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AN EVALUATION OF GREASE-TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS (Final Status Report No. 8)

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16. ABSTRACT

Because many future spacecraft or space stations will require mechanisms to operate for long periods of time in environments which are adverse to most bearing lubricants, a series of tests has been completed to evaluate 38 grease-type lubricants in R-4 size bearings in five different environments for a 1-year period. Four repetitions of each test were made to provide statistical samples. These tests were also used to select four lubricants for 5-year tests in selected environments with five repetitions of each test for statistical samples. In this completed program, 172 test sets have been completed. The three 5-year tests in (1) continuous operation and (2) start-stop operation, with both in vacuum at ambient temperatures, and (3) continuous vacuum operation at 93.3°C have been completed. In both the 1-year and 5-year tests, the best results in all environments have been obtained with a high viscosity index perfluoroalkylpolyether (PFPE) grease.

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(Final Status Report No. 8)

I. INTRODUCTION

This is the eighth and final report in a series of status reports to be issued covering a long-term test program to evaluate a number of fluid lubricants in ball bearings operating under various environmental conditions. The first report [1] discussed the general test program and gave the results of the first series of vacuum ambient temperature tests. Since that report, sufficient progress has been made to provide a comparison of many of the greases evaluated for ball-bearing lubricants in different environments; therefore, it is believed that the information also contained in the subsequent reports [2,3,4,5,6,7] will prove useful to those responsible for selecting lubricants for various space missions.

This program is an extension and expansion of pioneering work done by Young et al. [8] on fluid lubricated bearings operating in vacuum. Because many of the spacecraft planned for the future will require mechanisms that can operate for long periods of time in adverse environments, it was necessary to define the operating limits of available lubricants in these environments. As of October 1984, 680 sets of 1360 bearings have completed 1 year of testing and 60 sets of 120 bearings have completed 5 years of testing. The plan was to continue the test program using commercially available greases to determine statistically which lubricants would provide maximum bearing operating life with the environmental conditions under which they may be used. This procedure was used to eliminate all but four candidate lubricants for 5-year tests. These lubricants have been tested under selected environmental conditions to failure or for the 5-year period.

II. TEST EQUIPMENT

To provide a statistical sample of a number of lubricants operating under various environmental conditions, it was necessary to conduct a large number of tests simultaneously. Therefore, 20 test motors, each containing two test bearings, were set up in each chamber. Each test set consisted of four samples (eight bearings) of five different lubricants for the 1-year tests. One test set is shown in Figure 1. The bearings chosen for testing were size R-4, 0.635 cm I.D. by 1.59 cm O.D. (0.25 in. I.D. by 0.625 in. O.D.), 440 C steel (RC 60-65) with ribbon type stainless steel cages. An approximate 25 to 30 percent fill of the candidate greases was applied to each bearing, unless otherwise specified.

The motors used in these tests have the following characteristics:

1) Type — ac hysteresis, single phase, 60 cycle

2) Speed — 3600 rpm, synchronous

3) Current — 0.22 Amp.

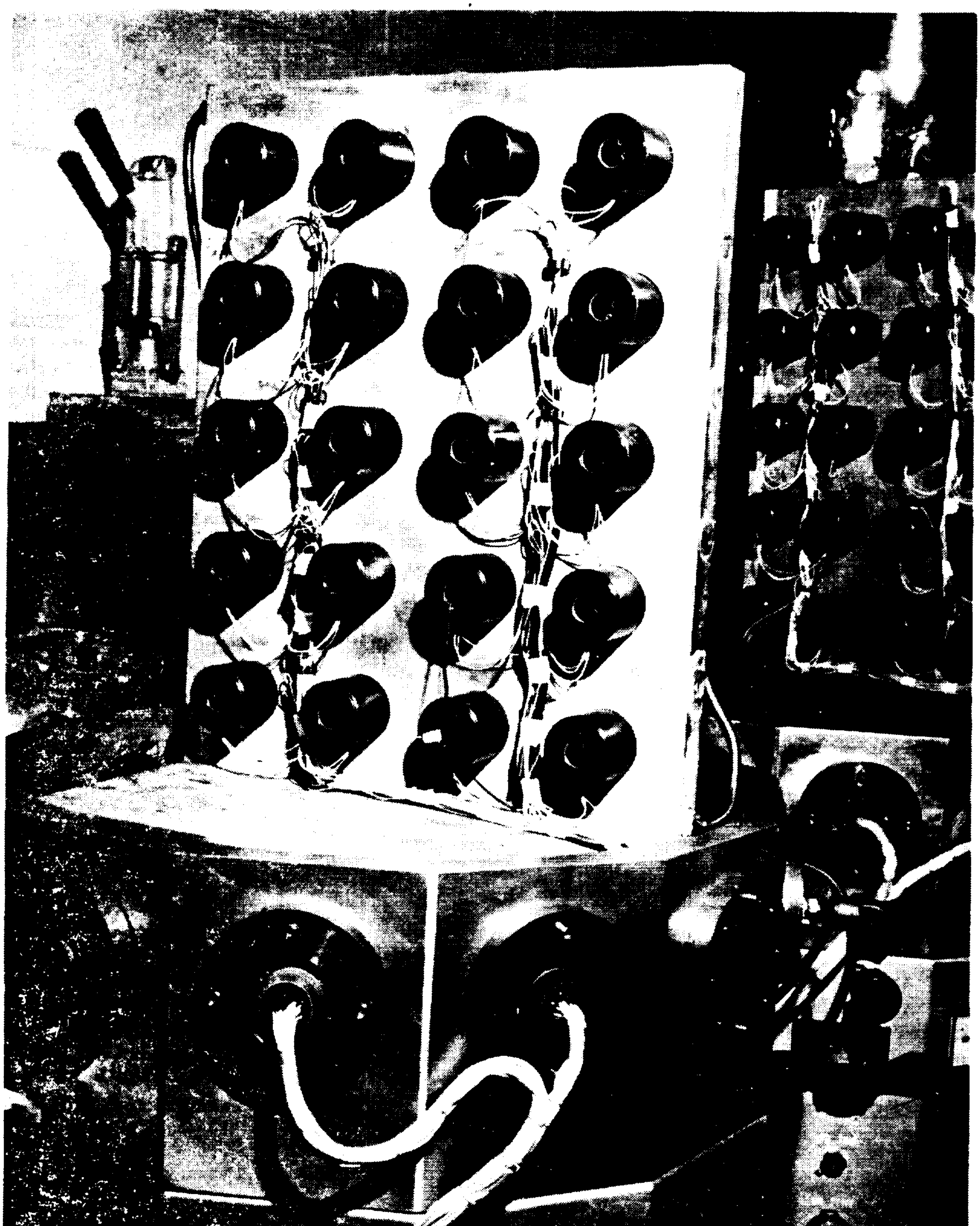

Figure 1. Test motors in vacuum chamber with bell jar removed.

Because these motors do not use brushes, no problems were encountered with brush dust contamination of the bearings. In addition, these motors use approximately the same current when stalled as when operating at 3600 rpm; consequently, a bearing failure does not cause motor damage from overheating. A disassembled motor bearing set is shown in Figure 2.

To control temperature, the motors are mounted in an aluminum plate which is furnished with passages so that thermal control fluids (water or liquid nitrogen) may be used to control the motor temperature. Temperature is measured by thermocouples attached to the mounting plate and to selected motor cases.

Each mounting plate with its motor set is placed in a glass bell jar vacuum system. These bell jars are part of a 12-position vacuum system which is capable of maintaining pressures in the 1.3×10^{-4} N/m^2 (1×10^{-6} torr) range during test operation. The same bell jars are used for the oxidation and low temperature start tests.

III. TEST PROCEDURE

Since most bearings operating in space are not subject to a radial load, the major load to the test bearings is a thrust load applied by a wave washer. The motors, specially ordered from the manufacturer, are shimmed to maintain a 2.27 kg (5 lb) thrust load on both bearings. This is equivalent to a 1.28×10^9 N/cm^2 (185 000 psi) Hz stress on the balls and inner races. The 3600 rpm speed allows 216 000 rev/h on each bearing until failure. Each bearing which survives the 1-year test will have completed approximately 1 892 000 000 revolutions.

At the beginning of the test program, 25 lubricants from seven general chemical classes were selected for evaluation, with 13 lubricants being added after the test program had begun. These lubricants were selected to represent most of the military grease specifications, as well as special nonspecification materials which had shown promise in space applications. The code designations given do not necessarily indicate different chemical compositions; the greases designated PFPE-4, PFPE-5, and PFPE-6 are from the same supplier, but with different base oil viscosities.

A general description of these greases is given in Table 1. It was planned to add additional lubricants to the test program (13 lubricants have been added since the start of the program) if data on new lubricants indicated that they had characteristics that would make them good candidates for one or more of the environments used in the test program.

The environments for the test program were as follows:

1) 10.134×10^4 N/m^2 (14.7 psi) air at 90 percent relative humidity (oxidation tests)

2) 6.894×10^4 N/m^2 (10 psi) O_2 at 90 percent relative humidity (oxidation tests)

3) Vacuum, ambient temperature (38°C)

4) Vacuum, high temperature (93.3°C)

5) Vacuum, ambient temperature, with start-stop operation

6) Low temperature start.

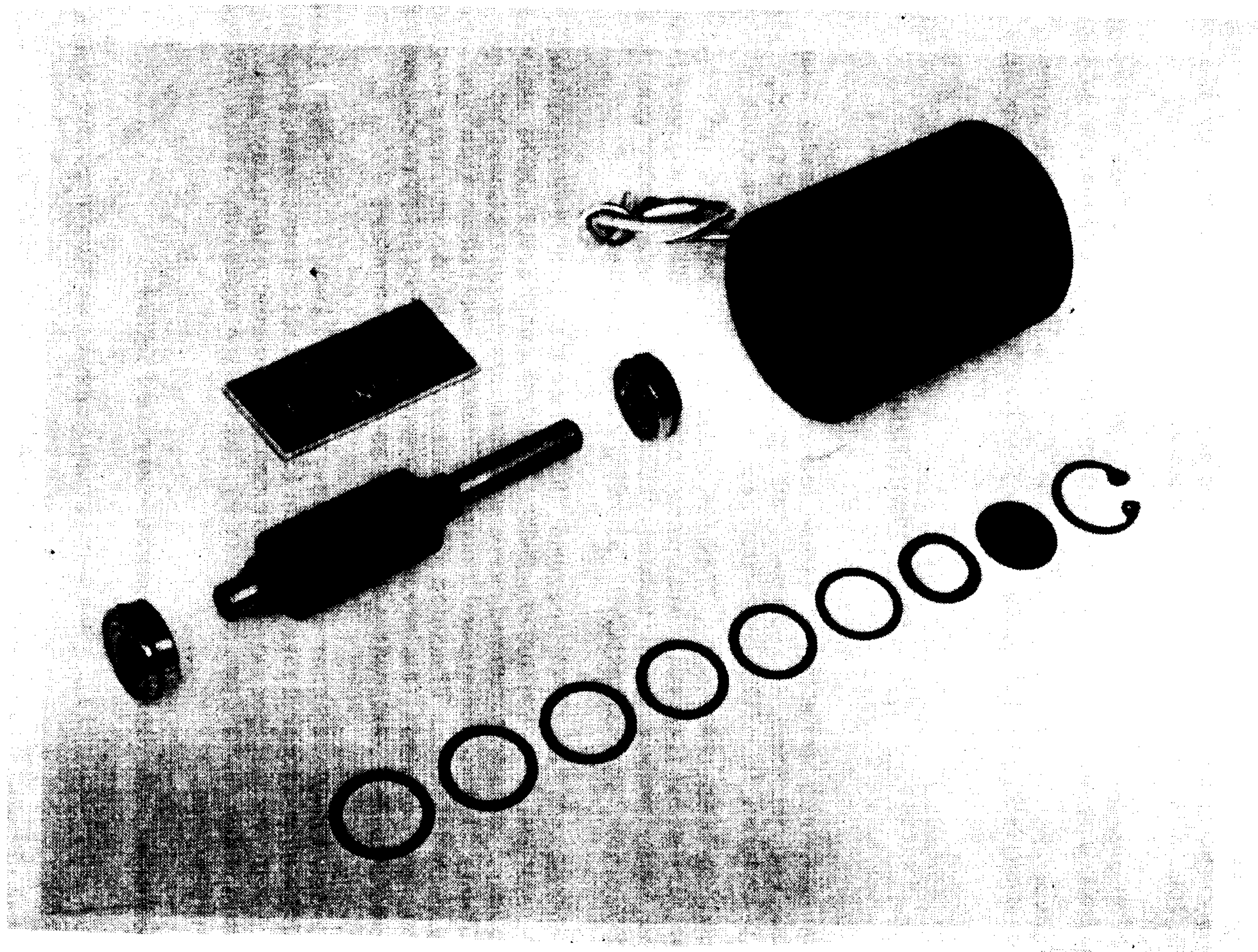

Figure 2. Disassembled ac motor with R–4 bearings.

TABLE 1. DESCRIPTION OF TEST LUBRICANTS

Manufacturer Designation	Lubricant Code	MIL Spec	Gen. Chem. Class of Base Oil	Thickener	38C Oil Viscosity (cs)	Oil Viscosity Index	Description of Greases
KG80	M-1	83176	Highly Refined Mineral	Inorganic	158	101	Instrument Brg.
SRG 200	M-2		Highly Refined Mineral	Inorganic	400	110	Brg.
Aeroshell 5	M-3	3545B	Mineral	Microgel	300		Hi Temp Acft
Royco 24R	M-4	10924B	Mineral	Li Soap			General Purpose
Royco 49	M-5	23549A	Mineral	MoS_2-Nonsoap			General Purpose
Royco 49B		23549B	Mineral	MoS_2-Nonsoap			General Purpose
Aeroshell 14	M-6	25537A	Mineral	Ca Soap	14		Oscillating Brg.
Aeroshell 16	M-7	25760A	Synthetic Mineral	Microgel	38		Brg., Wide Temp. Range
Apiezon L	M-8		Straight Chain Hydrocarbon	None			Vacuum
Unitemp 500	M-9		Mineral-Diester	Na Soap	55		Brg., Wide Temp. Range
Mobilgrease 28	M-10	81322	Synthetic Hydrocarbon	Nonsoap			Hi Temp. Acft.
Conoco HD #2	M-11		Mineral	Synthetic	108		Hi Temp. Corr. Resistant
BP 2110	M-12		Mineral	Graphite-Lead	119.7	107	Brg., Vacuum
Exxon Andok C	M-13		Mineral	Na Soap	110		Long Life Anti-Friction
Supermil 06752	ES-1	25760A	Diester	Arylurea			Brg., Wide Temp.
Aeroshell 17	ES-2	21164C	Diester	Microgel	14		Wide Temp. with MoS_2
Aeroshell 7	ES-3	23827A	Diester	Microgel	14		Acft. Instrument
L-11G	ES-4		Diester	Li Soap + MoS_2	14		Acft. Instrument
Exxon 5182	ES-5		Synthetic Ester	Li Soap	162	160	Hi Temp. Acft.
Beacon 325	ES-6	23827A	Synthetic Ester	Li Soap	11.8		Low Temp.
BP 8135	ES-7		Ester	Graphite-Lead	27.5	137	Brg., Vacuum
DC No. 33	Si-1		Silicone	Li Soap	750		Vacuum
G-351	Si-2		Silicone	Li Soap			Hi Temp. Ball Brg.
Supermil 31052	Si-3	25013D	Silicone	Organic Dye			Ball and Roller Brg.
G-330M	Si-4		Silicone				General Purpose
G-341L	Si-5		Silicone				Acft. and Instrument
3L27-2	Si-X		Silicone	Silica			Rad. Res't. Brg. Experimental
FS-1281	FS-1		Fluoro-Silicone	Silica			Vac. Low Speed Brg.
FS-1290	FS-2		Fluoro-Silicone				Chem. Inert Brg.
Kel-F No. 90	FCC-1		Fluoro-Carbon	Silica			Chem. Inert Hi Temp.
803	PFPE-1		PFPE	Fluorotelomer	424	129	Hi Vac. Brg.
3L-38RP	PFPE-2		PFPE	Fluorotelomer	129	350	Chem. Inert Hi and Low Temp.
3L-38RP Baked*			PFPE	Fluorotelomer			
631A	PFPE-3		PFPE	Fluorotelomer	153	110	Chem. Inert Brg.
240AZ	PFPE-4		PFPE	Fluorotelomer	18	23	Chem. Inert Low Temp.
240AB	PFPE-5		PFPE	Fluorotelomer	85	113	Chem. Inert Vacuum, Hi Temp.
240AC	PFPE-6		PFPE	Fluorotelomer	270	134	Chem. Inert Vacuum, Hi Temp.
3L-38-MS	PFPE-7		PFPE	Fluorotelomer			Chem. Inert Wide Temp. with MoS_2

* Vacuum baked at 100°C (212°F) for 20 hr.

The fine: status of the test program is given in Table 2.

The evaluations for all tests, except the low temperature tests, were based primarily on a go/no-go system. The motor torque is low and the inertia of the system is low; therefore, when the bearing tends to seize, the motor stops without further damage to the bearings. The following data are taken during the test:

1) Total test time
2) Vacuum or atmospheric conditions
3) Temperature
4) Total cycles, if appropriate.

The bearings are weighed before and after testing, and the percent of weight loss of lubricant is calculated.

In the low temperature start tests, the motors are installed in the cooling plate, and the system is evacuated to prevent frost formation. LN_2 is circulated through the cooling plate. The temperature is measured with thermocouples in contact with the outer race of the front bearing. Before cooling is initiated, the motors are operated for 30 min to channel the grease. The temperature is then dropped to -100°C and held approximately 30 min. The temperature is then allowed to rise slowly using a thermocouple on the mounting plate for control. After each 3°C rise, the motors are switched on for approximately 5 sec, and the temperatures of the front bearings are recorded. When each motor starts and comes up to full speed, the front bearing temperature is used as the low temperature starting capability of the lubricant. The starting torque of the motors used in this test is 1.05×10^{-2} N m (1.5 in. oz). Each low temperature test is repeated at least twice, and an average temperature is taken of the four motors and two tests.

IV. TEST RESULTS

A. Low Temperature Start Tests

Twenty-six of the candidate lubricants have been evaluated for low temperature start capability. Unfortunately, the temperature at which the bearings will stall is a function of the volume of grease in the bearing, as well as the viscosity of the grease; therefore, some variation in stall temperature is sure to occur. To help overcome this difficulty, four motors are tested with each lubricant and at least two tests are made on each motor. The resulting stall temperatures are then averaged. Results of these tests are shown in Table 3. Ordinarily, the vacuum stability requirements and the low temperature starting torque requirements are mutually exclusive because a low viscosity fluid provides better low temperature capabilities and a high viscosity fluid tends to be more vacuum stable. The results of these tests are; therefore, rather surprising since the PFPE-2 grease, which has a 38°C viscosity of 130 cs, has superior low temperature capabilities and is also one of the most vacuum stable greases evaluated. These capabilities are somewhat more understandable when it is noted that the base oil for this grease has a viscosity index of 350 and a molecular weight of over 9000.

TABLE 2. FINAL STATUS OF LUBRICANT TESTS

		Test Conditions					
		Oxidizing Environment c	Oxidizing Environment d	Vacuum (38°C)	Vacuum (93.3°C)	Vacuum (Start-Stop)	Low Temperature Start
KG 80	M-1	a	a	a	a	a	a
SRG 200	M-2			a	a	a	a
Aeroshell 5	M-3	a	a	a,b	a,a,b	a,a,b	a
Royco 24R	M-4			a			a
Royco 49	M-5			a	a	a	a
Royco 49B		a	a			a,a	
Aeroshell 14	M-6			a			a
Aeroshell 16	M-7			a			
Apiezon L	M-8			a			
Unitemp 500	M-9			a			
Mobilgrease 28	M-10	a	a	a	a	a	
Conoco HD #2	M-11	a	a	a	a	a	a
BP 2110	M-12	a	a	a	a	a	a
Andok C	M-13	a	a	a	a	a	a
Supermil 06752	ES-1	a		a		a	a
Aeroshell 17	ES-2			a			
Aeroshell 7	ES-3				a	a	a
L-11G	ES-4			a			a
Exxon 5182	ES-5	a	a	a	a	a	a
Exxon 325	ES-6	a	a	a	a		a
BP 8135	ES-7	a	a	a	a	a	a
DC No. 33	Si-1	a		a			
G-351	Si-2	a	a	a,b	a,a,b	a,a,b	a
Supermil 31052	Si-3			a	a	a	a
G-330M	Si-4			a	a		a
G-341L	Si-5	a	a	a	a	a	a
3L27-2	Si-X	a		a	a		
FS-1281	FS-1	a		a			
FS-1290	FS-2	a	a	a	a,a	a	
Kel-F No. 90	FCC-1				a		
803	PFPE-1	a	a	a,b	a,a,b	a,a,b	a
3L-38RP	PFPE-2	a	a	a,b	a,a,a,b	a,a,b	a
3L-38RP Baked*		a		a	a	a	a
631A	PFPE-3	a	a	a	a	a	a
240Az	PFPE-4	a	a	a	a	a	a
240AB	PFPE-5	a	a	a	a	a	
240AC	PFPE-6	a	a	a	a	a	a
3L-38 MS	PFPE-7	a	a	a	a	a	a

a. Test complete, 1 year or 2 days (low temperature test only)
b. Test complete, 5 year
c. Air, 90% RH
d. 10 psi O_2, 90% RH

*Vacuum baked at 100°C for 20 hr.

TABLE 3. LOW TEMPERATURE START, °C

Lubricant	1	2	3	4	Average
Si-3	-62.8	-78.9	-76.1	-70.0	-71.9
PFPE-7	-68.6	-68.6	-68.6	-68.6	-68.6
PFPE-2	-61.4	-57.5	-72.5	-82.2	-68.4
PFPE-2 Baked	-68.1	-66.7	-64.7	-64.7	-66.0
M-4	-58.9	-70.8	-60.0	-58.9	-62.1
M-6	-56.7	-55.0	-60.3	-60.3	-58.1
ES-4	-53.9	-57.8	-55.8	-55.0	-55.6
ES-1	-51.1	-53.8	-51.1	-51.1	-51.8
Si-5	-49.2	-49.2	-49.2	-49.2	-49.2
ES-3	-53.9	-41.1	-56.1	-42.1	-48.3
PFPE-1	-44.3	-44.3	-49.4	-48.0	-46.5
ES-5	-42.5	-42.5	-46.4	-46.4	-44.5
ES-7	-43.6	-42.8	-43.6	-43.6	-43.4
M-12	-42.8	-42.8	-42.8	-44.2	-43.2
ES-6	-41.4	-41.4	-41.4	-41.4	-41.4
PFPE-4	-36.1	-36.1	-36.1	-36.7	-36.3
Si-4	-34.4	-34.4	-34.4	-34.4	-34.4
M-13	-30.3	-31.7	-30.3	-30.3	-30.7
M-5	-23.1	-20.3	-26.4	-21.1	-22.7
M-11	-21.9	-21.9	-21.9	-21.9	-21.9
Si-2	-16.7	-16.7	-16.1	-16.1	-16.4
M-3	-16.1	-10.3	-16.1	-18.1	-15.2
M-1	- 6.7	- 4.4	- 4.4	- 4.4	- 4.98
PFPE-6	- 4.4	- 4.4	+ 1.1	- 4.4	- 3.02
PFPE-3	- 0.56	0.0	0.0	0.0	- 0.14
M-2	+ 3.30	+ 3.30	- 8.30	+ 3.30	+ 0.40

B. Continuous Vacuum Ambient Temperature Tests

Ten 1-year tests have been completed; the results are given in the first part of Table 4. Sixty-four motors (16 lubricants) have had no failures resulting from lubricant depletion, but motor No. 3 of lubricant M-3 had a drive motor failure. Also, the first 13 lubricants listed have had less than a 20 percent average weight loss.

One 5-year test has been completed; the results are given in the second part of Table 4.

The average temperatures (ten 1-year tests) have been as follows:

Front bearing — 96°F (35.6°C)
Rear bearing — 143°F (61.7°C)
Mounting plate — 73°F (22.8°C).

The average temperatures (one 5-year test) have been as follows:

Front bearing — 107°F (41.7°C)
Rear bearing — 134°F (56.7°C)
Mounting plate — 74°F (23.3°C).

TABLE 4. RESULTS OF VACUUM TESTS AT 38°C

Lubricant	Hours to Failure[a]					Weight Loss (%)[b]				
	1	2	3	4	Average	1	2	3	4	Average
PFPE-2	8760	8760	8760	8760	8760	5.1	6.9	8.1	5	6.3
Si-2	8760	8760	8760	8760	8760	3.5	12	6	4.5	6.5
M-5	8760	8760	8760	8760	8760	7.5	5	8	6.5	6.8
PFPE-2[d]	8760	8760	8760	8760	8760	7.7	5.4	8.8	5.7	6.9
Si-4	8760	8760	8760	8760	8760	9.4	8.6	5.7	5.7	7.4
ES-5	8760	8760	8760	8760	8760	7.6	8.6	6.4	7.5	7.5
M-12	8760	8760	8760	8760	8760	6.5	12.4	12.6	6.1	9.4
PFPE-6	8760	8760	8760	8760	8760	6	13.5	12.5	7	9.8
M-3	8760	8760	c	8760	8760	5.9	13.1	11.9	8.2	9.8
PFPE-3	8760	8760	8760	8760	8760	10	15.5	8.5	8	10.5
FS-2	8760	8760	8760	8760	8760	7	21	17.5	10.5	14
ES-7	8760	8760	8760	8760	8760	14.3	13.7	12	16.6	14.2
PFPE-1	8760	8760	8760	8760	8760	10.5	33	15	17	18.9
M-10	8760	8760	8760	8760	8760	26	20.5	19	23	22.1
M-13	8760	8760	8760	8760	8760	28	41.8	31.9	28.2	32.5
M-2	8760	8760	8760	8760	8760	66	49	40	50	51.3
M-11	8513	8760	8760	8760	8698	20.1	19.6	15.4	22	19.3
Si-5	4739	8760	8760	8760	7755	9.5	5.4	11.4	3.1	7.4
PFPE-7	4397	8760	8760	8760	7669	27.2	6	2.5	2.3	9.5
M-1	8760	8760	3700	8760	7495	21.5	27.5	23	25	24.3
Si-1	8760	8760	1709	8760	6997	35	25	41	22.5	30.9
PFPE-4	684	8760	8760	8760	6741	26	11.5	13	9	14.9
ES-1	3524	8760	8437	4397	6280	24.5	39.5	23.5	18.5	26.5
M-7	2530	8760	8760	3367	5854	53.8	46.8	54.3	41.9	49.2
PFPE-5	2096	3517	8760	8760	5783	33.5	40.5	3.5	3.5	20.3
Si-X	1041	6015	8760	5710	5382	27.5	28	40	47.5	35.8
M-8	392	8760	8524	1976	4913	3.3	0.8	0.8	22.5	6.9
ES-6	3563	5199	8760	1894	4854	61	67.8	59.6	68.3	64.2
M-9	2543	1487	1199	8760	3497	34.2	27.6	49.3	24.4	33.9
Si-3	5613	2164	1659	456	2473	52.5	27	43.5	24.5	36.9
M-4	2671	859	311	160	1000	74.5	73.5	82	78	77
ES-2	427	696	743	911	694	61.4	56.1	72.3	61.8	62.9
ES-4	559	593	559	823	634	30.5	32.5	39	41	35.8
FS-1	174	245	831	511	440	7.5	14.5	22.5	15.5	15
M-6	473	219	336	286	329	67	76	68.5	70.5	70.5

Lubricant	Hours to Failure[a]						Weight Loss (%)[b]					
	1	2	3	4	5	Average	1	2	3	4	5	Average
PFPE-1	31918	22676	43800	21140	32173	30341	52.1	32.7	7.51	43.2	46.7	36.4
PFPE-2	43800	43800	43800	43800	43800	43800	7.2	16.1	8.5	12	9.9	10.7
M-3	43800	43800	43800	43800	43800	43800	15.9	18.2	11.4	9.6	13.7	13.8
Si-2	19323	21424	32086	43800	1411	23609	35.7	33.5	47.7	10.4	37.6	33

a. Or to end of test (1 year = 8760 hr and 5 years = 43800 hr).
b. Percent of weight loss of total weight of grease added to the two bearings of each motor (motor Nos. 1 through 4 or motor Nos. 1 through 5).
c. Drive motor failed.
d. Baked in vacuum at 100°C for 20 hr.

C. Continuous Vacuum High Temperature Tests

Seven 1-year tests have been completed; the results are given in the first part of Table 5. Forty-four motors (11 lubricants) have had no failures resulting from lubricant depletion, but motor No. 2 of lubricant M-2 had a drive motor failure. Also, the first seven lubricants listed have had less than a 20 percent average weight loss.

One 5-year test has been completed; the results are given in the second part of Table 5.

The temperature in these high temperature tests is controlled by regulating the cooling water supply to the mounting plate so as to maintain its temperature at 65.5°C (150°F). The average temperatures (seven tests) have been as follows:

Front bearing — 170°F (76.7°C)
Rear bearing — 203°F (95.0°C)
Mounting plate — 153°F (67.2°C).

The average temperatures (one 5-year test) have been as follows:

Front bearing — 175°F (79.4°C)
Rear bearing — 189°F (87.2°C)
Mounting plate — 150°F (65.5°C).

D. Continuous Oxidation Ambient Temperature Tests

During the development of the Skylab thermal control fan, problems were encountered with bearings operating in a highly oxidizing atmosphere; therefore, it was believed that a highly oxidative environment should form a part of the present evaluations.

The first set of tests was made in air at 90 percent relative humidity. However, it appeared that a pure oxygen environment might be more severe; therefore, an additional set of tests was made in 10 psi pure oxygen at 90 percent relative humidity. Although no temperature measurements were made during these two tests, the bearing operating temperatures have been relatively close to subsequent ambient temperature tests, since the operating procedure for controlling cooling water flow to the motor mounting plates has been identical. Thermocouples were added on the subsequent seven tests.

Nine 1-year tests have been completed; the results are given in Table 6. Forty-four motors (eleven lubricants) in the air tests have had no failures resulting from lubricant depletion, but motor No. 3 of lubricant Si-1 had a drive motor failure. Also, the first eight lubricants listed in these air tests have had less than a 20 percent average weight loss. Sixty motors (fifteen lubricants) in the oxygen tests have had no failures resulting from lubricant depletion, but motor No. 3 of lubricant PFPE-3 had a drive motor failure. Also, the first six lubricants listed in these oxygen tests have had less than a 10 percent average weight loss.

The average weight loss of the 25 air tests is 19.9 percent. The average weight loss of the 20 oxygen tests is 18.6 percent. The air tests are more severe than the oxygen tests. Since this trend continued, the original assumption that oxygen tests might be more severe was incorrect.

TABLE 5. RESULTS OF VACUUM TESTS AT 93.3°C

Lubricant	Hours to Failure[a]					Weight Loss (%)[b]				
	1	2	3	4	Average	1	2	3	4	Average
PFPE-2	8760	8760	8760	8760	8760	13	13.5	14	17	14.5
PFPE-2[d]	8760	8760	8760	8760	8760	14.2	14.2	17.3	14.4	15
PFPE-6	8760	8760	8760	8760	8760	19.5	9	19.5	13.5	15.5
PFPE-5	8760	8760	8760	8760	8760	14	21.5	12	15.5	16
PFPE-1	8760	8760	8760	8760	8760	18	12.5	24.5	12	17
M-5	8760	8760	8760	8760	8760	15	24.5	14.5	15.5	17.4
PFPE-3	8760	8760	8760	8760	8760	18	16.5	24	19	19.5
M-3[e]	8760	8760	8760	8760	8760	27.4	25	24.6	23	25
M-3	8760	8760	8760	8760	8760	29.5	35	27	34.5	31.5
M-1	8760	8760	8760	8760	8760	29	37	32	43	35.5
M-2	8760	c	8760	8760	8760	55	31	50	47.5	46
FS-2	6813	8760	8760	8760	8273	59	35.5	30.5	35	40.5
M-5[e]	4979	8760	8760	8760	7815	31.6	28.3	15.4	11.4	21.7
M-12	8760	4745	8760	8760	7756	18	42.6	29.3	34.5	31.1
PFPE-2[e]	4979	8760	6659	8760	7290	79.3	12.9	40	4.9	34.3
Si-2	8760	2870	8760	8760	7288	23	51	23.5	36	33.4
PFPE-1[e]	6980	8760	8760	4187	7172	27.6	10.7	11.4	28.5	19.6
M-11	8760	5658	2432	8760	6403	34.9	41.7	23.7	43.6	36
Si-4	1218	8760	7940	6609	6132	50.5	9	27	25	27.9
Si-2[e]	4691	8760	8760	2156	6092	30.5	20.4	17.9	19.9	22.2
PFPE-7	2073	2057	8760	8760	5413	50	49.5	26.3	16.3	35.5
Si-5	8760	755	515	8760	4698	6.7	11.8	12.2	10.7	10.4
M-13	1905	1673	1362	5995	2734	70.7	67	60.2	75.1	68.3
ES-5	2432	1445	4442	1327	2412	23.8	32.7	40.8	34.9	33.1
Si-3	686	2290	1702	2327	1751	47.5	41	48.5	35.5	43.5
PFPE-4	3193	350	2523	282	1587	54	39	63	44	50
M-10	1091	1338	2222	1274	1481	68.7	73.8	48.3	63.3	63.5
ES-6	1031	1761	729	594	1029	83.9	73.6	79.1	61.9	74.6
FCC-1	353	1280	521	166	580	47	53	47.5	54	50.5
Si-X	174	101	1047	68.5	348	70.5	59.5	56	62.5	62.5
ES-7	161	57	125	177	130	54.7	56	56.9	85.5	63.3
ES-3	82	73	70	71	74	85.5	91.5	83.5	88	87.1

Lubricant	Hours to Failure[a]						Weight Loss (%)[b]					
	1	2	3	4	5	Average	1	2	3	4	5	Average
PFPE-1	27063	3971	5754	9012	26278	14416	26.3	28.7	22.8	23.7	35.8	27.5
PFPE-2	c	38749	26647	43800	42452	37912	14.4	71.2	53.6	15.7	42.6	41.5
M-3	38764	37886	26285	19557	43800	33258	40.2	49.6	33.2	51.8	24.5	39.9
Si-2	17877	25881	1759	21393	20277	17437	35	53.3	38.8	44.2	42.3	42.7

a. Or to end of test (1 year = 8760 hr and 5 years = 43800 hr).

b. Percent of weight loss of total weight of grease added to the two bearings of each motor (motor Nos. 1 through 4 or motor Nos. 1 through 5).

c. Drive motor failed.

d. Baked in vacuum at 100°C for 20 hr.

e. 10-15 percent fill, all others 25-30 percent fill.

TABLE 6. RESULTS OF OXIDIZING TESTS

14.7 psi Air at 90% Relative Humidity										
	Hours to Failure[a]					Weight Loss (%)[b]				
Lubricant	1	2	3	4	Average	1	2	3	4	Average
PFPE-1	8760	8760	8760	8760	8760	5	5.5	5	5.5	5.3
PFPE-3	8760	8760	8760	8760	8760	5.9	5.4	7.2	6.3	6.2
M-3	8760	8760	8760	8760	8760	6.8	5.7	6.3	9.6	7.1
FS-2	8760	8760	8760	8760	8760	4.8	8.5	9	8.5	7.7
Si-5	8760	8760	8760	8760	8760	8	7.1	12.2	6.6	8.5
ES-1	8760	8760	8760	8760	8760	12.5	12	11.5	12	12
M-10	8760	8760	8760	8760	8760	11.9	12.1	9.5	16.7	12.6
M-13	8760	8760	8760	8760	8760	31.9	15.5	15.2	12.3	18.7
M-11	8760	8760	8760	8760	8760	29.9	35	26.7	38.5	32.5
Si-X	8760	8760	8760	8760	8760	35.5	40.5	43	42	40
Si-1	8760	8760	c	8760	8760	48.5	47	40	46	45.4
M-12	8688	8760	8760	8760	8742	24.3	8.9	5.8	3.9	10.7
PFPE-4	8760	8760	8760	8357	8659	25	33.5	33.6	41.4	33.3
PFPE-5	8760	7147	8760	8598	8316	8.3	35.6	5.9	30.2	20
ES-6	8760	8760	8760	6456	8184	20.8	28	32.7	47.4	32.2
M-5[e]	4884	8760	8760	8760	7791	32	5.7	5.2	5.9	12.2
Si-2	8760	8760	6065	5287	7218	7.6	8.5	44.1	34.7	23.7
ES-7	8760	8760	2445	8760	7181	6.9	6.6	15.2	9	9.4
M-1	8760	8760	2116	8760	7099	16.8	19.5	24.5	12.1	18.2
ES-5	1714	8760	8760	8760	6999	19.5	12.7	14.8	19.5	16.6
FS-1	8760	405	8760	8760	6671	3	3.5	3	4.5	3.5
PFPE-2	8760	7709	5699	2480	6162	19.2	36.4	34	32.3	30.5
PFPE-7	4117	8760	5699	5467	6011	47.2	10.8	30.7	49.8	34.6
PFPE-7	7938	4473	8262	3077	5938	26.1	44.5	17.3	39.7	31.9
PFPE-2[d]	1955	851	995	8760	3140	30.4	29.6	30.9	3	23.5

10 psi Oxygen at 90% Relative Humidity										
	Hours to Failure[a]					Weight Loss (%)[b]				
Lubricant	1	2	3	4	Average	1	2	3	4	Average
ES-7	8760	8760	8760	8760	8760	2.6	1.5	1.6	1.8	1.9
Si-2	8760	8760	8760	8760	8760	9.6	1.7	4	3.7	4.8
M-3	8760	8760	8760	8760	8760	6.3	4	6.3	6	5.7
M-5[e]	8760	8760	8760	8760	8760	10.3	4	3.5	7.4	6.3
M-12	8760	8760	8760	8760	8760	12.9	7.2	7	3.8	7.7
ES-5	8760	8760	8760	8760	8760	7	10.5	10.6	5.6	8.4
PFPE-1	8760	8760	8760	8760	8760	6.7	3.8	20.8	8.8	10
PFPE-6	8760	8760	8760	8760	8760	15.7	10.2	9.3	14.3	12.4
Si-5	8760	8760	8760	8760	8760	14.7	11.8	13	17.3	14.2
FS-2	8760	8760	8760	8760	8760	14.4	13.7	13.2	20	15.3
PFPE-3	8760	8760	c	8760	8760	11.3	11.6	32.4	12.1	16.9
M-1	8760	8760	8760	8760	8760	20	19	17.8	22.6	19.9
ES-6	8760	8760	8760	8760	8760	24.7	27.8	13.7	17.4	20.9
M-10	8760	8760	8760	8760	8760	19.4	22.8	21.8	20.4	21.1
PFPE-4	8760	8760	8760	8760	8760	50.9	30	70.7	39	47.7
M-13	8760	8760	8760	8369	8662	52	44.5	51	64.5	53
PFPE-7	8760	8760	8760	7946	8557	3.4	2.3	2.4	1.8	2.5
PFPE-2	8760	4795	8760	8760	7769	6.7	47.1	11.8	11.3	19.2
M-11	8369	8689	3806	8477	7335	54.1	47.8	59.6	51.8	53.3
PFPE-5	3119	6399	8760	8760	6760	38.1	31.9	24.8	27.7	30.6

a. Or to end of test (1 year = 8760 hr).
b. Percent of weight loss of total weight of grease added to the two bearings of each motor (motor Nos. 1 through 4).
c. Drive motor failed.
d. Baked in vacuum at 100°C for 20 hr.

The average temperatures (seven 1-year tests) have been as follows:

Front bearing — 84°F (28.9°C)
Rear bearing — 115°F (46.1°C)
Mounting plate — 82°F (27.8°C).

E. Start-Stop Vacuum Ambient Temperature Tests

Since many mechanisms do not operate continuously, it was decided to simulate the boundary conditions which exist between the balls and races of a bearing during acceleration and deceleration. Timers are used to shut off the motors for 10 sec every 150 sec (24 cy/hr) or for 20 sec every 180 sec (20 cy/hr).

Seven 1-year tests have been completed/ the results for the first five are given in the first part of Table 7. Fifty-two motors (thirteen lubricants) have had no failures resulting from lubricant depletion. Also, the first nine lubricants listed have had less than a 20 percent average weight loss.

One 5-year test including the results of the last two 1-year tests for motors specified by note e has been completed; the results are given in the second part of Table 7.

Cycle counters are used at the start-stop stations to record the total number of cycles. The total cycles of the five 1-year and one 5-year tests were as follows:

1) 202 382
2) 188 342
3) 174 206
4) 177 337
5) 210 382
6) 1 051 568.

The average temperatures (seven 1-year tests) have been as follows:

Front bearing — 94°F (34.4°C)
Rear bearing — 119°F (48.3°C)
Mounting plate — 70°F (21.1°C).

The average temperatures (one 5-year test) were as follows:

Front bearing — 123°F (50.6°C)
Rear bearing — 170°F (76.7°C)
Mounting plate — 105°F (40.6°C).

V. FUTURE PLANS

Since all but four lubricants were eliminated for the 5-year test program, a rating sheet (Table 8) was devised to eliminate those lubricants which performed poorly under the various test environments. The ratings are made by assigning the number 1 to the lubricant which performs the best in a particular test, the number 2 to the second best, etc. Where several lubricants are considered equal, the positions are averaged and assigned to all the equivalent lubricants. Table 8 is used

TABLE 7. RESULTS OF START-STOP TESTS

Lubricant	Hours to Failure[a]					Weight Loss (%)[b]					Cycle Time (s)
	1	2	3	4	Average	1	2	3	4	Average	
PFPE-6	8760	8760	8760	8760	8760	8	3	6.5	4	5.4	180
PFPE-1	8760	8760	8760	8760	8760	4.5	5	3.5	10	5.8	150
PFPE-2[c]	8760	8760	8760	8760	8760	5.7	6.1	6.7	6.1	6.2	180
PFPE-2	8760	8760	8760	8760	8760	7	8.5	4.5	7.5	7	150
ES-5	8760	8760	8760	8760	8760	7.1	7.4	8.8	5.2	7.1	180
M-3	8760	8760	8760	8760	8760	12	6	8.5	10.5	9.3	180
PFPE-7	8760	8760	8760	8760	8760	17.2	15.6	18.8	10.5	15.5	150
PFPE-3	8760	8760	8760	8760	8760	9.5	20.5	12	28	18	180
ES-7	8760	8760	8760	8760	8760	24.7	11	15	25.9	19.2	150
M-5[d]	8760	8760	8760	8760	8760	21.5	22.8	17.3	20	20.4	150
M-11	8760	8760	8760	8760	8760	24.3	21.1	20.6	17.3	20.8	180
M-5	8760	8760	8760	8760	8760	23	31	12	25	22.8	180
M-13	8760	8760	8760	8760	8760	37.8	34.6	26	19.1	29.4	150
M-1	8760	8760	6790	8760	8268	6.5	14	36.5	11	17	180
Si-3	5409	8760	8760	8760	7922	32	12.5	12	14	17.5	180
M-12	8760	8760	4232	8760	7628	14.7	14.6	46.4	15.8	22.9	150
M-10	6261	6313	8760	8760	7524	47.4	46.6	22.8	37.1	38.5	180
PFPE-5	8760	8760	8760	2817	7274	5	3.5	1.5	23	8	150
ES-1	5783	8760	5497	8760	7200	44.5	16	57	15	33.5	180
M-2	8760	8760	1848	8760	7032	27	26	46	20	30	180
Si-2	8760	1557	8760	8760	6957	3	9.5	5	5	5.5	150
FS-2	685	8760	8760	5684	5972	15	19	21.5	25.5	20.5	150
Si-5	5577	8760	629	8760	5932	40.3	5.1	31.8	8.5	21.4	180
PFPE-4	4977	4737	5926	6586	5557	84	76.5	66.5	70	74.3	180
ES-3	3345	3501	2117	4340	3326	76	69.5	68.5	68	70.5	180

Lubricant	Hours to Failure[a]						Weight Loss (%)[b]						Cycle Time (s)
	1	2	3	4	5	Average	1	2	3	4	5	Average	
PFPE-1	43800	43800[e]	43800	11116	43800	37263	18.7	18.9	39.5	39.4	15.7	26.4	150
PFPE-2	43800	43800	43800	43800[e]	43800	43800	19.6	8.5	12	15.9	13.5	13.9	150
M-3	43800	39210	24431[e]	19544[e]	20276[e]	29452	27.6	29.7	20.4	24.7	22.8	25	150
Si-2	38661	40174	15905[e]	29133	39040[e]	32583	18	20.6	23.2	13	24.5	19.9	150

a. Or to end of test (1 year = 8760 hr and 5 years = 43800 hr.
b. Percent of weight loss of total weight of grease added to the two bearings of each motor (motor Nos. 1 through 4 or motor Nos. 1 through 5).
c. Baked in vacuum at 100°C for 20 hr.
d. Royco 49B (Table 1).
e. Drive motor failed. Bearings not removed from armatures. Since the last status report, armatures with bearings assembled in new motors were further tested in Start-Stop tests.

TABLE 8. LUBRICANT RATING CHART

Lube Code		Oxidizing Environment b	c	Vacuum (38°C)	Vacuum (93.3°C)	Vacuum Start-Stop	Low Temperature Start	Decision (See Note)
KG80	M-1	19	8	20	6	14	23	
SRG 200	M-2			8.5	6	20	26	
Aeroshell 5	M-3	6	8	8.5	6,6^{c}	7	22	
Royco 24R	M-4			31			5	EL
Royco 49	M-5			8.5	6	7	19	
Royco 49B		16	8		13^{c}	7		
Aeroshell 14	M-6			35			6	EL
Aeroshell 16	M-7			24				EL
Apiezon L	M-8			27				EL
Unitemp	M-9			29				EL
Mobilgrease 28	M-10	6	8	8.5	27	17		
Conoco HD #2	M-11	6	19	17	18	7	20	
BP2110	M-12	12	8	8.5	14	16	14	
Exxon Andok C	M-13	6	16	8.5	23	7	18	
Supermil 06752	ES-1	6		23		19	8	EL
Aeroshell 17	ES-2			32				EL
Aeroshell 7	ES-3				32	25	10	EL
L-11G	ES-4			33			7	EL
Exxon 5182	ES-5	20	8	8.5	24	7	12	
Beacon 325	ES-6	15	8	28	28		15	
BP 8135	ES-7	18	8	8.5	31	7	13	
DC No. 33	SI-1	6		21				EL
G-351	Si-2	17	8	8.5	16,20^{c}	21	21	
Supermil 31052	Si-3			30	25	15	1	EL
G-330M	Si-4			8.5	19		17	EL
G-341L	Si-5	6	8	18	22	23	9	
3L27-2	Si-X	6		26	30			EL
FS-1281	FS-1	21		34				EL
FS-1290	FS-2	6	8	8.5	12	22		
Kel-F No. 90	FCC-1				29			EL
803	PFPE-1	6	8	8.5	6,17^{c}	7	11	
3L-38RP	PFPE-2	22	18	8.5	6,15^{c}	7	3	
3L-38RP Baked		25		8.5	6	7	4	
631A	PFPE-3	6	8	8.5	6	7	25	
240AZ	PFPE-4	13	8	22	26	24	16	
240AB	PFPE-5	14	20	25	6	18		
240AC	PFPE-6	24	8	8.5	6	7	24	
3L-38-MS	PFPE-7	23	17	19	21	7	2	

Note: EL - eliminate from further testing.

a. Air, 90% RH.

b. 10 psi O_2, 90% RH.

c. 10-15 percent fill, all others 25-30 percent fill.

to illustrate the comparative principle only; however, using this chart, it was previously decided to eliminate 15 of the materials from further testing because they performed poorly in either the vacuum ambient or vacuum high temperature tests.

Since the last status report, four more oxidizing environment and two start-stop tests have been completed.

Due to the present and future emphasis on the Space Station program and since this is the last report in this series of status reports of the lubricants specified in Table 1, a new series of status reports is forthcoming on an updated group of lubricants which will be replacing those for the most part in the aforementioned table.

VI. CONCLUSIONS

Since testing has been completed in this program, the following conclusions, from the 1-year and 5-year vacuum tests data, have been made:

1) As a whole, the chemical class listed as PFPE in Table 1 has given the best results in all the vacuum tests completed.

2) In the 1-year vacuum ambient temperature tests, PFPE-2 (as manufactured and vacuum baked) and PFPE-6, Si-2 and Si-4, M-5 and M-12, and ES-5 have given the best results with less than a 10 percent average weight loss. In the 5-year vacuum ambient temperature tests, PFPE-2 and M-3 have given the best results with less than a 14 percent average weight loss.

3) In the 1-year vacuum high temperature tests, M-5 and all the PFPE greases, except PFPE-4 and PFPE-7, have given the best results with less than a 20 percent average weight loss. In the 5-year vacuum high temperature test, one PFPE-2 motor and one M-3 motor completed the test with weight losses of 15.7 and 24.5 percent, respectively.

4) In the 1-year start-stop tests, ES-5, M-3, and PFPE greases (except PFPE-3, PFPE-4, and PFPE-5) have given the best results with less than a 10 percent average weight loss. In the 5-year start-stop test, PFPE-2 has given the best results with a 13.9 percent average weight loss. Since there were seven motor failures in the test, further testing has been completed on the armatures with bearings (see note e of Table 7).

5) A 25 to 30 percent fill of a grease gives better results, on the whole, than a 10 to 15 percent fill.

6) The use of PFPE-2 as received gives better results, on the whole, than using PFPE-2 after a vacuum bake at 100°C for 20 hours.

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APPROVAL

AN EVALUATION OF GREASE TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS
(Final Status Report No. 8)

By E. L. McMurtrey

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

E C McKannan for
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