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AN EVALUATION OF GREASE TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS

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AN EVALUATION OF GREASE TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS (Status Report No. 3)

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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 is continuing to evaluate 29 grease type lubricants in R-4 size bearings in five different environments for a 1 year period. Four repetitions of each test are made to provide statistical samples. These tests have also been used to select four lubricants for 5 year tests in selected environments with five repetitions of each test for statistical samples. At the present time, 65 test sets have been completed and 23 test sets are underway. Two (5 year) tests have already been started in (1) continuous operation and (2) start-stop operation, with both in vacuum at ambient temperatures. To date, in the 1 year tests, the best results in all environments have been obtained with a high viscosity index perfluoroalkylpolyether grease.

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AN EVALUATION OF GREASE TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS (Status Report No. 3)

I. INTRODUCTION

This is the third 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. A previous 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 being evaluated for ball bearing lubricants in different environments; therefore, it is believed that the information contained in this series of reports[2] will prove useful to those responsible for selecting lubricants for various space missions.

This program is an extension and expansion on pioneering work done by Young, et al.[3] 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 is necessary to define the operating limits of available lubricants in these environments. As of November 1977, 260 sets of 520 bearings have completed 1 year of testing, and 100 sets of 200 bearings are undergoing tests. The present plan is to continue the test program using commercially available and recently developed greases to determine statistically which lubricants will provide maximum bearing operating life and the environmental conditions under which they may be used. This procedure has been used to eliminate all but four candidate lubricants for 5 year tests. These lubricants are now being tested under selected environmental conditions to failure or for a 5 year period.

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1. Demorest, K.E. and McMurtrey, E.L.: An Evaluation of Various Ball Bearing Lubricants Operating in Various Environments (A Status Report). ASLE Preprint 75AM-2D-3.

2. Demorest, K.E. and McMurtrey, E.L.: Status Report No. 2, October 1976.

3. Young, W. C. et al.: Lubrication for Spacecraft Applications, Lubrication Engineering, No. 22, Vol. 6, June 1966, pp. 219-227.

II. TEST EQUIPMENT

To provide a statistical sample of a number of lubricants operating under various environmental conditions, it is necessary to conduct a large number of tests simultaneously. Therefore, 20 test motors, each containing two test bearings, are set up in each chamber. Each test set consists 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 are 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 10 to 15 percent fill of the candidate greases is applied to each bearing.

The motors used in these tests have the following characteristics:

a. Type — ac hysteresis, single phase, 60 cycle

b. Speed — 3600 rpm, synchronous

c. Current — 0.22 amp.

Because these motors do not use brushes, no problems are 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 tests.

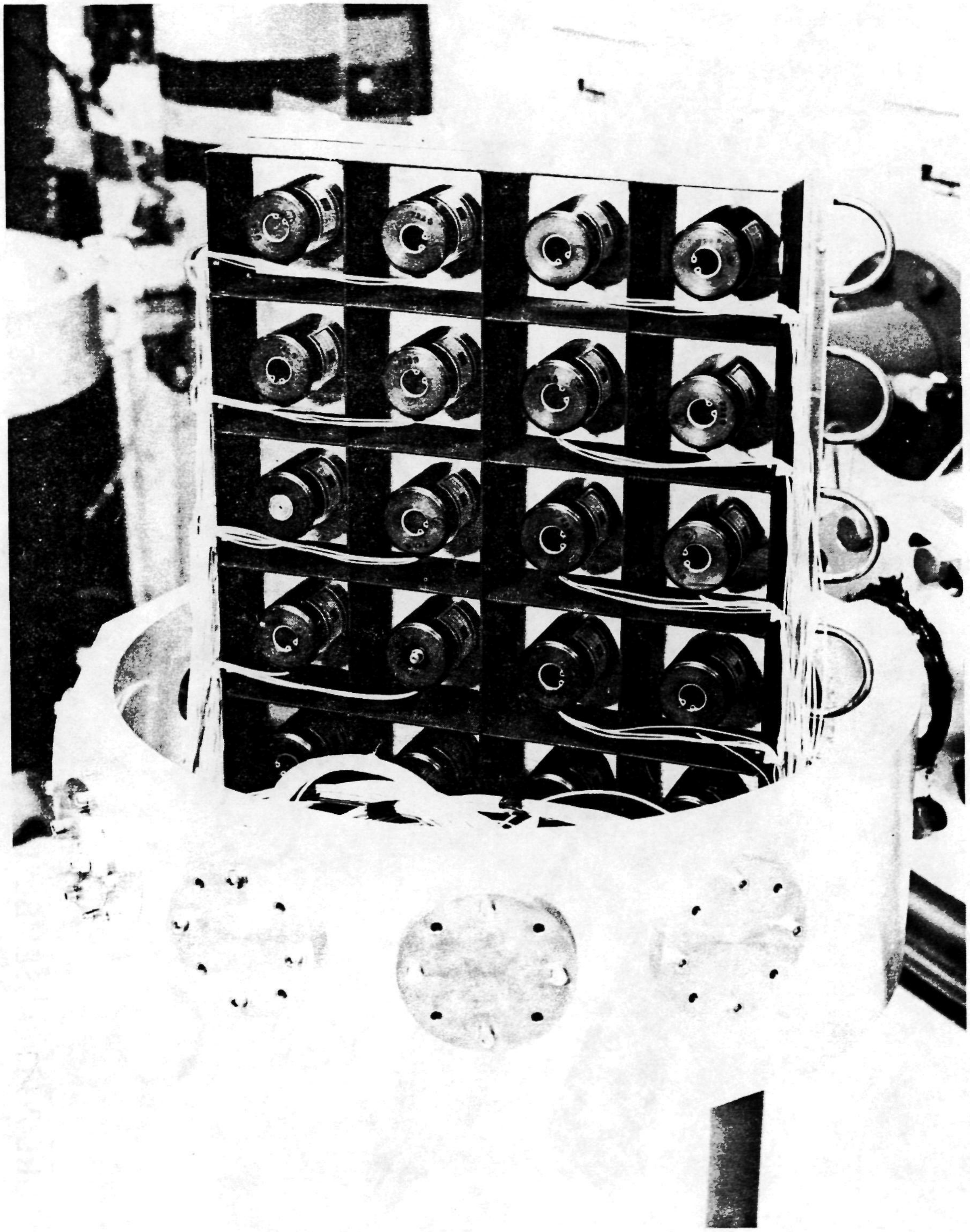

FIGURE 1 - TEST MOTORS IN VACUUM CHAMBER WITH BELL JAR REMOVED

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

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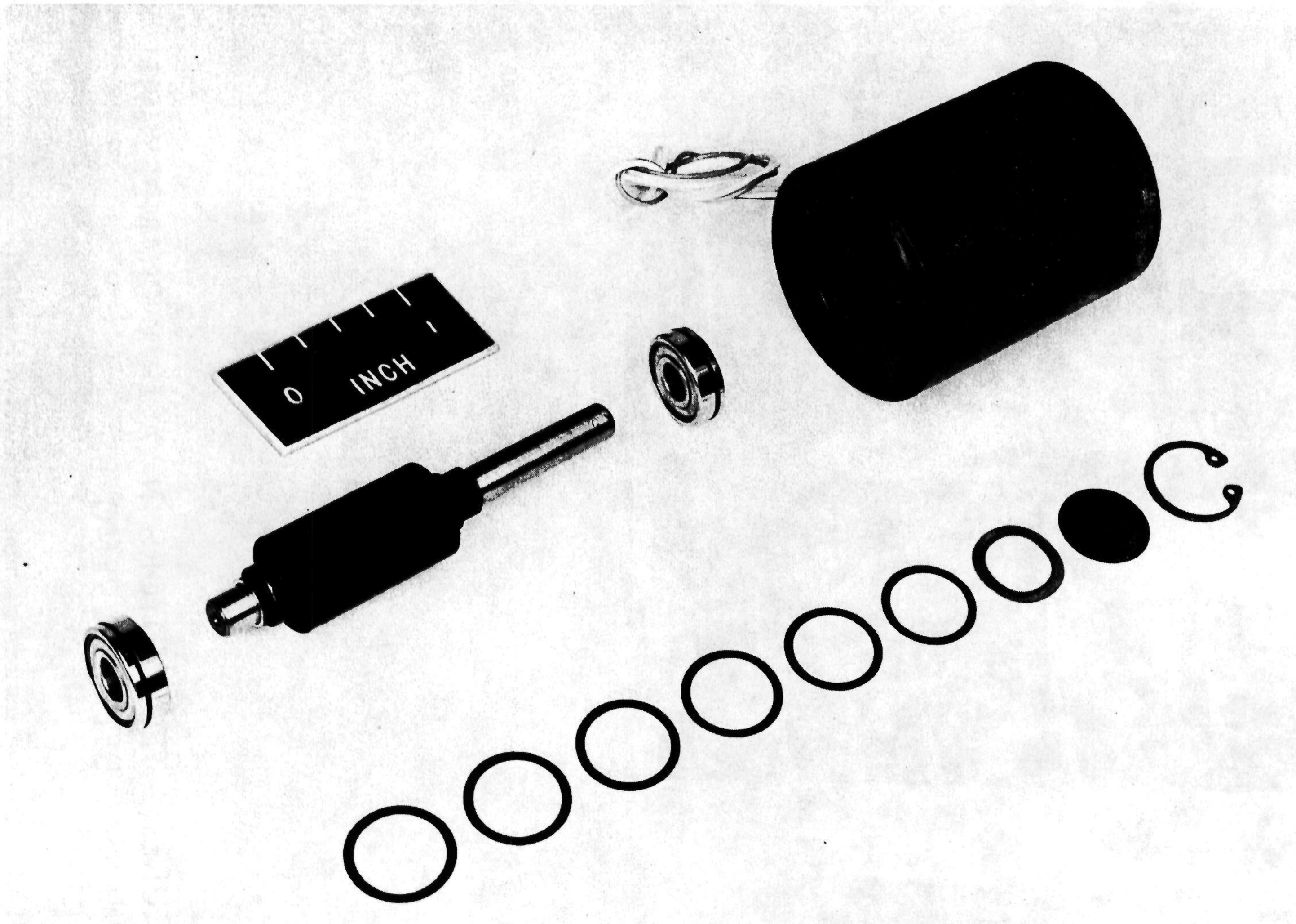

FIGURE 2 - DISASSEMBLED AC MOTOR WITH R-4 BEARINGS

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

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/m^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 4 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 is planned to add additional lubricants to the test program (four lubricants have been added) if data on new lubricants indicate that they have characteristics that would make them good candidates for one or more of the environments being used in the test program.

The environments for the test program to date are as follows:

a. 6.895×10^4 N/m^2 (10 psi) O_2 at 90 percent relative humidity (oxidation tests)

b. Vacuum, ambient temperature (38°C)

c. Vacuum, high temperature (93.3°C)

d. Vacuum, ambient temperature, with start-stop operation

e. Low temperature start.

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

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TABLE 1. DESCRIPTION OF TEST LUBRICANTS

Lubricant Code	Mil Spec	General Chemical Class of Base Oil	Thickener	38C Oil Viscosity (cs)	Oil Viscosity Index	Description
M-1	83176	Highly refined mineral	Inorganic	158	101	Instrument bearing grease
M-2		Highly refined mineral	Inorganic	400	110	Bearing grease
M-3	3545B	Mineral	Microgel	300		High temperature aircraft grease
M-4	10924B	Mineral	Li soap			General purpose grease
M-5	23549A	Mineral	MoS_2-nonsoap			General purpose grease
M-6	25537A	Mineral	Ca soap	14		Oscillating bearing grease
M-7	25760A	Synthetic mineral	Microgel	38	38	Bearing grease, wide temperature range
M-8		Straight chain hydrocarbon	None			Vacuum grease
M-9		Mineral-diester				Bearing grease, wide temperature
M-10	81322A	Synthetic hydrocarbon	Nonsoap			High temperature aircraft grease
ES-1	25760A	Diester	Arylurea			Bearing grease, wide temperature
ES-2	21164C	Diester	Microgel	14		Wide temperature grease with MoS_2

TABLE 1. (Continued)

Lubricant Code	Mil Spec	General Chemical Class of Base Oil	Thickener	38C Oil Viscosity (cs)	Oil Viscosity Index	Description
ES-3	23827A	Diester	Microgel	14		Aircraft instrument grease
ES-4		Diester	Li soap + MoS_2	14		Aircraft instrument grease
ES-5		Synthetic ester	Li soap	162	160	High temperature aircraft grease
Si-1		Silicone	Li soap	750		Vacuum grease
Si-2	15719A	Silicone	Li soap			High temperature ball bearing grease
Si-3	25013D	Silicone	Organic dye			Ball and roller bearing grease
Si-4		Silicone	Li soap			General purpose grease
Si-X		Silicone	Silica			Radiation resistant bearing grease, experimental
FS-1		Fluorosilicone	Silica			Vacuum grease, low speed bearing
FS-2		Fluorosilicone				Chemical inert bearing grease
PFPE-1		PFPE	Fluorotelomer	424	129	High vacuum bearing grease
PFPE-2		PFPE	Fluorotelomer	129	350	Chemical inert high and low temperature grease

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TABLE 1. (Concluded)

Lubricant Code	Mil Spec	General Chemical Class of Base Oil	Thickener	38C Oil Viscosity (cs)	Oil Viscosity Index	Description
PFPE-3		PFPE	Fluorotelomer	153	110	Chemical inert bearing grease
PFPE-4		PFPE	Fluorotelomer	18	23	Chemical inert low temperature grease
PFPE-5		PFPE	Fluorotelomer	85	113	Chemical inert vacuum grease, high temperature
PFPE-6		PFPE	Fluorotelomer	270	134	Chemical inert vacuum grease, high temperature
FCC-1		Fluorocarbon	Silica			Chemical inert high temperature grease

TABLE 2. PRESENT STATUS OF LUBRICANT TESTS

Lube Code		Test Conditions				
		Oxidizing Environ- ment	Vacuum (38°C)	Vacuum (93.3°C)	Vacuum (Start- stop)	Low Temperature Start
KG-80	M-1	●	●	●	●	●
SRG-200	M-2		●	●	●	●
Aeroshell 5	M-3		●, ϴ	●	O, ϴ	●
Royco 24R	M-4		●			●
Royco 49	M-5		●	O	O	●
Aeroshell 14	M-6		●			●
Aeroshell 16 E	M-7		●			
Apiezon L E	M-8		●			
Unitemp 500 E	M-9		●			
Mobilgrease 28	M-10		O			
Supermil 06752 E	ES-1	●	●		●	●
Aeroshell 17E	ES-2		●			
Aeroshell 7	ES-3			O	O	●
L-11G E	ES-4		●			
Exxon 5182	ES-5					
DC No. 33 E	Si-1	●	●			
G-351	Si-2	●	●, ϴ	●	●, ϴ	●
Supermil 31052	Si-3		O	●	●	●
G-330M	Si-4			O		
3L27-2 E	Si-X	●	●	●		
FS-1281 E	FS-1	●	●			
FS-1290	FS-2		●	●, O	●	
Kel-F No. 90 E	FCC-1			●		
803	PFPE-1	●	●, ϴ	●	●, ϴ	●
3L-38RP	PFPE-2	●	●, ϴ	●, O	●, ϴ	●
631A	PFPE-3		O	●	●	●
240 AZ	PFPE-4	●	●	●	O	●
240 AB	PFPE-5		O	●	●	
240 AC	PFPE-6		O	●	O	●

● Test complete, 1 year

O Test underway, 1 year

ϴ Test underway, 5 year

Suffix letter E denotes lubricant eliminated from further testing.

The evaluations for all tests, except the low temperature tests, are 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:

a. Total test time

b. Vacuum or atmospheric conditions

c. Temperature.

The bearings are weighed before and after testing and the weight loss of lubricant is calculated. The bearings are then photographed and cleaned, and selected bearings are subjected to scanning electron microscope (SEM) examination. Chemical analysis is made where applicable.

In the low temperature 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 s, and the temperature of the front bearings is 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 Tests

At the present time, 15 of the candidate lubricants have been evaluated for low temperature 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 Figure 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.

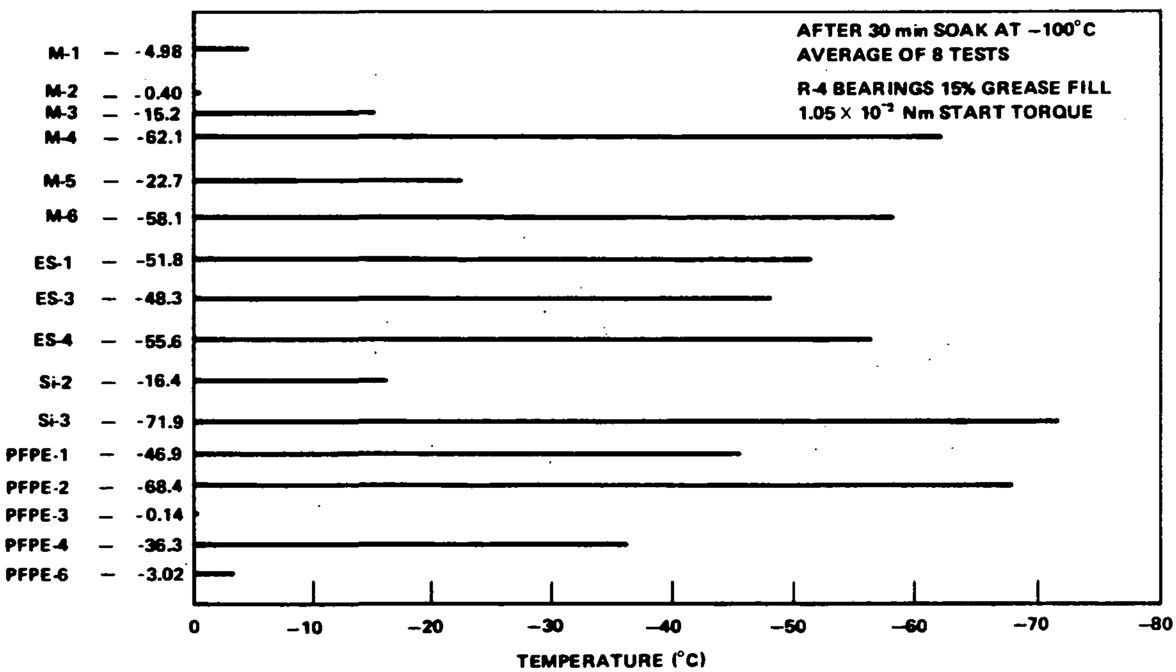

Figure 3. Low temperature start capability.

B. Standard Vacuum Weight Loss Tests

Since the capabilities of a grease type lubricant operating in vacuum are a function of the outgassing rate, all of the lubricants are being evaluated in a standard outgassing test. The outgassing rate is determined using a Knudsen cell with a 0.508 cm diameter hole. Approximately 50 to 60 mg of the grease are placed in the Knudsen cell, and the cell is attached to an electronic balance having an accuracy of 5×10^{-5} gm. The system is pumped down to 1.333×10^{-4} N/m^2 (1×10^{-6} torr) using an LN_2 trapped diffusion pump. The temperature is then raised in 11.1°C increments and held for 1 h at each increment. The test is continued until the temperature reaches 93.3°C (200°F) or until the grease exhibits 30 percent total weight loss, whichever comes first. Results of the vacuum weight loss tests, to date, are shown in Figures 4, 5, 6, 7, and 8. The weight loss shown in these figures is a function of temperature and time since the vacuum system is maintained at approximately 1.333×10^{-4} N/m^2 (1×10^{-6} torr) during the test. The information on the perfluoroalkylpolyether greases, except PFPE-4, shown in Figure 6 is of particular interest. The PFPE-1 grease is essentially the PFPE-3 material which has been vacuum distilled or outgassed to improve the vacuum stability of the material. It is obvious that this procedure is effective; however, it also increases the 38°C

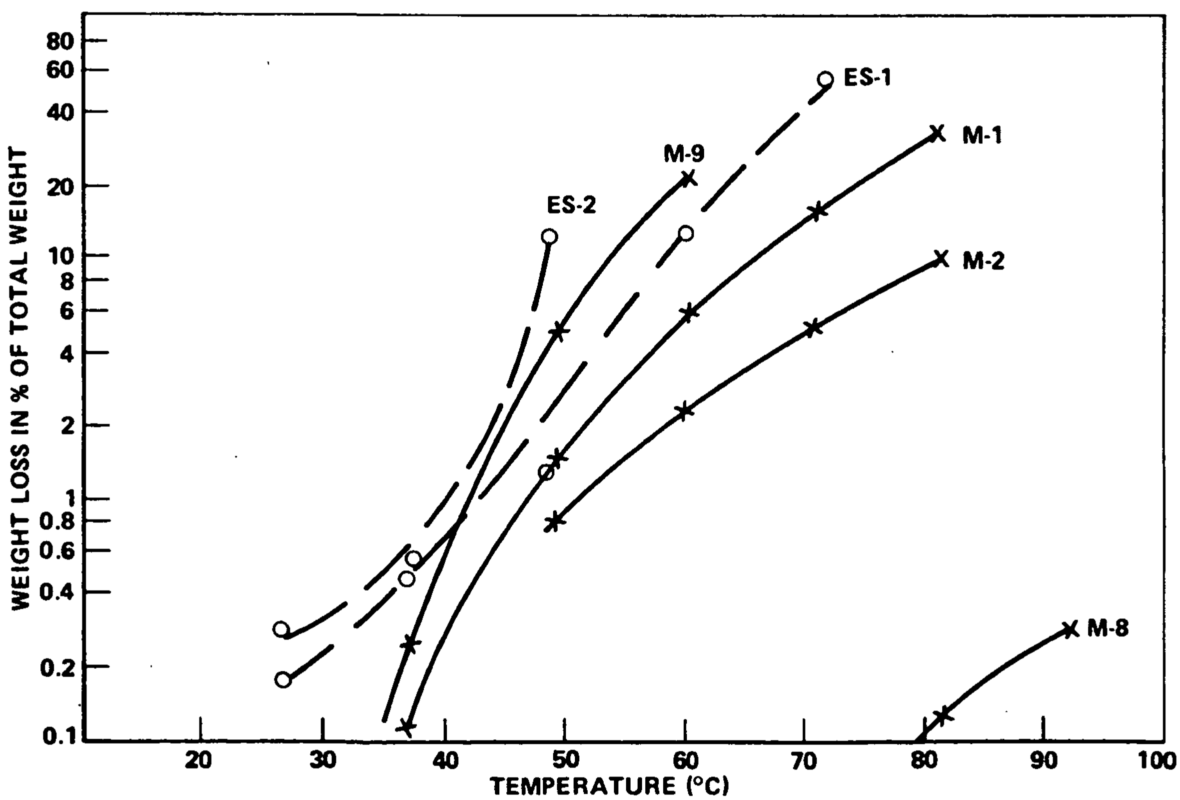

Figure 4. Vacuum weight loss versus temperature.

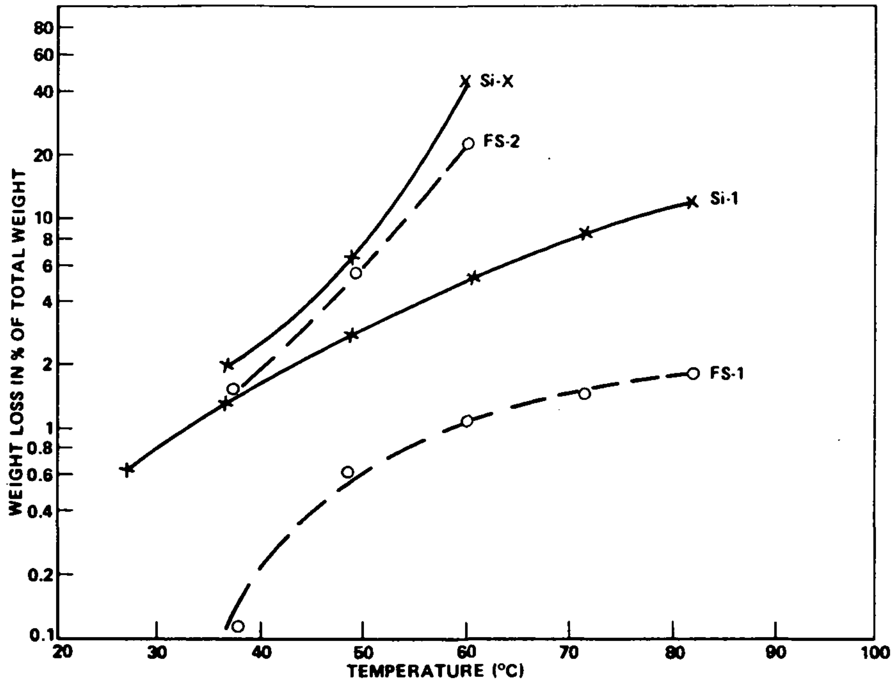

Figure 5. Vacuum weight loss versus temperature.

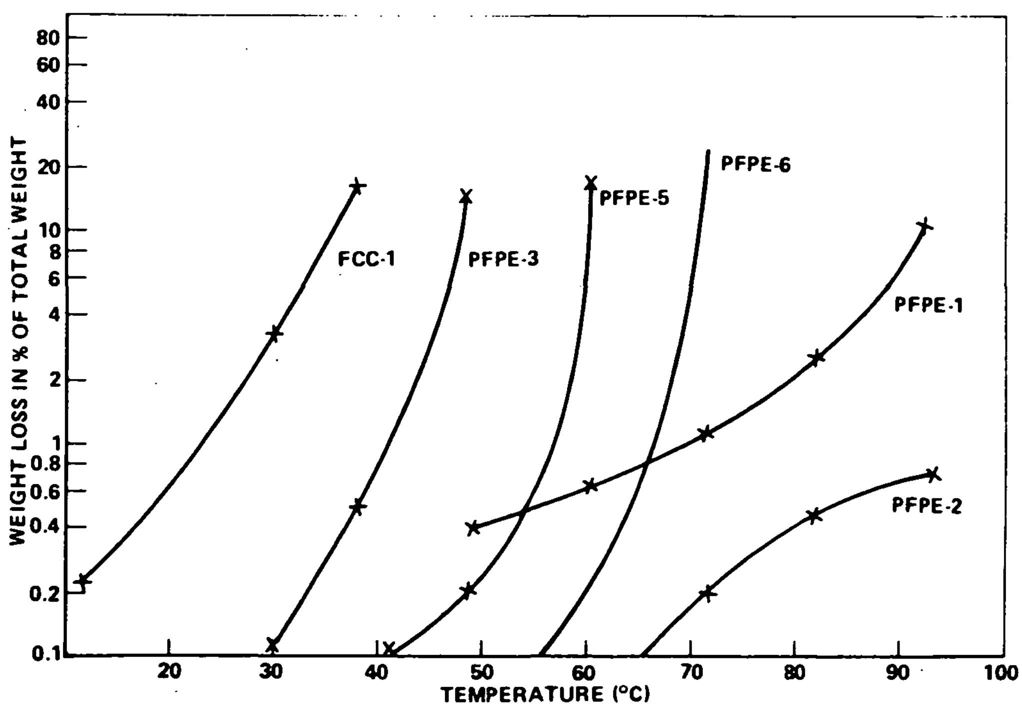

Figure 6. Vacuum weight loss versus temperature.

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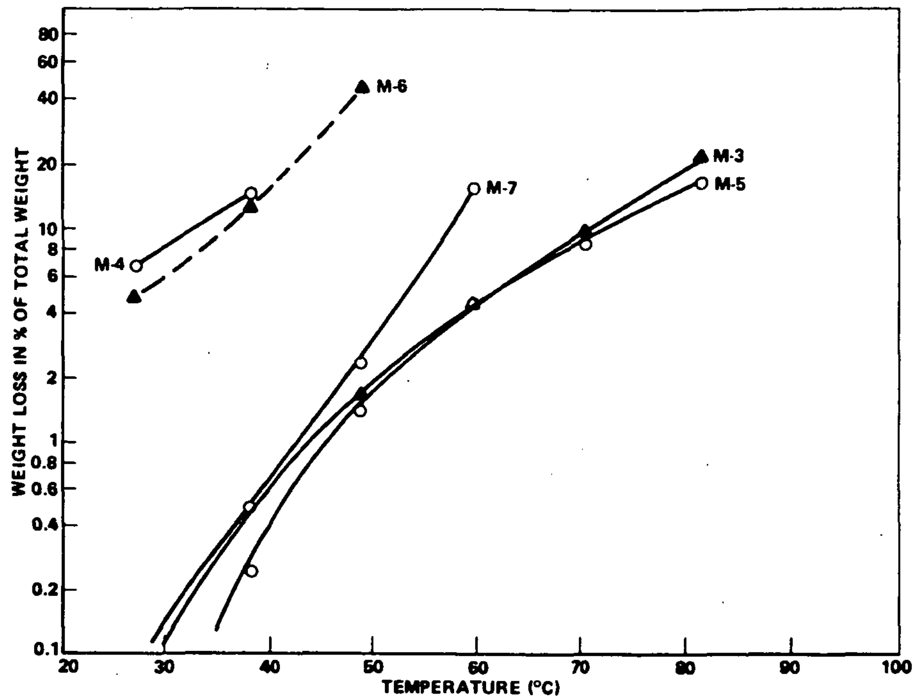

Figure 7. Vacuum weight loss versus temperature.

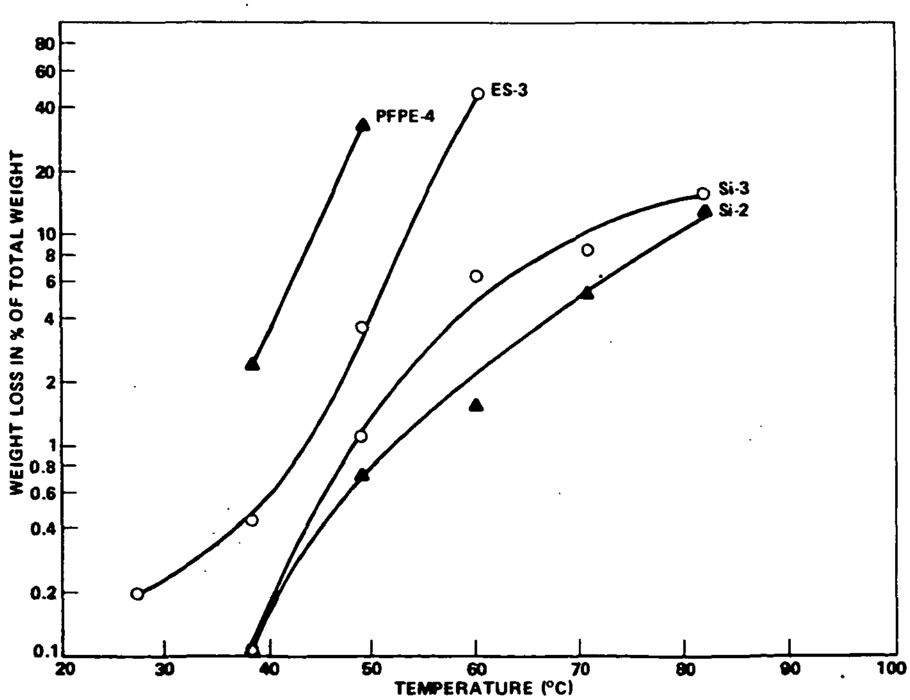

Figure 8. Vacuum weight loss versus temperature.

viscosity of the base oil from approximately 150 cs to 420 cs, which is an undesirable side effect. The PFPE-2 material, which is by far the most vacuum stable grease in this group, has a 38°C base oil viscosity of 130 cs.

C. Vacuum Ambient Temperature Bearing Tests

The results of the vacuum ambient temperature bearing tests are given in Table 3. In general, the perfluoroalkypolyether base greases, PFPE-1 and PFPE-2, performed the best with no failures encountered during the 1 year test period. The mineral oil grease, M-2, and the fluorosilicone grease, FS-2, also completed the test period without failure. At the completion of each test, weight loss of the grease in the bearings was measured. The results of these measurements for 20 greases are shown in Figure 9. Each of the bars shown in this figure gives the average weight loss of lubricant from the eight bearings tested with each grease.

The results of the first series of vacuum ambient temperature tests were discussed in the first status report.[4] A second series of tests was completed in September 1974. In this test two lubricants completed the 1 year test without failure. These were a highly refined mineral oil grease, M-2, and a fluorosilicone grease, FS-2. A low viscosity perfluoroalkylpolyether grease, PFPE-4, and another highly refined mineral oil grease, M-1, each had one failure during the test period. The poorest results were obtained with grease M-8, where three of the four tests failed within the 1 year period. It is noted, the M-8 grease, which has the highest failure rate and the lowest lubricant loss during the 1 year test, is in agreement with the weight loss data shown in Figure 4. A third set of these tests was completed in March 1976. The PFPE-2 had no failures during this test.

D. Vacuum High Temperature Tests

Fourteen lubricants have also completed the vacuum high temperature life tests. In these tests all of the perfluoroalkylpolyether base lubricants, except PFPE-4, and the highly refined mineral oil greases tested so far (M-1, M-2, and M-3) completed the 1 year period without any failures, while all the silicone grease tests, Si-3 and Si-X, the fluorocarbon grease tests, FCC-1, and the PFPE-4 grease tests failed. One each of a silicone grease, Si-2, and a fluorosilicone grease, FS-2, failed with the remaining three samples completing 1 year. Table 3 also gives results of these tests.

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4. Demorest, K.E. and McMurtrey, E.L.: Status Report, August 1974.

TABLE 3. EFFECTIVENESS OF LUBRICANTS IN VARIOUS ENVIRONMENTS

Environment	Lubricant	Hours to Failure[a] Maximum[b]	Minimum	Average	Failures of Total Test (%)
Vacuum ambient temperature	PFPE-2	8760	8760	8760	0
	Si-2	8760	8760	8760	0
	M-5	8760	8760	8760	0
	M-3	8760	8760	8760	0
	FS-2	8760	8760	8760	0
	PFPE-1	8760	8760	8760	0
	M-2	8760	8760	8760	0
	M-1	8760	3700	7495	25
	Si-1	8760	1709	6997	25
	PFPE-4	8760	684	6741	25
	ES-1	8760	3524	6280	75
	M-7	8760	2530	5854	50
	Si-X	8760	1041	5382	75
	M-8	8760	392	4913	75
	M-9	8760	1199	3497	75
	M-4	2671	160	1000	100
	ES-2	911	427	694	100
	ES-4	823	559	634	100
	FS-1	831	174	440	100
	M-6	473	219	329	100
Vacuum high temperature	PFPE-2	8760	8760	8760	0
	PFPE-6	8760	8760	8760	0
	PFPE-5	8760	8760	8760	0
	PFPE-1	8760	8760	8760	0
	PFPE-3	8760	8760	8760	0
	M-3	8760	8760	8760	0
	M-1	8760	8760	8760	0
	M-2	8760	8760	8760	0
	FS-2	8760	6813	8273	25
	Si-2	8760	2870	7288	25
	Si-3	2327	686	1751	100
	PFPE-4	3193	282	1587	100
	FCC-1	1280	166	580	100
	Si-X	1047	68.5	348	100

a. Lubricants are listed in order of effectiveness.

b. Or to end of test (1 year = 8760 h).

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TABLE 3. (Concluded)

Environment	Lubricant	Hours to Failure[a] Maximum[b]	Minimum	Average	Failures of Total Test (%)
Oxidizing	Si-2	8760	8760	8760	0
	PFPE-1	8760	8760	8760	0
	ES-1	8760	8760	8760	0
	M-1	8760	8760	8760	0
	PFPE-4	8760	8760	8760	0
	Si-X	8760	8760	8760	0
	Si-1	8760	8760	8760	0
	PFPE-2	8760	4795	7769	25
	FS-1	8760	405	6671	25
Start-stop, vacuum ambient	PFPE-1	8760	8760	8760	0
	PFPE-2	8760	8760	8760	0
	PFPE-3	8760	8760	8760	0
	M-1	8760	6790	8268	25
	Si-3	8760	5409	7922	25
	PFPE-5	8760	2817	7274	25
	ES-1	8760	5497	7200	50
	M-2	8760	1848	7032	25
	Si-2	8760	1557	6959	25
	FS-2	8760	685	5972	50

Temperature in the vacuum high temperature tests is controlled by regulating the cooling water supply to the mounting plate so as to maintain the temperature at 65°C (150°F). The thermocouples on the bearings then show a temperature of approximately 93°C on the front bearing and 107°C on the rear bearing.

At the conclusion of all vacuum tests, the bearings are reweighed and the loss of lubricant is calculated. Since the motors which fail are turned off and the temperature at the front and rear bearing is approximately 65°C, these bearings should show less weight loss than the bearings with the same lubricant which operate for a longer period of time. Results of the lubricant weight loss in vacuum at high temperature are shown in Figure 10.

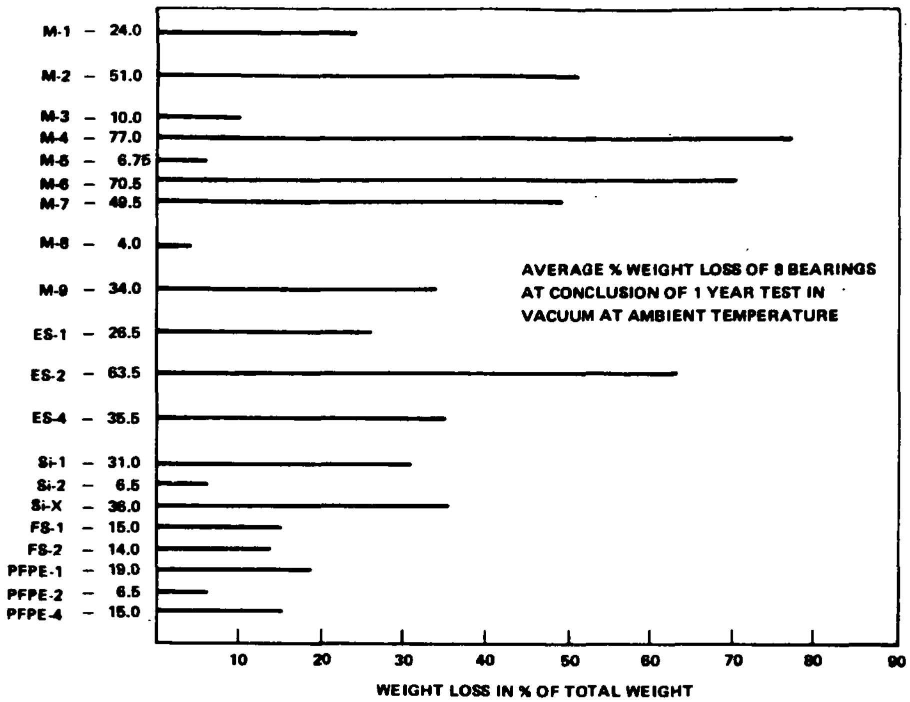

Figure 9. Weight loss during vacuum ambient temperature test.

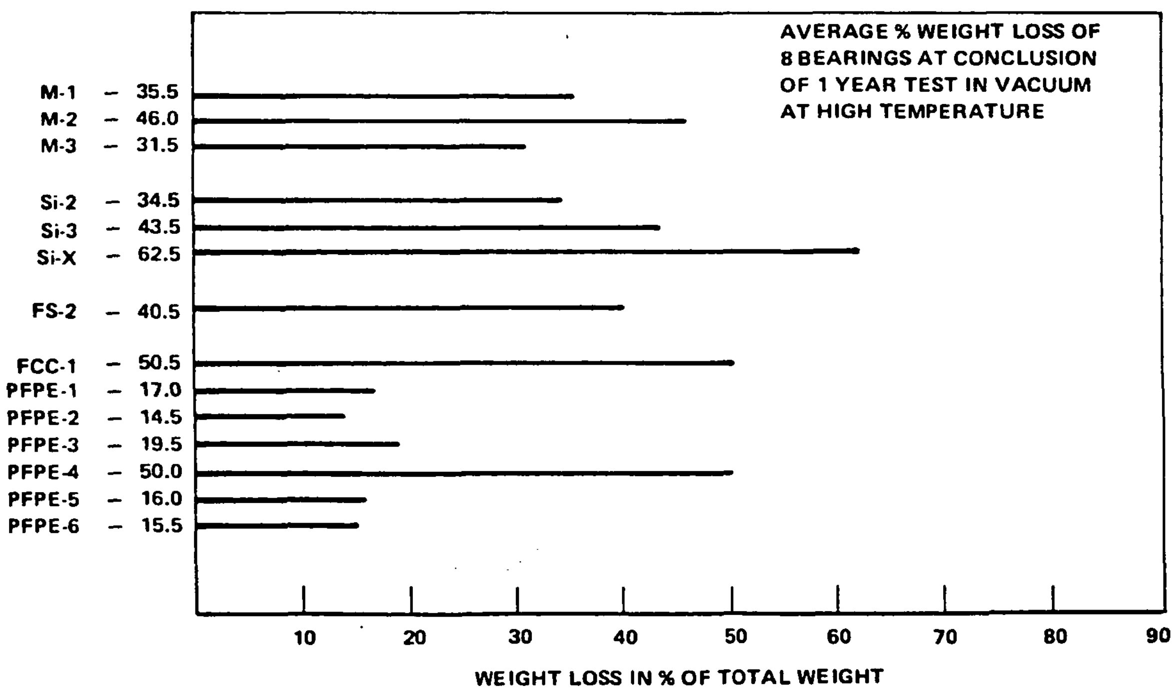

Figure 10. Weight loss during vacuum high temperature test.

Of the 14 lubricants which have completed the vacuum high temperature test, the best results have been obtained with the perfluoroalkylpolyether greases. All tests on PFPE-1, PFPE-2, PFPE-3, PFPE-5, and PFPE-6 completed 1 year of operation without failure. All of these bearings appear to be in relatively good condition, with the exception of the bearings lubricated with PFPE-5. This set of bearings appeared to be on the verge of failure. Comparative SEM photographs of one bearing lubricated with the PFPE-5 grease and one bearing lubricated with the PFPE-2 grease are shown in Figure 11. The balls of the PFPE-5 lubricated bearing are badly pitted, almost as though they had been subjected to a strong acid etch. Considering the condition of these bearings, it is surprising that they were able to complete the 1 year test period.

The poorest results were obtained with the experimental silicone, Si-X, and the fluorocarbon grease, FCC-1. All of the bearings lubricated with these two materials failed during the high temperature tests.

E. Oxidation 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 evaluation.

The first set of tests was made in air at 90 percent relative humidity. However, it appeared that a pure oxygen environment would be more severe; therefore, all additional tests are being made in 10 psi pure oxygen at 90 percent relative humidity. Results of the lubricant weight loss in the oxidizing atmosphere tests are shown in Figure 12. Table 3 also gives results of these tests.

F. Start-Stop 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 deceleration and acceleration. This test is set up in vacuum and held at ambient temperature. A timer is used to shut off the motors for 10 s every 150 s. Ten lubricants have been evaluated in this system. Results of the lubricant weight loss of the start-stop tests to date are shown in Figure 13. Table 3 also gives results of these tests. The total number of cycles of the two completed tests are 202 382 and 188 342.

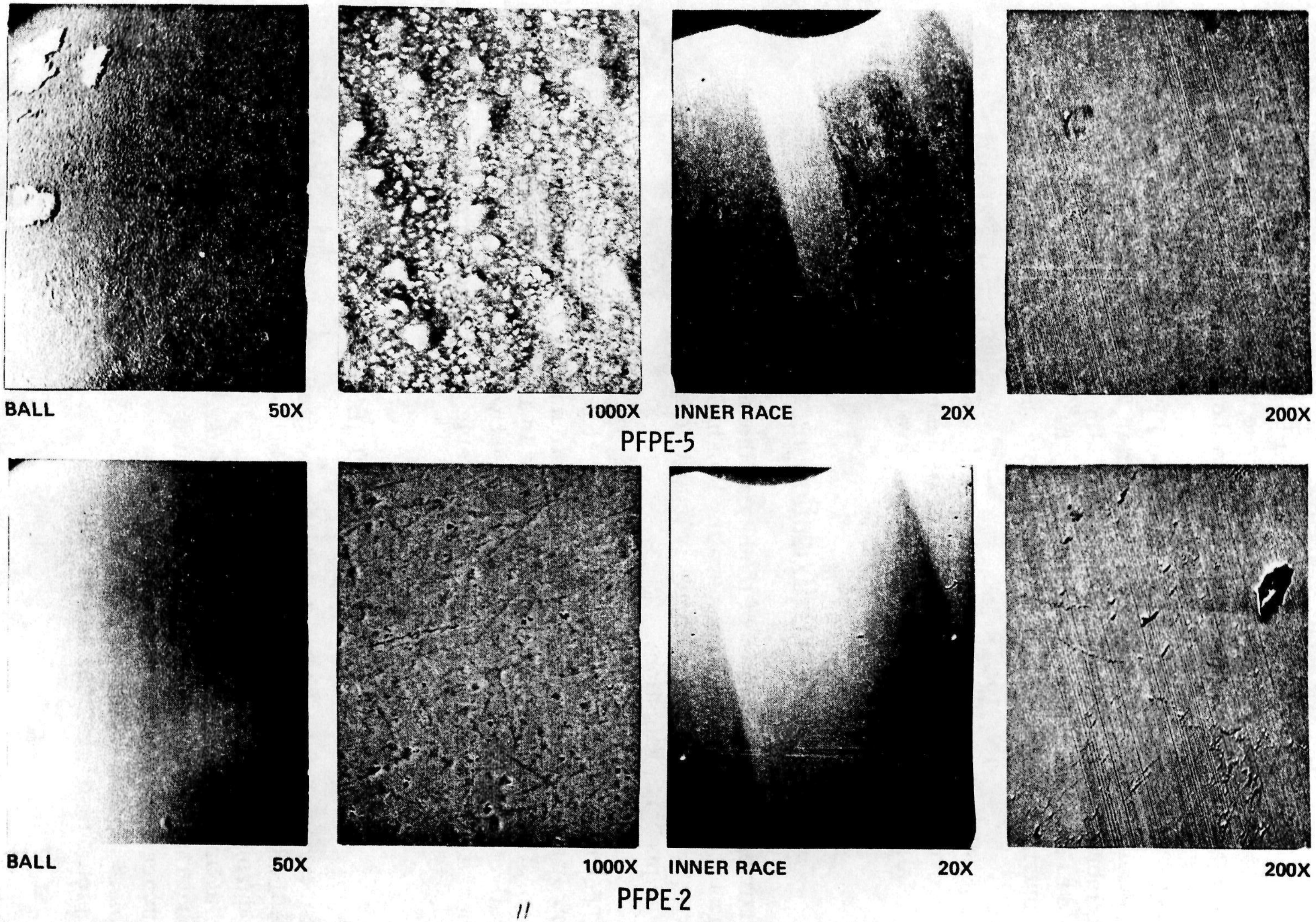

FIGURE 9. SEM'S OF BEARINGS - HIGH TEMPERATURE TEST

Figure 11. SEM's of bearings — high temperature test.

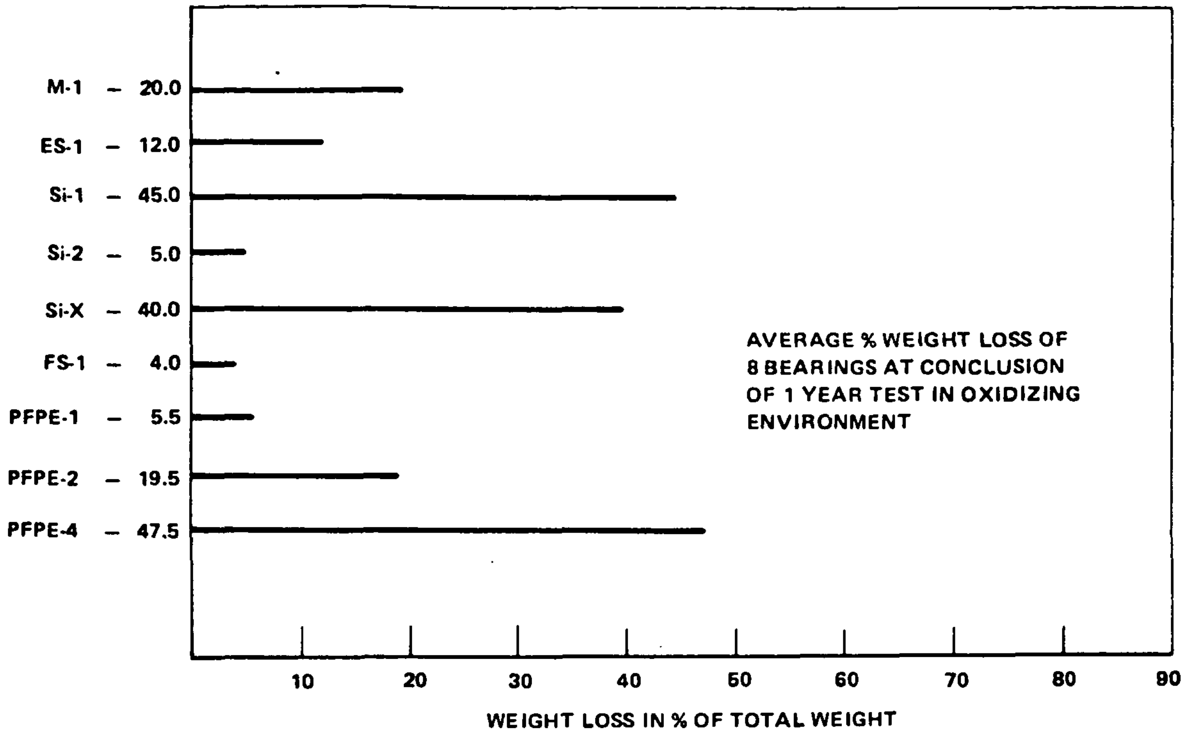

Figure 12. Weight loss during oxidizing environment test.

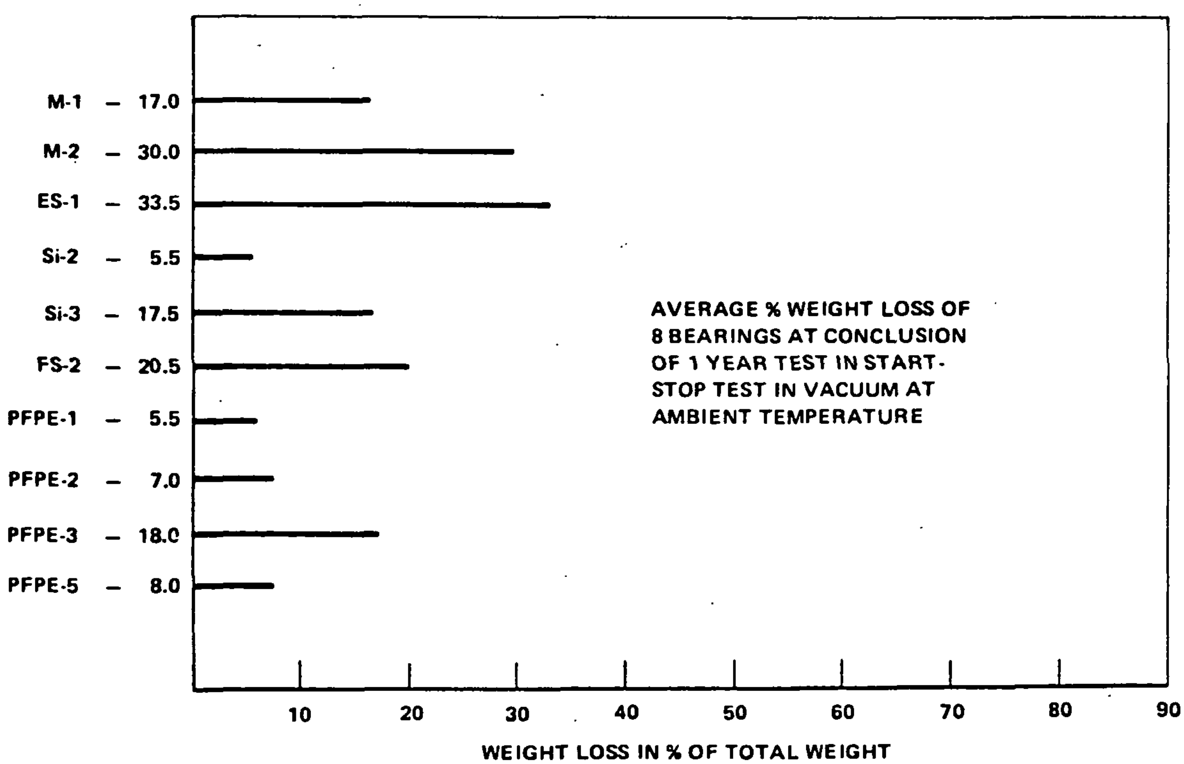

Figure 13. Weight loss during start-stop test at vacuum ambient temperature.

V. FUTURE PLANS

Since all but four lubricants have been eliminated for the 5 year test program, a rating sheet was devised to eliminate those lubricants which perform poorly under the various test environments. This rating sheet is presented in Table 4. 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 of the equivalent lubricants. The chart presented in Table 4 is used to illustrate the comparative principle only, because some of the tests are not complete and some of the greases have not yet been tested; however, using this chart, it was decided to eliminate 10 of the materials from further testing because they have performed poorly in either the vacuum or vacuum high temperature tests.

The present test program will continue with the four candidate lubricants for the 5 year test program. Also, four additional lubricants will be placed under test in selected environments for 1 year periods to see whether these lubricants warrant further testing. As many samples of each grease as possible will be evaluated during the 5 year tests. Since all of the present data are being generated on instrument size bearings having relatively low DN values, it is further planned to start a series of tests using size 107 bearings operating at 8000 to 9000 rpm. For these tests, the phenolic cages of the bearings will be impregnated with the base oils of the candidate greases. These tests will be made only in vacuum. Three bearing sets with each lubricant will be tested to failure or for 1 year.

VI. PRESENT STATUS

One hundred tests are now underway, and the status of these tests as of November 1977 is shown in Figure 14. Each line in this bar graph represents one test consisting of two bearings and one motor. The present test series is now progressing rapidly with two 5 year tests and three 1 year tests in operation.

TABLE 4. LUBRICANT RATING CHART

Lube Code		Oxidizing Environment	Vacuum (38°C)	Vacuum (93.3°C)	Vacuum (Start-Stop)	Low Temperature Start	Decision
KG-80	M-1	4	8	4.5	4	12	
SRG-200	M-2		4	4.5	8	15	
Aeroshell 5	M-3		4	4.5		11	
Royco 24R	M-4		16			3	
Royco 49	M-5		4			9	
Aeroshell 14	M-6		20			4	
Aeroshell 16	M-7		12				EL
Apiezon L	M-8		14				EL
Unitemp 500	M-9		15				EL
Mobilgrease 28	M-10						
Supermil 06752	ES-1	4	11		7	5	EL
Aeroshell 17	ES-2		17				EL
Aeroshell 7	ES-3					6	
L-11G	ES-4		18				EL
Exxon 5182	ES-5						
DC No. 33	Si-1	4	9				EL
G-351	Si-2	4	4	10	9	10	
Supermil 31052	Si-3			11	5	1	
G-330M	Si-4						
3L27-2	Si-X	4	13	14			EL
FS-1281	FS-1	9	19				EL
FS-1290	FS-2		4	9	10		
KEL-F No. 90	FCC-1			13			EL
803	PFPE-1	4	4	4.5	2	7	
3L-38RP	PFPE-2	8	4	4.5	2	2	
631A	PFPE-3			4.5	2	14	
240 AZ	PFPE-4	4	10	12		8	
240 AB	PFPE-5			4.5	6		
240 AC	PFPE-6			4.5		13	

Note: EL — eliminate from further testing.

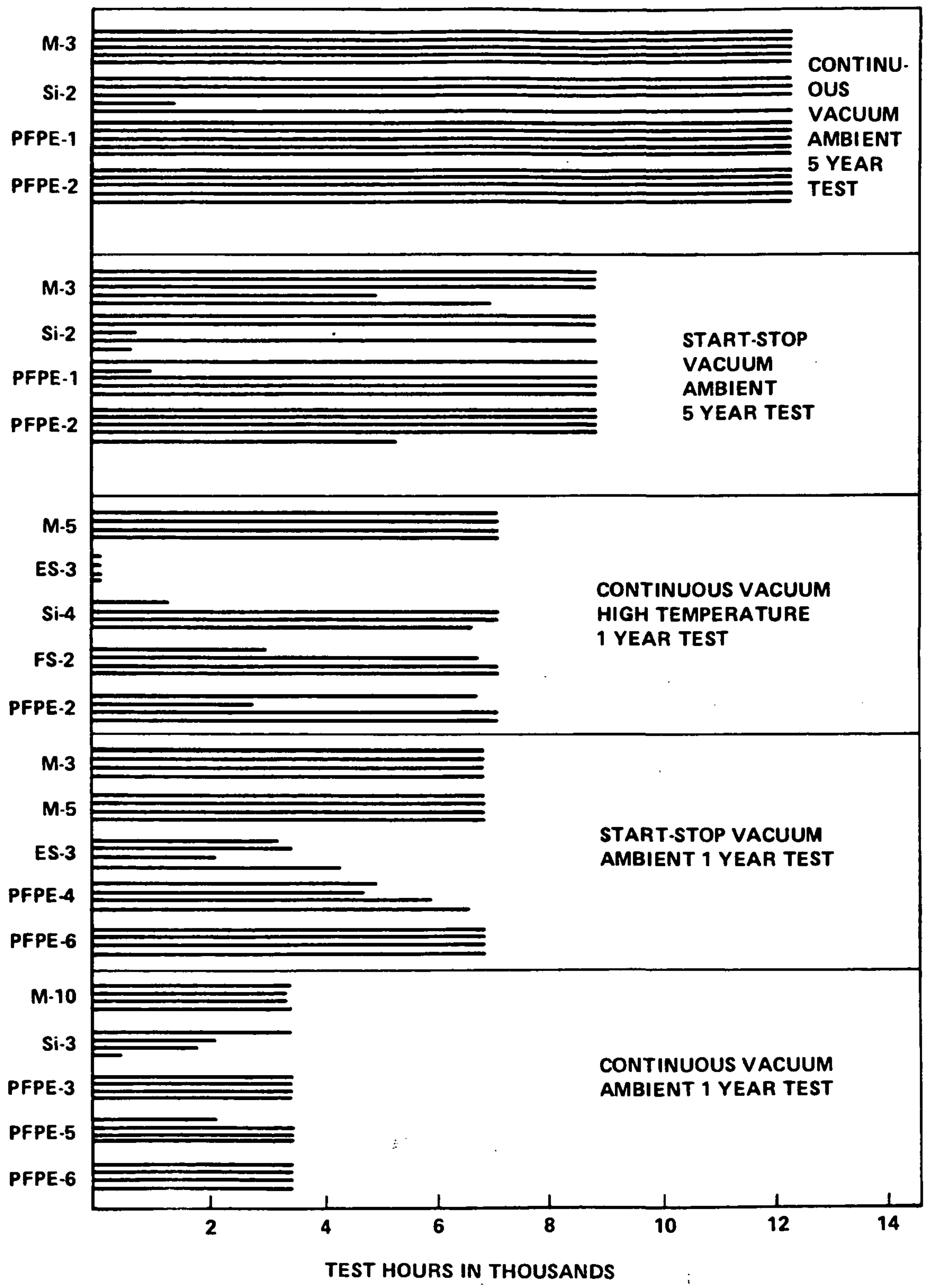

Figure 14. Present status of operating tests.

VII. CONCLUSIONS

A considerable amount of testing remains to be done in this program; however, from the data obtained to date certain conclusions can be made:

a. The PFPE-2 grease, based on a high viscosity index perfluoroalkyl-polyether oil having a 38°C viscosity of 130 cs and thickened with a fluorotelomer, shows great promise for space application because it is one of the most vacuum stable materials tested and also has the best low temperature capability of any material evaluated except Si-3. The full capabilities of this material have not yet been determined since no failures have been encountered in any of the vacuum tests made to date.

b. The PFPE-1, PFPE-3, and PFPE-6 perfluoroalkypolyether greases also provide good service in vacuum at high temperature. All of these materials are fairly viscous at room temperature and have a moderate viscosity index; therefore, they do not provide exceptionally low temperature starting capabilities.

c. Of the other chemical classes tested to date, a highly refined mineral oil, M-2, and a fluorosilicone based grease, FS-2, appear to give the best vacuum service.

APPROVAL

AN EVALUATION OF GREASE TYPE BALL BEARING LUBRICANTS OPERATING IN VARIOUS ENVIRONMENTS (Status Report No. 3)

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.

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