	16	'91	JPL	Resettable Binary Latch Mechanism for Use with Paraffin Linear Motors	D. Maus and S. Tibbitts	221	LATCH		
26	19	'92	GSFC	Space Station Freedom Common Berthing Mechanism	E. Illi	281	LATCH		
26	20	'92	GSFC	A Multipurpose Model of HERMES-COLUMBUS Docking Mechanism	J. J. Gonzalez-Vallejo, W. Fehse and A. Tobias	297	LATCH		
27	8	'93	ARC	Retention Latch Mechanism for the Wake Shield Facility	T. G. Vendrely	107	LATCH		
1	13	'66	USC	Mariner IV Science Platform Structure and Actuator Design, Development, and Performance	G. Coyle and E. Floyd	145	INST	LATCH	
1	21	'66	USC	Zero-G Testing of Satellite Inspection Mechanisms	R. N. Lahde	251	STE	LATCH	
24	4	'90	KSC	Development of the CLAES Instrument Aperture Door System	D. M. Stubbs	41	DEPLOY	LATCH	BRG

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28	1	'94	LeRC	Space Station Freedom Solar Array Containment Box Mechanisms	M. E. Johnson, B. Haugen & G. Anderson	1	SA	LATCH	
28	6	'94	LeRC	Development of an Interchangeable End Effector Mechanism for the Ranger Telerobotic Vehicle	R. Cohen & D. Akin	79	ROBOT	LATCH	
28	18	'94	LeRC	Design and Performance of the Telescope and Detector Covers on the Extreme Ultraviolet Explorer Satellite	J. L. Tom	199	DEPLOY	LATCH	
28	26	'94	LeRC	Deployable/Retractable Telescoping Tubular Structure Development	M. Thompson	323	BOOM	LATCH	
27	17	'93	ARC	Low-Melting-Temperature Alloy Deployment Mechanism and Recent Experiments	M. J. Madden	255	DAMP	DEPLOY	LATCH
1	11	'66	USC	Analysis of Aerospace Impact Problems	D. Hayes, C. Cawood and T. Kertesz	123	MISC		
1	15	'66	USC	Low-Temperature Effects on Materials for Aerospace Mechanisms	W. E. Henry	167	MISC		
1	23	'66	USC	Analysis of a Satellite Angle-of-Attack Sensor	W. E. Frye	277	MISC		
2	22	'67	USC	Self-Destruct Charge Ordnance Component of the Agenda D Vehicle Self-Destruct System	A. H. Smith	171	MISC		
3	6	'68	JPL	Development Philosophy for Snap Mechanisms	O. P. Steel III	45	MISC	BRG	
3	18	'68	JPL	Introduction to Rolamite	J. P. Ford	153	MISC	BRG	
4	12	'69	USC	Design of Aerospace Mechanisms-A Customer's Opinion	J. C. McSherry	91	MISC		
4	15	'69	USC	Flow-Control Valve Without Moving Parts	W. L. Owens Jr.	115	MISC		
5	8	'70	GSFC	Thermomechanical Piston Pump Development	E. E. Sabelman	65	MISC		
5	22	'70	GSFC	Apollo 11 Laser Ranging Retro-Reflector Array	J. E. McCullough	171	MISC		
6	5	'71	ARC	Textile Mechanical Elements in Aerospace Vehicle Parachute Systems	M. J. Lindgren and K. E. French	27	MISC		
6	6	'71	ARC	Heat Pipes for Spacecraft Temperature Control - Their Usefulness and Limitations	S. Ollendorf and E. Stipandic	33	MISC		
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7	13	'72	JSC	Apollo 15 Main-Parachute Failure	D. D. Arabian and J. E. Mechelay	137	MISC		
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8	17	'73	LRC	Rocket Engine Bipropellant Value Problems and Current Efforts	J. Fries	213	MISC	TRIBO	
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9	10	'74	KSC	Refurbishment of the Cryogenic Coolers for the Skylab Earth Resources Experiment Package	J. C. Smithson and N. C. Luska	133	MISC		
9	17	'74	KSC	Use of Computer Modeling to Investigate a Dynamic Interaction Problem in the Skylab TACS Quad-Valve Package	R. J. Hesser and R. Gershman	235	MISC		
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10	12	'76	JPL	Caging Mechanism for a Drag-Free Satellite Position Sensor	R. Hacker, J. Mathiesen and D. B. DeBra	125	MISC		
11	22	'77	GSFC	Viking Mechanisms: A Post-Mission Review	V. P. Gillespie	235	MISC		
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14	5	'80	LRC	Fluid Circulating Pump Operated by Same Incident Solar Energy Which Heats Energy Collection Fluid	E. R. Collins	47	MISC		
14	14	'80	LRC	Fuel/Hydraulic Transfer Valve Improves Reliability of Atlas Space Launch Vehicle	M. Ogman	155	MISC		
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16	21	'82	KSC	Space Shuttle External Tank Gaseous Oxygen Vent System	W. G. Franklin	299	MISC		
17	15	'83	JPL	Practical Small-Scale Explosive Seam Welding	L. J. Bement	227	MISC		
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20	19	'86	LeRC	Design and Development of a Large Diameter, High Pressure, Fast Acting Propulsion Valve and Valve Actuator	K. V. Srinivasan	265	MISC		
21	17	'87	JSC	A CAD/CAE Analysis of Photographic and Engineering Data	S. M. Goza and W. L. Peterson	235	MISC		
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23	19	'89	MSFC	Age Distribution Among NASA Scientists and Engineers	M. L. Ciancone	279	MISC		
24	25	'90	KSC	Circularity Measuring System	G. R. RohrKaste	341	MISC		
26	7	'92	GSFC	Spline-Locking Screw Fastening Strategy	J. M. Vranish	91	MISC		
1	5	'66	USC	Non-contaminating Separation Systems for Spacecraft (Project Zip)	A. B. Leaman	61	REL	SEP	
1	20	'66	USC	Simplified Space Mechanisms Using Subliming Solids	H. M. Kindsvater	239	REL	DAMP	
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2	11	'67	USC	Collet Release Mechanism	D. O. Ramos	85	REL		
2	20	'67	USC	Weld-Alloy	J. C. McDonald and J. C. Olsen	155	REL	SEP	
3	23	'68	JPL	Ball-Lock-Bolt Separation System	J. I. Moulton	197	REL		
5	15	'70	GSFC	Release Mechanism with Mechanical Redundancy	J. J. Paradise	121	REL		
6	8	'71	ARC	Rocket Nozzle Automatic Release System	J. B. Kimball	51	REL		
8	3	'73	LRC	Laser Initiated Explosive Device System	L. C. Yang, V. J. Menichelli and J. E. Earnest	25	REL		
8	16	'73	LRC	Development of Low-Shock-Pyrotechnic Separation Nuts	L. J. Bement and V. H. Neubert	179	REL		
8	27	'73	LRC	Multi-Point Release Mechanism	E. Groskopfs	329	REL		
10	7	'76	JPL	Pin Puller Impact Shock Attenuation	G. F. Audair, B. S. Leonard, R. E. Robbins and W. L. Proffitt	71	REL	DAMP	
10	17	'76	JPL	Design Evolution of a Low Shock Release Nut	D. H. Otth and W. Gordon	175	REL		
11	7	'77	GSFC	Cartridge Firing Device Designed for Attachment, Release, and Ejection of a Satellite	L. Pierron	67	REL	SEP	
12	11	'78	ARC	Design and Testing of a Memory Metal Actuated Boom Release Mechanism	D. G. Powley and G. B. Brook	119	REL		
12	15	'78	ARC	Space Shuttle Orbiter Separation Bolts	R. S. Ritchie	171	REL		
16	6	'82	KSC	Development of an Ultra-Low-Shock Separation Nut	W. Woebkenberg, D. N. Matteo and V. D. Williams	87	REL		
17	24	'83	JPL	Release-Engage Mechanism for use on the Orbiter, Evolution of	J. Calvert	357	REL		
18	1	'84	GSFC	**Design and Development of a Release for Space Shuttle Life-Science Experiments**	**H. M. Jones and R. G. Daniell**	1	REL		
23	3	'89	MSFC	The Design and Analysis of a Double Swivel Toggle Release Mechanism for the Orbiter Stabilized Payload Deployment System	G. L. King and T. Tsai	39	REL	SEP	
26	1	'92	GSFC	Development of a Non-Explosive Device for Aerospace Applications	J. D. Busch, W. E. Purdy and A. D. Johnson	1	REL		
27	7	'93	ARC	Integration of Pyrotechnics Into Aerospace Systems	L. J. Bement and M. L. Schimmel	93	REL		
28	29	'94	LeRC	Implementation of Heaters on Thermally Actuated Spacecraft Mechanisms	J. D. Busch & M. D. Bokaie	379	REL		
28	30	'94	LeRC	Payload Holddown and Release Mechanism	D. Chaput, M. Visconti, M. Edwards & T. Moran	395	REL		
28	31	'94	LeRC	Advanced Release Technologies Program	W. E. Purdy	413	REL		
1	17	'66	USC	Pyrotechnic Shock Isolation Mechanism	A. L. Ikola	189	DAMP	REL	
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9	23	'74	KSC	Hold-down arm Release Mechanism used on Saturn Vehicles	J. D. Phillips and B. A. Tolson	335	DEPLOY	REL	DAMP
14	7	'80	LRC	Actuated Latch Pin and its Development	P. J. Lawlor	69	LATCH	REL	
17	20	'83	JPL	Deployment and Release Mechanisms on the Swedish Satellite, Viking	S. Eriksson	305	DEPLOY	REL	
24	2	'90	KSC	Development of Shape Memory Metal as the Actuator of a Fail Safe Mechanism	V. G. Ford and M. R. Johnson	9	ACT	REL	
3	7	'68	JPL	Mechanisms for Restraining and Deploying a 50-kW Solar Array	T. Haynie and A. Kriger	55	SA	DEPLOY	REL
9	2	'74	KSC	Manipulator Arm for Zero-G Simulations	S. B. Brodie, C. Grant and J. J. Lazar	19	ROBOT		
10	2	'76	JPL	Mobile Planetary Lander Utilizing Elastic Loop Suspension	W. Trautwein	11	ROBOT		
14	11	'80	LRC	Triple-Axis Common-Pivot Arm Wrist Device for Manipulative Applications	L. Kersten and J. D. Johnston	111	ROBOT		
16	3	'82	KSC	**Design and Development of an End Effector for the Shuttle Remote Manipu System**	**R. G. Daniell and S. S. Sachdev**	45	ROBOT		
19	13	'85	ARC	Telepresence Work System Concepts	L. M. Jenkins	225	ROBOT		
19	14	'85	ARC	**Dual Arm Master Controller Development**	**D. P. Kuban and G. S. Perkins**	235	ROBOT		
20	10	'86	LeRC	Duty Cycle Testing and Performance Evaluation of the SM-229 Teleoperator	R. S. Stoughton and D. P. Kuban	133	ROBOT		
21	7	'87	JSC	The Design and Development of a Mobile Transporter System for the Space Station Remote Manipulator System	T. W. Carroll	93	ROBOT		
21	8	'87	JSC	Telerobotic Work System: Concept Development and Evolution	L. M. Jenkins	103	ROBOT		
21	9	'87	JSC	Traction-Drive, Seven-Degree-of-Freedom Telerobot Arm: A Concept for Manipulation in Space	D. P. Kuban and D. M. Williams	111	ROBOT	DRIVE	
22	20	'88	LRC	Space Station Mobile Transporter	J. Renshall, G. W. Marks and G. L. Young	271	ROBOT		
22	21	'88	LRC	Operational Experience and Design Recommendations for Teleoperated Flight Hardware	T. W. Burgess, D. P. Kuban, W. W. Hankins and R. W. Mixon	287	ROBOT		
22	22	'88	LRC	Robotic Joint Experiments under Ultravacuum	A. Borrien and L. Petitjean	307	ROBOT	DRIVE	
23	13	'89	MSFC	Double Lead Spoiral Platen Parallel Jaw End Effector	D. C. Beals	195	ROBOT		
23	15	'89	MSFC	Flight Telerobot Mechanism Design: Problems and Challenges	J. B. Dahlgren and E. P. Kan	223	ROBOT		
24	8	'90	KSC	Development of a Multipurpose Hand Controller for JEMRMS	N. Matsuhira, S. Iikura, M. Asakura and Y. Shinomiya	105	ROBOT		
24	9	'90	KSC	A Robot End Effector Exchange Mechanism for Space Applications	B. F. Gorin	121	ROBOT		

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24	26	'90	KSC	Development of Cable Drive Systems for an Automated Assembly Project	C. A. Monroe Jr	353	ROBOT	ACT	
25	2	'91	JPL	System Requirements and Design Features of Space Station Remote Manipulator System Mechanisms	R. Kumar and E. Hayes	15	ROBOT		
25	22	'91	JPL	A New Active Virtual Pivot Six-Degree-of-Freedom Hand Controller for Aerospace Applications	W. C. Marshall, K. M. Radke, R. E. DeMars, D. J. Lowry and L. Levitan	323	ROBOT		
26	5	'92	GSFC	Manipulator Design and Development for the Ranger Satellite Servicing Vehicle	R. D. Howard and D. L. Akin	61	ROBOT		
26	6	'92	GSFC	Experiences in the Development of Rotary Joints for Robotic Manipulators in Space Applications	K. Priesett	75	ROBOT		
26	18	'92	GSFC	A 22.2:1 Ratio, 300 Watt, 25 N-m Output Torque, Planetary Roller-Gear Robotic Transmission: Design and Evaluation	W. S. Newman, W. J. Anderson, W. Shipitalo and D. Rohn	263	ROBOT		
27	2	'93	ARC	A Compact Roller-Gear Pitch-Yaw Joint Module: Design and Control Issues	M. E. Dohring, W. S. Newman, W. J. Anderson and D. A. Rohn	21	ROBOT		
28	5	'94	LeRC	Design, Characterization, and Control of the Unique Mobility Corporation Robot	V. B. Velasco, Jr, W. S. Newmann, B. Steinetz, C. Kopf & J. Malik	63	ROBOT		
28	6	'94	LeRC	Development of an Interchangeable End Effector Mechanism for the Ranger Telerobotic Vehicle	R. Cohen & D. Akin	79	ROBOT	LATCH	
13	19	'79	JSC	Payload Installation and Deployment Aid for Space Shuttle Orbiter Spacecraft Remote Manipulator System	T. O. Ross	235	SEP	ROBOT	
23	14	'89	MSFC	Traction-Drive Force Transmission for Telerobotic Joints	D. M. Williams and D. P. Kuban	207	DRIVE	ROBOT	
24	11	'90	KSC	The Resupply Interface Mechanisms RMS Compatibility Test	S. W. Jackson and F. G. Gallo	143	LATCH	ROBOT	
3	7	'68	JPL	Mechanisms for Restraining and Deploying a 50-kW Solar Array	T. Haynie and A. Kriger	55	SA	DEPLOY	REL
4	1	'69	USC	Soil Sampler Development for Unmanned Probes	W. H. Bachle	3	SAMP	BOOM	DRIVE
4	11	'69	USC	Deployment Fixture for the Simulated Zero-Gravity Testing of a Large-Area Solar Array	J. A. Lackey	83	SA	STE	
4	20	'69	USC	Dragline Sample-Acquisition Mechanism	H. M. Alexander	149	SAMP	ACT	DRIVE
6	11	'71	ARC	Lunar Rock Splitter/Can Sealer	K. G. Johnson	73	SAMP	ACT	
8	7	'73	LRC	Development and Test of a Long-Life, High Reliability Solar Array Drive Actuator	D. L. Kirkpatrick	69	SA	ACT	DRIVE
8	20	'73	LRC	Viking Surface Sampler	R. B. Seger and V. P. Gillespie	245	SAMP		

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16	24	'82	KSC	Design of a 7kW Power Transfer Solar Array Drive Mechanism	J. S. Sheppard	341	SA	TRANS	
17	3	'83	JPL	Space Telescope - Solar Array Primary Deployment Mechanism	D. P. Chandler and A. Veit	39	SA		
19	7	'85	ARC	Design and Development of a Constant Speed Solar Array Drive	H. M. Jones and N. Roger	103	SA	ACT	
19	20	'85	ARC	Features of the Solar Array Drive Mechanism for the Space Telescope	R. G. Hostenkamp	315	SA	ACT	
20	20	'86	LeRC	Discrete Mechanism Damping Effects in the Solar Array Flight Experiment	E. D. Pinson	277	SA		
26	16	'92	GSFC	Milstar's Flexible-Substrate Solar Array -- Lessons Learned	J. Gibb	235	SA		
27	1	'93	ARC	Collecting Cometary Soil Samples? Development of the Rosetta Sample Acquisition System	P. A. Coste, M. Eiden and M. Fenzl	1	SAMP		
27	19	'93	ARC	Lockup Failure of a Four-Bar Linkage Deployment Mechanism	M. Zinn	283	SA	DEPLOY	
28	1	'94	LeRC	Space Station Freedom Solar Array Containment Box Mechanisms	M. E. Johnson, B. Haugen & G. Anderson	1	SA	LATCH	
28	2	'94	LeRC	INSAT-2A and 2B Deployment Mechanisms	M. N. Sathyanarayan, M. Nageswara Rao, B. S. Nataraju, N. Viswanatha, M. Laxmana Chary, K. S. Balan, V. Sridhara Murthy, Raju Aller & H. N. Suresha Kumar	17	SA	DEPLOY	BOOM
28	9	'94	LeRC	Space Station Freedom Solar Array Tension Mechansim Development	C. Allmon & B. Haugen	123	SA		
1	26	'66	USC	Extendable Structure for Solar Electric Power in Space	D. E. Lindberg	311	BOOM	SA	
5	5	'70	GSFC	Response Characteristics of a Thermal-Heliotrope Solar-Array Orientation Device	F. H. Morse	33	ACT	SA	
7	21	'72	JSC	Flexible Solar Array Mechanism	M. C. Olson	233	BOOM	SA	
7	25	'72	JSC	928-M^2 (10,000 Ft^2) Solar Array	D. E. Lindberg	287	BOOM	SA	
10	18	'76	JPL	Solar Array Drive System	F. D. Berkopec, J. C. Sturman and R. W. Stanhouse	185	ACT	SA	
11	10	'77	GSFC	**Trident I Third Stage Motor Separation System**	B. H. Welch, B. J. Richter and P. Sue	97	DEPLOY	SA	
11	21	'77	GSFC	Design and Development of a Solar Array Drive	T. Rees and J. H. Standing	217	ACT	SA	
12	5	'78	ARC	Mars Penetrator Umbilical	C. E. Bams	43	TRANS	SAMP	
15	8	'81	MSFC	Zero-Gravity Testing of Flexible Solar Arrays	D. T. Chung and L. E. Young	115	STE	SA	
16	16	'82	KSC	Deployment Mechanism for the Double Roll-Out Flexible Solar Array on the Space Telescope	T. R. Cawsey	223	DEPLOY	SA	
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4	1	'69	USC	Soil Sampler Development for Unmanned Probes	W. H. Bachle	3	SAMP	BOOM	DRIVE
4	20	'69	USC	Dragline Sample-Acquisition Mechanism	H. M. Alexander	149	SAMP	ACT	DRIVE
6	11	'71	ARC	Lunar Rock Splitter/Can Sealer	K. G. Johnson	73	SAMP	ACT	
8	20	'73	LRC	Viking Surface Sampler	R. B. Seger and V. P. Gillespie	245	SAMP		
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2	6	'67	USC	Yo-Yo Despin Mechanisms	K. S. Bush	41	SEP		
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4	13	'69	USC	Despin Assembly for the Tacomsat Communications Satellite	C. R. Meeks	95	SEP	ACT	
5	3	'70	GSFC	Aerospace Vehicle Separation Mechanisms Selection, Design, and Use Considerations	I. B. Gluckman	17	SEP	REL	
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6	15	'71	ARC	Gas-Powered Reentry Body Erection Mechanism	R. J. Muraca and K. D. Hedgepeth	101	SEP		
7	24	'72	JSC	Flying Ejection Seat	R. H. Hollrock and J. J. Barzda	275	SEP		
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9	13	'74	KSC	Dispersion Development Program	D. J. Carlson, R. J. Lusardi and W. H. Phillips	175	SEP		
10	16	'76	JPL	Simultaneous Spin/Eject Mechanism for Aerospace Payloads	G. D. Palmer and T. N. Banks	165	SEP		
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24	7	'90	KSC	The Development of an Expendable Launch Vehicle Interface for an STS Deployable Payload	E. Eubanks and J. Gibb	89	SEP	TRIBO	
25	18	'91	JPL	Payload Spin Assembly for the Commercial TITAN Launch Vehicle	W. Robinson and G. Pech	253	SEP		
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23	3	'89	MSFC	The Design and Analysis of a Double Swivel Toggle Release Mechanism for the Orbiter Stabilized Payload Deployment System	G. L. King and T. Tsai	39	REL	SEP	
10	5	'76	JPL	Design Principles of a Rotating Medium-Speed Mechanism	R. G. Hostenkamp, E. Achtermann and R. H. Bentall	52	ACT	TRIBO	SEP
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13. 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.

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