Lubrication of DC Motors, Slip Rings, Bearings, and Gears for Long-Life Space Applications

B. J. Perrin and R. W. Mayer
Ball Brothers Research Corporation
Boulder, Colorado

The Vac Kote lubrication system, which was developed in support of the Orbiting Solar Observatory program, is described. The system involves the use of fluid organic compounds, solid films, and grease formulations. Theoretical principles underlying lubrication in the high vacuum of space are discussed. A summary of flight performance and laboratory test data on Vac Kote-lubricated parts is given; such parts include torque motors, slip ring assemblies, bearings, linkages, solenoids, potentiometers, and gears.

I. Introduction

Lubrication of moving parts, in the high-vacuum environment of space, is one of the special considerations of space technology. Inadequate lubrication of sliding or rolling metallic surfaces exposed to this environment not only results in excessive wear and erratic performance, but usually also in cold welding of surfaces and catastrophic failure. In addition to its customary functions of reducing friction, supporting loads, reducing wear, and transferring heat, the successful space lubricant must also satisfy the unique requirements imposed by ultra-high vacuum, zero gravity, and radiation.

In the atmosphere, surfaces can be lubricated by conventional methods, and a thin oxide layer will often prevent metals from adhering, even when no lubricant is present. Water vapor and organic contaminants in the atmosphere also help lubricate the interfaces. None of these welding inhibitors is normally available in sufficient concentration, in a space environment, to provide adequate lubricant protection. Conventional lubricants are not satisfactory for space application since many evaporate or decompose rapidly. The lubricant material must have a very low vapor pressure in order to prevent premature exposure by evaporation of the contact interface.

In space, zero gravity eliminates the use of gravity feed and some pressurized lubricating systems. Any system must therefore rely upon the surface mobility of the lubricant material (both across the surface and away from it) and unconventional reservoir devices. Two transportation mechanisms can be used in a lubrication system designed for space applications:

1. Direct contact of interface with a near-proximity reservoir (a lubricant-saturated bearing retainer, for example).
2. Molecular migration of the lubricant to the interface from a remote reservoir (a small, lubricant-saturated, sintered, nylon matrix, for example).

II. Vac Kote Lubrication Process

Both a theoretical model of material characteristics and their interaction, and an engineering model, defining the application, are required to evaluate the ability of lubricants to provide long-life component performance in the space environment. M. M. Fulk, staff scientist, Ball Brothers Research Corporation (BBRC), developed a theoretical model in 1959–1960.[1] This model forms the basis of BBRC's long-life vacuum lubrication processes, collectively known as Vac Kote.

Vac Kote involves the use of fluid organic compounds, containing metallo-organic complexes and long-chain hydrocarbon molecules; solid films (consisting mainly of molybdenum disulfide); and grease formulations. The BBRC models are used to evaluate molecular characteristics of the interface materials, the environment anticipated, and the performance requirements. This evaluation determines the specific combination of materials and techniques to be used. Thin-film coatings are applied by vacuum processing and adhere to metal surfaces through molecular bonding. Solid film coatings are applied mechanically.

All organic materials are adversely affected by radiation. This factor must be considered in the choice of lubricant materials. Primary radiation sources in space are the Van Allen belts, solar radiation, and cosmic radiation. The amount of annual radiation dosage, from these sources, inside a 0.25-in.-thick aluminum housing has been estimated to be approximately 5×10^6 ergs/gram for a synchronous orbit of 22,000-mile altitude. Threshold damage of Vac Kote lubricant, due to radiation, has been determined to be approximately 5×10^{10} ergs/gram, indicating approximately 10,000 years survival of such radiation exposure.

The Vac Kote lubrication system is designed to provide lubrication during the ground handling and testing required prior to equipment use as well as during space operation. The low vapor pressure of the lubricant permits the use of conventional open configurations in the design of the drive mechanisms, eliminating the need for complex seals of uncertain reliability. Simple mechanical designs, material selection, and extremely low vapor pressure coatings control lubricant outgassing contamination of other spacecraft devices. The very low vapor pressure of Vac Kote lubricant and its replenishment mechanism provide long-term lubricant availability at all contact interfaces.

The basic steps in the Vac Kote lubrication process are:

1. Pretreatment inspection and performance testing.
2. Vac Kote vacuum application.
3. Vacuum chamber run-in.
4. Inspection and performance testing after vacuum run-in.

III. Theoretical Principles

BBRC's approach to determining the special properties of a lubricant for high-vacuum space applications is based upon conventional lubrication technology, expanded by applicable fundamental principles of molecular physics, surface physics, and physical chemistry. For most applications, under normal atmospheric conditions, conventional lubrication technology can be used to determine the lubricant characteristics for supporting loads, controlling friction, and transmitting heat. The unique requirements of a high-vacuum space environment require consideration of additional lubricant properties.

BBRC uses two basic models to analyze these additional considerations: (1) a theoretical model that provides the analytical tool for evaluating the interaction of interface materials, and (2) an engineering model for analyzing the performance of hardware components, mechanical geometry, and lubrication system under the conditions of operation, load, and environment peculiar to the specific application.

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[1] Fulk, M. M., *Mechanics of Wear and Interaction of Metal Surfaces*, TN65-303. Ball Brothers Research Corporation, Boulder, Colo., Nov. 1965.

The theoretical model uses the standard theory of dislocations to account for the mechanics of wear. This theory assumes that adhesive wear accounts for most of the destruction. The model uses the concept of quantum electrodynamic forces to explain surface interaction and holds that the dielectric properties of films can be made to interact with the electrodynamic field to reduce the interaction between surfaces. In general, the critical dielectric properties of the Vac Kote thin film lubricant between surfaces are employed to alter the electrodynamic field and thus shield one surface from another. This shielding is known to prevent the type of component surface destruction commonly referred to as "cold welding."

In practice, BBRC employs several conventional models, used in lubrication technology to determine surface finish, lubrication load carrying characteristics, and heat transfer characteristics, as a part of the complete solution. These models are presented in several lubrication handbooks. This paper presents only the unique model used at BBRC to determine the additional properties of lubricants required for high-vacuum applications.

Wear is the deterioration and/or failure of interacting objects in use. *Wear* and *friction* are generally concurrent, but are not necessarily related in the sense of being simply proportional to one another. The major causes of wear are:

(1) Corrosive destruction (electrolytic and/or chemical).

(2) Mechanical destruction (galling, spalling, scoring, scuffing, seizing, abrasion, erosion, fretting, melting, plowing, cracking, etc.).

Mechanical wear occurs in solids but not generally in fluids. Mechanically generated wear is fundamentally a plastic flow on the surface of a solid. It is also a fatigue and fracture problem that occurs both in the body and on the surface of a solid. The relative motion of a dynamic system induces energy in the solids. This energy cannot be simply dissipated as it is in fluids. Instead, it must be dissipated throughout the inhomogeneous crystalline structure of the solid. Propagation of this energy results in plastic flow and/or nucleates cracks and propagates these cracks at stress levels far below their static fracture strength. Basically, this is the result of the effects of dislocations in the crystalline structure of the surface material, their generation, propagation, energy storage, and general accumulation. Dislocations are irregularities in the crystalline structure of materials. Their existence has been demonstrated and is the consequence of an assembly of atoms or molecules in a quasi-static geometric array (the condition of atoms and molecules in stable solids). Wear is related to the energy pumped into the system minus the heat generated. If all the energy dissipated in the system appears as heat, wear is small. This energy input and resulting wear and heat can be reduced by lowering the interaction between surfaces. Friction is a resisting force that is displayed when relative motion is imposed upon a system, and, as a resistance force, friction acts to oppose the relative motion.

Surfaces of matter show many phenomena. One is the ability to interact with another surface and display a "friction force." Surfaces are not strictly the two-dimensional region that bounds a solid (or liquid). This anisotropy of the surface occurs in the material crystalline structure and energy distribution. This external friction of solids can be a combination of a number of factors that contribute to the resistance of motion between their interacting surfaces.

Some of the factors known to contribute to this surface-to-surface "friction" are:

(1) Interlocking of surface irregularities.

(2) Electrical fields.

(3) Anelasticity.

(4) Adhesion (solid-to-solid adsorption, "cold welding").

Plastic and/or elastic deformation allows interacting surfaces to get together intimately at "spots." These spots are solid-to-solid adsorption or adhesion and are as strong as the yield strength of the base materials. Static adhesion sometimes appears to drop almost to zero when the load is removed because the accumulated elastic stresses under the spot are released and break these junctions or spots. Shearing of these adherent spots consumes energy and sometimes causes destruction of the interface. It is now generally accepted that this solid-to-solid adsorption, adhesion, or cold welding, as it is often called, is one of the main sources of destructive action between surfaces.

All physical phenomena display four basic physical forces:

(1) Strong forces in the nucleus.

(2) Weak forces in the nucleus.

(3) Gravity.

(4) Electromagnetic forces.

The forces of greatest concern in technological problems are electromagnetic. As a matter of fact, all the ordinary chemical, mechanical, and biological effects are due to the interaction of electric charges and the fields they produce. These electromagnetic forces include atomic, molecular, and intermolecular binding forces. These forces, which emanate from the surface of solids to cause interaction, are identified by the general term "friction."

Electromagnetic forces appear in many guises. The charge is quantized into (+) or (−). The force can be attractive or repulsive and is velocity-dependent, changing from electrostatic to electromagnetic, depending on the relative velocity of source and observer. The agent of this force is the photon. If two bodies are "separated" by a vacuum, electromagnetic forces are the only interaction between them. If the gap is occupied by some other medium, there is the possibility of a nonelectromagnetic interaction, such as that caused by sound oscillation in the medium.

An electromagnetic field can be modified by adding a dielectric material between the surfaces of interest. For example, two charges, $+e$ and $-e$, separated by a distance r in vacuum, will interact with a force e^2/r^2. If, however, there is some medium between the two charges, then the interaction force is decreased and becomes $e^2/\varepsilon r^2$, where ε is the dielectric permeability (generally greater than 1).

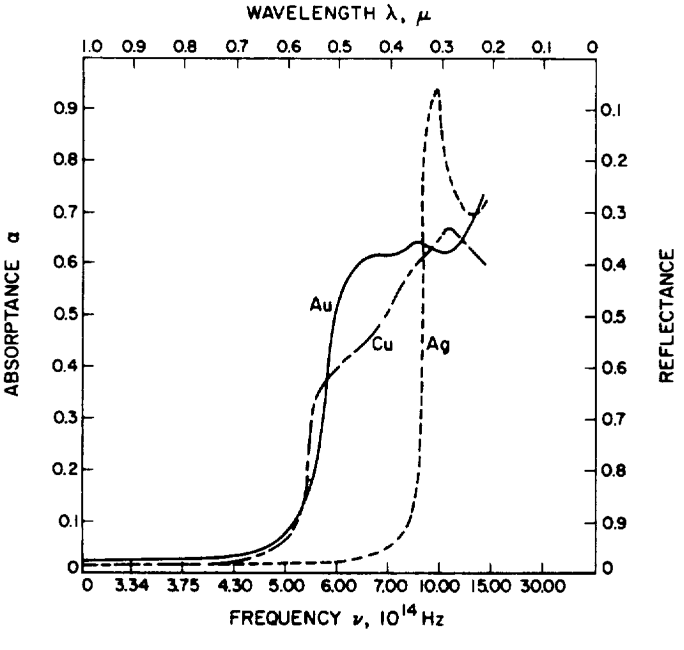

Fig. 1. Absorptance of Au, Ag, and Cu

Thus, the dielectric properties of the medium reduce electromagnetic interaction and act as a "shield" for the electric field (photons). Dielectric permeability is a measure of the medium's interaction with the electric field or photons.

If the interaction between solids is caused by the electromagnetic field (photons), then it seems reasonable to use the dielectric properties of a separate layer or film to reduce interaction between surfaces. There is a formal relation between the dielectric permeability ε, the index of refraction η, and the absorption coefficient k, as shown in the following equation:

$$\underset{\substack{\text{complex}\\\text{dielectric}\\\text{constant}}}{\varepsilon} = \underset{\substack{\text{real}\\\text{part}}}{\varepsilon_1(\eta)} + \underset{\substack{\text{imaginary}\\\text{part}}}{i\varepsilon_2(\eta)}$$

$$= \underset{\substack{\text{index of}\\\text{refraction}}}{[(\eta)} + \underset{\substack{\text{absorption}\\\text{coefficient}}}{ik(\eta)]^2}$$

This relationship is an expression of the theoretical model for determining the "shielding" properties of materials for use in lubricants.

The index of refraction η and the absorption coefficient k are both measures (albeit of different kinds) of the interaction of a medium with electromagnetic waves (photons). The index η alters the velocity of propagation, and k alters the intensity of the electromagnetic wave. Both are a result of the interaction of electromagnetic waves (photons) with the electron clouds present in the medium.

In general, the main microscopic property of bodies that determines the strength of electromagnetic interaction is the imaginary part of the dielectric constant. Thus, the main frequency of the electromagnetic interaction (photons) between objects is best determined by their absorption spectra. Figure 1 shows the absorption spectra for some metals. The frequencies of the electromagnetic field (or photons) that cause the interaction start at 10^{15} Hz; therefore, this is the frequency in which we are interested in the dielectric properties of films. The film on slip rings and similar equipment must be thin,

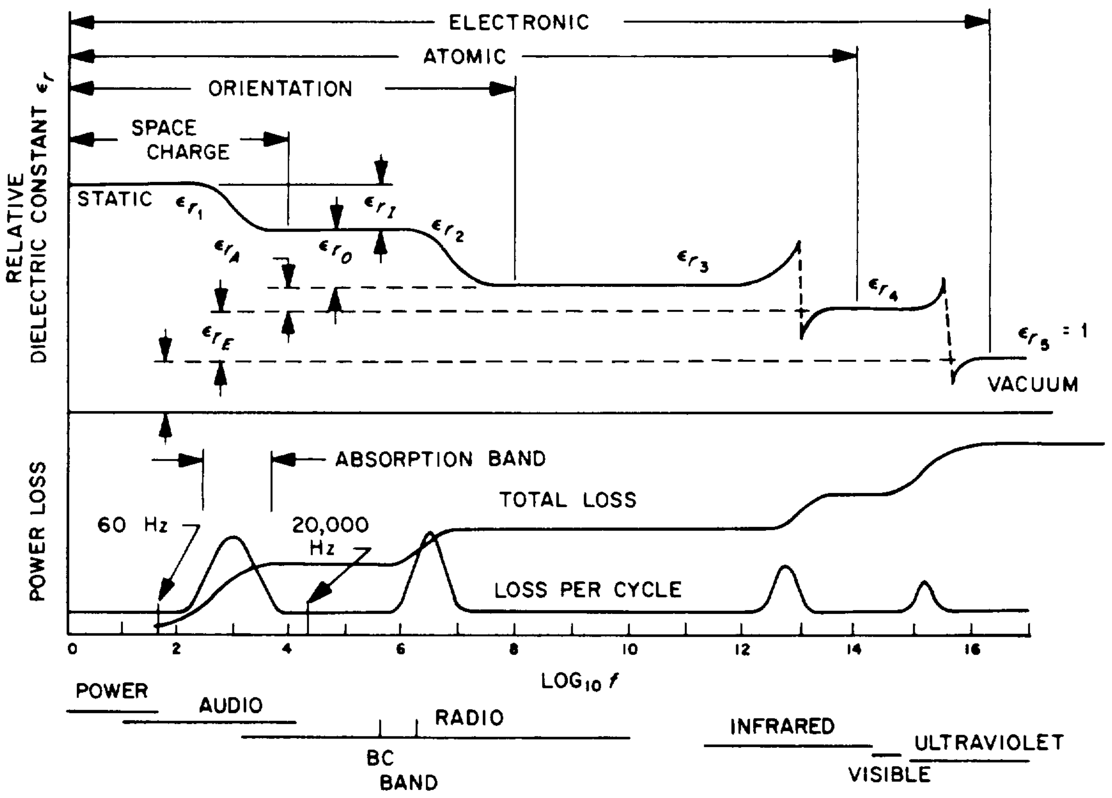

Fig. 2. Frequency dependence of relative dielectric constant and losses

$<<100$ Å thick, because of the need for electrical continuity. In thick films, dielectric permeability at other frequencies is of interest for such uses as ball bearings.

Figure 2 shows roughly the pattern of frequency dependence of dielectric permeability and losses. To reduce the electromagnetic interaction between metals, the electromagnetic field must be reduced by using films with maximum absorption and/or maximum anomalous dispersion and resonant absorption in the regions of interest.

Through the use of characteristic patterns, similar to Figs. 1 and 2, a lubricant is selected for use between interacting surfaces to alter the electromagnetic field.

IV. Applications and Results

A. The OSO Satellite

BBRC's Vac Kote lubrication system was developed in support of the *Orbiting Solar Observatory* (OSO) program. The first use of this lubrication system was in 1959 to lubricate a biaxial drive system on the spinning OSO. With the launch of OSO-I in 1962, Vac Kote became the first space-demonstrated, long-life lubrication system for moving metal-to-metal surfaces.

The accumulated total OSO satellite operation time in orbit, without measurable deterioration of the electrical and mechanical interfaces, now stands at 56 months. OSO-I was launched on March 7, 1962, and, when last interrogated after 24 months in orbit, showed no measurable deterioration of control and drive systems. Drive systems in OSO-II, launched Feb. 3, 1965, were performing equally well when the spacecraft was powered down after 9 months of continuous operation in orbit. This satellite was reactivated on March 3, 1966 (after 4 months of orbiting totally inactive). The control, drive, and data transmission systems operated normally. In May 1966, OSO-II drive systems were again called upon and operated within normal limits after 16 months in space. The drives of OSO-III, launched in March 1967, and OSO-IV, launched in October 1967, are continuing to function entirely within specifications.

B. Components Lubricated

Over 300 component operating years in vacuum have demonstrated that Vac Kote provides a reliable, long-life lubrication system for bearings, dc torque motors, slip rings, gears and sliding devices in the space environment. This operating time figure includes OSO orbit operating time and tests in vacuum at BBRC. It does not include the ground test and checkout time accumulated for hardware processed by BBRC for other program contractors. Further, the use of Vac Kote permits conventional open configurations instead of complex seals, resulting in savings in weight and higher reliability. The design life goal of systems which depend on such components is up to 5 years in space. There have been no reported failures of Vac Kote-lubricated flight-qualified hardware to date.

Both radial and thrust ball bearings have been used in most BBRC space applications that require rotating hardware. Sizes of Vac Kote-processed bearings range from 12-in.-OD thin-wall bearings to 0.25-in.-OD precision instrument bearings. Significant bearing performance data for both oscillatory and rotating motions in space have resulted from the OSO program. All OSO bearings have functioned without apparent increase in torque from satellite launch to subsequent shutdown. Any degradation due to increased bearing torque would have been detected by an increase in power consumption by the control system.

BBRC has conducted considerable motor and slip ring lubrication study, analysis, and investigation in vacuum, sponsored by NASA, industry, and BBRC. These studies include current density, contact construction, and interface-radiated noise, commutator/slip ring/brush material evaluation, slip-stick wear phenomena, plasma-generated emf, and high-current phenomena. The Vac Kote lubrication system has been an important factor in the success of drive systems in space to despin payloads and orient antennas, and in attitude-pointing subsystems.

Vac Kote-processed dc torque motors, slip rings, bearings, and gears have been used in the following aerospace programs and applications:

(1) OSO-I, OSO-II, OSO-III, and OSO-IV (solar array despin mechanism and elevation axis: dc torque motors, slip rings, and bearings, as well as bearings and moving parts of experimental payloads).

(2) ATS-II, ATS-IV (mechanical antenna despin assembly, camera bearings, and gears).

(3) OGO (experiment payload bearings).

(4) LES (experiment payload bearings and slip rings).

(5) *Apollo* Applications Program (experiment payload bearings and gears).

(6) ITS-III (mechanical antenna despin assembly: bearings).

(7) IDCSP/A, United Kingdom satellite (antenna despin assembly: bearings).

(8) AF-191 (mechanical antenna despin assembly: dc torque motor, slip rings, and bearings).

(9) Classified military reconnaissance (solar array drive: dc torque motors, slip rings, and bearings).

(10) Sounding rockets (despin mechanism and experiment pointing mechanism: bearings and gears).

(11) OAO (star tracker: dc torque motors, bearings, tachometers, sun slide mechanisms, and miscellaneous sliding parts).

(12) LIDOS (solar array drive: dc motor, bearings, and slip rings).

C. DC Torque Motors

Much of the motor lubrication research and testing activities at BBRC has been directed toward the dc torque motor. This device is ideally suited for space application because of its high torque-to-inertia ratio, light weight, and direct drive (no gearing). Both OSO orientation axes (azimuth and elevation) use dc torque motors. In addition, all rotating components tested at BBRC have been driven in vacuum by dc torque motors. As a result, considerable test data are available on these torque motors; more than 500×10^3 component hours and 200×10^6 component revolutions have accumulated in vacuum operation to date. After 4,800 hr (17.3×10^6 revolutions) operation in vacuum of 10^{-6} torr, these motors showed no signs of wear (see Fig. 3).

The brushes, as shown in Fig. 4, are barely "broken in." The vertical lines on the brush surface are the original surface tooling marks.

D. Slip Rings

BBRC has also conducted more than 6 years of research and testing in the field of lubrication of slip rings for space application. The slip ring lubrication problem is particularly difficult because of varied and stringent electrical and mechanical requirements. Several BBRC slip ring lubrication systems designed for 5-year space

Fig. 3. Vac Kote-treated 1.8-ft-lb torque motor for OSO satellite after 4800 h operation in vacuum of 10^{-6} torr (17.3×10^6 revolutions)

Fig. 4. Closeup of brushes

life have recently been incorporated into satellites. Figures 5 and 6 illustrate typical Vac Kote-treated slip ring brush performance obtained at BBRC.

Total life requirement of this test was 500 h at 10^{-8} torr. The light area on the brushes indicates a lubricant-brush-metal slurry which prevents brush-ring wear while providing electrical contact. Part of this slurry may remain on the ring when the brushes are removed.

E. Ball Bearings

Radial and thrust ball bearings have been used in most BBRC space applications requiring rotating hardware. Sizes of bearings that have been Vac Kote-processed range between 12-in.-OD thin-wall bearings and 0.25-in.-OD precision instrument bearings. To date, Vac Kote-processed bearings have recorded more than 1.9×10^6 component hours and 7.7×10^8 component revolutions of operation in vacuum. Figure 7 shows Vac Kote-treated balls after 8 months of vacuum testing, and Fig. 8 shows a Vac Kote-treated race after 8 months of vacuum testing.

Fig. 5. Vac Kote-processed slip ring brushes before vacuum life test

Fig 6. The same brushes as in Fig. 5, after test

The balls, loosely placed in the bore of the disassembled bearing, are free of blemishes or scratches. No indication of wear or degradation is observed. The rectangular mark on each ball is the camera reflected in the mirror-like surface.

The bearing race illustrates:

(1) Glossy reflection from undisturbed groove surface.

(2) Camera reflection.

(3) No evidence of degradation of ball track.

(4) Shadow on groove surface.

V. Summary of Flight Performance and Laboratory Test Data

A summary of significant Vac Kote lubrication tests and applications is shown in Table 1.

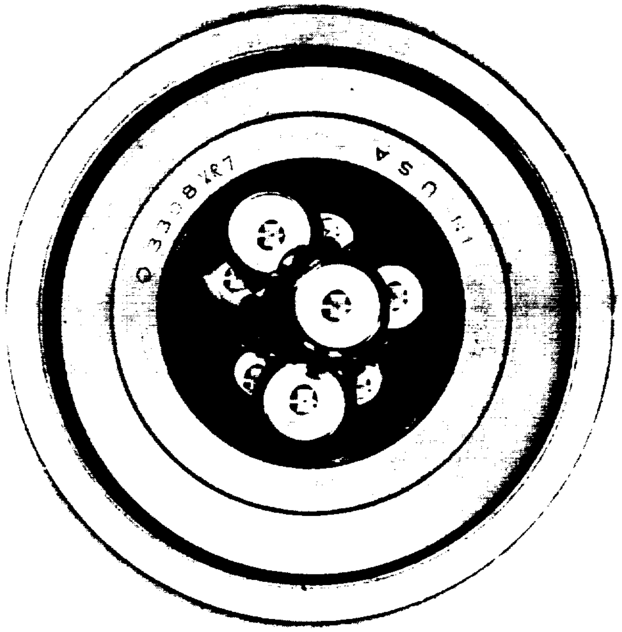

Fig. 7. Vac Kote-processed balls after test

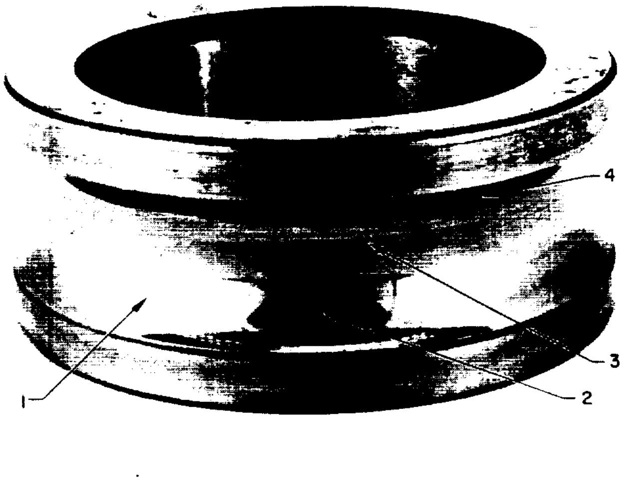

Fig. 8. Vac Kote-processed bearing races after test

Table 1. Vac Kote flight performance and laboratory test data summary[a]

Component	Program	Application	Vacuum exposure[b] duration, mo	Component		
				Number	Operating time, 10^3h	Operation, 10^6 revolutions
Torque motors	OSO I (S16)	Solar array despin	24.0	2^{c}	10.2	6.1
	OSO II (S17)		16.0	2^{c}	13.1	8.0
	OSO III		12.0^{d}	2^{c}	17.5	10.5
	OSO IV		4.5^{d}	2^{c}	6.6	4.0
			0.1	6	0.3	0.3
	OAO	Star tracker	3.5	100	20.0	3.0
			0.8	4	0.8	2.0
	Classified			4		11.6
	Classified	Despin mechanism	3.0	1		
	OAO (backup)	Star tracker	3.0	16	411.0	55.5
	Development and qualification	Despin mechanisms	12.0	80		
	OSO second source	Solar array despin	6.0	6	28.5	47.0
	IDCSPA/UK	Antenna despin	0.1	2	0.1	0.3
	AF 191	Antenna despin	0.1	6	0.4	0.6
	Classified	Solar array despin	0.1	16	1.0	1.5
	Total			249	509.5	150.4
Slip ring assemblies	OSO I (S16)	Signal, instrumentation, and power	24 0	1	5.1	6.1
	OSO II (S17)		16.0	1	6.5	8.0
	OSO III		12.0^{d}	1	8.8	10.5
	OSO IV		4.5^{d}	1	3.3	4.0
	LIDOS		4.0	1	2.8	0.3
	Classified		4.0	1	3.0	5.0
			4.0	1	3.0	5.0
			3.0	1		
			6.0	4	75.0	31.0
	OSO Development		6.0	25		
	LES			1		0.1
	Development			2		0.2
	OSO second source		6.0	6	26.5	47.0
	AF 191		0.1	5	0.4	0.7
	Classified		0.1	3	0.2	0.3
	Total			54	134.6	118.2
Bearings	OSO I (S16)	Despin mechanism	24.0	4^{c}	20.4	12.2
	OSO II (S17)		16.0	4^{c}	26.2	16.0
	OSO III		12.0^{d}	4^{c}	35.0	21.0
	OSO IV		4.5^{d}	4^{c}	13.2	8.0
	OSO qualification		8.0	44	158.4	312.6
			2.0	12	2.4	2.3
	OAO	Star tracker	4.0	12	30.6	0.8
	ATS	Camera and despin mechanism	11.0	22	16.7	100.2
	LIDOS	Despin mechanism	3.8	1	2.8	0.3
	ITS	Despin mechanism	0.1	275	13.7	24.7

[a] Significant tests to March 1, 1968.

[b] Maximum continuous time of one or more components.

[c] One motor despins solar array. One motor oscillates elevation control. In this table, revolutions are for 1 motor and 2 bearings on the despin drive. Oscillatory motions of elevation assembly components are not included.

[d] OSO III and OSO IV are still operating in space.

Table 1. (contd)

Component	Program	Application	Vacuum exposure[b] duration, mo	Component		
				Number	Operating time, 10^3h	Operation, 10^6 revolutions
	OAO	Star tracker	8.0	230		
	Development	Despin mechanism	8.0	622	1504.0	80.0
	OSO second source	↓	6.0	12	53.0	94.0
	IDCSPA/UK		0.1	9	0.1	3.0
	AF 191		0.1	28	1.6	3.2
	Classified		0.1	42	2.2	1.1
	Total			1325	1880.3	679.4
Linkages	OAO •	Star tracker	3.5	30	2.5	>1000 cycles
Solenoids	OAO	Star tracker	3.5	31	5.0	>1000 cycles
Potentiometers	Development	Antenna positioning	2	3		8 × 10^7 cycles
Gears	ATS	Camera and instrumentation		140		
	Development	Instrumentation	4	12	21.4	12.6 × 10^6 rev.

Panel Discussion

Bearings and Suspensions in Space

OVERLEAF: *Members of the panel were, left to right, William J. Kurzeka, Atomics International Division of North American Rockwell Corporation; H. I. Silversher, Lockheed Missiles & Space Company; William J. Schimandle, Jet Propulsion Laboratory, moderator; D. L. Kirkpatrick, General Electric Company; and George G. Herzl, Lockheed Missiles & Space Company*