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Lubrication of Space Systems — Challenges and Potential Solutions

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LUBRICATION OF SPACE SYSTEMS—CHALLENGES AND POTENTIAL SOLUTIONS

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Summary

President Bush has proposed that the United States undertake an ambitious mission of manned and robotic exploration of the solar system (Space Exploration Initiative, SEI), which will include an eventual manned mission to Mars. In addition to this mission, NASA has many other high technology programs planned such as the Space Station "Freedom," Mission to Planet Earth (a series of Earth observing satellites), space telescopes, planetary orbiters, etc. These missions will all require advanced mechanical moving components which will require wear protection and lubrication. The tribology practices used in space today are primarily based upon a technology base that is more than twenty years old. The question is: is this technology base good enough to meet the needs of these future long-duration NASA missions? This paper will discuss NASA's future space missions and some of the mechanism and tribology challenges that will be encountered. Potential solutions to these challenges using coatings technology will be explored.

1. Introduction

The space age has brought with it many lubrication challenges that had not been experienced in the past. The challenges included: exposure to very low ambient pressures, a radiation and atomic oxygen environment, the presence of meteoroids, the absence of a gravitational field, imposed weight limitation restrictions, low contamination by vapors, and the use of mechanical components that are not maintainable.

The challenges for the future appear to be even greater because on July 20, 1989, President Bush made the following statements: "In 1961, it took a crisis, the space race, to speed things up. Today, we do not have a crisis, we have an opportunity. To seize this opportunity, I am not proposing a 10-year plan like Apollo, I am proposing a long-range, continuing commitment. First, for the coming decade, the space station, Freedom; for the new century, back to the moon, back to the future. And this time, back to stay. And then, a journey into tomorrow, to another planet, a manned mission to Mars." This new mission has been designated by NASA the Space Exploration Initiative (SEI).

In addition to the previously mentioned items, the following new challenges for mechanical components and lubricating systems appear evident: systems which must be capable of up to 30 year operation on the space station or on planetary surfaces; systems which must be capable of operating over a temperature range of (-170°C to +111°C), in a vacuum of 10^{-12}, Torr and under extremely dusty conditions on the moon; and systems which must be capable operating under wide temperature ranges, in a low oxygen atmosphere and in a dusty, corrosive environment on the planet Mars.

The purpose of this paper is to review the state-of-the-art of tribology as it applies to space, to discuss the lubrication techniques that have been used in the past and to present their advantages and disadvantages, to examine what future NASA space missions are being considered and what their tribological challenges might be, and to present some potential new technologies that may be employed to answer these challenges.

2. Future NASA space missions

In addition to the Space Exploration Initiative (SEI) mentioned in the introduction, NASA has three other major mission areas. One mission is the Mission to Planet Earth, whose purpose is to understand the interaction between the oceans, the atmosphere and the solid Earth (weather); between living organisms and the environment; and between the environment and pollution. Another is the Astrophysics mission whose purpose is to understand the universe, and the last is a mission to develop and understand new processes in material and life sciences in space. Figure 1 shows a proposed time frame for completion of some of the hardware that will be needed to complete these missions. The figure separates the hardware classes into transportation, spacecraft, and large space systems.

3. Systems requiring lubrication

To determine if the current state-of-the-art of space mechanisms and tribology technology were adequate to meet the requirements of future NASA missions, a questionnaire was sent to industry and government personnel known to be working in the field. Unedited responses to the questionnaire are reported in Ref. 1. An analysis of the responses are reported in Ref. 2. The responders answered a number of questions including what are some current or anticipated needs. Essentially, 98 percent of those who responded to the questionnaire stated that new or improved mechanical component and tribology technology will be needed for future space missions.

4. Methods used to lubricate space systems

4.1. Liquids

There are many different liquid lubricants that have been used in space. The list includes: silicones, mineral oils, perfluoropolyalkylethers, polyalphaolifins, polyolesters, multiply-alkylated cyclopentanes, etc. For more details on these lubricants see Refs. 3 to 6.

Since excessive weight is a problem for satellites, large reservoirs of liquid lubricant and the resultant pumping systems (as used in aeronautical applications) are not appropriate. Instead, rolling element bearings are lubricated with small liquid reservoirs and/or porous cages. For a few applications, positive feed systems have been developed to meter and control the flow of lubricant to the contact areas to insure adequate lubricant supply [7]. Wick lubrication has also been proposed as a means of increasing the supply of lubricant [8].

4.2. Greases

A grease is a semi-solid liquid that consists of a liquid lubricant mixed with a thickener. Greases are used for a variety of space applications. These include: slow to high speed angular contact ball bearings, journal bearings, and gears. The primary reason for using a grease is that the grease can act as a reservoir for supplying oil to contacting surfaces. It can also act as a physical barrier to prevent oil loss by creep or by centrifugal forces. Descriptions of greases used for various space applications are given in Ref. 3.

4.3. Solids

Solid lubricants are used in space to lubricate various mechanical components such as: rolling element bearings, journal bearings, gears, bushings, electrical sliding contacts, clamps/ latches, bolts, seals, rotating nuts, robotic and telescoping joints, gas and magnetic bearings, fluid transfer joints, various release mechanisms, valves, harmonic drives, etc. The types of solid lubricants used for these space applications are listed in Table I.

The most common way to utilize a solid lubricant is to apply it to a metal surface as a film or coating. There are many methods of depositing solid lubricant films onto a surface. The easiest method is to rub or burnish powders onto a roughened metallic surface. The next simplest method is incorporate solid lubricant powders into a liquid binder system and then brush, dip or spray the mixture (much like a paint) onto the surface. More modern techniques include vacuum deposition methods such as sputtering and ion plating. For more details on application techniques see Ref. 9.

Solid lubricants can also be employed as solid bodies. Usually this is done by making a composite. A composite consists of a matrix material (to provide structural strength) and a solid lubricant material (to provide lubrication). Some polymer materials such as the polyimides have demonstrated that they can provide very low friction and wear properties by themselves without being made into a composite [10].

5. Comparison of liquid versus solid lubricating mechanisms

5.1 Liquid lubrication mechanisms

There are four defined regimes of liquid lubrication, hydrodynamic, elastohydrodynamic, boundary, and mixed. These regimes are directly proportional to the oil viscosity (Z) and to the relative velocity (V) and inversely proportional to the load (L). Figure 2, known as the Stribeck-Hersey curve [11], depicts these regimes in terms of friction coefficient versus the parameter of viscosity, velocity, and load (ZV/L).

As the thickness of the oil film decreases to values below 2.5×10^{-8} m(10^{-7} in.), the boundary lubrication regime comes into play. In this regime, asperity contact between the sliding surfaces takes place and the lubrication process becomes the shear of chemical compounds on the surface. This regime is dependent upon lubricant additives within the oil that produce compounds on the surface that have the ability to shear and provide lubrication. Boundary lubrication is highly complex, involving surface topography, physical and chemical adsorption, corrosion, catalysis, and reaction kinetics. This region of lubrication resembles thin film solid lubrication. For more information on the theory of lubrication and types of additives needed in oils see Ref. 12.

5.2 Solid lubrication mechanisms

When using solid lubricant films or coatings, there are two basic lubricating mechanisms that come into play [13]. One should be aware of which mechanism is operating before choosing a particular lubricant. The first mechanism is illustrated in Fig. 3. The mechanism involves the shear of a very thin film of solid lubricant (usually less than 2 μm thick) at the surface of the substrate. If the original film is thicker than this, it will either plastically deform or brittlely fracture. Sometimes a "secondary film" can form from wear debris and/or material that has been left behind in the surface topography of the wear track; but the likelihood is, if the film is too thick or the geometry is not correct, the secondary film may not form at all or a secondary film will form that has a very short life. Thus it is important not to apply the film too thick.

When this mechanism is in operation, applying the film to a rough surface tends to produce longer endurance lives because a better bond is achieved and the roughness provides a reservoir for solid lubricant material which restricts it from flowing from the contact area. Reference 14 compares the endurance lives obtained for MoS_2 films applied to polished, sanded and sandblasted surfaces. The sanded surface provided up to 20 times and the sandblasted surface provided up to 400 times the endurance life of the polished surface.

In the second mechanism, the film itself is capable of supporting the load and the wear process is one of gradual wear through the film. Figure 4 shows idealized cross-sectional schematics of a counterface sliding against a solid lubricant coating. The counterface in the schematic is sliding out of the page. The schematic illustrates that the coating has enough structural strength to support this particular load and that a thin, ordered layer has developed on the surface of the coating. In addition, a thin, ordered transfer film has developed on the counterface. Thus, the wear process is similar to the way a lubricating composite would wear. Studies have shown that the rate of film wear when this mechanism takes place is determined by the load and by the area of contact of the metallic slider [15].

In addition to the different wear mechanisms, there are also many factors or conditions that affect solid lubricant performance. One can not specify a wear rate or a friction coefficient without knowing all the operating conditions. The type of factors that affect solid lubricant performance are as follows: the type of substrate material and its surface finish, the type of counterface material and its surface topography, surface hardness of the substrate and counterface materials, the geometry of the sliding specimens, the contact stress, the temperature, the sliding speed, and the environment (atmosphere, fluids, dirt, etc.). Depending on the particular solid lubricant employed, changing the value of just one of these parameters can change the value of friction coefficient, wear rate, or endurance life. Also, a point to remember is that low friction does not necessarily correlate to low wear or long endurance lives. For a more detailed discussion of how these factors affect solid lubricant performance see Ref. 9.

6. Advantages/disadvantages of solid and liquid lubricants

Some of the various difficulties associated with using solid and liquid lubricants have been discussed in previous sections of this paper. Table II summarizes the relative merits of using liquid and solid lubricants for space applications.

7. Future space tribological challenges

7.1 Spacecraft

Kannel and Dufrane [16] conducted a study on the tribological problems which have occurred in the past and which are projected to occur for future space missions. Figure 5 [16] gives a qualitative chart which illustrates that despite significant advances in tribology, the demands on tribology for future space missions will grow faster than the solutions.

One problem that has occurred is loss of lubricant through vaporization, creep, degradation, etc. In an attempt to reduce vaporization (and also contamination), new synthetic lubricants such as the perfluorpolyalkylethers (PFPE) lubricants have been employed which have very low evaporation rates [5]. While in theory, these liquids appear to be exceptional lubricants, in operation some failures have occurred due to chemical breakdown. Researchers have shown that the presence of chemically active surfaces and/or wear particles combined with exposed radicals in the fluid will inevitably result in acidic breakdown of the lubricants [17-18]. Another problem with these lubricants is that traditional mineral oil additives are not soluble in them. Unfortunately very few materials are soluble in them.

Solid lubricant films have finite lives. As a general rule, they are not employed where they will experience more than 1 million sliding cycles. An additional problem with some films is that powdery wear particles are produced which can pose a contamination problem to sensitive services.

An alternate method of employing solids is to make a bearing cage out of a composite lubricant material and have the lubricant be transferred to the rolling balls and then to the inner and outer races [19]. Figure 6 shows a sketch of how this transfer film mechanism operates. Generally this form of lubrication is only successful under lightly loaded conditions. However, the technique is now being used to lubricate the ball bearings in the Space Shuttle turbopumps. This technique appears to work with some success in the liquid hydrogen pumps, but has not performed very well in the liquid oxygen pumps. NASA is currently investigating this problem.

Atomic oxygen is the major constituent in a low Earth orbit environment. NASA has just recently recognized it as being an important consideration in the design of long-lived spacecraft [20]. Experiments on two space shuttle missions (STS 5 & 6) as well as the Long Duration Exposure Facility (LDEF) have shown that changes to material surfaces can occur when exposed to atomic oxygen. Carbon, and silver have been found to react quickly enough to produce macroscopic changes in their structures. Carbon reacts to form volatile oxides. Silver forms heavy oxide layers which eventually flake or spall resulting in material loss. Polymers such as epoxies, polyurethanes, and polyimides also have been found to be reactive with atomic oxygen. Some representative reaction efficiencies are shown in Table III. Preliminary indications are that atomic oxygen also degrades molybdenum disulfide.

7.2 Planetary Surface Vehicles and Lunar Processing Plants

It is anticipated, that when a manned outpost is established on the moon, the high vacuum (10^{-12} Torr) combined with a very fine abrasive dust will have a very deleterious effect on sliding components, especially if they are unlubricated. The dust will accelerate the removal of protective oxide films on metals. This could especially be a problem with "track-type" vehicles. In addition to being abrasive, the dust is also positively charged; thus it will have a tendency to stick to everything. Lubricants, both liquid and solid will have to be sealed so that the dust can not invade them.

Another anticipated problem on the moon is wide temperature extremes. In the daytime the temperature can get to +111 °C while at night it can get down to -181 °C, as was found during the Apollo missions [21]. And since the moon's rotation rate is low, days and nights on the moon are 14 Earth days long. By contrast to the lunar temperatures, recorded temperatures extremes on the surface of the Earth range from -88.3 °C in Antarctica in 1960 and to 58.0 °C in Libya in 1922 [22]. Currently, there are no liquid lubricants that will operate at these cold lunar temperatures. Either the lubricants will have to be heated (which will expend precious energy) or solids employed. In addition there is no protective atmosphere to shield mechanical equipment and their tribological systems from solar and cosmic radiation.

7.3 Aerospace plane

The aerospace plane will take off from a runway and "fly" into space. Thus, the lubricants employed will have to operate both in air and in a vacuum. Presumably special lubricants will be needed. At this point in time, it is not known what the specific temperatures and lubricating conditions will be. However there is talk of active cooling of the aerodynamic surfaces, which indicates some lubricant surface areas may be at cryogenic temperatures. To achieve the desired thrust, some areas will be extremely hot. Thus a very wide range of lubricants may be needed.

7.4 Space simulation problems

Since the tribological properties of materials are extremely systems dependent, it is imperative that ground-based testing simulate as closely as possible the particular space application. The vacuum, load, speeds, etc., can be simulated fairly easily on the ground, but we can not simulate zero gravity. Also it is very hard to simulate the radiation/atomic oxygen environment of low Earth orbit (LEO).

Another problem that is difficult to simulate though ground-based testing is the forces and vibrations that mechanical components experience during launch. These parameters can cause a lubricant or component fail immediately or they can decrease the life that was predicted through ground based testing.

Problems can also occur through storage of satellites. Satellites are sometimes stored for years before launch. Oils tend to creep away from contact zones, solid lubricants can oxidize or absorb water and decrease their lubricating ability, etc.

7.5 Accelerated testing problems

Designers would like to know how long a particular mechanical component will operate before it fails. Presently the only way ascertain this is to operate the mechanism in a full scale ground test. The problem is that these tests have to run for years. Accelerated testing can be done on some solids lubricants, since wear rate is often speed independent. When this is the case, the sliding speed simply can be increased to increase the number of sliding cycles.

Liquid lubrication is not speed independent; therefore, speed can not be increased to accelerate the test. There is a need to obtain a better understanding of the failure mechanisms, so that mechanisms can be analytically modeled to simulate a life test. It may be possible to determine failure precursors on bearing surfaces (such as chemical changes or micro-cracks) using surface science which would allow us to predict bearing life under various testing conditions and to make corrections for extending bearing life.

8. Potential new lubrication technologies

8.1 Dense thin films of solid lubricants

Sputtered Molybdenum disulfide (MoS_2) coatings have been used as lubricants for many years [23]. Recent improvements in sputtering technology by programs conducted at the National Centre of Tribology in the UK [24] and by programs sponsored by the Strategic Defense Initiative (SDI) [25] have produced very dense, thin films of sputtered MoS_2 which have exhibited very low friction coefficients (as low as 0.01) and extremely long endurance lives (millions of revolutions in a space bearing). These films show considerable promise for space applications where billions of cycles are not required. It may be possible to use this technology to apply dense, thin films of other solid lubricant materials.

8.2 Powder lubrication

Heshmat [26] has been investigating the use of fine powders to lubricate rolling element and sliding bearings. His studies have indicated that the powders (under certain conditions) flow much like liquids in hydrodynamic lubrication. The results are preliminary, but there is some potential. The use of hard coatings with these powders probably would be beneficial.

8.3 Gas Bearings

An alternative to using oil or solids to lubricate a moving component is to use a high pressure gas film either externally pressurized as in a hydrostatic gas bearing or self-acting as in a hydrodynamic foil bearing. Gas bearings have been used for many years. One problem with them is that at start-up or shutdown the sliding surfaces come into contact, so they have to be hydrostatically elevated or some solid lubricant coating must be applied to the surfaces to lubricate these intervals [27]. Also overloads and shock loads can cause high speed sliding contact, which further demonstrates the need for a solid lubricant coating.

8.4 Magnetic Bearings

Magnetic bearings essentially use opposing magnetic fields to separate the sliding surfaces. Usually a combination of permanent and electromagnetic materials are used. Magnetic bearings are not widely used today, but they have considerable promise for future lubricating systems however. One of the problems that has inhibited their use has been the complicated and heavy electronic systems that had to be used to insure their success. With the development of improved electronics in recent years their future use appears very promising. Solid lubricant coatings are also needed with the use of these bearings as an ancillary backup.

8.5. Hard coatings

In general, hard coatings are not considered to be lubricants, but they do prevent wear and sometimes reduce friction. To date, not many "non-lubricating" coatings have been used in space applications. Miyoshi [28-29] has shown that these materials have considerable promise for use in space systems. They could be used in conjunction with layer lattice solid lubricants to help increase endurance lives. In addition, they might be used with liquids to improve friction and wear during boundary lubrication. There are many other potential applications.

8.6. In Situ Sputtering of Solid Lubricants

While it has not been attempted yet; this author suggests that since many space applications occur in a vacuum, it may be possible to develop sputtering system that could sputter a solid lubricant material onto a surface while it is in operation. This would be one way of resupplying solid lubricant films and essentially providing infinite endurance life.

9. Concluding Remarks

As far as tribological technology development is concerned, some incremental improvements in the technology have occurred over the last 20 to 30 years. We have a better understanding of elastohydrodynamic lubrication, some new lubricating and wear theories have been developed, and some new liquid and solid lubricants have been formulated. However, the big problems of being able to lubricate reliably for long periods of time in space, at high temperatures or at cryogenic temperatures have not been solved.

Specifically concerning space tribology, very little new technology has been developed since the Apollo years. The same technology is still being used today, twenty years later. The technology has worked adequately for most NASA missions that have flown to date; but as NASA and the DOD plan longer duration, more demanding missions, the technology will not be sufficient.

References

1. R.L. Fusaro, Government/industry response to questionnaire on space mechanisms/ tribology technology needs. NASA TM-104358 (1991).
2. R.L. Fusaro, Space mechanisms needs for future NASA long duration space missions. AIAA Preprint 91-3428 (1991).
3. E.L. McMurtrey, Lubrication handbook for the space industry. Part A: Solid lubricants. NASA TM-86556 (1985).
4. E. Zaretsky, Tribol. Int., 23 (1990)75.
5. Conley, P.L. and Bohner, J.J., in Proceedings of the 24th Aerospace Mechanisms Symposium, NASA CP-3062, 1990, p. 213.
6. C.G. Venier and E.W. Casserly, Lub. Eng., 47(1991)586.
7. G.E. James, in Proceedings of the 11th Aerospace Mechanisms Symposium, NASA CP-2038, 1977, p. 87.
8. S.H. Lowenthal, et al., in Energy for the Twenty-First Century, Proceedings of the 20th Intersociety Energy Conversion Engineering Conference (IECEC), Vol. 2, Society of Automotive Engineers, Warrendale, PA, 1985, p. 164.
9. R.L. Fusaro, Lubr. Eng., 43(1987)330.
10. R.L. Fusaro, in Polyimides: Synthesis, Characterization, and Applications, K.L. Mittal, (ed.), Vol. 2, Plenum Press, New York, 1984, p. 1053.
11. W.R. Jones, Jr., Boundary lubrication: revisited. NASA TM-82858 (1982).
12. R.E. Booser (ed.), CRC Handbook of Lubrication, Vol. 2, Theory and Design, CRC Press, Boca Raton, FL, 1984.
13. R.L. Fusaro, ASLE Trans., 24(1981)191.

14. R.L. Fusaro, Lubrication and failure mechanisms of Molybdenum Disulfide films; II - Effect of substrate roughness. NASA TP-1379 (1978).

15. R.L. Fusaro, Wear, 75(1982)403.

16. J.W. Kannel and K.F. Dufrane, in Proceedings of the 20th Aerospace Mechanisms Symposium, NASA CP-2423, 1986, p. 121.

17. D.J. Carrè, STLE Trans., 31(1988)437.

18. M.J. Zehe and O.D. Faut, STLE Trans., 33 (1990), 634.

19. D.E. Brewe, H.W. Scibbe, and W.J. Anderson, Film-transfer studies of seven ball-bearing retainer materials in 60 °R (33 °K) hydrogen gas at 0.8 million DN value. NASA TN D-3730 (1966).

20. L.J. Leger and K.F. Dufrane, in Proceedings of the 21st Aerospace Mechanisms Symposium, NASA CP-2470, 1987, p. 285.

21. S.R. Taylor, Planetary Science: A Lunar Perspective, Lunar and Planetary Institute, Houston, TX, 1982.

22. N. McWhirter and R. McWhirter (eds.), Guiness Book of World Records, Sterling Pub. Co., New York, 1979.

23. T. Spalvins, and J.S. Przybyszewski, Deposition of sputtered molybdenum disulfide films and friction characteristics of such films in vacuum. NASA TN D-4269 (1967).

24. E.W. Roberts, Thin Solid Films, 181(1989)461.

25. M.R. Hilton, et al., in Y.W. Chung and H.S. Cheng (eds.), Advances in Engineering Tribology, STLE SP-31, 1991, p. 37.

26. H. Heshmat, STLE Trans., 34(1991)433.

27. B. Bhushan, ASLE Trans., 23(1980)185.

28. K. Miyoshi in Applications of Diamond Films and Related Materials: Proceedings of the First International Conference, Y. Tzens, et al. (eds.), Elsevier, New York, 1991, p. 699.

29. K. Miyoshi, Mater. Sci. Forum, 54(1990) 375.

TABLE I.—Types of solid lubricants used in space.

- Soft metal films
  - Gold
  - Silver
  - Lead
  - Indium
  - Barium
- Lamellar solids
  - Molybdenum disulfide
  - Tungsten disulfide
  - Cadmium iodide
  - Lead iodide
  - Molybdenum diselenide
  - Intercalated graphite
  - Fluorinated graphite
  - Ptalocyanines
- Polymers
  - PTFE
  - Polyimides
  - FEP
  - UHMWPE
  - Peek
  - Polyacetal
  - Phenolic and epoxy resins
- Other low shear strength materials
  - Fluorides of Ca, Li, Ba, rare earths
  - Sulfides of Bi, Cd
  - Oxides of Pb, Cd, Co, Zn

TABLE II.—Relative merits of solid and liquid space lubricants.

Solid lubricants	Liquid lubricants
• Negative vapor pressure (no contamination)	• Finite vapor pressure (oil loss and contamination)
• Wide operating temperatures with no creep or vapor loss	• Lubrication temperature dependent (viscosity, creep, vapor pressure)
• No migration of lubricants	• Seals or barrier coatings needed to prevent creep
• No viscosity effects	• Friction speed and temperature dependent (viscosity effects)
• Minimal degradation	• Endurance life dependent on lubricant degradation/loss
• Good boundary lubricant that provides electrical conductivity	• Electrically insulating
• Accelerated testing has some validity	• Accelerated testing difficult if not impossible
• Good long term storage	• Long term storage difficult
• Poor thermal characteristics - No heat dissipation	• Liquid promotes thermal conductance between surfaces
• Lubrication dependent on operating conditions, e.g.: - Atmosphere (air, vacuum, etc.) - Load, contact geometry, etc.	• Lubrication relatively insensitive to air or vacuum
• Finite life	• Long life if properly used
• Difficult or impossible to re-apply	• Easy to reapply
• Heavy transfer can produce erratic torque at slow speeds	• Low mechanical noise in most lubrication regimes
• Some wear takes place - Opening up clearances - Producing wear debris	• No wear in hydrodynamic or elastohydrodynamic regime

TABLE III.—Reaction efficiencies of selected Tribo-materials with atomic oxygen in low Earth orbit [17].

Material	Reaction efficiency ($x10^{-24}cm^3$/atom)
• Kapton	3.0
• Mylar	3.4
• Tedlar	3.2
• Polyethylene	3.7
• Polysulfone	2.4
• 1034C graphite/epoxy	2.1
• 5208/T300 graphite/epoxy	2.6
• Epoxy	1.7
• Silicones	1.7
• PTFE	<0.05
• Carbon (various forms)	0.9 to 1.7
• Silver	Heavily attacked

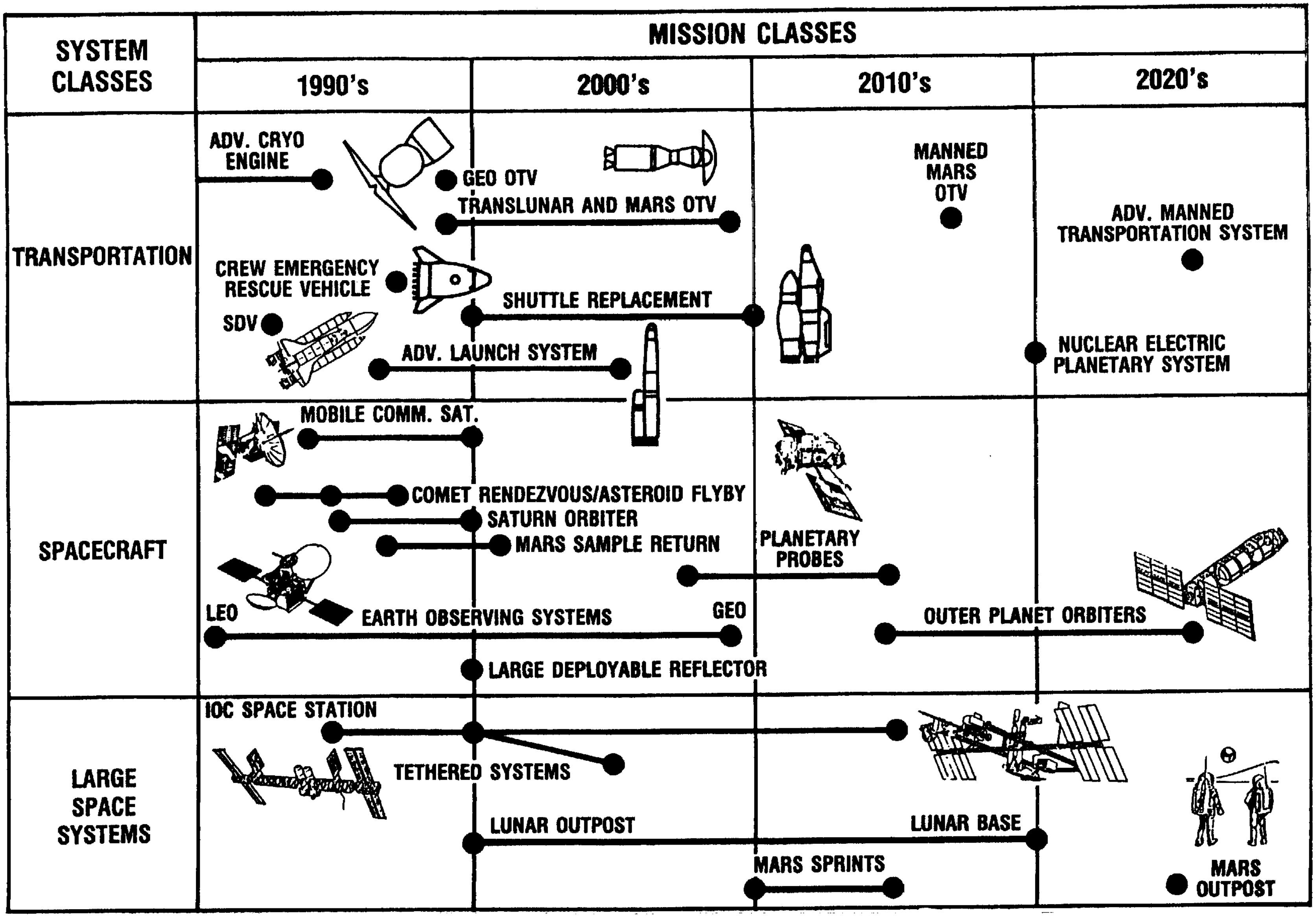

Figure 1.—Proposed time frame for future NASA missions.

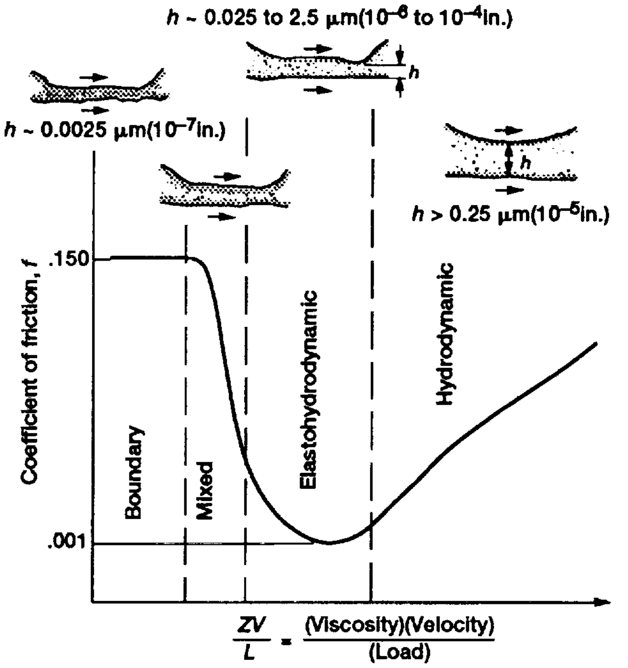

Figure 2.—Coefficient of friction as function of viscosity-velocity-load parameter (Stribeck-Hersey curve, Ref. 61); h = film thickness.

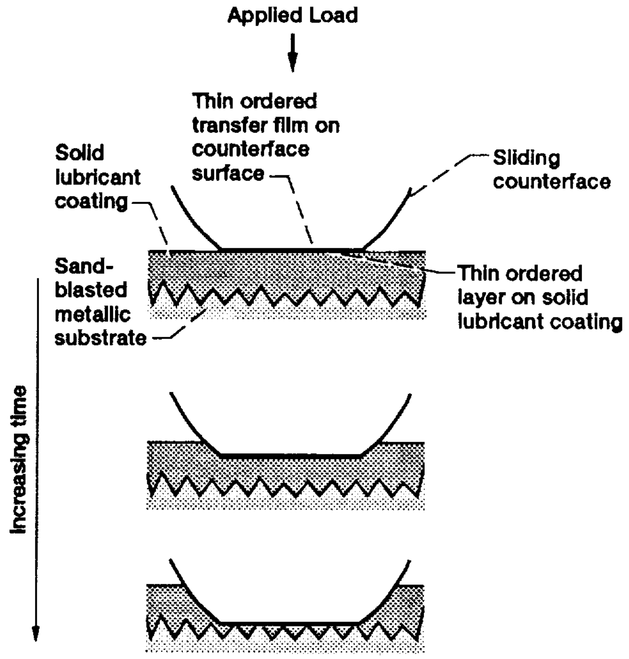

Figure 4.—Idealized cross section schematics of the wear occurring as a function of time to a relatively thick solid lubricant coating applied to a metallic substrate illustrating the lubricating mechanism when the coating is capable of supporting the applied load.

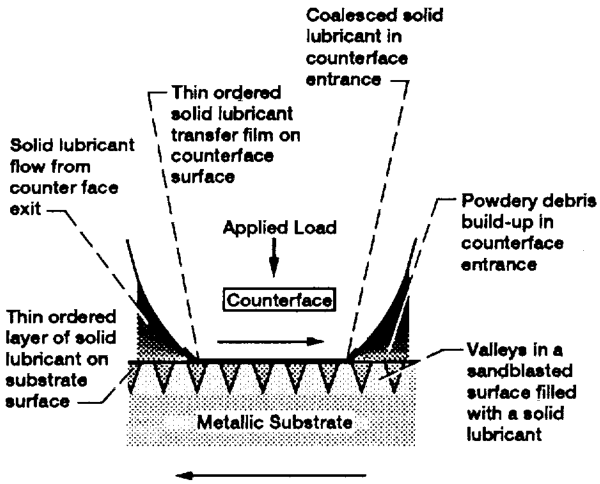

Figure 3.—Idealized cross-sectional schematic of sliding surfaces illustrating the lubricating mechanism of solid lubricant thin films applied to metallic substrates.

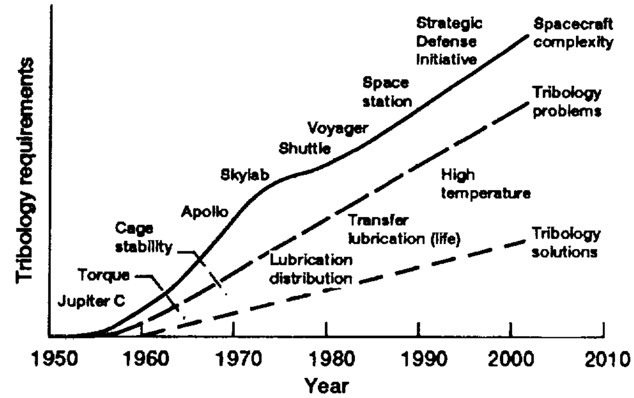

Fig. 5 Growth of tribology requirements with advances in space (Ref. 25).

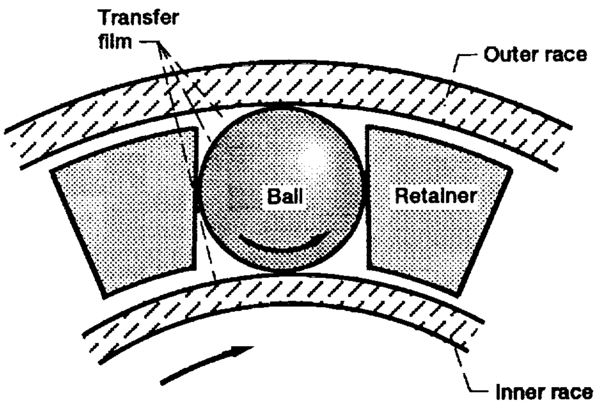

Figure 6.—Illustration of ball bearing film-transfer mechanism (Ref. 14).

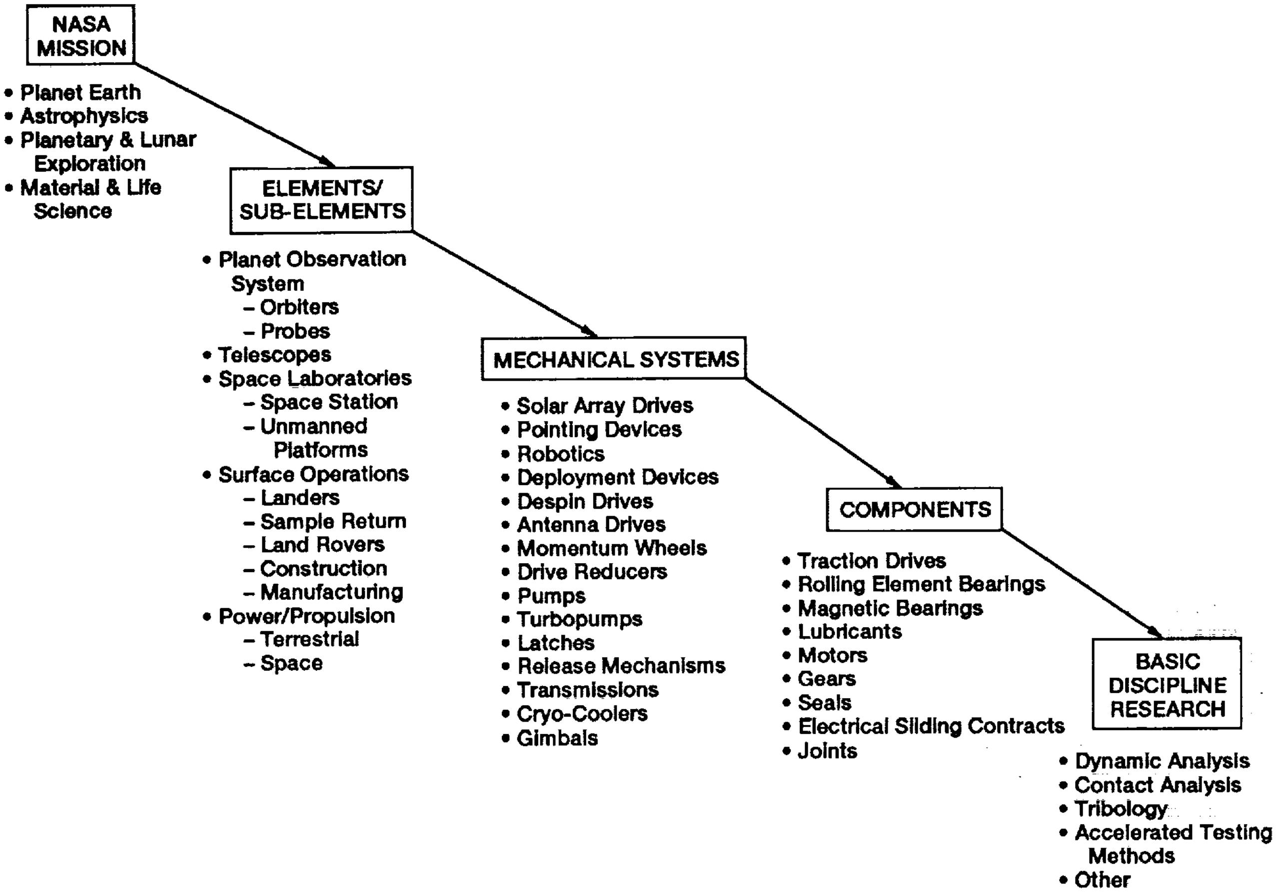

Figure 7.—Flow chart for developing mechanisms technology for a variety of future NASA missions.

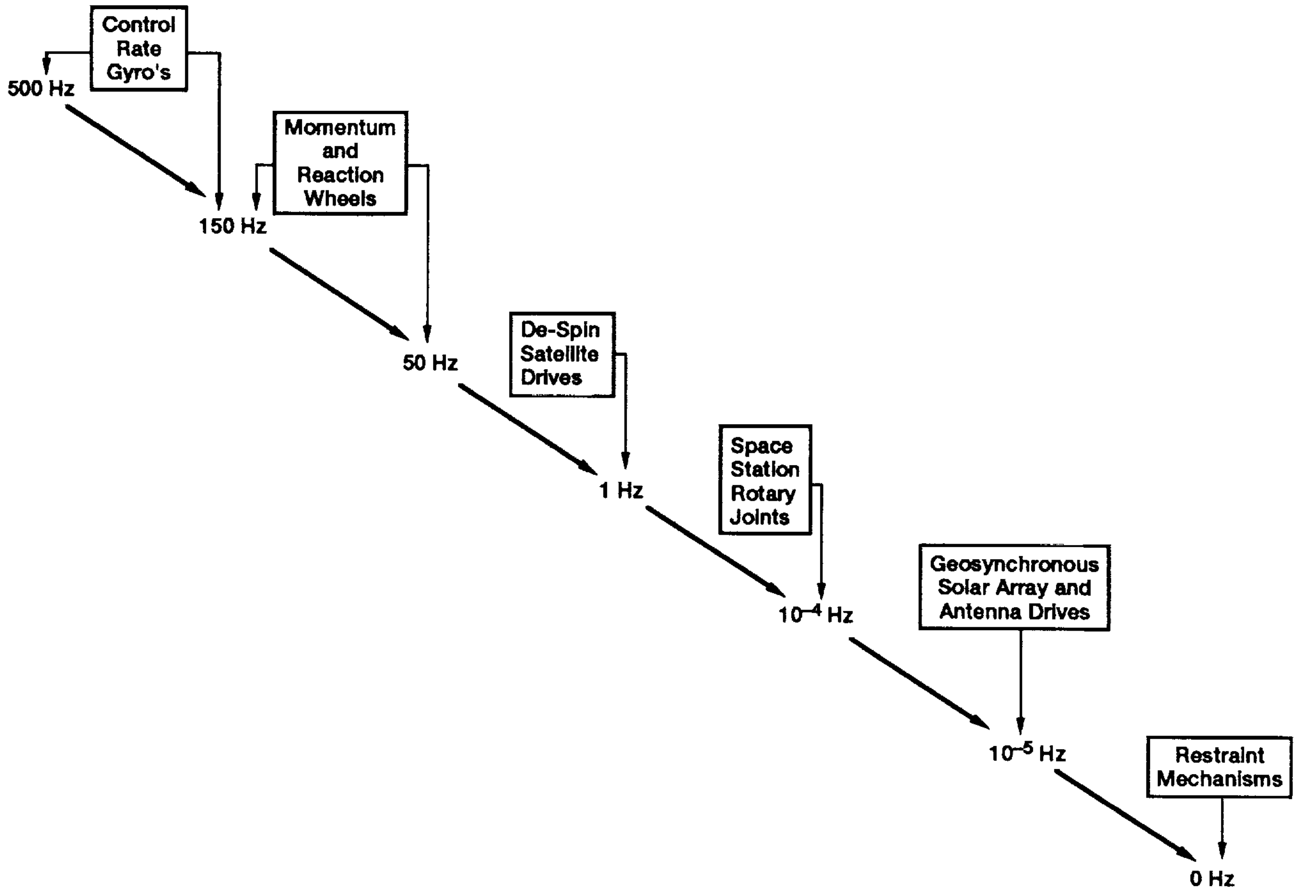

Figure 8.—Spectrum of speeds seen by space mechanisms.

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13. ABSTRACT ***(Maximum 200 words)***

President Bush has proposed that the United States undertake an ambitious mission of manned and robotic exploration of the solar system (Space Exploration Initiative, SEI), which will include an eventual manned mission to Mars. In addition to this mission, NASA has many other high technology programs planned such as the Space Station "Freedom," Mission to Planet Earth (a series of Earth observing satellites), space telescopes, planetary orbiters, etc. These missions will all require advanced mechanical moving components which will require wear protection and lubrication. The tribology practices used in space today are primarily based upon a technology base that is more than twenty years old. The question is: is this technology base good enough to meet the needs of these future long-duration NASA missions? This paper will discuss NASA's future space missions and some of the mechanism and tribology challenges that will be encountered. Potential solutions to these challenges using coatings technology will be explored.

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