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LUBRICATION EVALUATION

by

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FOREWORD

This report summarizes an evaluation of lubricants for spacecraft applications conducted by the Materials Sciences Laboratory.

Section 1 presents information on the performance of various oils, greases, bonded solid film lubricants (e.g., molybdenum disulfide), and special self-lubricating retainer materials (e.g., reinforced Teflon) on instrument-size ball bearings operating in simulated space conditions of vacuum, temperature, and radiation.

Section 2 presents information on the performance of various bonded solid film lubricants under simple sliding conditions in air.

In both sections, the data are complete from the start of the program to March 1, 1966.

Appendix A discusses the friction and adhesion of metals, with particular emphasis on cold welding. Appendix B is a code identifying the proprietary lubricants tested at LMSC; this appendix can be removed for distribution outside LMSC.

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Section 1

LUBRICANTS FOR INSTRUMENT-SIZE BALL BEARINGS

1.1 SCOPE

Experiments have been conducted to evaluate the performance of various types of lubricants on ball bearings operating in a simulated space environment. Lubricants evaluated have included oils, greases, bonded films of solid lubricants such as molybdenum disulfide, and composites of self-lubricating materials such as reinforced Teflon. The lubricants have been evaluated on lightly-loaded, instrument-size ball bearings operating at 8000 rpm. Simulated space conditions have included vacuum down to 10^{-9} torr, temperatures up to 300°F, and radiation doses up to 4×10^{7} roentgens.

1.2 LUBRICATION WITH OIL

1.2.1 Oils

Tests have been completed or are in progress on 33 different mineral and synthetic oils, as follows:

Code No.	Chemical Type
O-1 to O-9	Petroleum
O-10 to O-20	Silicone
O-21 to O-26	Diester
O-27 to O-33	Other synthetics

Table 1-1 summarizes information on the chemical types, pour points, and viscosities.

Failures have occurred in as little as 164 hours, while one oil was still lubricating satisfactorily after 33,649 hours.* Approximately one-half of the oils failed to

*Test results are current to March 1, 1966

Table 1-1

IDENTIFICATION OF LUBRICATING OILS TESTED

Code	Chemistry	Pour Point (°F)	Viscosity (centistokes) at Temperatures Indicated -40°F	100°F	175°F	300°F
	Petroleum Oils					
O-1	Paraffinic oil plus oxidation inhibitor and load-carrying additive	+10				
O-2	Paraffinic oil	Below -65	43,000	83	18	4.6
O-3	Paraffinic oil (0-2) with oxidation inhibitor and load-carrying additive	Below -65	43,000	83	18	4.6
O-4	Petroleum oil	+50		8,500	825	
O-5	Petroleum oil			4,300	430	
O-6	Petroleum oil			97	17.3	
O-7	Petroleum oil			39	8.5	
O-8	Napthenic-base oil with hindered-phenol type oxidation inhibitor			78	13.7	
O-9	Colloidal dispersion of molybdenum disulfide in petroleum oil					
	Silicone Oils					
O-10	Chlorophenylmethyl polysiloxane		1,000	50	20	7.5
O-11	Chlorophenylmethyl polysiloxane oil (0-10) with 50% more volatile fraction removed by distillation					
O-12	Molybdenum disulfide dispersion in chlorophenylmethyl polysiloxane oil (0-10) (2/3 oil, 1/3 MoS_2 by volume)					
O-13	Fluorosilicone oil		(26,000)	140	37	9.5
O-14	Fluorosilicone oil		(300,000)	500	120	25
O-15	High-phenyl content polysiloxane			221	41.5	8.1

Table 1-1 (cont.)

Code	Chemistry	Pour Point (°F)	Viscosity (centistokes) at Temperatures Indicated			
			-40°F	100°F	175°F	300°F
	Silicone Oils (cont.)					
O-16	Dimethyl polysiloxane					
O-17	Low-phenyl content polysiloxane, stripped of light ends					
O-18	Medium-phenyl content polysiloxane					
O-19	Methylphenyl polysiloxane with 35% more volatile fraction removed by distillation					
O-20	Halogenated phenylmethyl polysiloxane plus organometallic anti-wear additives		1,000	60	30	12.5
	Diester Oils					
O-21	Dioctyl sebacate		1,400	12.7	4.6	
O-22	Diester oil meeting MIL-L-6085			13.5	5	
O-23	Dibasic acid ester			12.6	4.7	
O-24	Dispersion of molybdenum disulfide in dibasic acid ester 0-23			14	5	
O-25	Dibasic acid ester			31	6.9	
O-26	Dispersion of molybdenum disulfide in dibasic acid ester 0-25			34	6.5	
	Other Synthetic Oils					
O-27	Trifluoromethyl-phenoxy-phenoxy-phosphonitrile			270	24	4.4
O-28	Hexa-2-ethylbutoxy disiloxane		725	32	15.5	6.4
O-29	15% dioctyl sebacate in hexa-2-ethylbutoxy disiloxane O-28		675	24.4	11.2	4.4
O-30	Diphenylbis-n-dodecylsilane			38	9.5	
O-31	Triaryl phosphate			19	5	
O-32	Triaryl phosphate			47	8.4	
O-33	Isomeric 5-ring polyphenyl ether			360	26	4.3

lubricate in vacuum in less than one-half year. Sufficient tests have been conducted to demonstrate the feasibility of lubricating small ball bearings with certain oils for 3 years, and more, of continuous operation under light loads, speeds of 8000 rpm, temperatures of 175°F, and higher, and in a vacuum of 10^{-8} torr.

1.2.2 Equipment and Procedures

Before detailed results from these studies are presented, the experimental equipment and procedures are described:

Bearing Types. All ball bearings were standard, deep-groove (Conrad), single-row, radial type of the R-3 size (0.1875-inch bore × 0.500-inch O.D.), and had metal, outer-race contacting shields. Bearings were ABEC* Class 7 quality with 0.0005 to 0.0008 inch radial clearance. Both 440C stainless steel and 52100 chrome steel bearings were tested. Most of the bearings had standard machined, two-piece, reinforced Synthane** retainers, as shown in Figure 1-1, or standard, ribbon-type retainers of pressed steel. A few tests with special one-piece balanced crown-type retainers of a linen-base phenolic laminate, shown in Figure 1-2, were unsuccessful.

Tests at 8000 rpm indicated that the machined Synthane retainers were superior to the steel, ribbon-type retainers. No difference in performance between 440C stainless steel and 52100 chrome steel bearings has been found to date.

Lubricant Applications. Before oil was applied to bearings with ribbon retainers, the bearings were run-in with a light viscosity oil for 24 hours at 8000 rpm and then ultrasonically cleaned. The amount of oil for testing varied from 25 to 50 mg. Bearings with Synthane retainers were not run-in before lubrication. Approximately 50 mg of the test oil (range from 15 to 90 mg) was vacuum impregnated into the retainer of each bearing in the fully assembled condition. Vacuum impregnation was done below 100 microns, either at room temperature (early tests) or at 200°F (since June 1962).

*ABEC stands for Annular Bearing Engineers' Committee
**Synthane is a proprietary, paper-base phenolic laminate

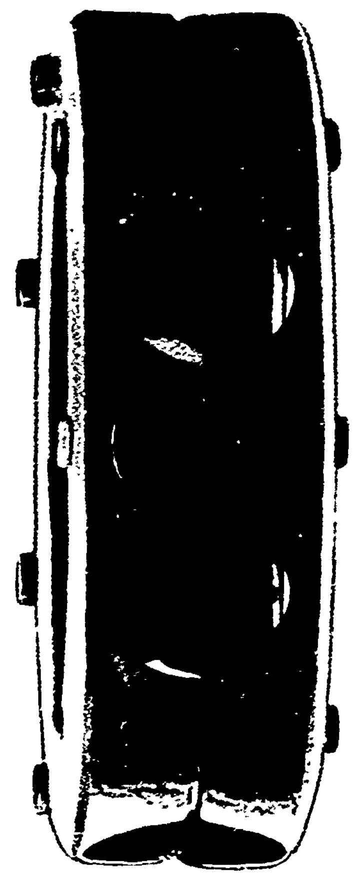

Fig. 1-1 Two-Piece, Pinned Phenolic Retainer

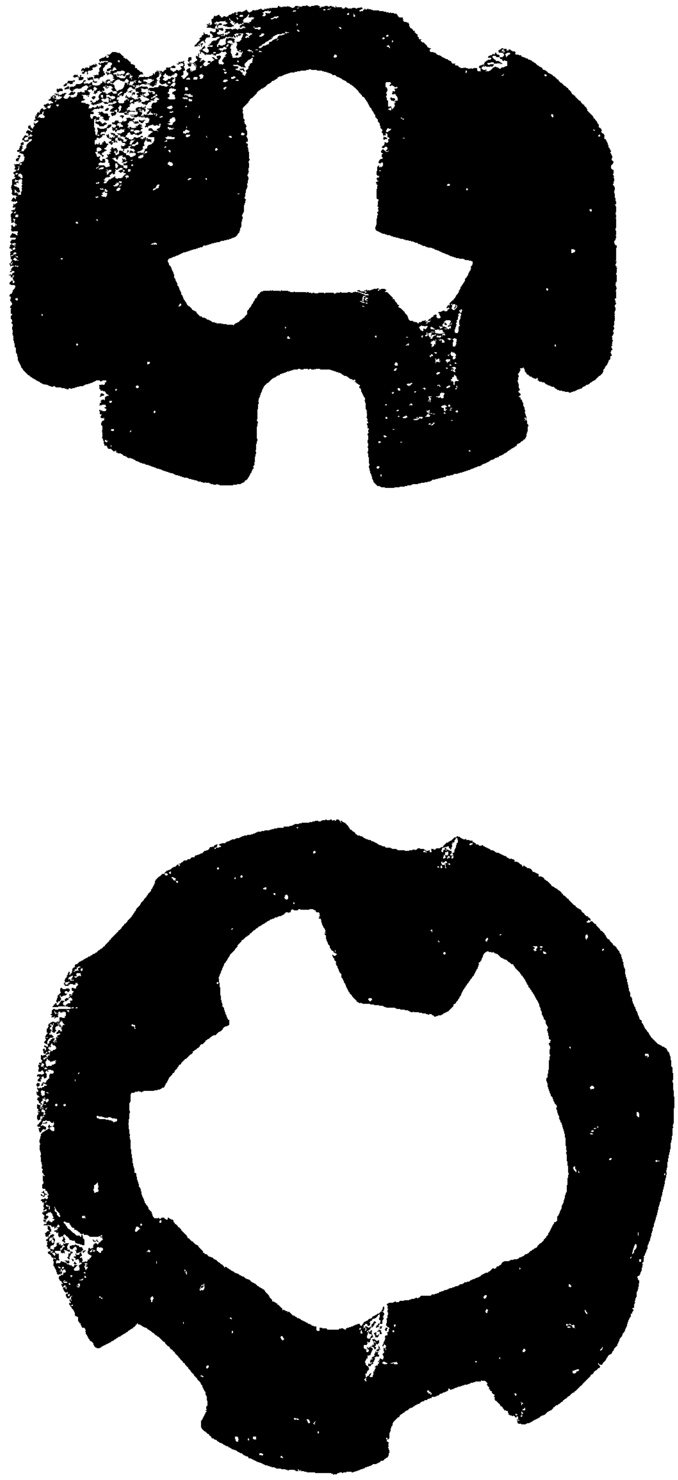

Fig. 1-2 One-Piece, Balanced Crown-Type Retainer of a Linen-Base Phenolic Laminate

No oil was added to the bearing after testing had begun, the object of the tests being to determine how long the initial supply of oil was adquate.

Test Fixtures. Test fixtures were fractional horsepower induction motors on which the ball bearings with the test lubricants were conventionally mounted to support the rotor. Both bearings on any one motor received the same lubricant.

Figure 1-3 shows a disassembled motor of the type first used. The motor shaft was machined to 0.1875 inch diameter, and the bearing housings were opened to expose the bearings more directly to the vacuum. The exposed stator windings can be seen in the photograph. In the absence of convection cooling, the motors overheated when operated above 100 volts in vacuum. Overheating caused excessive outgassing and breakdown of the varnish insulation which, in turn, short circuited the stator windings. Thereafter, the motor voltage was kept in the range 70 to 90 volts during operation in vacuum. This type of motor was not used for elevated temperature testing.

Figure 1-4 shows a second type of motor being used. The stator on this motor has been "canned" in a stainless steel jacket to prevent outgassing, and Teflon insulation is used on the stator windings so that the motor can operate at higher temperatures than possible with the first motor. This motor has been successfully operated in vacuum for over 4300 hours at a bearing temperature of 300°F.

Figure 1-5 is a circuit diagram of the motor control panel. The circuit for each motor was fused to cut off the power to the motor and a timer when the rotor stalled.

Bearing Loads. The radial loads on the bearings are those due to the weights of the rotors. The radial loading for the first motor was 155 to 166 grams (5.6 ounces); for the second, 270 to 280 grams (9.7 ounces). These loads are divided between the two bearings and are of the same order of magnitude as the equivalent radial loads transmitted to the bearings when the torque output of the motors is transmitted through small gears, as in fine-pitch gear trains used for servomechanisms.

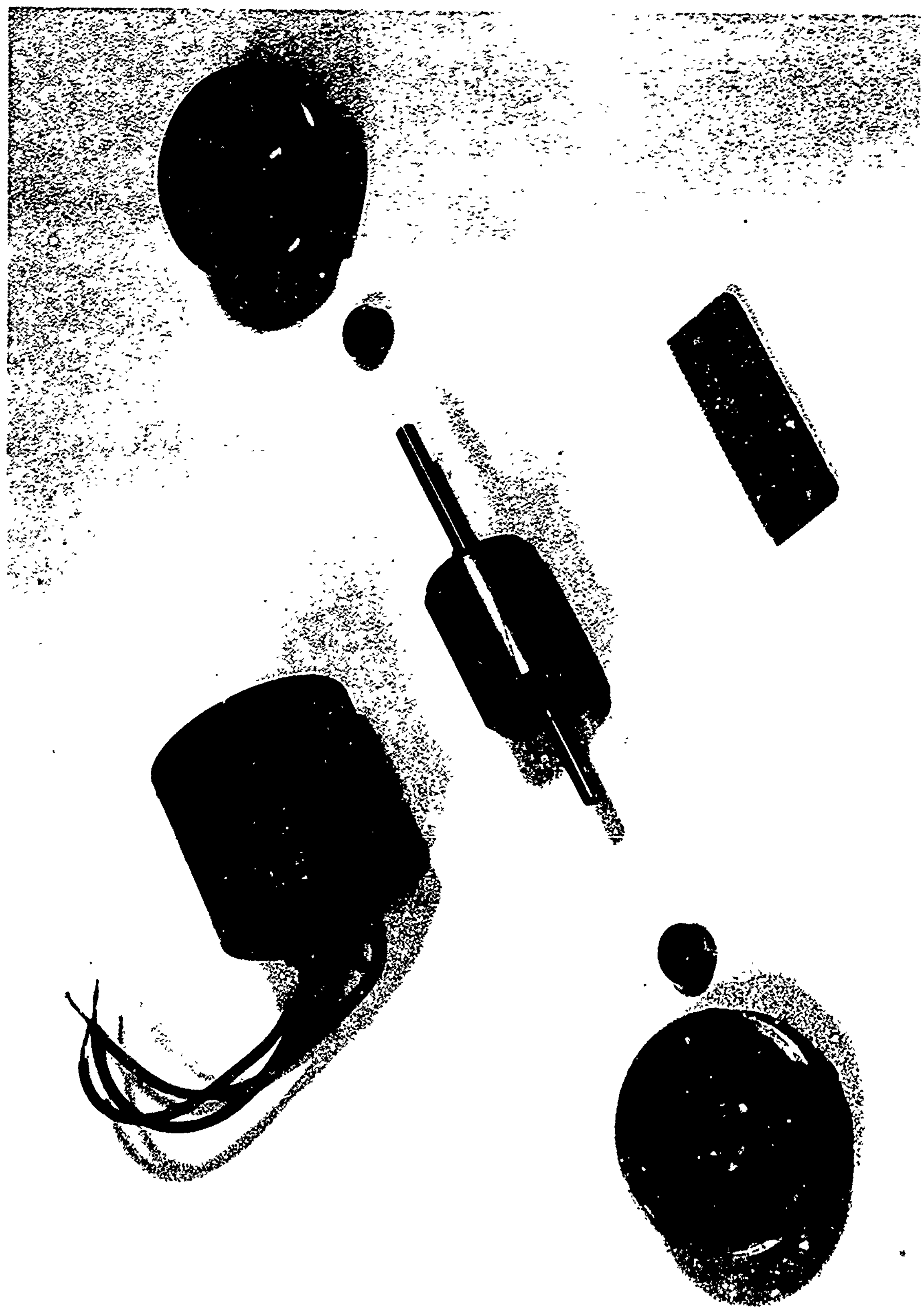

Fig. 1-3 Test Motor Originally Used (Type 1)

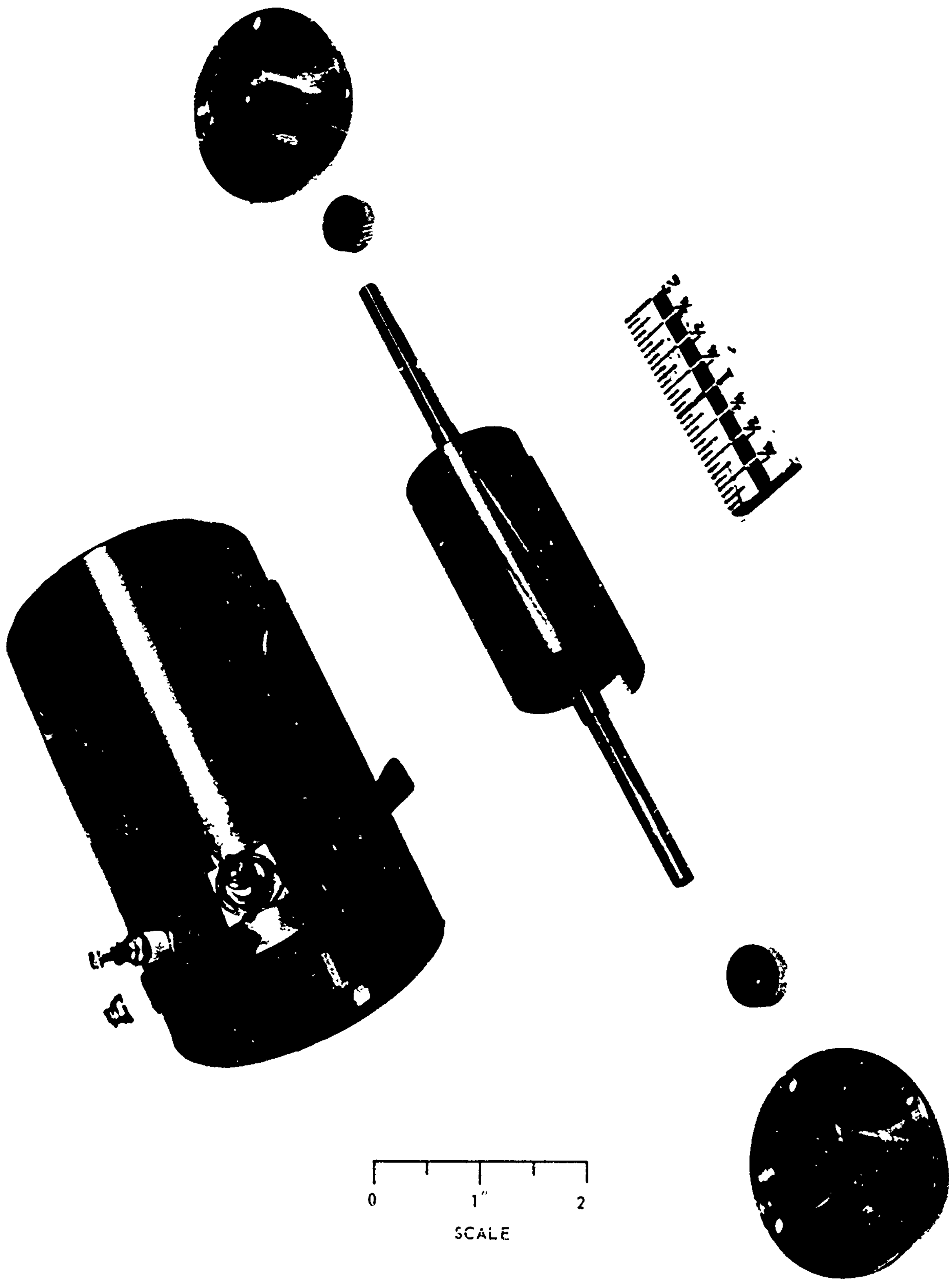

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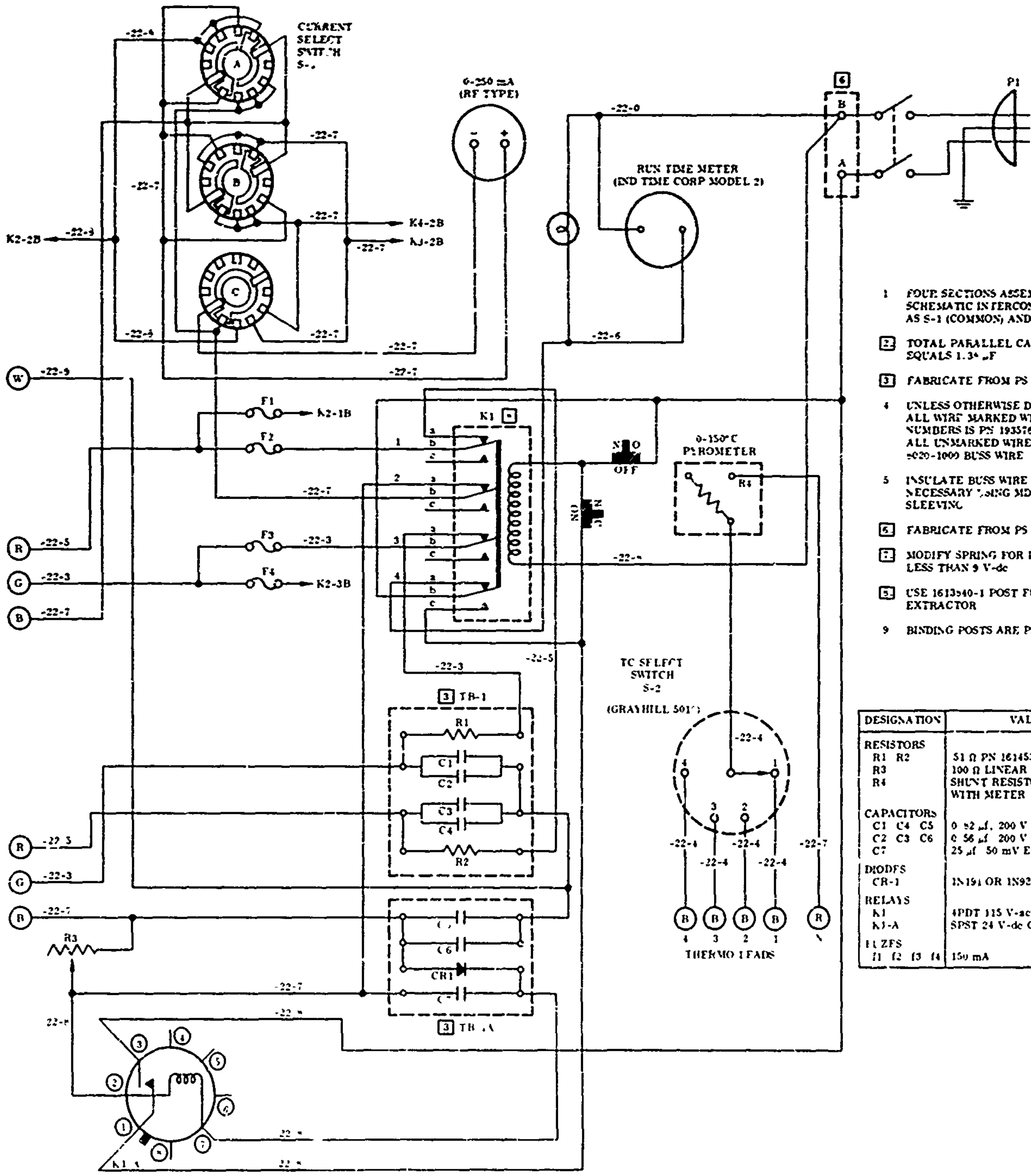
Fig. 1-4 Test Motor With "Canned" Stator (Type 2)



1 FOUR SECTIONS ASSEMBLED PER SCHEMATIC INTERCONNECTED AS S-1 (COMMON) AND P1

[2] TOTAL PARALLEL CAPACITY EQUALS 1.34 μF

[3] FABRICATE FROM PS 1-2735-3

4 UNLESS OTHERWISE DESIGNATED ALL WIRE MARKED WITH DASH NUMBERS IS PS 1935764-XX-X ALL UNMARKED WIRE IS BELDEN #020-1000 BUSS WIRE

5 INSULATE BUSS WIRE WHERE NECESSARY USING MD 20-22-9 SLEEVING

[6] FABRICATE FROM PS 1-2735-3

[7] MODIFY SPRING FOR PULL-IN AT LESS THAN 9 V-dc

[8] USE 1613540-1 POST FUZE EXTRACTOR

9 BINDING POSTS ARE PS-1-3749-X

DESIGNATION	VALUE
RESISTORS	
R1 R2	51 Ω PN 1614533-1
R3	100 Ω LINEAR POT
R4	SHUNT RESISTOR INCLUDED WITH METER
CAPACITORS	
C1 C4 C5	0 .52 μf, 200 V [2]
C2 C3 C6	0 .56 μf 200 V [2]
C7	25 μf 50 mV ELECTROLYTIC
DIODES	
CR-1	1N191 OR 1N92
RELAYS	
K1	4PDT 115 V-ac COIL
K1-A	SPST 24 V-dc COIL [7]
FUZES	
f1 f2 f3 f4	150 mA [8]

Fig. 1-5 Circuit Diagram of Motor Control Panel

Vacuum Systems. After a set of motors had operated for several hours in air to assure satisfactory installation, a chamber was placed over the motors and evacuated. Most of the tests with oils were conducted in systems employing oil diffusion pumps and liquid nitrogen traps or zeolite traps, and a number of tests were conducted with ion pumps. No effect on performance was noted for the different types of systems, and tests discussed in Section 1.3 indicated that oil migration had no effect on performance.

Figure 1-6 shows a typical chamber evacuated by a 6-inch oil diffusion pump. Eight motors can be run simultaneously in the 18-inch diameter × 30-inch high bell jar of this system. The system is provided with a liquid nitrogen trap that is optically tight and is so designed that oil from the diffusion pump would have to migrate over a surface at liquid nitrogen temperature in order to get into the chamber. Pressure is measured with a modified Bayerd-Alpert ionization gauge that is connected to the baseplate by 0.625-inch inside diameter tubulation. This particular unit normally sustains a pressure of 2 to 3×10^{-8} torr with eight motors in operation; for short periods, it has operated at 9×10^{-9} torr.

Other systems evacuated by oil diffusion pumps maintain pressures during testing of 1×10^{-9} torr (6 inch D.P., stainless steel chamber) to 2×10^{-7} torr (4 inch D.P., glass bell jar, high-temperature tests with greases). The lowest pressure maintained for periods of several hours during tests with oils has been 6×10^{-10} torr.

Figure 1-7 shows a typical chamber evacuated by an ion pump. Several sizes of chambers and pumps have been used, ranging from 6 inches inside diameter by 10 inches long to 14 inches inside diameter by 20 inches long stainless steel chambers and 90 to 360 litres/sec pump speeds. Pressures in these systems, when used to evaluate oils, have ranged from 2×10^{-6} to 4×10^{-8} torr, as measured by the pump current.

Radiation. Figures 1-8, 1-9, and 1-10 show the test fixture used to evaluate lubricants in a combined environment of vacuum and radiation. Three motors were mounted on a support rod attached to the end flange of the vacuum chamber, as shown in

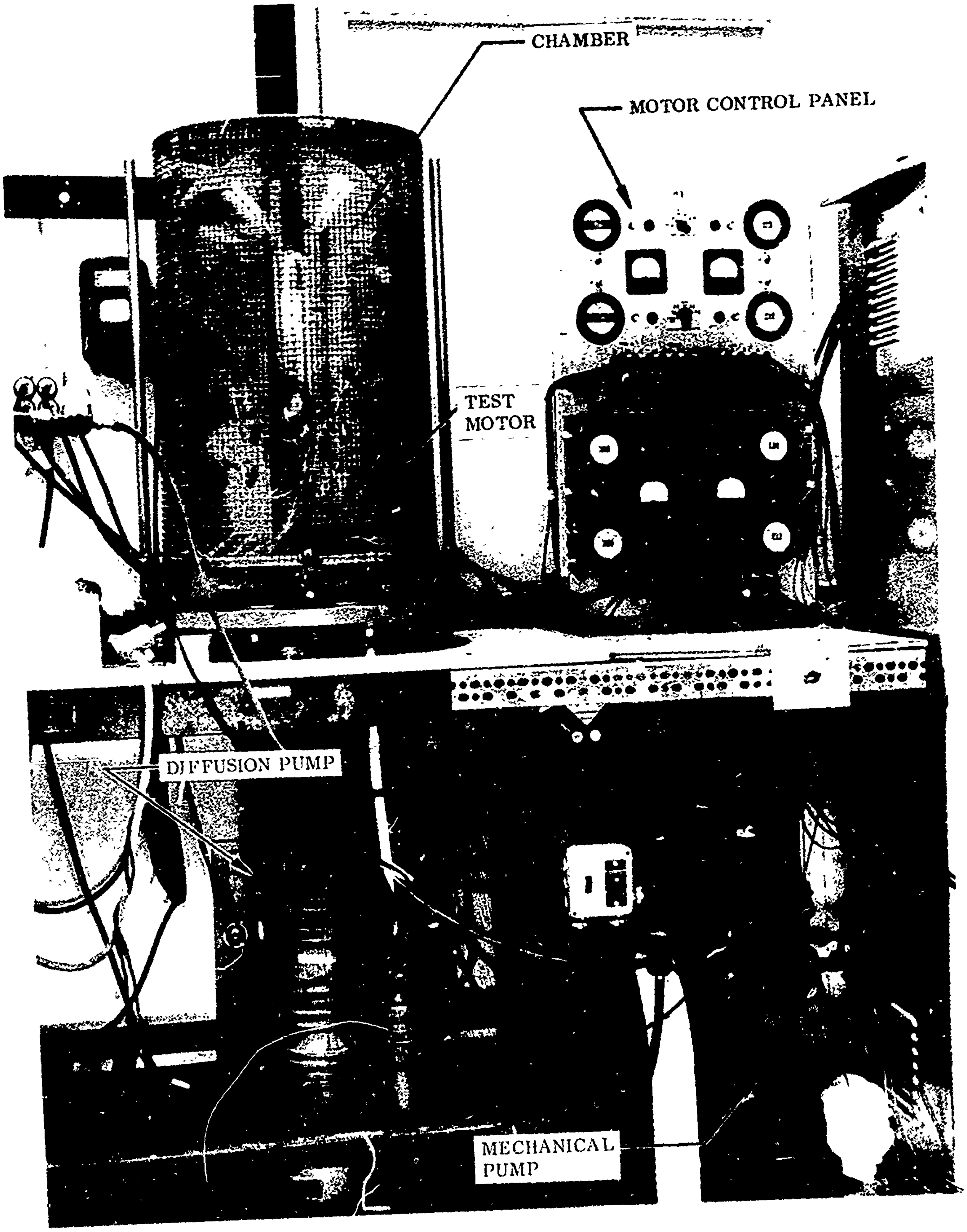


Fig. 1-6 Test Chamber With Oil Diffusion Pump

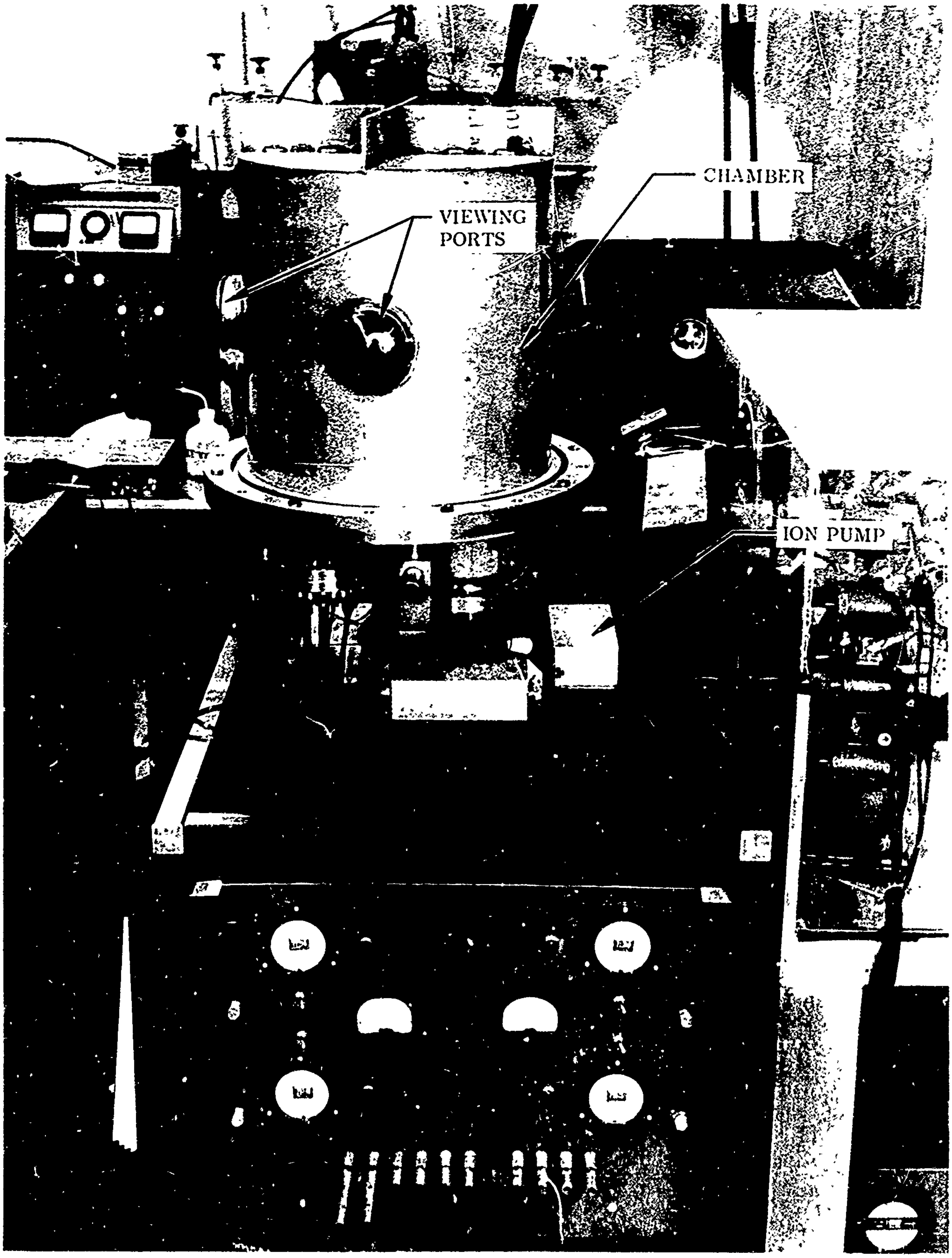


Fig. 1-7 Test Chamber With Ion Pump

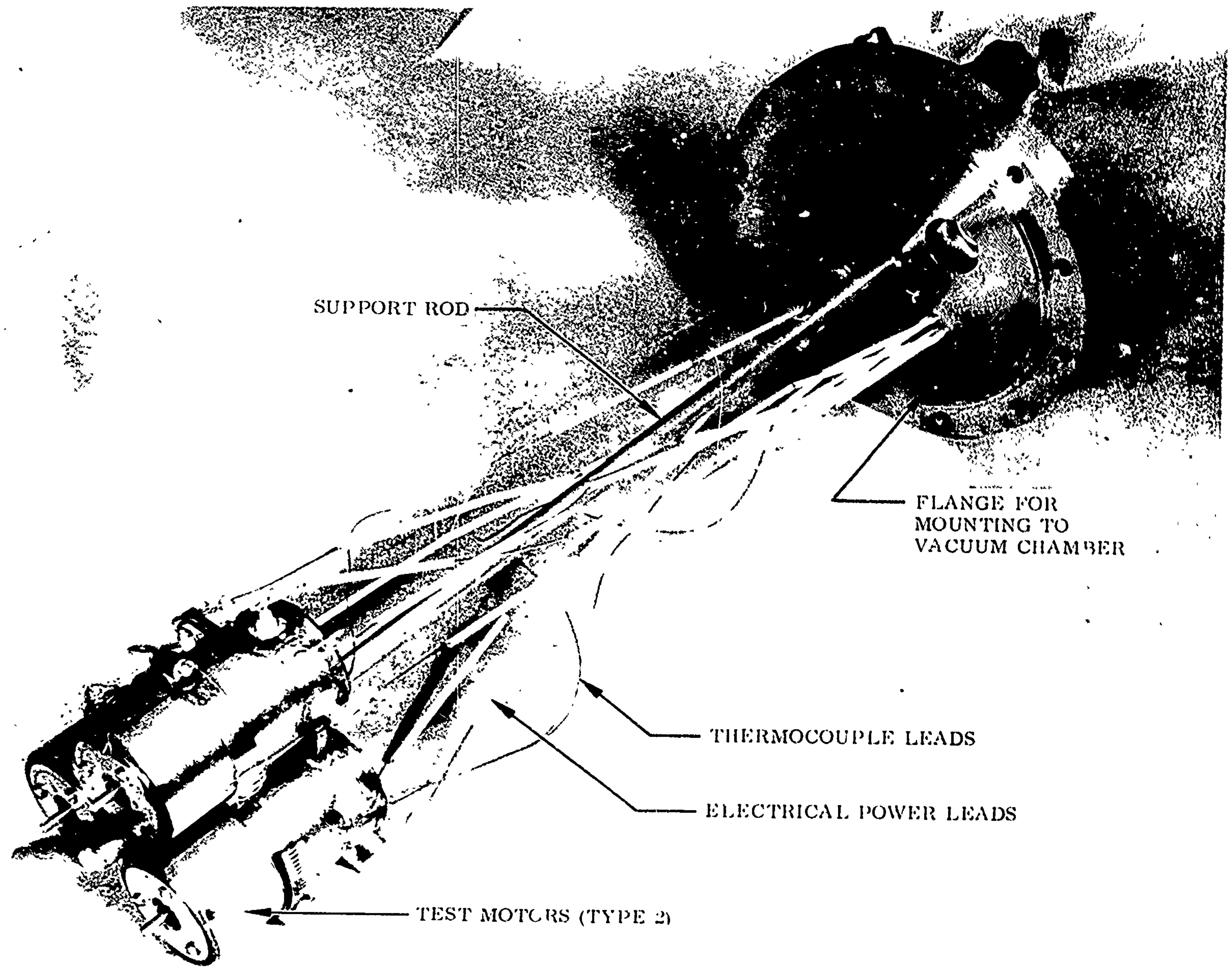


Fig. 1-8 **Motor Support for Vacuum-Radiation Tests**

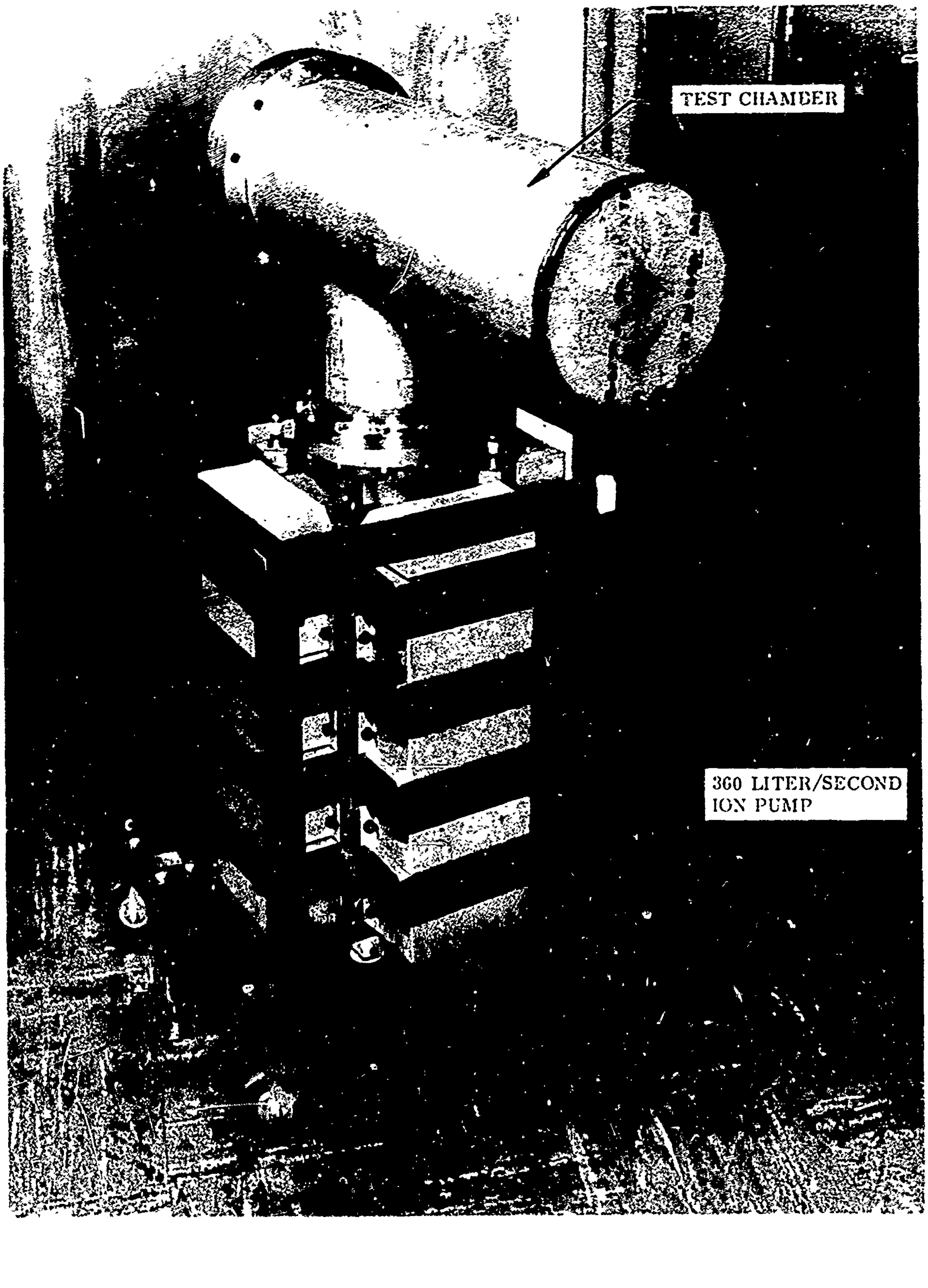


Fig. 1-9 Test Chamber for Vacuum-Radiation Tests

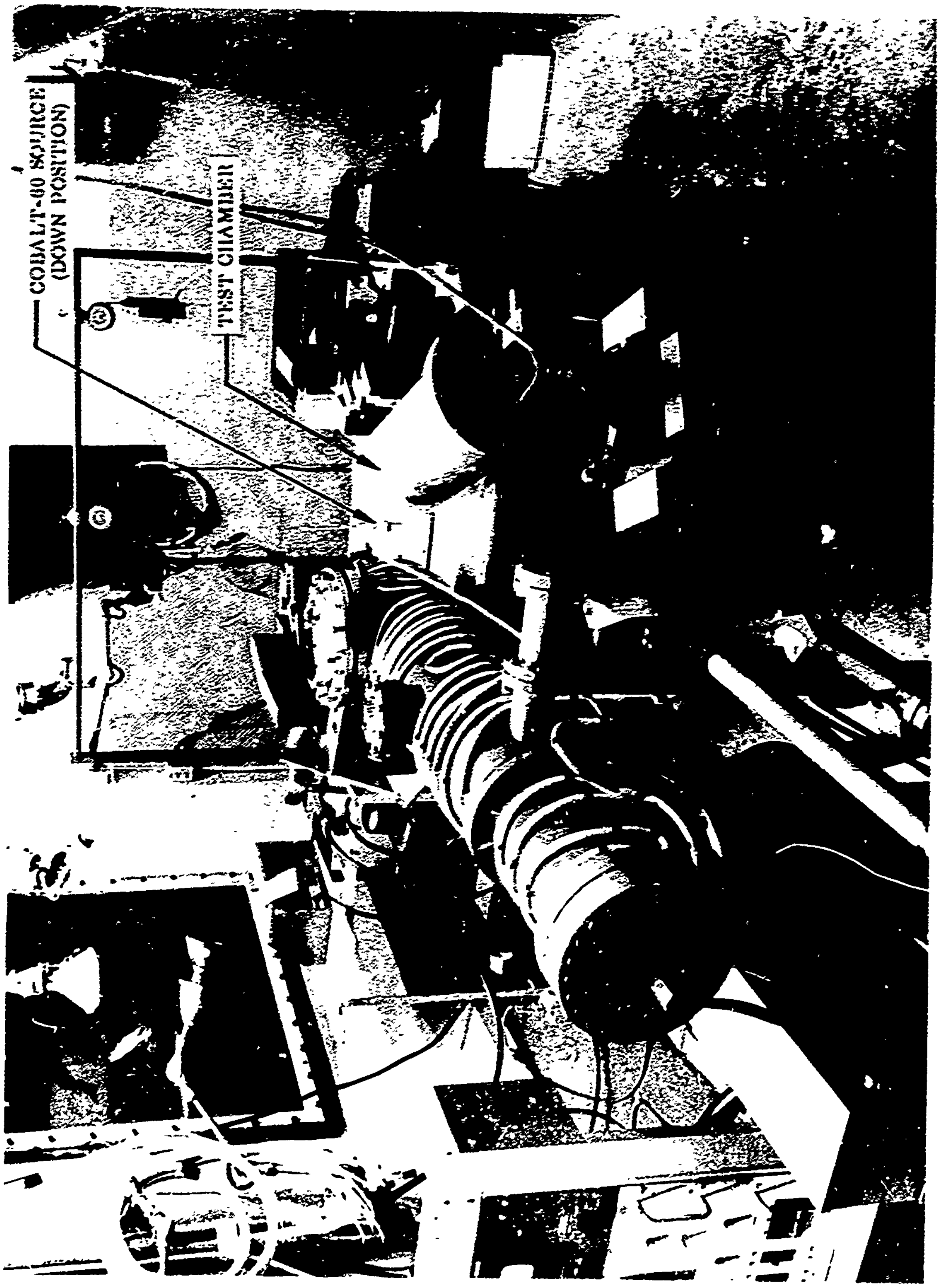


Fig. 1-10 Test Assembly in Cobalt-60 Cell for Vacuum -Radiation Tests

Figure 1-8. The motors were then inserted into a stainless steel chamber, which was evacuated by a 360 liter/second ion pump, as shown in Figure 1-9. After the motors had started operating in vacuum, the assembly was wheeled into position about the Cobalt-60 radioisotope source, as shown in Figure 1-10.

The lubricants were not irradiated continuously during testing, as periodically the equipment had to be withdrawn in order to accommodate other tests. Thus, the average dose rates over the total test duration are less than the dose rates during actual irradiation.

At the start of the first test under combined vacuum and radiation, the source strength was 560 curies; it has since decayed to a strength of approximately 400 curies. As a result, dose rates have decreased from 4200 ± 10% roentgens per hour to a present rate of approximately 3000 roentgens per hour. The energy of the two gamma rays emitted from the Cobalt-60 source are at 1.17 MeV (million electron volts) and 1.33 MeV, giving an average energy level of 1.25 MeV.

Camma radiation provides suitable simulation of space radiation for these tests. Organic materials, such as oils and greases, undergo both radiation-induced polymerization, leading to increases in viscosity, and fragmentation, frequently leading to acidic and corrosive products. These chemical changes are initiated by ionization phenomena caused by the radiation. Since the energy required to form an ion pair is virtually independent of the energy of the incident radiation, the ionization effects can be correlated with the doses absorbed in the material. Thus, the effects of gamma radiation on the performance of oils and greases can be directly correlated to the effects of other types of penetrating radiation, provided that the effects are compared on the basis of the absorbed dose and the dose rate is not so high as to cause secondary effects, such as overheating.

Bearing Speed. Bearing speed was 8000 rpm measured periodically with a Strobotac unit. Rotation was unidirectional.

Bearing Temperature. Bearing temperatures were measured by iron-constantan thermocouples mechanically attached to the bearing housings and ranged from 160 to 200°F in most tests. Temperature rise above ambient was due to the frictional heating of the bearings and power losses in the motor. Lubricants that performed well at 160 to 200°F were tested further at 250°F. Figure 1-11 shows one of the two test chambers used for elevated temperature testing. The motors are surrounded by cylinders of copper sheet which are heated radiantly by Nichrome wire resistance heaters.

Performance Criteria. The two criteria used to evaluate bearing lubricants are the coast time and the lifetime. The coast time is the time required to slowdown from 8000 rpm to a full stop when the power to the motor is cut off. The coast time indicates the running torque of the pair of bearings and is determined about once a week. Coast times were recorded (see data tables) when a time change occurred at approximately 500-hr intervals for short tests, or at 1000-hr intervals for the longer ones.

The lifetime was the period of operation until the increase in bearing torque was sufficient either to stall the motor or to prevent its being restarted after measuring the coast time. Stalling doubled the motor current and caused circuit fuses to blow, thereby cutting off the power to the motor and its associated timer.

1.2.3 Results and Discussion

Table 1-2 presents detailed results for oils that provided one year, or more, of operation under the normal experimental conditions, and Table 1-3 summarizes results for oils that failed to lubricate in less than one year. The test results are current to March 1, 1966.

Tests are indicated to be failed, still running, or discontinued. Discontinued tests are those which were still operating well at the time the test was discontinued.

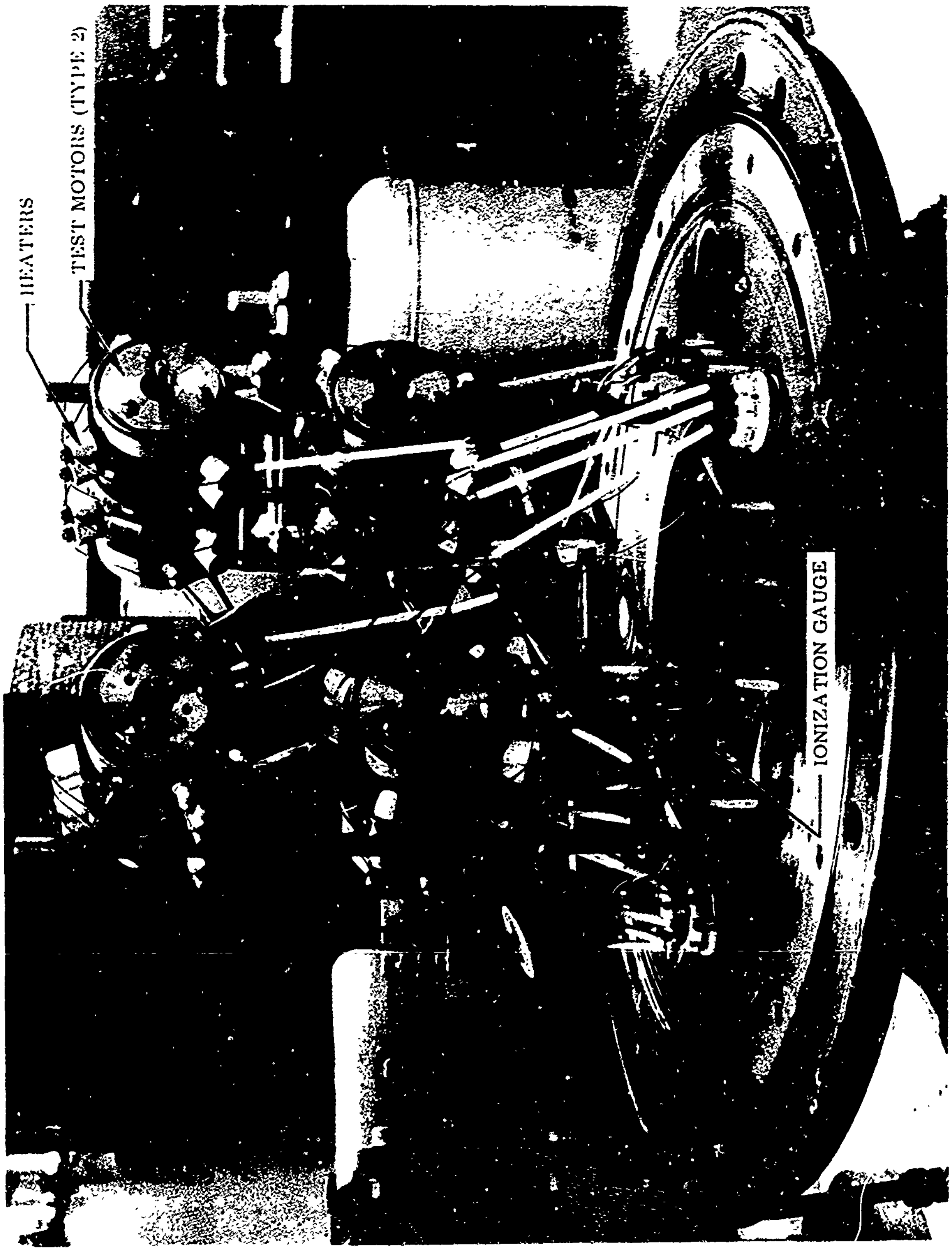


Fig. 1-11 Assembly for Testing in Vacuum at Elevated Temperatures

Table 1-2

TEST RESULTS FOR BEST-PERFORMING OILS

Code	Lubricant	Vacuum System	Bearing Type(a)	Bearing Number	Initial Weight of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results(b)
O-1	Paraffinic-base petroleum oil with additive	Ion Pump	3	1	50	158	140 to 220	5×10^{-6} to 3×10^{-8}	1:05	923	Failed at 14,340 hr. Almost complete loss of oil in both bearings. One bearing still in good condition. Second bearing filled with black powder (apparently decomposed oil) and oil residue.
				2	49				0:47	2,497	
									1:22	3,303	
									1:23	4,039	
									1:19	5,046	
									1:20	6,052	
									1:00	6,998	
									1:56	8,031	
									1:34	8,985	
									2:42	10,160	
									3:03	11,122	
									2:10	12,154	
									4:03	12,997	
									3:51	13,884	
		Diffusion Pump	4	1	50	276	250	1×10^{-7} to 8×10^{-8}	13:06	550	Still running after 8,941 hr.
				2	35				15:35	1,390	
									17:39	1,605	
									20:25	1,868	
									15:02	2,540	
									12:04	3,062	
									3:35	7,236	
		Diffusion Pump	9	1	45	278	210 to 250	1×10^{-7} to 8×10^{-8}	10:27	550	Still running after 8,914 hr. First 6,680 hr were at 210 to 215°F; balance has been at 250°F.
				2	46				10:45	1,390	
									12:30	1,605	
									14:10	1,868	
									13:00	3,035	
									17:04	7,209	
		Ion Pump	9	1	42	273	160 to 170	2×10^{-8} to 3×10^{-9}	–	–	Still running after 20,426 hr, including 15,887 hr exposed to gamma radiation from a cobalt-60 source. Total dose received by bearing closest to source is approximately 5.5×10^{7} roentgens.
				2	35						

O-2	Experimental paraffinic-base petroleum oil	Diffusion Pump	4	1 2	52 49	162	130 to 170	1×10^{-7} to 1×10^{-8}	1:34 1:19 1:0 1:17 1:32 1:26 1:35 1:34 1:26 1:28 1:31 1:12 1:43 1:24 1:30	22 1,122 2,151 3,044 3,977 5,130 6,082 7,086 8,002 8,936 10,227 11,344 13,046 14,141 21,384	Still running after 23,454 hr.
O-3	Paraffinic-oil (O-2) plus oxidation inhibitor and load-carrying additive	Diffusion Pump	4	1 2	54.2 49.9	160	130 to 175	1×10^{-7} to 1×10^{-8}	1:47 2:31 2:0 3.06 1:49 1:37 1:34 1:36 1:25 1:28 1:17 1:39 1:48 2:02 1:51 1:41	22 1,098 2,127 3,020 4,043 5,177 6,030 6,974 8,150 9,091 10,125 11,242 12,191 13,304 14,036 21,190	Still running after 23,248 hr.
O-4	Petroleum base oil, low vapor pressure	Diffusion Pump	3	1 2	50 58	159	160 to 215	3×10^{-7} to 1×10^{-8}	0:16 0:20 0:18 0:18 0:16 0:16 0:17 0:17 0:16 0:15 0:15 0:17 0:18 0:16 0:18 0:15 0:15 0:15 0:16	1,313 2,544 3,353 4,508 5,450 6,504 7,442 8,418 9,487 10,584 11,475 12,672 13,674 14,925 16,025 17,226 18,126 19,081 19,900	Test discontinued at 20,019 hr. Both bearings were still satisfactory, and oil was still present in the bearings. Neither bearing showed a change in torque from the start to the finish.

Code	Lubricant	Vacuum System	Bearing Type(a)	Bearing Number	Initial Weight of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results(b)
O-4 (cont.)	Petroleum base oil, low vapor pressure	Air	3	1	49	157	90 to 143	760	0:08	1,601	Test discontinued at 24,383 hr. One bearing dry with badly worn retainer and fivefold increase in torque; second bearing almost dry.
				2	52				0:08	2,418	
									0:15	3,229	
									0:38	3,567	
									0:29	4,529	
									0:42	5,561	
									0:27	6,547	
									0:36	7,486	
									0:35	8,491	
									0:32	9,618	
									0:31	10,533	
									0:37	11,434	
									0:33	12,514	
									0:32	12,705	
									0:34	13,798	
									0:39	14,976	
									0:34	15,858	
									0:40	17,155	
									0:46	18,221	
									0:58	19,037	
									0:51	19,997	
O-4a	Petroleum oil, dissolved in 20% xylene for application	Ion Pump	1	1	46	166	165 to 210	1×10^{-6} to 1×10^{-7}	0:43	47	Failed at 8,961 hr running time in vacuum. Motor was idle an an additional 9,000 hr in vacuum. One bearing was jammed due to decomposed oil and had coke-like deposits on the shields. Second bearing ran roughly and the oil had thickened to a wax-like consistency. Temperature rose to 234°F during final 50 hr.
				2	43				0:43	869	
									0:40	2,079	
									0:29	3,207	
									0:28	4,096	
									0:30	5,001	
									1:04	5,142	
									1:10	6,051	
									1:04	7,319	
									2:20	8,157	
									1:39	8,816	

O-5	Low vapor pressure	Diffusion Pump	3	1 2	41 40	–	175 to 220	1×10^{-6} to 1×10^{-9}	0:34 0:31 0:24 0:31 0:31 0:26 0:31 0:29 0:27 0:28 0:28 0:29 0:27 0:26 0:25 0:25 0:28	192 956 2,034 2,984 3,486 4,188 5,000 6,424 7,285 8,074 9,231 10,067 10,916 12,091 18,916 23,134 24,437	Still running at 29,634 hr.
O-10	Chlorophenyl-methyl polysiloxane	Diffusion Pump	2	1 2	26 33	156	160 to 190	6×10^{-6} to 4×10^{-7}	–	–	Failed at 4,574 hr. Black wear debris in bearings. One bearing "frozen."
		Diffusion Pump	4	1 2	28 21	162	150 to 185	2×10^{-7} to 9×10^{-9}	2:54 3:14 3:02 2:56 3:38 5:06 5:18 4:49 5:06 5:38 5:21 4:21 5:08 3:05 1:04 1:13	108 916 2,069 2,912 3,966 5,088 6,072 7,067 8,162 8,993 10,189 11,069 12,145 12,579 12,904 13,516	Failed at 13,052 hr. Both bearings filled with wear products from the retainer and decomposed oil. Retainer ball pockets of both bearings worn oval.
		Diffusion Pump	3	1 2	32 33	274	250	9×10^{-8} to 4×10^{-9}	6:25 8:44 10:13 9:55 10:29 12:20 12:24 12:43 14:56 14:00 11:30 11:10	28 489 1,290 1,939 3,021 4,217 5,103 6,346 7,203 8,784 9,934 10,457	Failed at 13,575 hr. Total of which the last 10,731 hr was at 250°F and balance was at 190°F, or lower. Both bearings were dry with a small amount of black debris. One bearing had retainer cut in half; second bearing had ball pockets worn oval.

Code	Lubricant	Vacuum System	Bearing Type[a]	Bearing Number	Initial Weight of Oil (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results[b]
O-10 (cont.)	Chlorophenyl-methyl polysiloxane	Diffusion Pump	4	1 2	32 36	275	5,231 hr. at 150 to 210, rest at 250	9×10^{-8} to 4×10^{-9}	7:12 7:10 19:46 11:34 9:14 7:05 6:24 8:17 11:50 10:23 9:14	28 728 2,139 3,129 4,130 5,016 6,260 7,118 8,699 10,370 14,544	Still running after 16,249 hr.
		Diffusion Pump	9	1 2	20 28	275	250	9×10^{-8} to 4×10^{-9}	6:57 9:43 11:06 9:55 13:58 8:29 9:00 0:32	28 172 1,327 2,304 3,175 4,107 4,973 5,570	Failed at 5,571 hr, of which 2,282 hr was at 250°F, and balance was at 150 to 210°F. Both bearings were dry and filled with black debris. One retainer was broken.
		Diffusion Pump	9	1 2	25 40	278	250	9×10^{-8} to 4×10^{-9}	7:54 7:20 11:32 13:53 10:24 7:40 8:42 13:00	28 949 1,939 3,016 3,964 5,041 6,093 6,952	Failed at 7,141 hr, of which 4,961 hr was at 250°F, and balance was at 140 to 176°F. Both bearings were dry and filled with black wear debris. Retainers were worn, and one retainer was cracked in two places.
		Ion Pump	3	1 2	52 46	273	170 to 280	2×10^{-8} to 7×10^{-9}	–	–	Test discontinued after 5,556 hr operation in vacuum with 4,097 hr exposure to radiation from a cobalt 60 source. Total radiation received was 1.7×10^{7} roentgens (± 10%). Oil did not appear changed; the retainers were not worn or otherwise damaged.
		Ion Pump	3	1 2	54.5 41.5	273	150 to 160	2×10^{-8} to 3×10^{-9}	–	–	Still running after 13,881 hr including 15,887 hr exposure to radiation. Total radiation received is 5.5×10^{7} roentgens. (Bearings have accumulated 8,726 hr of idle time in vacuum.)

O-11	Chlorophenyl-methyl polysiloxane with 50% more volatile fraction removed by distillation	Diffusion Pump	3	1 2	61.7 62.0	157	170 to 200	4×10^{-7} to 3×10^{-8}	1:56 1:06 9:14 9:19 9:17	759 1,342 1,577 2,256 3,150	Failed at 3,335 hr. One bearing filled with black wear debris; second bearing dry but otherwise in good condition.
		Diffusion Pump	2	1 2 3	30 29 53	157	130 to 200	5×10^{-6} to 1×10^{-6}	–	–	Number 2 bearing failed at 1,856 hr and was replaced with No. 3 bearing, which failed after 409 hr. Number 1 bearing still good after 2,265 hr.
		Air	3	1 2	54.5 52.9	159	100 to 140	760	0:49 1:12 2:27 3:49 3:57 4:14 4:00 4:18 4:00 3:35 4:25 3:18 3:27 3:22 3:28 2:55 3:27 2:46 1:06	1,565 2,383 3,051 3,843 4,997 5,986 7,038 7,978 8,916 10,116 11,063 12,068 12,970 14,083 14,930 16,450 17,000 18,184 19,002	Failed at 19,075 hr. Both bearings were dry and had some wear debris and decomposed oil residue.
O-13	Fluorosilicone oil	Diffusion Pump	3	1 2	81 80	157	140 to 190	1×10^{-3} to 1×10^{-8}	0:53 0.39 1:00 1:11 1:09 1:10 1:14 1:11 1:15 0:55 1:06 1:06	162 925 2,023 3,019 4,047 5,225 6,026 6,937 8,137 9,207 10,066 10,972	Still running after 33,649 hr.

O-15	High phenyl content silicone oil	Diffusion Pump	3	1	68	273	160 to 205	1×10^{-6} to 4×10^{-7}	2:00	342	Still unning after 23,996 hr.
				2	68				1:49	1,036	
									1:50	2,020	
									1:49	3,077	
									1:40	4,085	
									1:44	4,925	
									1:35	6,099	
									2:06	7,199	
									1:48	8,027	
									1:49	8,974	
									1:38	10,520	
									1:53	11,105	
									1:55	12,755	
									1:55	13,933	
									2:07	15,276	
									2:09	16,973	
O-27	Trifluoromethyl-phenoxy phosphonitrile	Ion Pump	3	1	83	166	155 to 170	1×10^{-6} to 4×10^{-8}	1:22	394	Failed at 9,640 hr. One bearing was dry but still operating satisfactorily; second bearing was also dry and had a worn and broken retainer and badly worn balls.
				2	80				1:24	1,087	
									1:20	2,019	
									1:00	3,483	
									1:10	4,369	
									1:00	5,110	
									1:46	6,021	
									1:26	7,101	
									1:50	8,367	
		Diffusion Pump	3	1	58	157	145 to 160	3×10^{-8} to 1×10^{-8}	1:12	69	Still running after 15,012 hr.
				2	62				1:11	1,079	
									1:09	2,011	
									1:04	3,046	
									1:00	3,527	
									1:12	4,425	
									1:07	6,300	
									1:23	13,542	

(a) Bearing Types:

1. 440C stainless steel, ribbon retainers, double shielded.
2. 52100 chrome steel, ribbon retainers, double shielded.
3. 440C stainless steel, Synthane retainers, double shielded.
4. 52100 chrome steel, Synthane retainers, double shielded.
5. 440C stainless steel, ribbon retainers, unshielded.
6. 440C stainless steel, special retainer material, double shielded.
7. 440C stainless steel, special retainer material, unshielded.
8. 52100 chrome steel, phenolic retainer, unshielded.
9. 52100 chrome steel, balanced linen-base phenolic retainer, double shielded.
10. 440C stainless steel, ribbon retainers, double shields of Teflon.

All bearings are deep-groove type except 6 and 7, which are angular-contact type.

(b) Data are as of 1 March 1966.

Table 1-3

SUMMARY OF TEST RESULTS FOR OILS THAT FAILED TO PROVIDE ONE-YEAR LIFETIMES IN VACUUM

Code	Material	Bearing Type[a]	Lifetime In Vacuum (hr)
	Petroleum Oils		
O-6	Petroleum oil	3	1713
O-7	Petroleum oil	3	790
O-8	Naphthenic-base oil with hindered-phenol type oxidation inhibitor	4	743
O-9	Colloidal dispersion of molybdenum disulfide in petroleum oil		2938
	Silicone Oils		
O-12	Dispersion of molybdenum disulfide in silicone oil	1	177
O-16	Dimethyl polysiloxane	4	345
O-17	Low phenyl content polysiloxane stripped of light ends	3	1185
O-18	Medium phenyl content polysiloxane	4	2603
O-19	Methylphenyl polysiloxane stripped of 35% more volatile fraction	2 4	458 6066
O-20	Halogenated phenylmethyl polysiloxane plus organo-metallic anti-wear additives	3	2474
	Diester Oils		
O-21	Dioctyl sebacate	3 4	3584 899
O-22	Diester-base oil meeting MIL-L-6085	4 4 4	249 330 1409

Table 1-3 (cont.)

Code	Material	Bearing Type(a)	Lifetime In Vacuum (hr)
	Diester Oils (cont.)		
O-23	Diester oil	3	801
O-24	Dispersion of molybdenum disulfide in diester oil 0-23	4	1766
O-25	Diester oil	3	2740
O-26	Dispersion of molybdenum disulfide in diester oil 0-25	4	2746
	Other Synthetic Oils		
O-28	Hexa-2-ethylbutoxy disiloxane	1 3	4244 5309
O-29	15% dioctyl sebacate, 85% hexa-2-ethylbutoxy disiloxane	1 3	359 468
O-30	Diphenylbis-n-dodecylsilane	3	1367
O-31	Triaryl phosphate	2 3	164 763
O-32	Triaryl phosphate	4	336
O-33	Isomeric 5-ring polyphenyl ether	3	2476

(a) 1 – 440C stainless steel, ribbon retainers
2 – 52100 chrome steel, ribbon retainers
3 – 440C stainless steel, Synthane retainers
4 – 52100 chrome steel, Synthane retainers

Of the oils tested to date, the fluorosilicone oil Code O-13 (250 cs) has achieved the longest operating lifetime in vacuum; bearings lubricated with this oil are still operating after 33,649 hours (approximately 3 years, 10 months). Oil O-14 (1000 cs), a higher viscosity grade of the same oil, failed in 17,492 hours.

Oil O-10, also a silicone oil, has received the greatest amount of testing, and has consistently performed for more than one year in vacuum at temperatures up to 250°F when used with standard, Synthane retainers. All three of these tests survived beyond 13,000 hours (one year, six months). An early test with this oil applied to a pair of bearings with steel, ribbon-type retainers failed in 4575 hours, and two tests with balanced, crown-type retainers of a linen-base phenolic laminate failed in 7141 hours, or less. Two tests with oil O-10 oil under combined radiation and vacuum indicate that it is satisfactory up to radiation doses of at least 4×10^7 roentgens.

Two modifications of oil O-10 oil failed to improve its performance, In the first of these, the oil was molecularly distilled to remove the 50 percent more volatile fraction to determine whether or not the less volatile residue would operate better in vacuum. Although the stripped version lubricated well in air, providing a lifetime of 19,075 hours, its lifetime in vacuum was from 409 to 3335 hours, which is substantially less than the lifetime of the unstripped version in vacuum. A dispersion of molybdenum disulfide powder in oil O-10 was also unsuccessful, failure occurring after only 177 hours of operation.

Oil O-1, a refined petroleum oil with additives that is commonly used on the spin-axis bearings of gyroscopes, has also performed well. One bearing failed after 14,340 hours under the normal experimental conditions, and two other pairs of bearings are still operating in vacuum after more than 8900 hours at temperatures up to 250°F. Another pair of bearings lubricated with oil O-1 is still running after 20,426 hours of combined vacuum and radiation to 4×10^7 roentgens. The O-1 oil is more viscous than oil O-10 (250 centistokes versus 50 centistokes at room temperature) and results in more bearing torque, although both oils provide acceptably low bearing torques for most applications. At subzero temperatures, however, oil O-10 would be definitely superior to oil O-1 in this characteristic.

Four other oils that have performed well, both from the standpoint of lifetime and bearing torque, are O-15 (a high-phenyl content silicone oil), O-27 (a phosphonitrile), O-2 (an experimental, refined petroleum oil), and O-3 (the O-2 oil with additives). The phosphonitrile oil is especially interesting because of its potential as a high-temperature, radiation-resistant lubricant.

Both O-4 and O-5 oils have also provided long lifetimes, in excess of 20,000 hours to failure, but they are too viscous to be considered for normal use. These two oils might be useful in equipment operating at higher-temperatures, provided that starting at low temperatures was not required.

The results of diester oils are also noteworthy. These oils are used in the MIL-L-6085 formulations commonly used for lubricating instrument mechanisms, such as tape recorders, that are housed in sealed packages. None of the diester oils gave very long lifetimes in vacuum. The straight diester, dioctyl sebacate (Code O-21), gave the longest lifetimes (3584 hours, one test; 899 hours, second test) and failures appeared to be due to loss of lubricant. The compounded diesters meeting the MIL-L-6085 specification (O-22 and O-23) gave shorter lifetimes (249 to 1409 hours, four tests), and the failed bearings contained abrasive residues and were worn. A specially formulated diester (O-25) operated a little better (2717 hours, test discontinued).

Bearings with machined retainers of Synthane have had longer operating times than those with either steel ribbon retainers or balanced, crown-type retainers of a linen-base phenolic laminate. This is demonstrated by the results with the O-10 oil.

The dominant mode of failure with oils has been the partial or complete loss of lubricant with resultant wear and formation of fine wear particles, principally from the retainer. It is not clear whether the loss of lubricant is due to evaporation or creepage, although it is worth noting that no general correlation has been found between vapor pressure and lifetime and that silicone oils, which are generally regarded as being most prone to creep away from lubricated areas, have given excellent lifetimes. A second failure mode has been the partial loss of oil together with the decomposition of part of the remainder, leading to the formation of large oil residue particles bonded together with retainer wear debris. A typical failure of the second type is shown in Figure 1-12; these bearings had been lubricated with the polyphenyl ether (O-33) and failed at 2476 hours. The dryness of the bearings should be apparent in the figure, and strips of decomposed lubricant can be seen between the shield and the outer race of one bearing.

A test with O-18 silicone oil, which is the same oil as used in the diffusion pumps, gave a lifetime of 2603 hours in vacuum. Thus, even under the most favorable conditions, the diffusion pump oil provides a lifetime that is an order of magnitude less than that obtained with the longest-lived lubricants. This indicates that any pickup of diffusion pump oil by ball bearings under test must be extremely slight and must not have a significant effect on the test results.

In another test to verify this conclusion, a motor with two unshielded, dry bearings with Synthane retainers was mounted in the position closest to the pump in a vacuum chamber with an oil diffusion pump. The motor was allowed to remain idle in this position for 1000 hours, which should have been sufficient to collect a significant amount of whatever lubricating vapors were present in the system, and it was then turned on and operated until failure. The bearings failed in 2400 hours, and both retainers were severely worn. A second motor was operated in a similar manner in an ion pumped system, and again the bearings suffered severe retainer wear over a period of 2400 hours. (Actually, retainer wear in the ion pumped system was slightly less, and the bearings were still operating after 2400 hours.)

A further comparison of tests conducted in oil diffusion pumped systems and ion pumped systems indicates that the test results have not been affected by the type of vacuum system used.

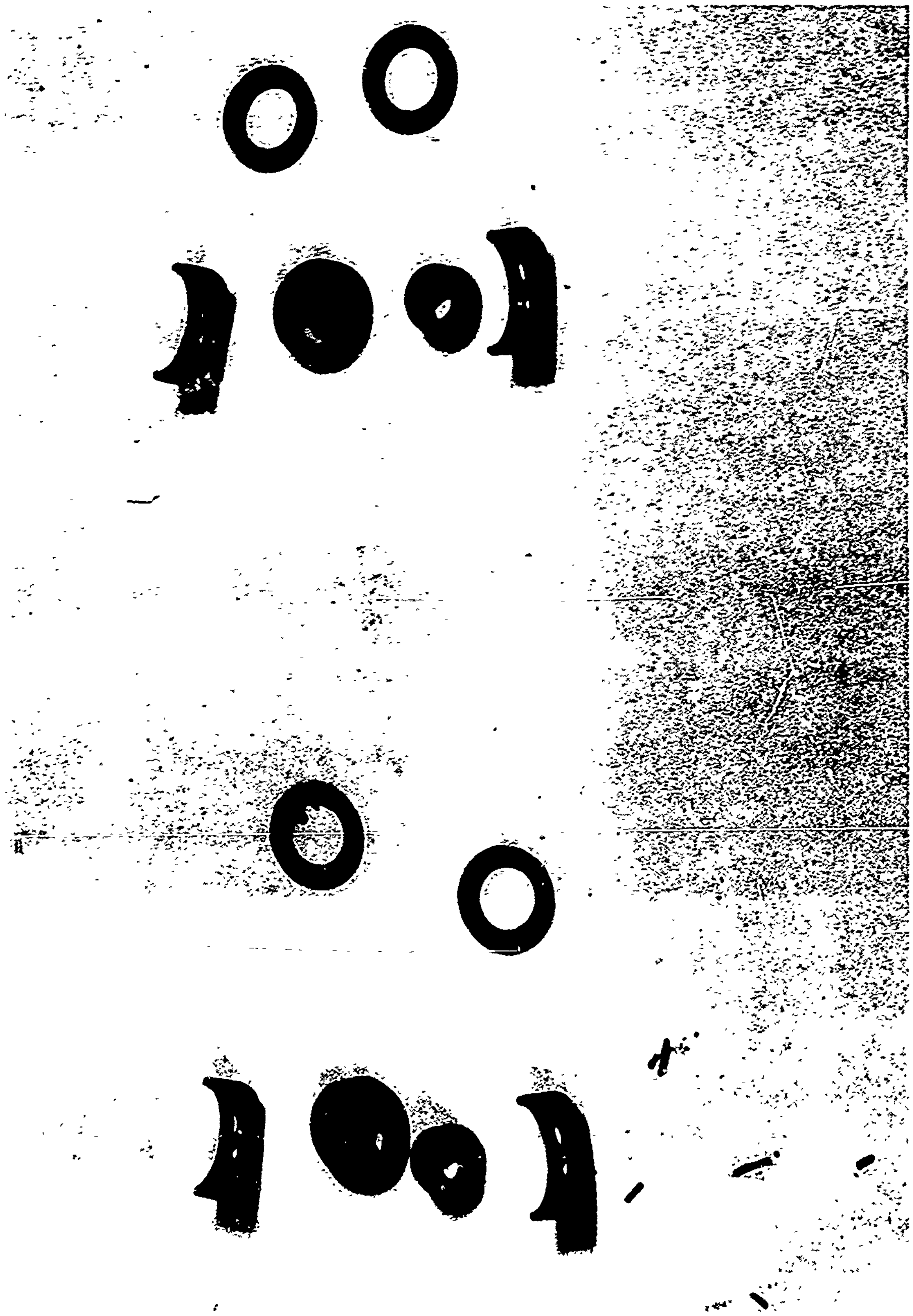


Fig. 1-12 Failed Oil-Lubricated Bearing

Operation in vacuum can drastically reduce the lubricant lifetime below that obtained for operation in air. This is shown by the comparison presented in Table 1-4. Note that the first failure of these four oils in air occurred after more than two years of continuous operation, whereas three of the four lubricants failed to survive five months of operation in vacuum (in fact, one lubricant failed in slightly less than two months in vacuum). The only lubricant in this series of tests that operated for an extended time in vacuum is the low-vapor pressure mineral oil, Code O-4, which is too viscous for normal use. These results demonstrate that in order to lubricate equipment satisfactorily with oils for long-time operation in space, either the devices must be housed in pressurized and sealed containers, some means of lubricant replenishment must be provided, or the lubricants must be carefully selected from those that have demonstrated satisfactory operation in vacuum.

Generally, ball bearing lifetime with oil lubrication increased with viscosity, and the increase was most pronounced at low viscosities. This is shown in Figure 1-13, which is a plot of operating lifetime against oil viscosity (at the bearing housing temperature) for most of the oils tested. For any specified viscosity, there is a wide range of lifetimes. The curve is not well defined for viscosities above 200 centistokes because oils with these viscosities have not yet resulted in failures, but the curve would probably reach a maximum lifetime at some viscosity around 100 centistokes. Diester oils generally have lifetimes less than 1000 hours, and Figure 1-13 suggests that this is due to their low viscosity. Some of the long-lived oils would have very limited applicability because of their high viscosities and pour points. The existence of a correlation between lifetime and viscosity suggests that hydrodynamic films are an important mode of lubrication under the conditions tested here. However, the wide scatter in lifetimes at a given viscosity indicates that other factors, such as boundary lubrication, are also important.

Attempts to correlate lubricant lifetime in vacuum with vapor pressure have been very unsatisfactory. Increases of lifetime with increasing vapor pressure that have been observed for families of oils may actually be due to accompanying increases in viscosity. For example, Figure 1-14 is a plot showing the vapor pressure and

Table 1-4

OPERATING LIFETIME OF LUBRICATING OILS ON BALL BEARINGS IN AIR AND VACUUM

Code	Lubricating Oil	Operating Conditions and Lifetimes[a]	
		Air	Vacuum
O-4	Low vapor pressure mineral oil	24,383 hr, SR[b]	20,019 hr, SR[e]
O-10	Silicone oil, distilled to remove volatiles	19,075 hr, failed	3,335 hr, failed
O-33	Polyphenyl ether	24,354 hr, SR[c]	2,476 hr, failed
O-30	Diphenyl-bis-n-dodecylsilane	24,339 hr, SR[d]	1,367 hr, failed

(a) Vacuum was 4×10^{-7} to 3×10^{-8} torr; Speed was 8,000 rpm; Bearings were R-3 size, 440C stainless steel; Synthane retainers, double shielded; SR = Still running when tests were discontinued at times indicated.
(b) One bearing was dry and its retainer was badly worn after 24,383 hr; other bearing still had small amount of oil left and was beginning to wear.
(c) Both bearings still in excellent condition with 50% or more of original amount of oil remaining.
(d) Both bearings almost dry and retainers badly worn.
(e) Both bearings still in good condition with no significant increase in torque.

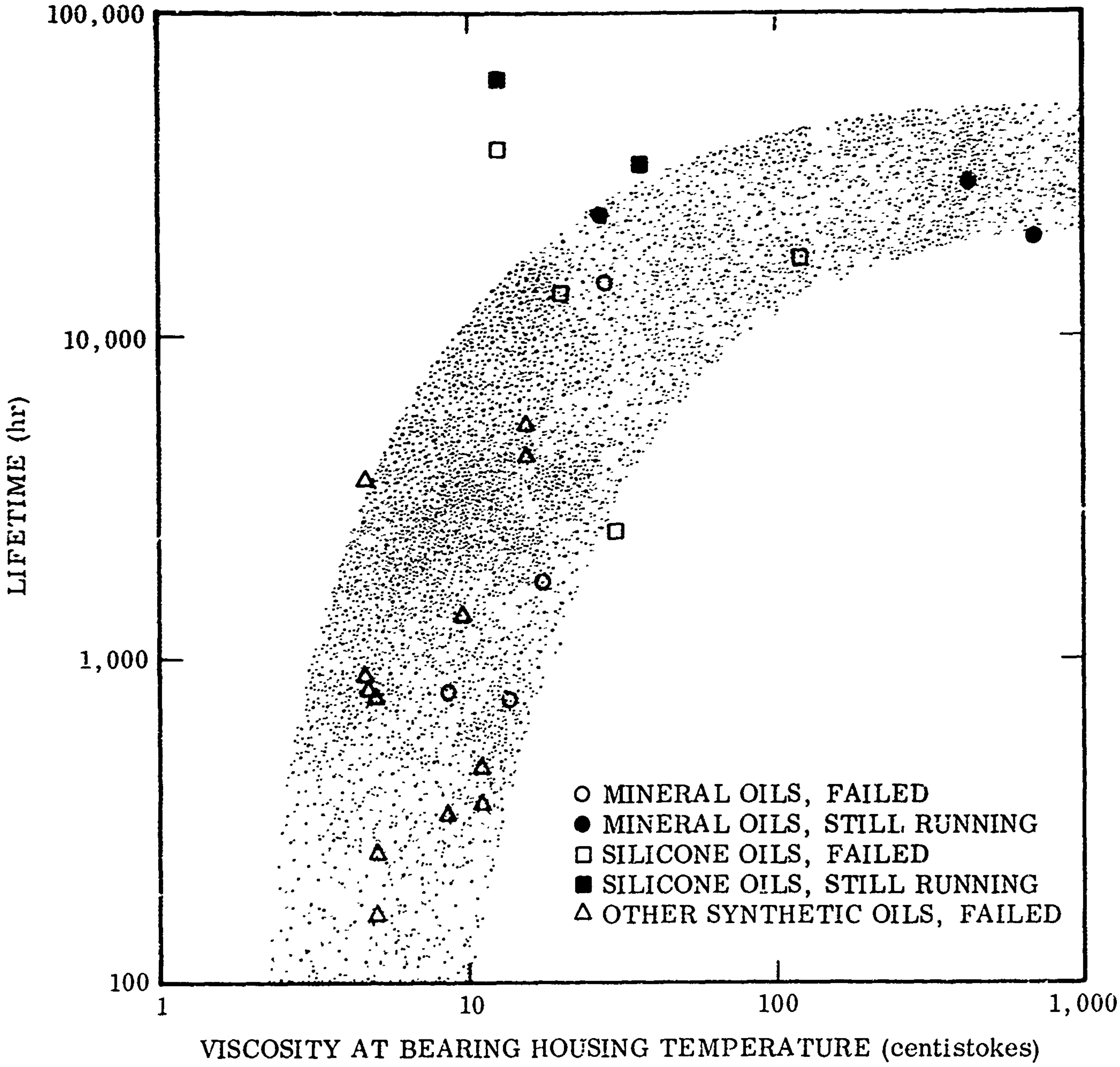


Fig. 1-13 Lifetime and Correlation Between Viscosity for Various Oils

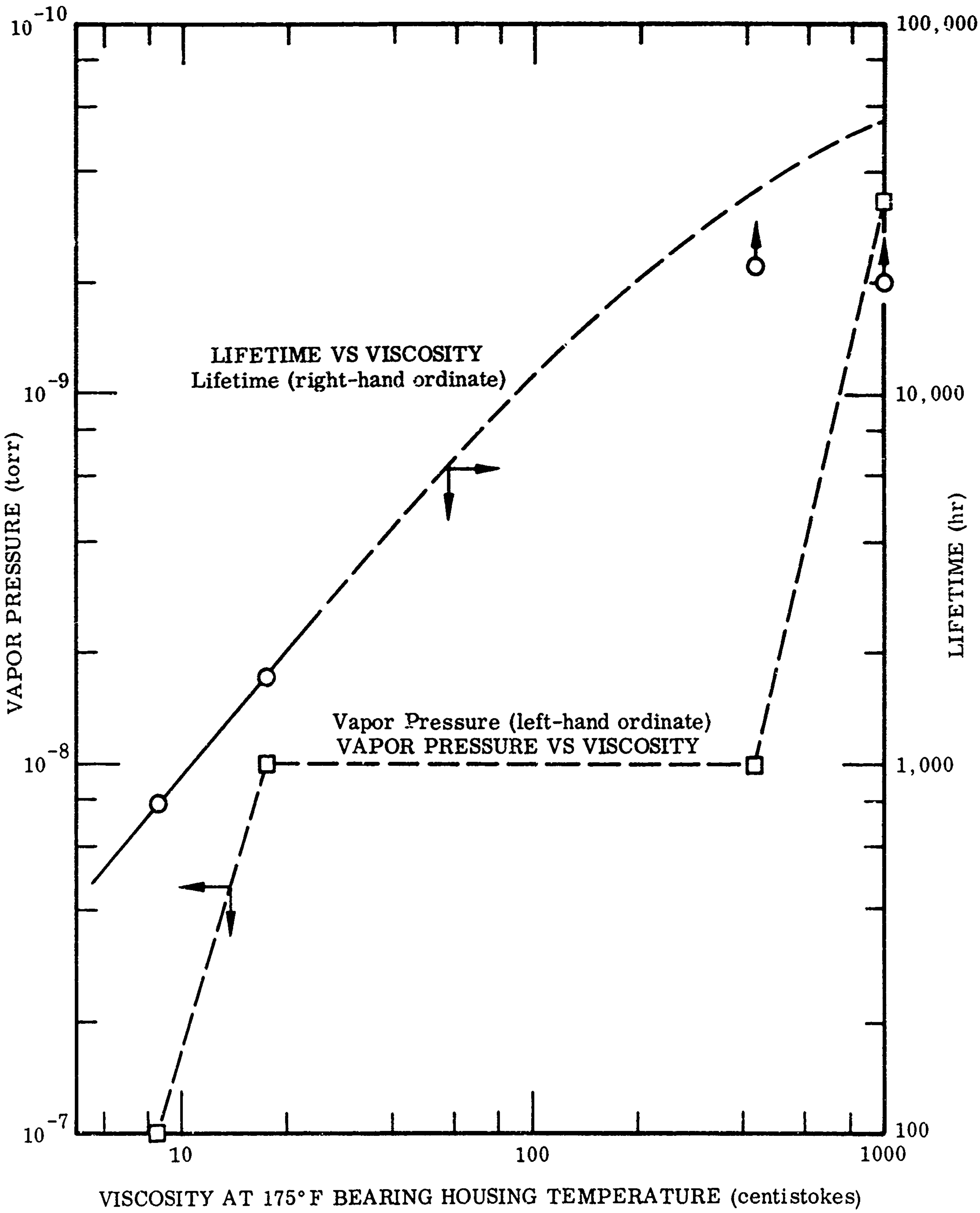


Fig. 1-14 Variation of Vapor Pressure and Lubricating Lifetime With Viscosity of Selected Mineral Oils

lubricating lifetimes in vacuum for four oils of a family of highly refined mineral oils plotted as functions of viscosity. Although the data on vapor pressures is accurate only to within an order of magnitude, there does appear to be a trend for longer lifetimes to be associated with lower vapor pressures. However, the lower vapor pressures are also associated with higher viscosities, and it may be that the variations in viscosity is the dominant factor here in controlling the lifetime and that the variations in vapor pressure have a secondary or minor effect on lifetime. This is also borne out by the results of two tests on two grades of fluorosilicone oil, O-13 and 0-14. Although vapor pressure data are unavailable on these two oils, the vapor pressure of the 1000-centistoke grade is probably lower than that of the 250-centistoke grade, yet the lifetime of the 250-centistoke grade is longer. This also argues that viscosity has a more important effect on lifetime than vapor pressure. More data on vapor pressure, viscosity, and lubricant performance are needed to test possible correlations here.

Halogenated and high-phenyl silicone oils have given longer lifetimes in vacuum than either dimethyl or phenylmethyl silicone oils with low or medium phenyl contents, as indicated in Figure 1-15. This observation supports the conclusion that increasing the polarity of the oils increases the tenacity with which they attach themselves to metal surfaces and provides better lubricant films. Dimethylsilicone, being a symmetrical chain molecule, has the lowest polarity of the oils indicated in Figure 1-15. Replacing some of the methyl groups with phenyl groups gives higher polarity, and partial halogenation of the phenyl group gives the highest polarity of all. The improved performance in vacuum noted with increasing polarity roughly parallels similar improvements in air.

Attempts to find a measure of "lubricity" against which to correlate bearing performance have been limited by the lack of consistent data on "lubricity." Figure 1-16, for example, shows an attempt to correlate lifetime with the results of Shell 4-ball tests. Results of Shell 4-ball tests for the same conditions of testing are very limited, and Figure 1-16 contains data for only three oils. The three points show no correlation between lifetime and scar diameter, indicating that this type of test may very well

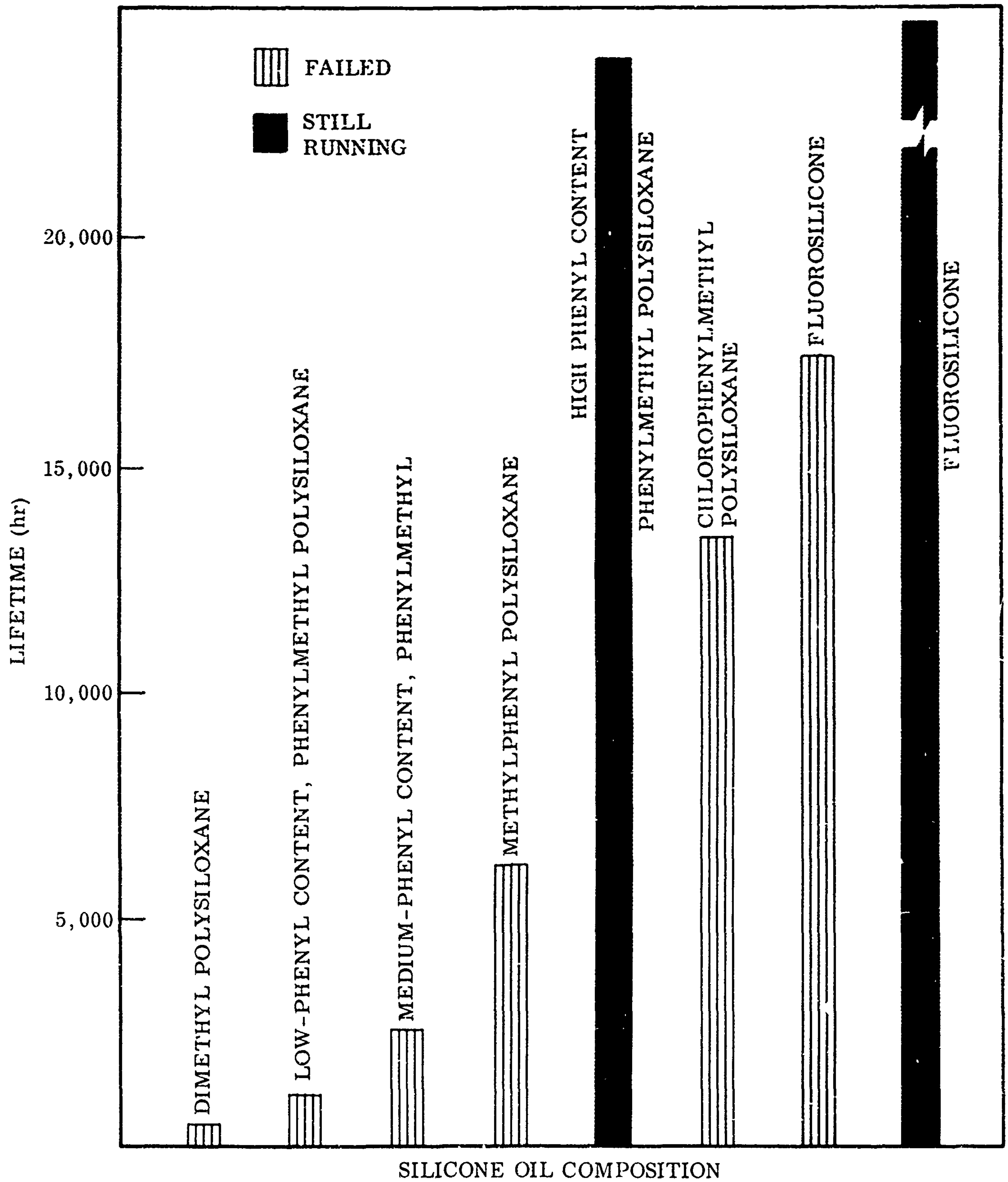


Fig. 1-15 Effect of Silicone Oil Composition on Bearing Lifetime in Vacuum

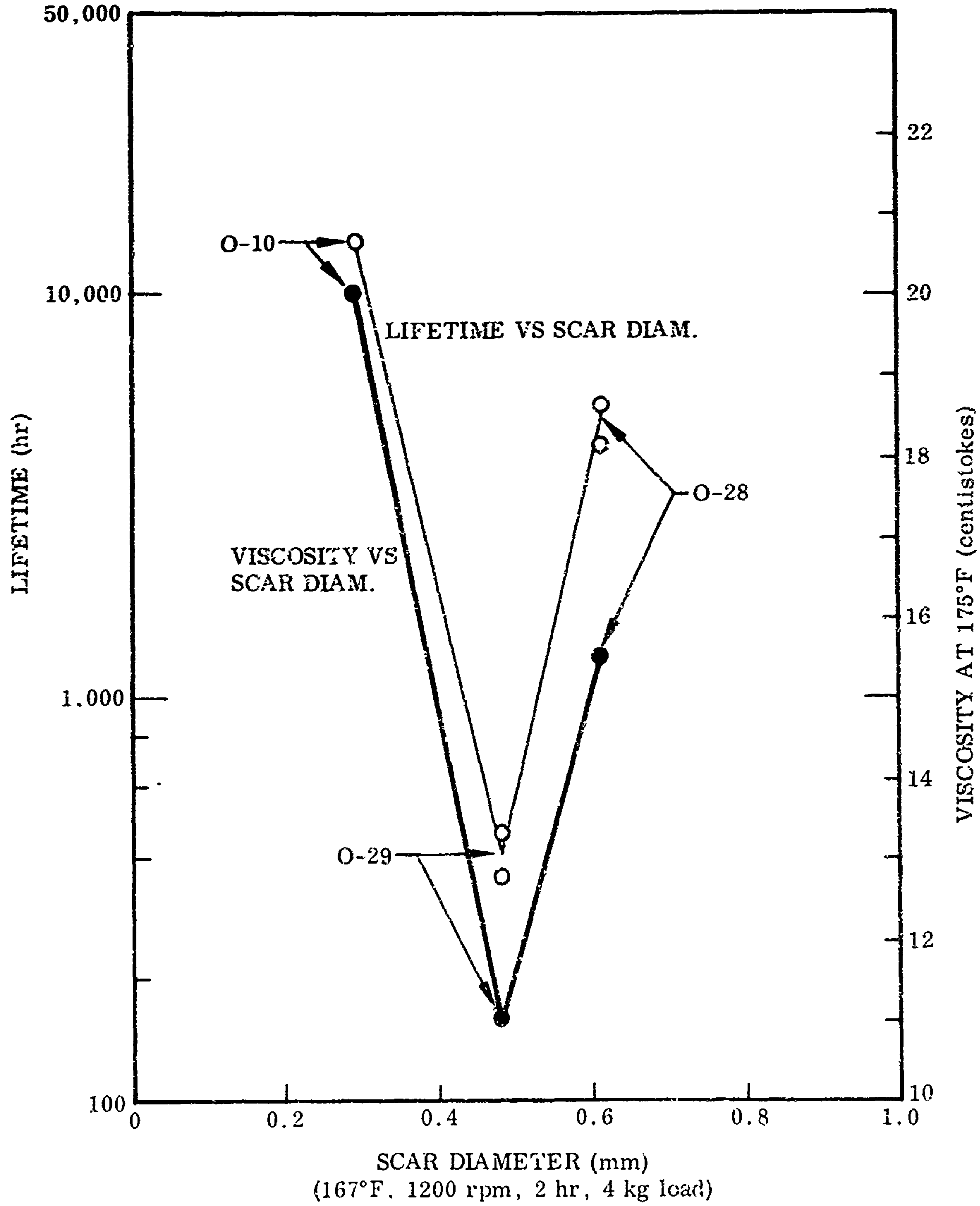


Fig. 1-16 Relationships Between Oil Lubricity (as Measured by Scar Diameter), Lifetime, and Viscosity

not provide a satisfactory measure of lubricity for correlating with ball bearing performance. The auxiliary plot of viscosity vs scar diameter on Figure 1-16 verifies that viscosity and scar diameter do not correlate (as expected, since the 4-ball tests measure properties of the boundary film rather than the hydrodynamic film) but that the lifetime depends more on viscosity than on the results of the 4-ball tests.

1.3 LUBRICATION WITH GREASE

1.3.1 Greases

Tests on greases, similar to those on oils, have been conducted to evaluate their performance in vacuum. Tests have been completed or are in progress on 15 different greases of the following types:

Code No.	Chemical Type of Base Oil
G-1 to G-4	Petroleum
G-5 to G-14	Silicone
G-15	Diester

Tables 1-5 and 1-6 include a more complete description of the base oil and thickeners used in the greases tested.

Lifetimes have varied from 340 hours (2 weeks) to over 33,000 hours (3 yrs 10 months). Approximately one-half of the greases tested failed in less than 6 months.

1.3.2 Equipment and Procedures

The experimental equipment and procedures used with the greases were similar to those described earlier for oils, with the following exceptions:

1. All but a few bearings were of 4400C stainless steel and had ribbon type retainers and double shields. Two pairs of bearings were run without shields in an atmosphere of 90 percent N_2 – 10 percent He at one atmosphere pressure. Another two pair of bearings was provided with rubbing seals of Teflon.

2. The amount of grease per bearing varied from 40 to 111 mg.
3. In addition to tests at average temperatures of 155 to 190°F, tests at 225 and 300°F are being conducted. These tests use radiant heaters attached to the motors.

1.3.3 Results and Discussion

Table 1-5 summarizes test results for seven greases, none of which provided six months of operation. Table 1-6 presents detailed results for eight greases that provided one year, or more, of operation under normal test conditions.

Greases based on halogenated silicones and phenylmethyl silicones have given the longest operating times in vacuum, including operation in vacuum at moderately elevated temperatures and exposed to gamma radiation. They have also operated with acceptably low torque levels at the test temperatures.

Of the greases tested to date, the silicone-base grease G-8 has achieved the longest operating lifetime in vacuum. A single pair of bearings lubricated with this grease are still operating satisfactorily after 33,100 hours (3 years, 9 months).

Grease G-5, also a silicone-base grease, has received the greatest amount of testing. Eight tests have been completed in vacuum, two of these being in a combined vacuum and radiation environment. One test in vacuum at about 175°F gave satisfactory performance for 23,829 hours, at which time the test was discontinued; one test in vacuum at 225°F failed in 22,694 hours; and one test in vacuum at about 300°F failed after 4359 hours. From these results, it appears that lifetimes of two years, and more, are possible in vacuum up to temperatures of 225°F, but that shorter lifetimes result at higher temperatures. Under a combined vacuum and radiation environment, lifetimes beyond one year at temperatures up to at least 175°F and radiation doses up to 10^7 roentgens, at least, appear reasonable. Two additional tests in vacuum alone were run with the Code G-5 grease in bearings with Teflon seals; both of these tests failed due to electrical malfunction, which overheated the motors and degraded

Table 1-5

TEST RESULTS FOR GREASES THAT FAILED TO PROVIDE SIX-MONTHS LIFETIME IN VACUUM

Code	Material	Lifetime (hr)
G-2	Petroleum oil with sodium stearate thickener	969
G-3	Petroleum oil with complex calcium soap thickeners	1,866
G-4	Petroleum oil with sodium soap thickener	3,160
G-12	Fluorosilicone oil with soap thickener	3,797
G-13	Fluorosilicone base grease	340
G-14	High vacuum silicone grease	485
G-15	MIL-G-3278 grease (diester oil with lithium soap thickener)	3,820

Table 1-6

TEST RESULTS FOR BEST-PERFORMING GREASES

Code	Lubricant	Vacuum System	Bearing Type	Bearing Number	Initial Weight of Grease (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
G-1	Petroleum oil with sodium soap thickener	Ion Pump	1	1 2	24 28	267	125 to 142	9×10^{-8} to 6×10^{-8}	3:56 7:30 6:14 3:36 2:45	235 382 1,024 1,558 2,059	Test discontinued at 2,064 hr. Both bearings still running satisfactory but grease had hardened to a wax-like consistency.
		Ion Pump	1	1 2	31.1 36.0	271	120 to 140	9×10^{-8} to 6×10^{-8}	11:20 17:16 12:51 12:35 16:08	235 382 1,023 1,558 2,059	Test discontinued after 2,063 hr. Results same as above.
		Diffusion Pump	1	1 2	73.6 70.9	159	120 to 150	5×10^{-8} to 2×10^{-8}	3:16 6:45 9:31 10:08 9:13 6:53 2:14 2:11 0:45 0:35 1:18 0:42	69 330 581 1,568 2,539 3,044 3,907 4,160 4,585 5,803 6,528 6,957	Test stopped after 13,362 hr due to motor whine. Bearings not examined yet.
			1	1 2	74 79	267	90 to 100	760 (90% N_2-10% He)	1:29 2:14 3:52	147 1,108 4,052	Test discontinued at 4,052 hr. both bearings had fine, black, magnetic material on the outside of the shields near the outer race. The outer race appeared to have rotated in the bearing housing. In both bearings the grease appeared unchanged.

G-1 (cont.)	Petroleum oil with sodium soap thickener		5	1 2	61.0 62.9	273	90 to 95	760 (90% N_2-10% He)	1:57 2:24 3:04 4:24	145 648 1,754 4,660	Test discontinued at 4660 hr. One bearing appeared unchanged. Second bearing had fine, black material at both edges of the bore. Grease in both bearings appeared unchanged.
G-5	Chlorophenyl methyl polysiloxane oil (Code O-10) with lithium soap thickener	Diffusion Pump	1	1 2	91 101	160 and 158	132 to 220	2×10^{-6} to 2×10^{-8}	1:53 2:05 2:15 2:16 3:17 2:35 2:10 1:02 1:47	2,233 3,050 4,052 5,013 6,046 6,983 8,090 9,000 9,587	Failed at 9,612 hr. The grease in both bearings had darkened and hardened. One bearing was jammed, the second was almost jammed.
		Diffusion Pump	1	1 2	55 65	276	135 to 198	2×10^{-6} to 2×10^{-7}	3:31 2:42 3:49 4:22 5:32 7:21 10:50 11:39 8:43 9:21 8:49 9:00 10:51 10:47 9:10 10:50 10:28 11:38 13:33 14:21 12:00 11:39 10:14	153 1,053 1,984 3,004 3,758 4,261 5,058 6,458 7,580 8,614 10,048 11,223 12,077 13,081 13,920 15,038 16,076 17,120 18,274 19,020 20,322 21,599 22,800	Test discontinued at 23,820 hr. Bearings were still in good condition and operating satisfactorily when test was stopped. In addition to the running time of 23,820 hr, the bearings were also exposed to vacuum for 5,488 hr in a non-rotation condition, after each such period (including times up to 648 hr), the motors restarted satisfactorily.

Code	Lubricant	Vacuum System	Bearing Type	Bearing Number	Initial Weight of Grease (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
G-5 (cont.)	Chlorophenyl methyl polysiloxane oil (Code O-10) with lithium soap thickener	Diffusion Pump	1	1 2	67 56	273	221 to 230	1×10^{-6} to 1×10^{-7}	2:44	153	Failed at 22,694 hr. In one bearing the grease had dried out and left a yellow-brown wax-like residue. The other bearing had a partially dried out black grease residue; its retainer was broken, the balls were out of the pockets, and the balls and races were badly worn. In addition to the running time of 22,694 hr, the bearings were also exposed to vacuum for 5,488 hr in a nonrotation condition; after each such period (including time up to 648 hr), the motors restarted satisfactorily.
									4:13	1,045	
									6:14	1,975	
									5:19	2,995	
									9:34	4,251	
									10:47	5,048	
									5:53	6,448	
									6:09	7,274	
									5:09	8,074	
									5:40	9,052	
									7:03	10,038	
									7:13	11,213	
									6:50	12,067	
									5:58	13,072	
									5:36	14,079	
									5:56	15,028	
									2:50	16,066	
									2:40	17,111	
									4:32	18,264	
									5:15	19,010	
									2:38	19,872	
									0:26	20,296	
									0:30	21,573	
									0:42	22,358	
		Diffusion Pump	1	1 2	54 56	277	290 to 300 (except for 682 hr at 145 to 190)	5×10^{-5} to 4×10^{-7}	3:02	153	Failed at 4,359 hr. Grease in both bearings had hardened to a wax-like consistency.
									3:07	1,053	
									3:59	1,985	
									1:40	3,004	
									1:45	4,264	

G-5 (cont.)	Chlorophenyl methyl polysiloxane oil (Code O-10) with lithium soap thickener	Ion Pump	1	1 2	70 75	274	180 to 190	2×10^{-8} to 7×10^{-9}	–	–	Test discontinued after 5,554 hr including 4,097 hr exposure to radiation from a cobalt 60 source. Total radiation received was 1.7×10^7 roentgens (±10%). Both bearings were in good condition.
		Ion Pump	1	1 2	76 80	274	150 to 165	2×10^{-8} to 3×10^{-9}	–	–	Bearing farther from source failed at 10,114 hr due to grease becoming a hard, dark mass. Bearing closer to source was in satisfactory condition with the grease slightly darkened and hardened. Test resumed with failed bearing replaced. Motor stalled and could not be restarted at 12,607 hr operating time in vacuum and 14,129 hr exposure to radiation [4.1×10^7 roentgens (±10%)] on bearing closer to source. Replacement bearing has 2,473 hr operating time and 5,272 hr exposure to radiation.
		Ion Pump	10		75 approximately; lubricant applied by vendor	275	150 to 200	3×10^{-7}	0:50 1:36 1:05	241 888 1,628	Stopped at 1,723 hr due to electrical malfunction that overheated the motor. Lubricant had begun to harden and the shields were distorted.
		Ion Pump	10		100 approximately; lubr[illegible]nt applied by vendor	270	1[illegible]0 to 270	3×10^{-7}	0:24 0:17	241 888	Stopped at 1,110 hr due to electrical mal[illegible]ction that overheated the motor, resulting in lubricant decomposition.
			1	1 2	75 84	274	90 to 100	760 (90% N_2-10% He)	1:26 1:54 2:04	147 1,108 4,052	Test discontinued at 4,652 hr. Both bearings were satisfactory with the grease unchanged.

Code	Lubricant	Vacuum System	Bearing		Initial Weight of Grease (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
			Type	Number							
G-5 (cont.)	Chlorophenyl methyl polysiloxane oil (Code O-10) with lithium soap thickener		5	1	73	272	90 to 95	760 (90% N_2-10% He)	1:30	147	Test discontinued at 6,462 hr. One bearing appeared satisfactory with the grease unchanged. In the second bearing the bulk of the grease appeared unchanged, but there was a build-up of fine, black material, some of which was magnetic, at the edges of the inner surface of the outer race.
				2	67				1:56	1,108	
									2:40	4,652	
G-6	Methylphenyl silicone oil with dye thickener (Meets MIL-G-25013 and MIL-G-27343)	Diffusion Pump	1	1	96	157	155 to 210	1×10^{-3} to 1×10^{-8}	0:34	2	Test discontinued at 20,147 hr. Both bearings were in good condition. There was little loss of grease and the grease had not hardened.
				2	84				2:20	163	
									2:36	953	
									1:55	2,013	
									3:33	2,912	
									5:10	4,063	
									4:49	5,071	
									3:58	6,064	
									4:20	6,902	
									4:43	7,200	
									3:43	8,264	
									6:28	9,224	
									6:46	9,993	
									9:50	11,193	
									6:17	11,986	
									6:19	13,194	
									8:36	14,036	
									2:16	14,997	
									3:15	16,049	
									4:10	17,229	
									4:10	18,093	
									4:05	19,310	
									5:02	19,882	

G-6 (cont.)	Methylphenyl silicone oil with dye thickener (Meets MIL-G-25013 and MIL-G-27343	Diffusion Pump	1	1 2	76 81	277	12,346 hr at 250 – rest at 130 to 160	8×10^{-7} to 2×10^{-7}	3:25 4:49 6:50 9:23 7:39 6:50 7:05 8:28 7:45 6:40 7:16 6:46 4:50 3:50 4:36 5:44 9:42	121 1,161 2,077 2,895 4,003 5,166 6,030 7,246 8,250 9,101 9,901 11,055 11,801 13,103 14,380 15,672 17,139	Still running satisfactorily after 18,844 hr. Test was discontinued after running 16,610 hr in vacuum, and motors were exposed to air for 8 months in a non-rotating condition before restarting in vacuum.
		Ion Pump	1	1 2	84 89	273	180 to 195	2×10^{-8} to 7×10^{-9}	–	–	Failed at 5,518 hr running time. Lubricant in bearing closer to source had become a dry sandy residue. Bearing farther from source appeared satisfactory with no apparent change in the grease. Exposure time to gamma radiation from a cobalt 60 source was 4,097 hr. Total dosage received was 1.7×10^{7} roentgens (± 10%).
G-7	Silicone oil with aryl substituted urea thickener (Meets MIL-G-25013)	Diffusion Pump	1	1 2	64 74	157	150 to 175	5×10^{-8} to 2×10^{-8}	2:41 2:23 2:25 3:01 2:50 2:59 3:00 3:34 4:45	139 1,059 2,048 3,019 4,641 6,319 7,010 7,440 14,682	Still running at 16,742 hr.

Code	Lubricant	Vacuum System	Bearing		Initial Weight of Grease (mg)	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
			Type	Number							
G-7 (cont.)	Silicone oil with aryl substituted urea thickener (Meets MIL-G-25013)	Diffusion Pump	1	1 2	93 71	158	130 to 170	5×10^{-8} to 2×10^{-8}	1:00	139	Still running after 16,749 hr.
									1:25	1,057	
									2:07	2,046	
									2:48	3,017	
									2:40	4,638	
									3:00	5,587	
									4:20	6,316	
									3:47	7,436	
									6:49	14,679	
G-8	Silicone oil with organic thickener and solid lubricant	Diffusion Pump	1	1 2	50 60	158	150 to 200	1×10^{-3} to 1×10^{-8}	2:33	162	Still running after 33,100 hr.
									4:03	719	
									5:53	1,130	
									6:35	1,970	
									7:43	2,954	
									6:20	4,085	
									6:35	5,045	
									6:08	6,150	
									5:34	7,014	
									4:59	8,043	
									5:24	9,062	
									5:31	10,088	
									5:25	10,988	
									4:47	11,943	
									4:22	13,121	
									4:38	14,128	
									4:40	15,137	
									4:51	16,086	
									5:17	14,165	
									5:23	18,074	
									5:70	19,045	
									5:78	20,188	
									4:43	20,991	
									5:20	21,939	
									5:36	23,056	
									5:33	23,788	
									5:24	31,030	

G-9	Aryl urea thickened high phenyl content methylphenyl silicone	Diffusion Pump	1	1	61	273	140 to 200	1×10^{-6} to 1×10^{-9}	1:53	688	Test stopped after 25,319 hr.
				2	67				2:28	1,481	
									2:32	2,085	
									3:10	2,947	
									3:31	3,933	
									4:00	5,206	
									4:05	6,683	
									3:57	8,026	
									9:06	8,957	
									3:57	10,018	
									3:41	10,961	
									4:24	11,992	
									4:47	13,358	
									4:56	14,503	
									5:17	15,681	
									5:37	16,736	
									4:10	17,695	
									4:05	18,721	
G-10	Ammeline thickened inhibited, high phenyl content silicone oil	Diffusion Pump	1	1	69	274	140 to 195	1×10^{-6} to 1×10^{-9}	3:28	667	Test stopped after 25,223 hr.
				2	79				4:54	1,480	
									1:55	2,082	
									1:43	2,943	
									1:25	4,050	
									2:52	5,207	
									2:54	6,694	
									3:52	8,037	
									2:55	9,184	
									1:50	10,040	
									2:10	11,242	
									3:35	12,015	
									2:35	13,380	
									1:50	14,525	
									2:40	15,703	
									2:57	16,759	
									2:47	17,718	
									3:00	18,744	
G-11	Silicone oil with organic thickener and solid lubricant	Diffusion Pump	1	1	50.7	158	150 to 200	5×10^{-8} to 1×10^{-8}	3:34	162	Failed at 12,889 hr. One bearing still satisfactory. In the other the grease began to harden and the bearing races were dry.
				2	47.3				3:00	1,184	
									2:46	1,999	
									4:09	3,004	
									3:22	4,110	
									5:15	5,148	
									3:46	5,949	
									3:39	7,187	
									3:50	7,957	
									2:58	9,025	
									3:29	9,965	
									4:11	11,064	
									4:42	12,093	
									5:10	12,717	

the grease. Finally, two tests on this grease have been conducted in an atmosphere of 90 percent nitrogen – 10 percent helium at one atmosphere pressure; both of these tests were discontinued after 4652 hours, with all bearings satisfactory and the grease unchanged. (The fine, black debris at the edges of the inner surface of the outer race of one of the bearings indicates fretting wear was occurring between the bearing and mounting, probably due to improper fitting.)

Two tests on grease G-6 have operated in vacuum without failure for more than two years, with a good portion of one test being at a temperature of 250°F. In a combined vacuum and radiation environment, this grease failed in 5518 hours (about 7.5 months) and a dose of about 1.7×10^7 roentgens, at which point the grease in one bearing had decomposed to a dry, sandy residue.

Grease G-1 is the only petroleum-base grease that has survived over one year in vacuum. Two tests with this grease were discontinued after 2063 and 2064 hours in vacuum, at which time the bearings were still operating satisfactorily, even though the grease had hardened to a wax-like consistency and coast-down times varied widely. A third test in vacuum was stopped after 13,362 hours due to motor whine. The bearings have not yet been examined to determine their condition, but there was a significant loss in their coast-down time after about 4 months of operation in vacuum. Two additional tests have been run in an atmosphere of 90 percent nitrogen – 10 percent helium; the bearings in both of these tests were still operating satisfactorily and the grease appeared unchanged when these tests were discontinued after 4652 and 4660 hours.

A single pair of bearings lubricated with diester grease meeting the MIL-G-3278 specification (G-15) failed after 3820 hours in vacuum. This is somewhat better than the lifetimes achieved with diester oils in vacuum, although the performance is again poorer than the silicone- or petroleum-base lubricants.

Most failures were due to loss of oil from the grease thickener resulting in clogging of the bearing. Figure 1-17 shows results of a failure of the Code G-5 grease. After 9612 hours of operation, the grease had darkened and hardened, as shown in the photograph, so that one bearing was frozen tight and the torque of the other had increased to two or three times its original value.

1.4 LUBRICATION WITH BONDED FILMS OF SOLID LUBRICANTS

1.4.1 Bonded Films

Tests have been completed on ball bearings lubricated with 10 different bonded films of solid lubricants, most of them containing molybdenum disulfide. Table 1-7 indicates the compositions of the films tested. [Three of these lubricants have also been tested under sliding friction conditions (Section 2).] Lifetimes in vacuum have ranged from as short as 7.8 hours to as long as 2554 hours (less than 3.5 months), except for one test that had additional lubrication from a Teflon retainer.

1.4.2 Equipment and Procedures

The experimental equipment and procedures used to evaluate bonded films of solid lubricants were similar to those described earlier for the tests with oils, with the following exceptions:

1. All bearings were of 440C stainless steel, deep-groove type, unshielded. Most of the bearings had steel, ribbon-type retainers, and a few of them had retainers of Synthane or Teflon.
2. The films were applied to the bearing parts by the film vendors, and the bearings were then assembled by the bearing manufacturer. The film was applied only to the races and retainers in some cases, to the races and balls in other cases, and to all parts in still other cases. The bearings were rough and tight before testing; to improve their performance, the bearings were operated back and forth slowly by hand and blown out with clean, dry gas. This hand operation was repeated several times. After the

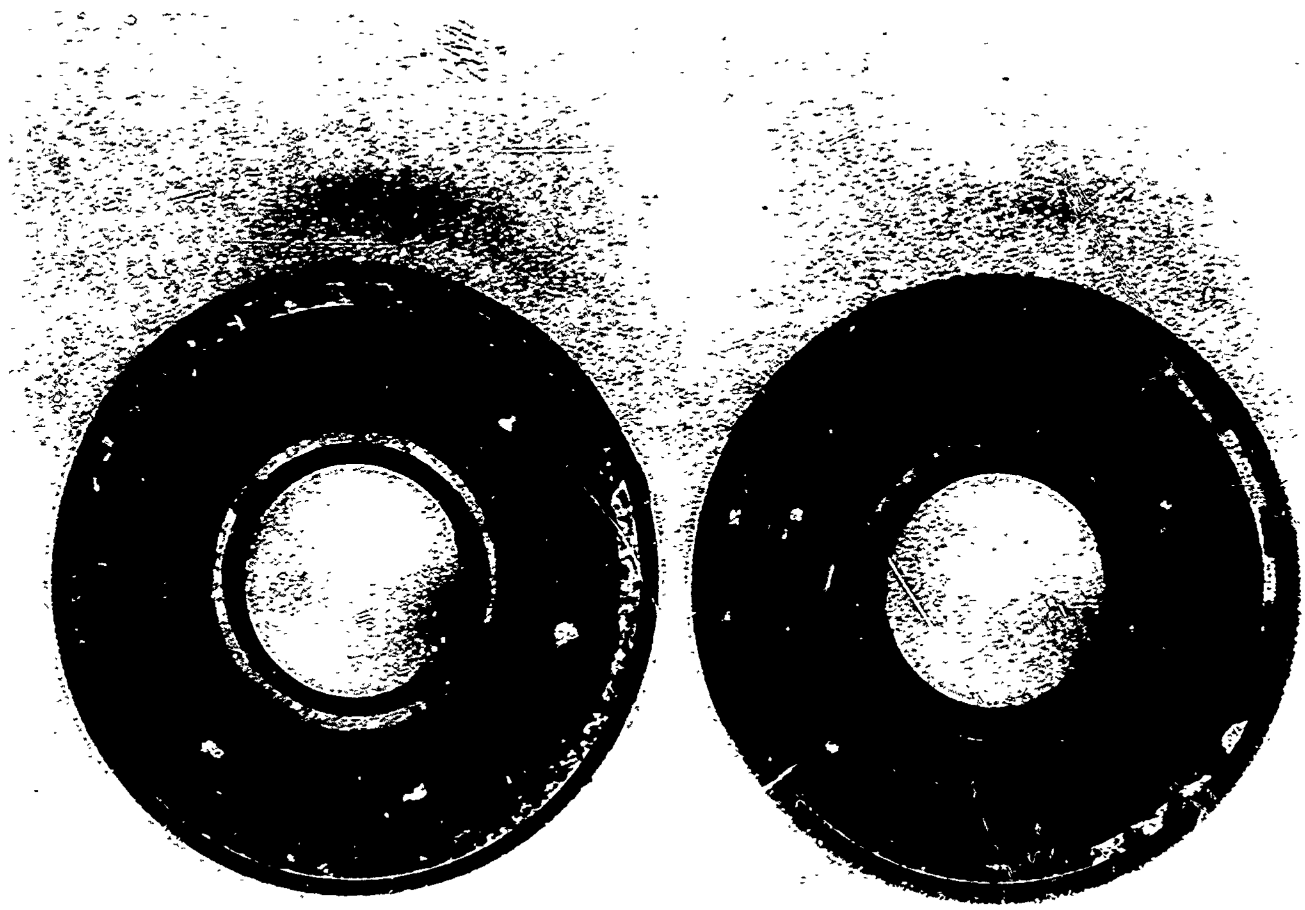


Fig. 1-17 Failed Grease-Lubricated Ball Bearing

Table 1-7

DRY FILM LUBRICANTS TESTED

Code	Description	Tested on Ball Bearings (Section 1)	Tested in Sliding Friction (Section 2)
S-1	Coating of molybdenum disulfide applied over silver matrix	yes	yes
S-2	Sodium silicate bonded molybdenum disulfide	yes	yes
S-3	Ceramic bonded molybdenum disulfide	no	yes
S-4	Molybdenum disulfide bonded by low temperature curing ceramic	yes	no
S-5	Molybdenum disulfide bonded by low temperature curing ceramic	yes	no
S-6	Silicone bonded molybdenum disulfide	no	yes
S-7	Epoxy bonded molybdenum disulfide	yes	no
S-8	Proprietary coating	yes	no
S-9	Molybdenum disulfide "soft" coating	yes	no
S-10	Molybdenum disulfide "hard" coating	yes	no
S-11	Proprietary molybdenum disulfide coating	no	yes
S-12	Plated molybdenum disulfide	no	yes
S-13	Molybdenum disulfide powder applied by burnishing	yes	no
S-14	Graphite applied by impingement process	yes	yes
S-15	Proprietary coating	no	yes

hand operation, the bearings were operated at 4 rpm for approximately 10 minutes. This low-rpm run-in operation was repeated several times until the bearing had run 30 to 60 minutes. The procedure was repeated at 8000 rpm for 20 to 30 minutes. After run-in, the bearings rotated smoothly with low torque.

3. Start-stop-reverse tests were conducted as well as unidirectional tests. In the start-stop-reverse tests, the bearings were operated on a cycle of 52 minutes at 8000 rpm in one direction, 8 minutes with the power off, then 52 minutes at 8000 rpm in the opposite direction, 8 minutes with the power off again, then repeat.
4. All tests were conducted in ion pumped systems.

1.4.3 Results and Discussion

Table 1-8 presents detailed results for the two bonded films that performed best on ball bearings, and Table 1-9 summarizes results obtained with the other films tested. The performances of the bonded solid films on instrument-size ball bearings have been relatively poor; these lubricants are characterized by short lifetimes and poor reproducibility.

Lubricant S-1 (a coating of molybdenum disulfide over a silver matrix) has given lifetimes over 1000 hours in vacuum, including start-stop-reverse conditions of testing, when applied to the races, retainers, and balls; when applied to the races and retainers only, lifetime in vacuum was reduced to 457 hours. Lifetimes with S-1 and with retainers of Teflon or Synthane are better than with steel, ribbon-type retainers, but not as good as achieved with the reinforced Teflon retainers alone (see Section 1.5). Operation in air has been better than in vacuum.

Lubricant S-2 (a coating of molybdenum disulfide bonded with sodium silicate) has given a lifetime of 2213 hours in vacuum (one test with 159-gram rotor, motor type 1), but generally its lifetimes have been considerably shorter and have varied unpredictably.

Table 1-8

TEST RESULTS FOR BEST PERFORMING DRY FILM LUBRICANTS

Code	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
S-1	Coating of molybdenum disulfide applied over silver matrix, applied to races, retainers, and balls	275	160 to 184	6×10^{-7} to 4×10^{-8}	30:27 7:42 8:20 2:50	144 693 1,366 1,533	Failed at 1,533 hr. One bearing had a broken retainer; second was still satisfactory.
		273	160 to 170	8×10^{-7} to 2×10^{-8}	15:11 5:54 3:06	214 379 1,054	Start-stop reverse test. One bearing failed with broken retainer at 1,080 hr. Bearing was replaced and test continued. Other original bearing failed at 1,198 hr, also with a broken retainer.
		273	95 to 120	760	9:19 9:02 8:04 9:00 7:57 7:56	213 1,043 1,998 2,584 2,989 3,922	Failed at 4,261 hr. One bearing had the retainer broken in several places; second bearing was satisfactory.
	Applied to races and and retainers only	275	150 to 170	6×10^{-7} to 2×10^{-7}	15:50	144	Failed at 457 hr. Retainer of one bearing broken; second was still satisfactory.

Table 1-8 (cont.)

Code	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
S-1 (cont.)	Applied to races and balls in a bearing with a modified Teflon retainer	270	137 to 145	2×10^{-6} to 2×10^{-7}	17:17	42	Discontinued test at 8,117 hr. Ball pockets of both retainers were badly worn.
					13:52	354	
					10:04	1,093	
					7:06	2,095	
					5:46	2,953	
					4:42	4,195	
					3:20	5,056	
					5:38	5,943	
					8:40	7,354	
					10:34	7,783	
		–	100 to 110	760	5:00	72	Still running at 11,425 hr.
					5:22	952	
					5:21	1,984	
					4:11	3,349	
					5:08	5,142	
					5:07	6,049	
					5:12	7,014	
					5:22	8,358	
					5:42	8,668	
		–	105 to 110	760	7:01	72	Still running at 11,470 hr.
					5:50	1,011	
					5:33	2,033	
					5:01	3,398	
					6:13	5,190	
					5:51	6,097	
					5:54	7,062	
					6:16	8,044	
					5:48	8,717	

Table 1-8 (cont.)

Code	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
S-1 (cont.)	Applied to races and balls in a bearing with paper-base phenolic retainers	275	137 to 143	2×10^{-6} to 7×10^{-7}	15:38 16:58 17:14 7:30 6:33	42 1,093 1,668 2,095 2,339	Failed at 2,554 hr. One bearing had the ball pockets of the retainer bandly worn and the retainer was broken in two places. No lubricant was visible on the balls or races. Second bearing had an intact retainer and lubricant left on the balls and races but was running roughly and had worn ball pockets.
		–	106 to 112	760	6:13 5:25 2:13 2:00	72 988 1,271 1,495	Failed at 1,639 hr. Retainer of one bearing broken in several places and ground apart. Retainer of second bearing was badly worn.
		–	106 to 112	760	8:02 7:16 6:45 6:17 5:57 5:57 6:23 6:35	72 1,011 2,043 3,003 5,300 6,808 8,012 8,827	Still running at 11,583 hr.
S-2	Sodium silicate bonded MoS_2 applied to races and retainers only, after grit blasting	159	160 to 180	8×10^{-6} to 9×10^{-8}	1:07 6:17 4:49 5:56 4:31	 771 1,419 2,021 2,181	Failed at 2,213 hr. Bearings were excessively worn and balls were forcing their way out of the retainer pockets. Final torque was excessive. Speed dropped to 7,000 rpm and temperature rose to 200°F at failure.

Table 1-8 (cont.)

Code	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
S-2 (cont.)	Sodium silicate bonded MoS_2 applied to races and retainers only, after grit blasting	162	100 to 180	6×10^{-6} to 1×10^{-7}	–	–	Test stopped at 876 hr. One original bearing still good, the other failed at 238 hr; replacement failed after 174 hr.
		275	170 to 200	8×10^{-7} to 2×10^{-7}	11:37	167	Failed at 245 hr (start-stop-reverse test). Balls in one bearing jammed and broke the retainer; other bearing was still satisfactory.
		159	140 to 185	2×10^{-6} to 2×10^{-7}	6:53 5:18 2:41 3:0	82 223 391 726	Failed at 772 hr (start-stop-reverse test). One bearing frozen by wear debris, second bearing had slight increase in torque but ran rough due to wear debris in raceway.
		275	RT to 172	5×10^{-6} to 9×10^{-8}	7:43 6:43	61 231	Failed at 343 hr. One bearing had broken retainer; second was satisfactory.
		274	RT to 122	760	–	–	One bearing failed at 132 hr; its replacement failed after 114 hr. Other bearing failed at 246 hr. All 3 failures were due to broken retainers.

Table 1-8 (cont.)

Code	Lubricant	Rotor Weight (gm)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
S-2 (cont.)	Applied to races and retainers after special pretreatment	157	160 to 170	8×10^{-6} to 8×10^{-7}	5:14 3:39 4:21 3:56	56 753 1,232 1,761	One bearing failed at 1,862 hr with a broken retainer; the other was still satisfactory.
		158	RT to 140	760 to 2×10^{-7}	–	–	One bearing failed at 28 hr due to a freeze-up; the other was still in good condition.
		157	150 to 158	8×10^{-6} to 8×10^{-7}	4:14 6:50 4:30	56 656 1,664	Failed at 1,796 hr. One bearing completely failed, second bearing was running rough.
		157	150	10^{-3} to 2×10^{-7}	–	–	Failed at 25 hr; one bearing froze-up, second bearing still in fair condition.
	Applied to the races, retainers and balls after special pretreatment	275	180 to 190	3×10^{-3} to 2×10^{-7}	9:41	226	One bearing failed at 483 hr, second bearing satisfactory.
		269	180 to 200	3×10^{-3} to 4×10^{-7}	21:29	225	Failed at 296 hr; both bearings froze up.

Table 1-9

TEST RESULTS FOR DRY FILM LUBRICANTS THAT GAVE LIMITED PERFORMANCE ON BALL BEARINGS

Code	Material	Lifetime (hr)
S-4	Molybdenum disulfide bonded with low temperature ceramic to races and retainers	135
	Bonded to races, retainers, and balls	29
S-5	Molybdenum disulfide bonded with low temperature ceramic to races and retainers	157
	Bonded to races, retainers, and balls	27
S-7	Epoxy bonded molybdenum disulfide applied to races and retainers	One bearing failed at 308 hr; second at 467 hr
		771 hr (start-stop-reverse test)
		88
	Applied after special surface treatment	305 (start-stop-reverse test)
S-8	Proprietary coating applied to races and retainers	One bearing failed at 166 hr; second satisfactory
	Applied to races, retainers, and balls	209
S-9	Molybdenum disulfide "soft" coating applied to races and retainers	230
	F-7 applied to races, retainers, and balls	213
S-10	Molybdenum disulfide "hard" coating applied to races and retainers	296
S-13	F-8 applied to races, retainers, and balls	220
S-14	Graphite applied to races and retainers by impingement process	One bearing failed at 8 hr; second at 670 hr
		10 (start-stop-reverse test)
		88

Failures with bonded solid films have been due primarily to wear-through of the film and to the resultant wear of the retainer and enlargement of the ball pocket. In some cases the retainers have broken and, in a few cases, the balls have come out of the retainers. Figure 1-18 illustrates a typical failure of bearings lubricated by applications of S-1 to the races, retainers, and balls. Failure occurred at 1533 hours, and the split retainer and shiny races and balls indicate wear-through of the film. The other bearing was in satisfactory condition and could have continued in operation.

1.5 SPECIAL RETAINER MATERIALS

1.5.1 Materials

Ten different special retainer materials have been tested for use with ball bearings under vacuum conditions; these include both reinforced plastics and powder metal composites, some inherently self-lubricating and others impregnated with oil to make them self-lubricating. Tables 1-10 and 1-11 indicate the materials tested, along with the test results.

1.5.2 Equipment and Procedures

The experimental equipment and procedures used to evaluate the special retainer materials were similar to those described earlier for the tests with oils, with the following exceptions:

1. All bearing were of the angular contact type and had machined, single-piece retainers of the special materials. Bearing races and balls were of 440C stainless steel, and both double shielded and unshielded bearings were used. Bearing size was R-3 as before. There was no run-in before testing.
2. All bearings were tested in the second type of motor, with radial loads applied by the rotor weight of 275 grams. Axial load was varied from zero to one pound by means of cupped washers inserted in the bearing housings.
3. All tests were conducted in ion-pumped systems.
4. Start-stop-reverse tests, similar to those with bonded molybdenum disulfide films were conducted as well as unidirectional tests.

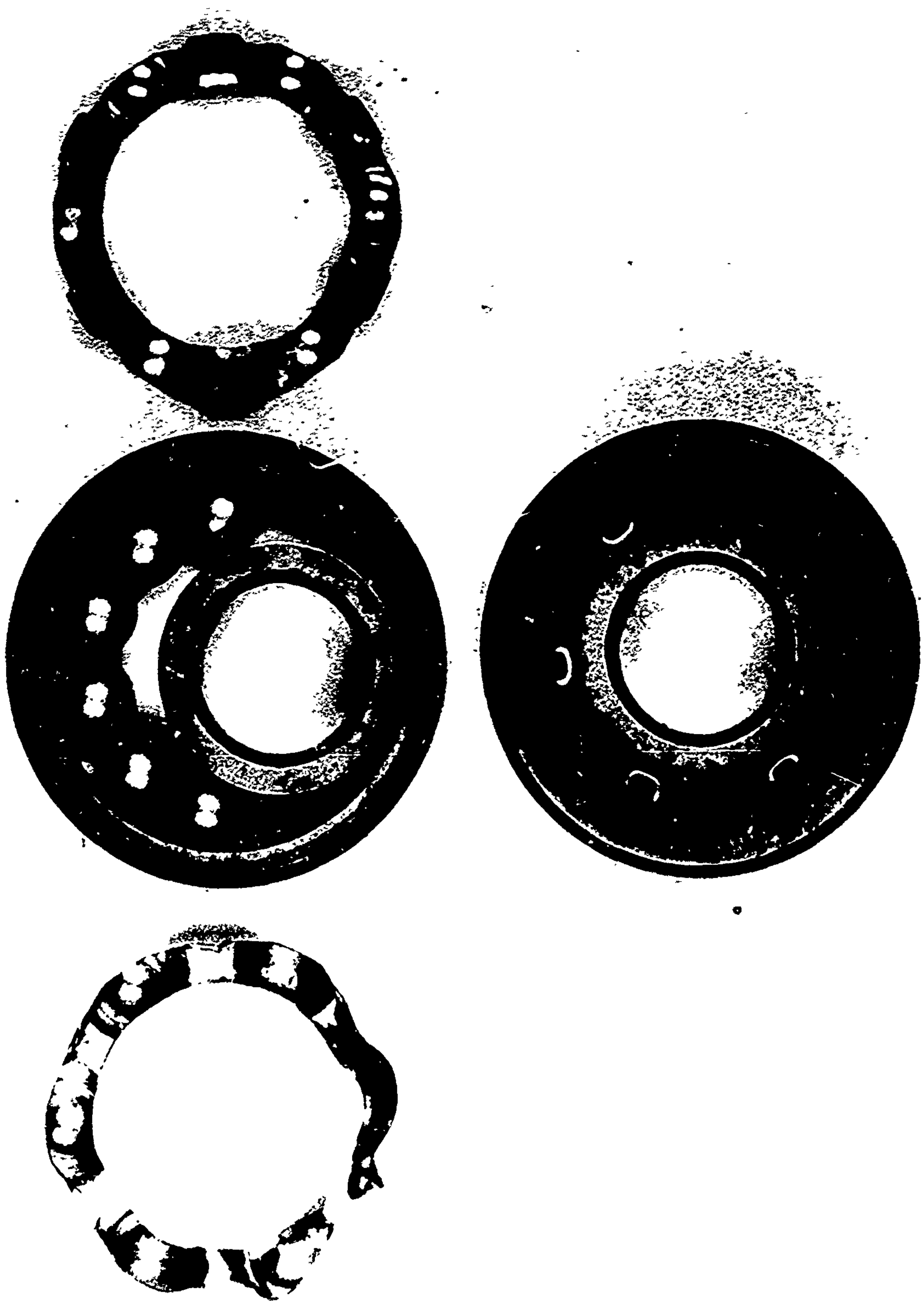


Fig. 1-18 Failed Dry Film-Lubricated Ball Bearing

Table 1-10

TEST RESULTS WITH BEST-PERFORMING SPECIAL RETAINER MATERIAL

(Material code R-1, reinforced Teflon; all tests conducted with machined retainers of R-1 material in angular contact ball bearings with balls and races of 440C stainless steel; bearings were installed in motors with 274-gram average weight rotors)

Axial Thrust Load (lb)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
1/4	125 to 210	4×10^{-7} to 2×10^{-8}	2:35	62	Discontinued at 12,636 hr. Ball pockets of both retainers were worn oval with a build-up of wear debris at edge of ball pocket.
			3:17	400	
			3:35	843	
			4:09	2,007	
			2:26	3,324	
			2:09	4,320	
			2:40	5,137	
			3:10	6,091	
			3:00	7,121	
			3:40	8,084	
			3:43	9,115	
			5:17	10,414	
			5:28	12,108	
			4:51	12,636	
1/4	125 to 180	5×10^{-7} to 6×10^{-8}	1:39	214	Failed at 8,624 hr (start-stop-reverse test). Ball pockets of both bearing retainers worn oval. Wear debris from the retainer apparently jammed the bearings. Bearing restarted in vacuum satisfactorily several times after being held in a non-rotating condition for periods up to 3 weeks.
			1:46	1,220	
			3:02	1,491	
			4:33	2,378	
			15:38	3,930	
			10:36	4,195	
			3:50	4,434	
			3:45	5,466	
			3:25	6,831	
			2:44	7,977	
No load for first 518 hr; 1 lb for remainder of test (2,662 hr)	145 to 170	4×10^{-6} to 6×10^{-8}	18:25	279	Failed at 3,180 hr. Ball pockets of both retainers worn oval.
			21:30	446	
			8:42	547	
			3:01	835	
			8:44	1,355	
			11:28	2,311	
			8:42	2,863	
			2:18	3,150	

Table 1-10 (cont.)

Axial Thrust Load (lb)	Bearing Housing Temperature (°F)	Pressure (Torr)	Coast Time (min:sec)	Elapsed Test Time (hr)	Results
1/4	90 to 140	760	1:12	212	Test discontinued after 30,050 hr with both bearings still in operable condition. Ball pockets of retainers were enlarged but not broken. Motor was filled with wear debris from the retainer.
			1:39	1,042	
			2:12	2,052	
			2:57	2,946	
			4:18	4,358	
			3:20	5,123	
			2:41	6,091	
			3:55	7,004	
			4:23	7,960	
			2:55	8,465	
			4:07	13,011	
			4:45	14,210	
			4:43	15,270	
			5:36	16,347	
			5:42	18,142	
			5:23	19,870	
			5:14	21,666	
			5:09	22,775	
			4:49	28,776	
1/2	130 to 145	1×10^{-7} to 3×10^{-8}	6:15	209	Failed at 10,771 hr. One retainer had several ball pockets worn into one another and the retainer was broken in two places. Second retainer was similar to the test at 1/4 above with the ball pockets worn slightly more.
			5:55	1,045	
			4:48	2,047	
			4:03	3,049	
			4:08	4,194	
			3:49	5,034	
			3:26	6,164	
			4:03	7,097	
			2:30	7,963	
			2:31	9,004	
			2:25	10,051	
			0:24	10,698	
1	125 to 140	1×10^{-7} to 3×10^{-8}	0:43	209	Discontinued at 11,248 hr. Retainers of both bearings were worn oval with a build-up of wear debris at the edges of the ball pockets.
			6:28	568	
			4:00	1,044	
			7:13	1,885	
			11:50	2,046	
			5:18	2,881	
			4:15	3,697	
			4:22	4,673	
			4:15	5,704	
			3:34	6,667	
			3:47	7,697	
			5:10	9,021	
			4:55	10,721	
			4:08	11,248	

Table 1-11

TEST RESULTS WITH RETAINERS THAT GAVE LIMITED PERFORMANCE

Code	Retainer Material	Axial Thrust Load (lb)	Lifetime (hr)
R-2	60% Teflon, 40% glass fibers with molybdenum disulfide filler	1	28
		1/2	62
		1/4	5,110
		1/4	67
		1/4	90 (reversal test with 90 reversals)
		1/4	18,842 (test in air)
R-3	Sintered nylon containing molybdenum disulfide	1/4	43
		1	27
R-4	Micro-porous sintered nylon impregnated with chlorophenyl methyl polysiloxane oil (code 0-10)	1	160
		1	331
R-5	Porous plastic impregnated with silicone oil	none	229
R-6	Aromatic polyimide	none	136
R-7	Epoxy-molybdenum disulfide	1/4	1,332
		1/2	738
R-8	Pressed porous graphite impregnated with silver	1/4	141
R-9	55% sintered bronze, 27% Teflon and 18% molybdenum disulfide	1/4	2,727
		1/4	478 (test in air)
R-10	50% bronze, 50% molybdenum disulfide	1/4	2,692
		1/4	140 (test in air)

1.5.3 Results and Discussion

Table 1-10 presents detailed results for the best performing special retainer material Code R-1, a reinforced Teflon composite. Table 1-11 summarizes results for the other nine special retainer materials.

Code R-1 retainers have consistently given lifetimes in excess of 8,000 hours at axial preloads below 1 pound. Two tests with 1-pound preloads gave lifetimes of 3,180 and 11,248 hours. Failures have been due to wear of the ball pockets resulting in enlargement of the pockets, jamming of wear particles between bearing parts, and sometimes breaking of the retainer. Figure 1-19 shows the failure of the Code R-1 retainers after 3,180 hours; the enlargement of the ball pockets and a crack between two pockets can be seen.

Results with Code R-2 (Table 1-10) indicate that failures are accelerated by increases in the amount of axial preload.

Figure 1-20 shows a failure of retainers of a sintered nylon containing molybdenum disulfide (R-3), which failed after only 27 hours. Both of these retainers are broken, as can be seen in the photograph.

Generally, it appears that the performance of all of the special retainer materials tested is limited by wear resistance and strength, even for materials that have low coefficients of friction.

1.6 CONCLUSIONS AND RECOMMENDATIONS

General conclusions reached from the studies conducted on the performance of ball bearings in vacuum and combined space environments include the following:

- Operation in vacuum can drastically reduce lubricant lifetime below that obtained for operation in air. In order to operate equipment in space for long period, the mechanisms must be housed in pressurized and sealed

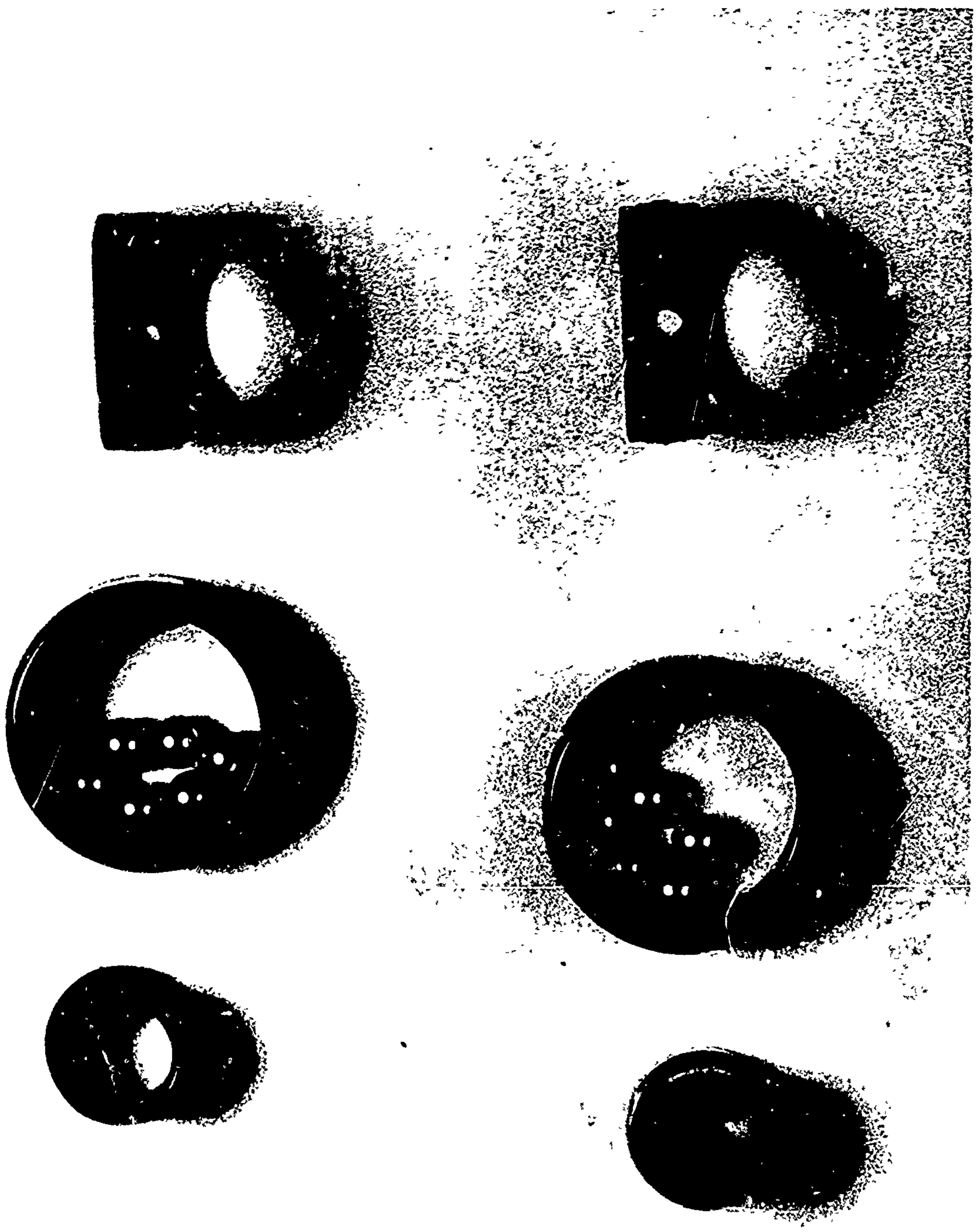


Fig. 1-19 Failed Bearings With Retainers of Reinforced Teflon

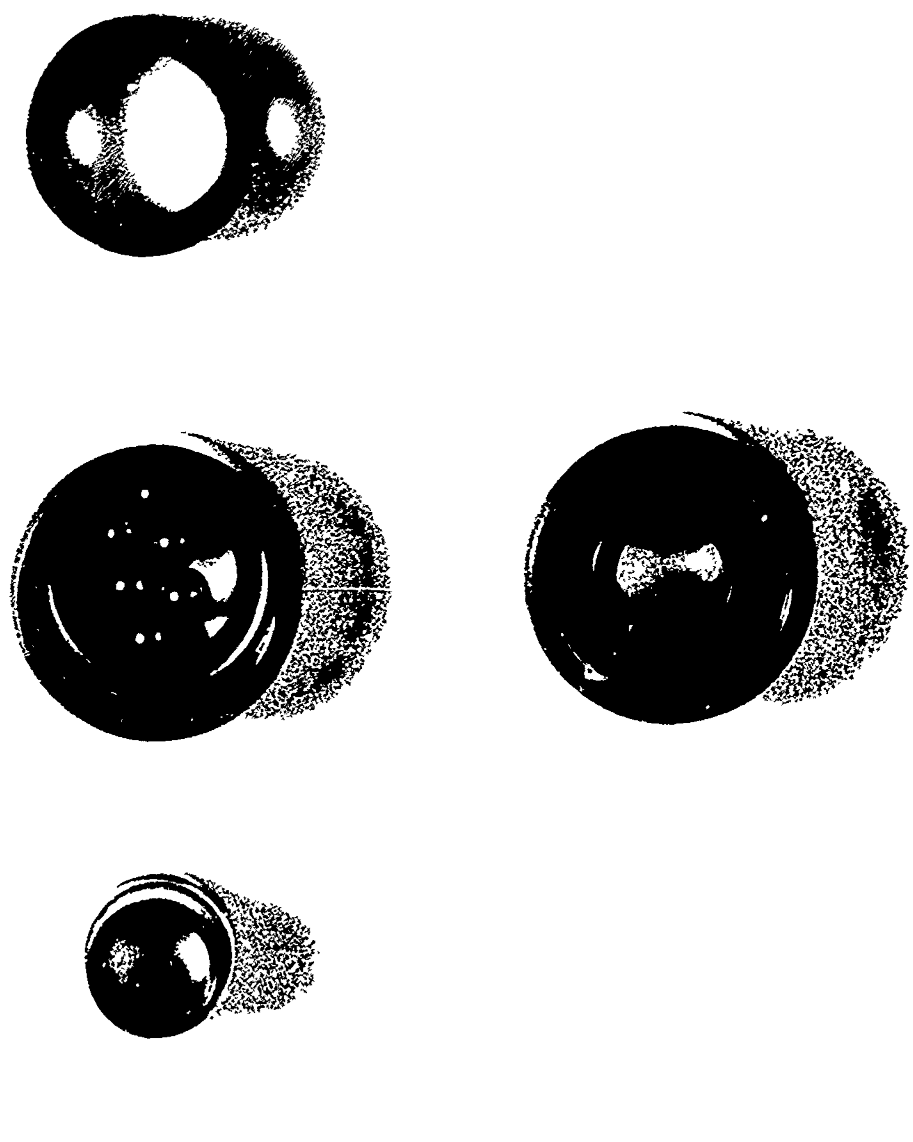


Fig. 1-20 Failed Bearings With Retainers of Sintered Nylon Plus MoS_2

units, some means of lubricant replenishment must be provided, or the lubricants must be carefully selected from those that have demonstrated satisfactory operation in vacuum.

- Oils and greases provide the best type of lubrication for ball bearings exposed to vacuum. Special considerations that may favor other types of lubricants (e.g., molybdenum disulfide films and reinforced Teflon) include cryogenic temperatures, high temperatures, and excessive exposure to nuclear radiation.
- Selected oils and greases have demonstrated lifetimes in vacuum of 3 years, and more, under the conditions noted above. They have also demonstrated lifetimes in vacuum of over 15 months when exposed simultaneously to a dose of 10^7 r of gamma radiation from a Cobalt 60 source.
- Generally, ball bearing lifetime with oil lubrication increased with viscosity, and the increase was most pronounced at low viscosities. The use of oils with extremely high viscosities is limited, however, by excessive bearing torque and inability to operate a low temperatures. Oils with room-temperature viscosities of 50 to 250 centistokes appear most useful for providing both long lifetimes and good torque characteristics.
- Ball bearings with retainers of reinforced Teflon, a self-lubricating material, have operated successfully in vacuum for over 10,000 hours provided that bearing loads were light. Bonded solid film lubricants have given shorter lifetimes and generally poor reproducibility of results, although under good conditions they have given lifetimes up to 3 months under the same conditions as above.
- Bearing failures have been preceded by lubricant failures. With oils, the lubricant failure has been due to the partial or complete loss and decomposition of the lubricant followed by rapid wear; with greases, to the drying out of the greases and stoppage of the bearings by the hard, soapy residue; with bonded films of solid lubricants, to wear through of the films followed by rapid wear and jamming; and with reinforced Teflon retainers, to excessive wear of the ball pockets.

Future studies are recommended in the following three general areas:

1. Screening of promising lubricants should be continued under simulated space conditions to establish the ability of the lubricants to meet the requirements of satellite systems, such as those used for communication and navigational purposes, in which lifetimes are more extended than in present satellite systems. Where preliminary screening has established the feasibility of long-time lubrication with selected lubricants, replicate tests should be conducted to establish the reliability of the results.
2. The effects of service conditions on performance should be evaluated more thoroughly. Future work should extend testing to a wider range of loads, speeds, temperatures, and amounts of oil or grease lubricant and should derive statistical correlations between these variables and the lifetimes or other performance specifications. The practical value of this work would include (1) developing techniques for predicting mean-times-to-failure and reliability for a recommended lubricant under specific service conditions and (2) developing techniques for accelerated testing (i.e., using results from short-time tests at one set of conditions to predict long-time behavior at other conditions).
3. The fundamentals of lubrication under space conditions and of the lubricant properties that are important for these conditions should be studied more thoroughly. Correlations between lubricant viscosity and lifetime should be refined, for example, so that the location of a particular lubricant in the scatter-band of this type of correlation can be defined more exactly from additional properties of the lubricant that can be measured in simple laboratory tests.

Section 2

BONDED SOLID FILM LUBRICANTS UNDER SLIDING FRICTION

2.1 SCOPE

Tests have been conducted to evaluate the performance of various bonded solid film lubricants under conditions of sliding friction in air.

2.2 MATERIALS

Table 2-1 lists the materials tested and their characteristics. These materials were applied to the outer surface of the Timken test rings.

2.3 EQUIPMENT AND PROCEDURES

All tests were conducted in an Alpha-Molykote Model LFW-1 tester according to Technique 46 of the Coordinating Research Council. Figure 2-1 is an overall view of the tester, and Figure 2-2 shows the test pieces in detail.

The test pieces include a block (0.625-in. × 0.375-in. × 0.250-in.) of Starrett No. 496 oil-hardening steel, which has been hardened to Rockwell C57-60 and finished to 6-12 microinches, RMS. The block is drilled for inserting a thermocouple to measure temperatures during testing. The block is held stationary against a rotating ring (1.375 inches diameter) of SAE 4620 steel, which has been hardened to Rockwell C58-63 and finished to 15 microinches, RMS. The solid film lubricant is coated on the outer surface of the ring, and the block is usually uncoated.

Table 2-1

RESULTS OF SLIDING FRICTION TESTS

Code	Lubricant	Coefficient of Friction	Test Temperature (°F)	Lifetime (hr: min)
S-1	Molybdenum disulfide applied over silver matrix	0.010 to 0.016	120 to 140	36:22
		0.010 to 0.016	120 to 140	39:18
		0.010 to 0.016	135 to 145	36:35
		0.011 to 0.016	138 to 147	29:07
	average	0.010 to 0.016	128 to 143	35:20
S-2	Ceramic bonded molybdenum disulfide	0.019 to 0.035	145 to 160	31:00
		0.021 to 0.032	150 to 170	37:10
		0.019 to 0.034	150 to 165	35:35
		0.021 to 0.038	150 to 165	33:45
		0.022 to 0.032	157 to 167	38:19
	average	0.020 to 0.034	150 to 165	35:08
S-3	Ceramic bonded molybdenum disulfide	0.016 to 0.024	150 to 175	9:06
		0.016 to 0.024	150 to 185	10:30
		0.016 to 0.032	150 to 190	12:00
		0.021 to 0.028	160 to 175	13:05
	average	0.017 to 0.027	153 to 181	11:02
S-6	Silicone bonded molybdenum disulfide	0.016 to 0.024	145 to 150	4:50
		0.016 to 0.024	155 to 165	6:19
		0.016 to 0.024	150 to 160	8:20
		0.010 to 0.024	160 to 170	4:48
	average	0.015 to 0.024	153 to 161	6:04
S-11	Proprietary molybdenum disulfide coating applied over phosphated mild steel	0.011 to 0.014	135 to 145	24:05
		0.014 to 0.017	135 to 150	36:09
		0.009 to 0.011	135 to 140	18:55
		0.014 to 0.017	140 to 150	13:04
	average	0.012 to 0.015	136 to 146	23:03

Table 2-1 (cont.)

Code	Lubricant	Coefficient of Friction	Test Temperature (°F)	Lifetime (hr: min)
S-11	Proprietary molybdenum disulfide coating applied over 17-4 steel[a]	0.011 to 0.017	135 to 145	12:37[a]
		0.011 to 0.016	130 to 140	11:14[a]
		0.013 to 0.017	140 to 145	9:34[a]
	average	0.013 to 0.017	135 to 143	14:28
S-12	Plated molybdenum disulfide	0.022 to 0.025	155 to 160	25:20
		0.019 to 0.024	150 to 160	22:24
		0.020 to 0.024	150 to 165	25:17
		0.019 to 0.025	140 to 160	19:54
	average	0.020 to 0.025	149 to 161	23:14
S-12	Plated molybdenum disulfide, improved process	0.019 to 0.024	140 to 150	20:31
		0.017 to 0.025	140 to 160	12:10
		0.019 to 0.022	140 to 150	20:16
		0.019 to 0.030	145 to 160	11:52
	average	0.019 to 0.025	141 to 155	16:02
S-14	Bonded graphite applied by impingement process	(b)	(b)	00:06
		(b)	(b)	00:09
	average			00:08
S-15	Proprietary thin dry film	(b)	(b)	0:02
		(b)	(b)	0:03
	average			0:02
S-15	Above coating applied to both block and ring	(b)	(b)	0:02
		(b)	(b)	0:02
	average			0:02

(a) Test rings were supplied by lubricant vendor. They were out of round and did not mate with test block, so results have been compromised.
(b) Test too short to determine value.

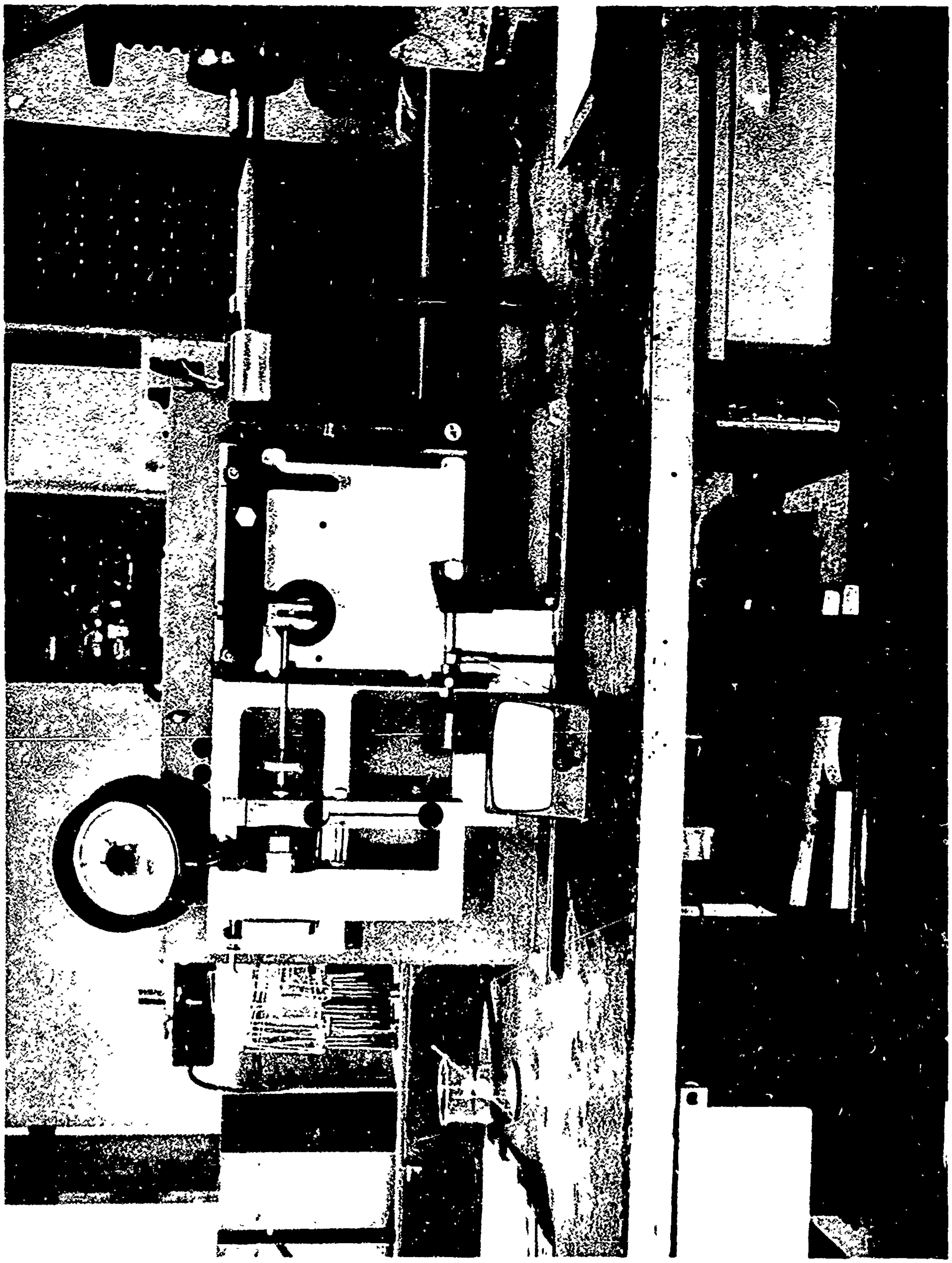


Fig. 2-1 Alpha-Molykote Model LFW-1 Lubricant Tester

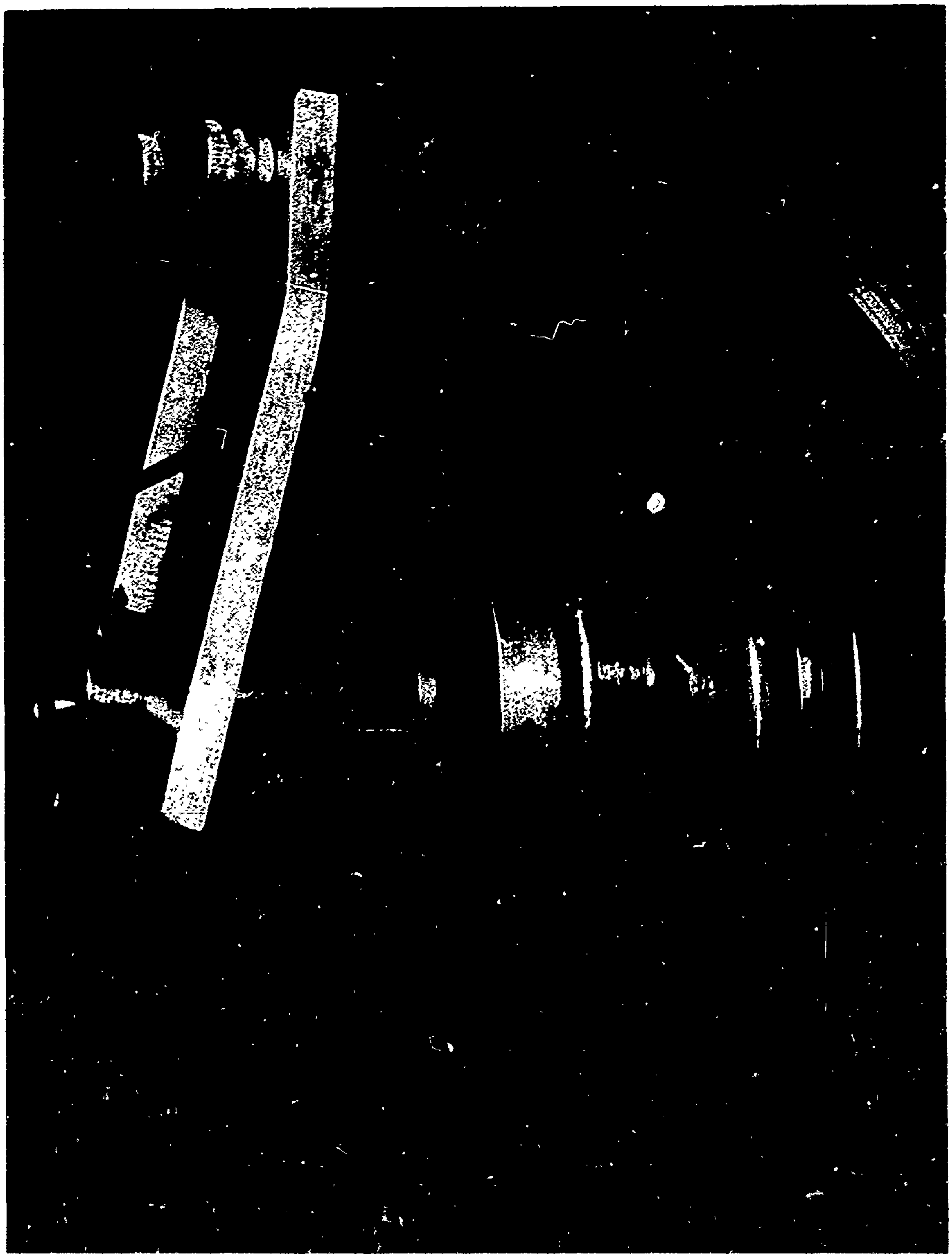


Fig. 2-2 Test Specimen Mounted in Alpha-Molykote Tester

The test ring rotates at a speed of 72 rpm, which gives a surface sliding speed of 25 feet per minute, and the load is increased according to the following schedule (CRC Technique 46):

Time (Minutes)	Specimen Load (Pounds)
0 to 1	30
1 to 2	120
2 to 3	210
3 to 4	300
4 to 5	390
5 to 6	480
6 to 7	510
7 to 8	540
8 to 9	570
9 to 10	600
10 to end of test	630

Failure occurs, and the test is ended, when the coefficient of friction increases to 0.10.

2.4 RESULTS AND DISCUSSION

Table 2-1 gives test results. It is worth noting that the Code S-1 lubricant not only gave the best performance of those tested under conditions of sliding friction (i.e., lowest coefficient of friction and longest lifetime) but that this lubricant also gave the best results on ball bearings.

Although thin films applied by impingement methods were very poor under these test conditions, they are known to be effective under other test conditions where contact stresses are less severe.

Appendix A
FRICTION AND ADHESION OF METALS

The purpose of this appendix is to discuss the friction and adhesion of metals, with special reference to cold welding under the vacuum conditions of space.

A.1 VACUUM CONDITIONS IN SPACE

Figure A-1 summarizes pertinent facts about the variation of pressure and related quantities with altitude. For orientation, two reference points are indicated on the top scale – towards the left-hand side is indicated the apogee of Sputnik I (approximately 560 miles, or 3 million feet), and at the right-hand side is sea level (zero altitude).

The second scale from the top in Figure A-1 indicates the pressure in either torr or millimeters of mercury, which are the units that are generally used to express pressures below one atmosphere. For all practical purposes, the units of torr and millimeters of mercury are identical.*

Quantities that are related to pressure and that are important to friction and cold welding in space are indicated on the lower four scales of Figure A-1. The first of these scales indicates the number of molecules in one cubic centimeter, and the scale immediately below it indicates the mean free path, which is the average distance that an atom or molecule will travel before colliding with another atom or molecule. At the altitudes at which spacecraft will operate, the mean free path is on the order of

*A pressure of 1 mm Hg is defined as a pressure sufficient to support a column of mercury exactly 1 mm high at 0°C (32°F) and under standard gravitational acceleration. A pressure of 1 torr is defined as 1/760-th of one standard atmosphere. Since the standard atmosphere is not quite exactly equal to the normal atmosphere of 760 mm Hg, there is a discrepancy of about 1 part per million between 1 mm of mercury and 1 torr.

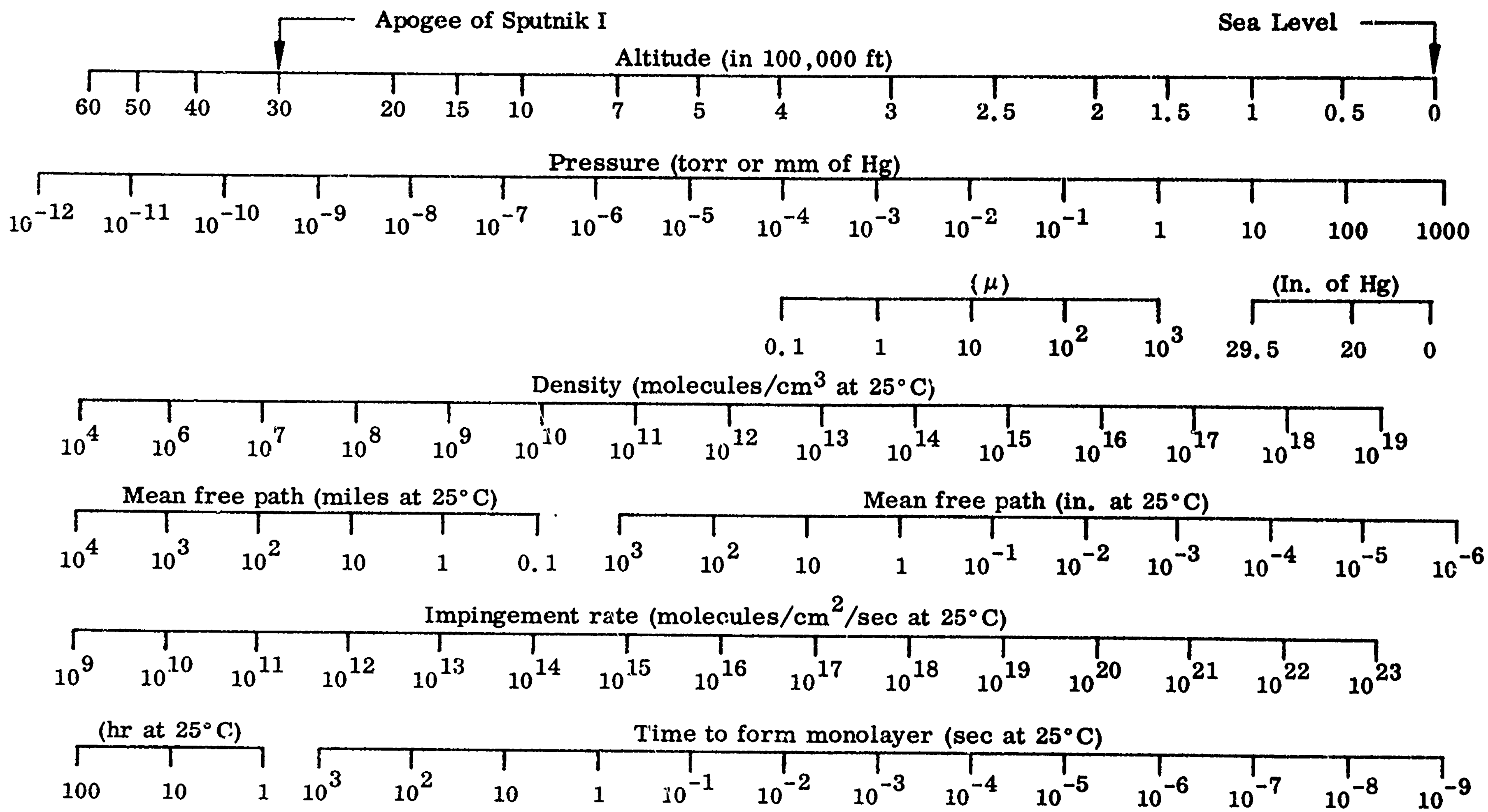


Fig. A-1 Variation of Pressure and Related Quantities With Altitude miles, and more, even though there are still millions of molecules per cubic centimeter. The consequences of the large mean free path in space are that (1) radiation is the only means of heat transfer to and from a body, so that power losses in equipment and frictional heating are not as easily dissipated as in the normal atmosphere, and (2) evaporation and sublimation are more rapid, so that conventional lubricants such as oils and greases are more subject to evaporation losses.

Two other important quantities are indicated on the lower scale in Figure A-1. These are the impingement rate, or the number of molecules that strikes each square centimeter of surface area per second (based on gas molecules having a molecular weight of 28) and the theoretical monolayer time, or the time that it would take to form a surface film one atom or molecule thick (based on the fact that it takes about 5×10^{14} molecules per square centimeter to form a monolayer and assuming that every molecule that strikes the surface is adsorbed). Since the sticking probability of molecules that strike a surface is less than one, the actual time to form a monolayer will be somewhat greater than the theoretical monolayer time indicated in Figure A-1. The important point is that once contaminating films that are present in the normal atmosphere on earth are removed in space, several hours are necessary to form new films. A number of research studies, such as those reviewed in the following section of this report, indicate that when contaminating films are removed from metal surfaces, the metal parts can weld together with strengths that approach those of the parent metals. This is the problem of cold welding that must be overcome for space operation.

While it is true that many spacecraft items, such as horizon sensors and gyroscopes, can be sealed from the space environment so that they are not required to operate in a vacuum, surfaces at or near the outsides of space vehicles are not so easily sealed from the vacuum of space. Mechanisms such as solar array orientation devices, louvers for active thermal-control systems, and docking surfaces of manned spacecraft can involve contact of surfaces that are well exposed to space. Where such surfaces come into contact with one another, the avoidance of their cold welding together requires a selection of materials that have minimum tendencies for cold welding and avoiding conditions of loading and sliding across the interfaces that promote cold welding.

A.2 FRICTON AND ADHESION OF METALS

Early workers ascribed the friction of two solids sliding over one another as due to the interlocking of surface irregularities, and the frictional work to the energy dissipated in raising one set of surface roughnesses over the other. It was believed that the function of a lubricating film was to fill in the "valleys" and form smooth surfaces so that the hard bodies could not come into contact with one another, interlock, and thus cause friction.

The more modern theories of boundary lubrication interpret frictional resistance as the net result of the effects of two concurrent conditions, namely, the shearing of welded junctions formed between points of contact and the ploughing out of the softer material to an appreciable depth below the surface by the harder material's riding over it. For hard materials in contact with one another, analysis indicates that the ploughing term is relatively small and that friction is largely due to the shearing of the welded junctions. Experiments indicate that there is a one-to-one correspondence between coefficients of friction and coefficients of adhesion (Ref. A.1).

Three important points in the adhesion theory of friction and wear (or the welded junction theory) are as follows:

- The area of true contact is only a small fraction of the apparent contact area.
- High localized temperatures are generated at the points of contact by frictional heating.
- The two surfaces interact with each other.

Area of true contact. When clean metal surfaces are placed together, they touch only where their asperities or high spots meet, and their real area of contact is much smaller than the apparent area. The greater the force pressing the surfaces together, the more the asperities are crushed down and suffer plastic deformation. This action increases both the number and size of the contacts involved in supporting the load so that the area of real contact increases. For example, two flat surfaces of hard steel with a yield strength of 150,000 psi would have a true contact area of only 0.001 percent of the apparent contact area under a normal pressure of 1.5 psi and would have a true contact area of 0.1 percent of the apparent contact area under a normal pressure of 150 psi.

Surface temperatures of rubbing solids. When solids slide over one another, high surface temperatures are generated even under moderate conditions of load and speed. The high temperatures are confined to very thin surface layers at the contacting points and are of very brief duration. For example, for a constantan cylinder sliding on a steel surface under a load of 4.1 pounds and a sliding speed of 120 inches/second, temperature flashes of 1000°C (1832°F) were measured that lasted for less than 10^{-4} second (Ref. A.2).

Surface temperatures produced by frictional heating increase with the sliding speed and the load. The poorer the thermal conductivity of the materials, the higher the temperatures that are generated. Even under the most severe conditions, however, surface temperatures cannot generally exceed the melting point of the bodies.

Local heating has an important effect on a number of surface phenomena, including the abrasion and seizure of metals, the deterioration of lubricating films, volatilization and decomposition of oils and other surface films, "frictional welding," and the initiation of chemical reactions and chemical decomposition under friction and impact.

Interaction of surfaces. Sliding between metal surfaces is not a continuous, smooth process but often proceeds in a series of starts and stops. The friction rises to a maximum during the "stick" and falls rapidly during the "slip," and there are corresponding changes in the area of contact and the surface temperature. Experiments indicate that, under the intense pressure acting at the summits of the surface irregularities, localized adhesion or welding between the metal surface takes place. The metallic junctions that are formed must be sheared if the surfaces are to slide past one another, and the force required to shear the junctions and permit sliding is proportional to the product of the shear strength of the junctions and the area of real contact.

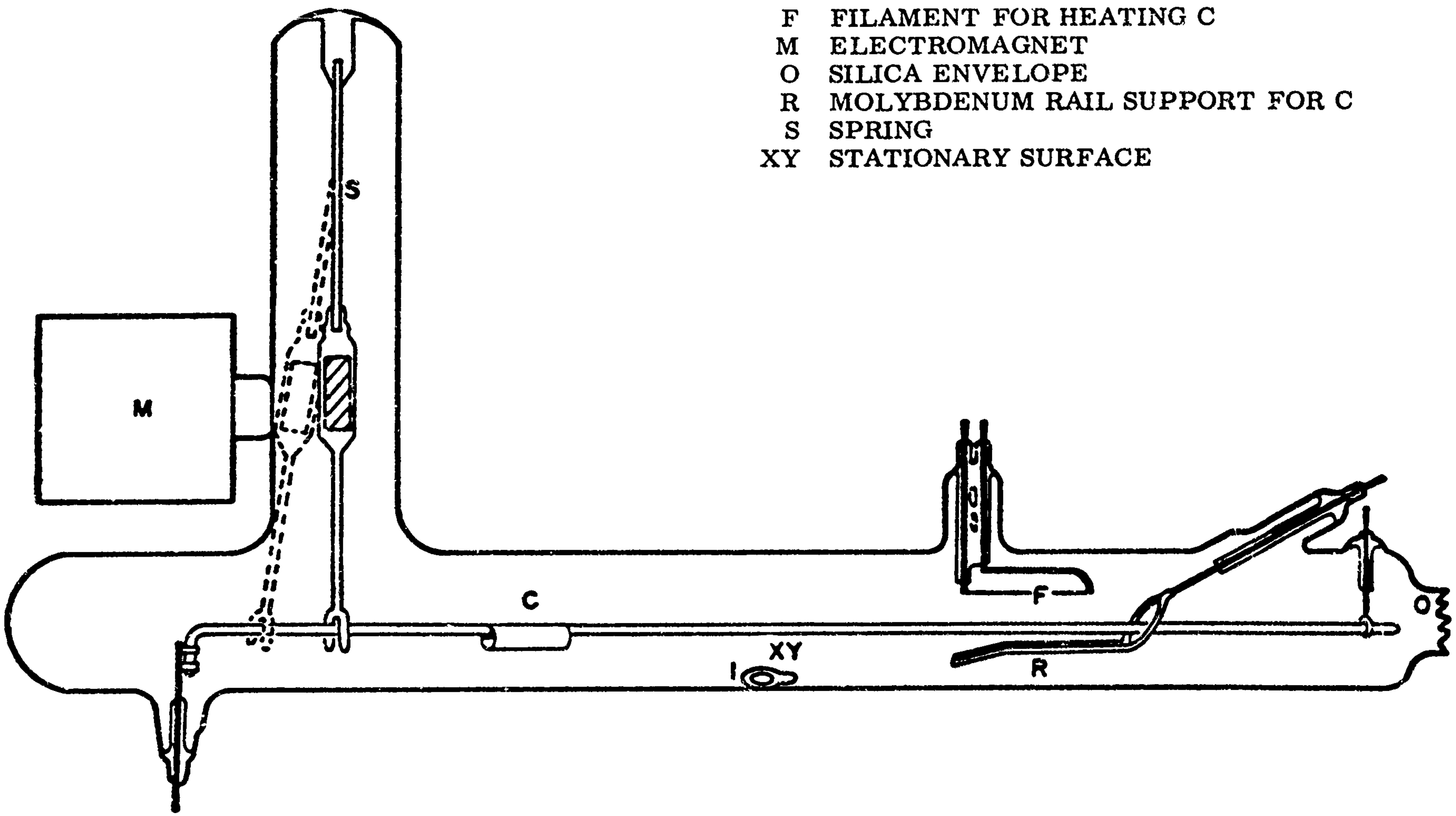
Physically or chemically adsorbed gas films, such as oxides, are normally present on even the cleanest metal surfaces in the normal atmosphere. (As Figure A-1 indicates, a surface that was cleaned at one atmosphere pressure would be recontaminated by a monolayer in less than 10^{-8} second.) These films prevent bare metal-to-metal contact and the formation of strong welded junctions, so that the coefficient of friction is less than when bare metal-to-metal contact is obtained. This fact has been demonstrated by a series of laboratory experiments, beginning with the classic studies of Bowden and Tabor at Cambridge about 25 years ago and continuing to the present time.

Figure A-2 shows the equipment used in the first of these studies (Ref. A.3). The method consisted essentially of propelling a metal cylinder C along a wire XY and photographically estimating its deceleration. From the resulting data, the frictional force between the two surfaces could be calculated.

The cylinder was propelled by the spring S which was released by the electromagnet M. The lower surface XY was degassed by passing a heating current through it, and the cylinder C was degassed by lifting it off the lower surface with the molybdenum rail support R and heating it by electron bombardment from the filament F. The entire apparatus, except for the electromagnet, was encased in a silica envelope O which was connected to the vacuum system.

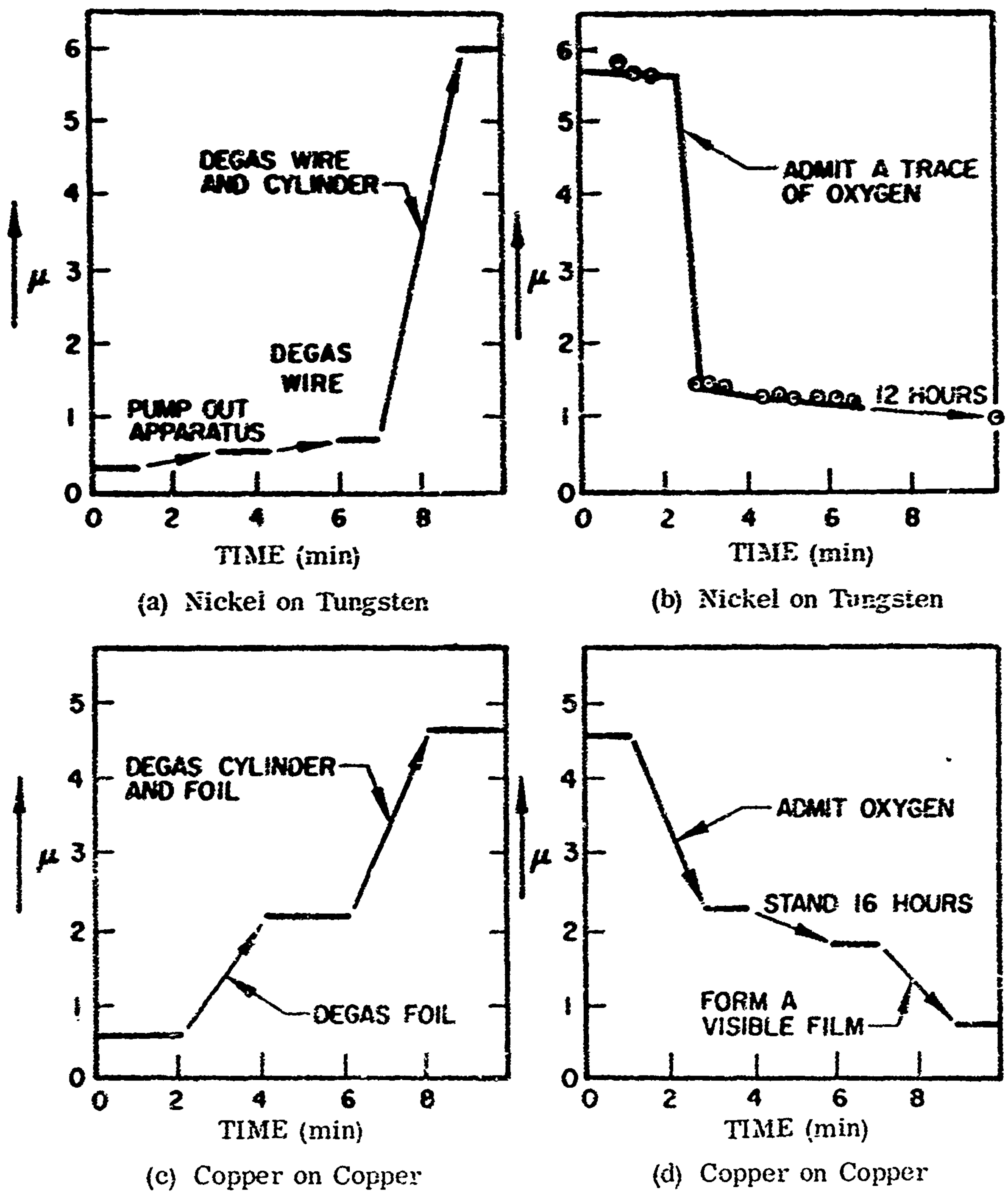
Both metals were kept at a temperature just below that at which excessive evaporation might occur during the final stages of degassing. During the friction measurements, the pressure in the envelope was maintained below 10^{-6} mm Hg and, except when otherwise stated, the friction was measured immediately after the degassed surfaces had cooled to room temperature.

Figure A-3 presents the main results of the experiment using nickel on tungsten and copper on copper. Figure A-3(a) and (c) show that the coefficient of friction was initially about 0.5, and that, after degassing in vacuum and cooling to room temperature, the coefficient increased by a factor of 10 or more. When the clean surfaces were allowed to stand at room temperature in a vacuum of 10^{-5} to 10^{-6} mm Hg, the coefficient of friction steadily decreased, presumably because of the gradual



C MOVING SURFACE
F FILAMENT FOR HEATING C
M ELECTROMAGNET
O SILICA ENVELOPE
R MOLYBDENUM RAIL SUPPORT FOR C
S SPRING
XY STATIONARY SURFACE

Fig. A-2 Apparatus for Measuring Friction Between Outgassed Metal Surfaces



(a), (c) Effect of Removing Adsorbed Film of Oxygen and Other Contaminants From Metal Surfaces

(b), (d) Effect of Adding a Trace of Oxygen to Clean Outgassed Metals

Fig. A-3 Effects of Surface Films on Coefficient of Friction recontamination of the surfaces by residual gases in the apparatus. Figure A-3 (b) and (d) show that when a trace of oxygen was deliberately admitted, there was a sudden large reduction in friction, followed by a slower reduction that continued with time. On the other hand, admitting pure hydrogen or nitrogen had little effect on the friction of the clean surfaces.

Figure A-4 shows another apparatus used in a second study (Ref. A.4). The upper surface A and the lower surface B were fashioned in the form of hollow cylinders to facilitate heating by high-frequency induction. The upper surface was a moving specimen with a small curved protrusion to provide localized contact. The lower surface was fixed and had a flattened face. Surface A was connected by silica link C to a sealed bulb of soft iron D. The sealed bulb D was moved by electromagnet E and hence moves surface A. The frictional force on A was measured by the silica spring device F, and the high-frequency induction coil G provided the necessary heating. The entire apparatus, except for the electromagnet, was encased in a silica envelope H which was connected to the vacuum system.

The main difference between the appartus shown in Figure A-4 and the one presented in Figure A-2 is that the upper surface A was dragged slowly over the lower surface B instead of being propelled along it. Also, the load was appreciably higher, on the order of 15 grams, as compared to less than 1 gram for the equipment shown in Figure A-2. Further, the region of contact between the surfaces was more clearly defined as it occurred between the small curved protrusion of surface A and the flat face of surface B. Degassing was accomplished by the high-frequency induction heating coil, and a vacuum of about 10^{-6} mm Hg was employed.

"Clean" nickel surfaces prepared in air had coefficients of friction of about 1.4. The surfaces were then heated to 1000°C (1832°F) in vacuum to remove contaminant films. On cooling in vacuum to room temperature, the coefficient of friction of the degassed surfaces readily reached a value of 9. Admitting air or a trace of oxygen reduced the friction, but hydrogen had no measurable effect. On surfaces that were even more thoroughly degassed, large-scale seizure occurred on contact. Separation of these surfaces was possible only by prying them apart, and the friction was too high to be measured.

A MOVING UPPER SURFACE WITH SMALL CURVED PROTRUSION
B FIXED LOWER SURFACE WITH FLATTENED FACE
C CONNECTING SILICA LINKS
D SEALED SOFT IRON BULB
E ELECTROMAGNET
F SILICA SPRING DEVICE
G INDUCTION HEATING COIL
H SILICA ENVELOPE

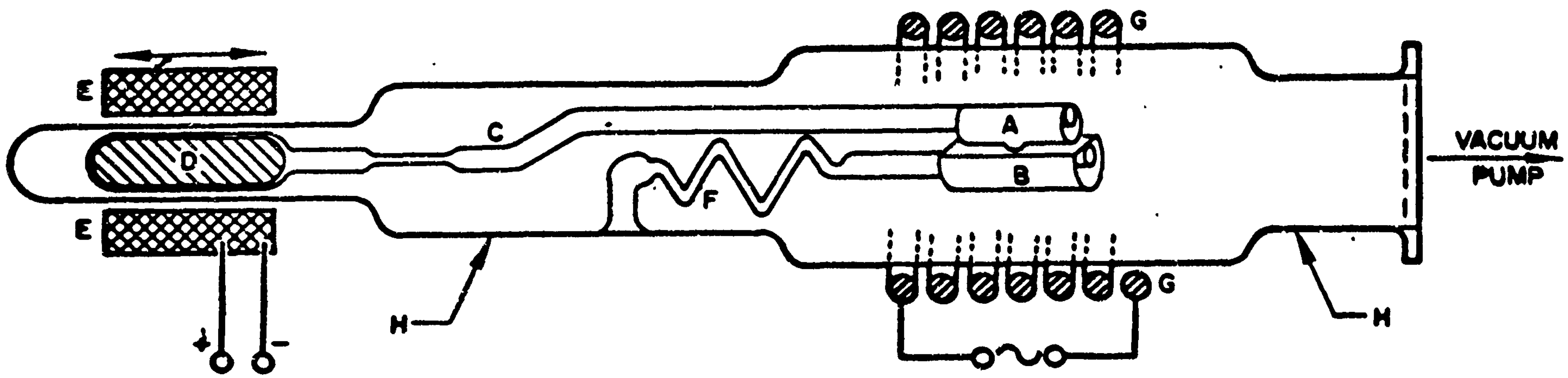


Fig. A-4 Apparatus for Measuring the Friction Between Outgassed Metal Surfaces

These early experiments, as well as others that have been conducted since, demonstrate the effectiveness of even trace amounts of surface contaminants in reducing the friction and wear of metals. While this fact makes it necessary to use refined vacuum techniques and surface preparation in order to measure the friction and wear of truly clean metal surfaces, it also presents a practical advantage in that only small amounts of a suitable vapor are needed to reduce friction and wear. The reduction in the coefficient of friction produced by small amounts of residual vapors in an ultrahigh vacuum system has been demonstrated in a number of experiments. For example, data cited in Ref. A.5 indicates that even at a pressure of 1×10^{-6} torr, enough oxygen is present in the system to provide low coefficients of friction for several combinations of metal, including 52100 chromium steel and 440C stainless steel.

Campbell (Ref. A.6) notes that organic contaminants present in the normal atmosphere are very beneficial in extending the lifetime and improving the performance of switches used in telephone communication systems. If the surfaces of the switches are thoroughly degreased electrolytically (by anodic treatment in hot chromic acid) and operated in clean air, they wear very rapidly and their lifetime is reduced to one-hundredth or less of the normal lifetime in "dirty" air. Tests at LMSC on sliding electrical contacts operating in ultrahigh vacuum also confirm the benefits of trace amounts of outgassing materials (Ref. A.7). A partial pressure of only 10^{-6} torr of a silicone oil was sufficient to reduce electrical noise by more than an order of magnitude (as compared to operation in a dry vacuum of 1×10^{-7} torr) and provided a lifetime in vacuum of over 4000 hours with no sign of failure.

The tenacity with which monolayers are attached to surfaces is important in defining the "lubricity" of the surface film and its resistance to removal by evaporation, sublimation, or wear. Monolayers are stable at vacuum levels well below the bulk vapor pressure of the material, and polar compounds are more strongly adsorbed to surfaces than are non-polar compounds. For example, in the studies reported in Ref. A.8, approximately 10 percent of the last monolayer of octadecane was still present on a steel surface at room temperature at a pressure of only 6×10^{-6} torr, despite the fact that the vapor pressure of octadecane at room temperature is 9.4×10^{-4} torr, which is two orders of madnitude higher. Substantially complete monolayers of the polar compounds n-dodecylamine and dodecanol-1 were retained at room temperature and a pressure of 10^{-6} torr, despite the fact that the vapor pressures of these two materials at room temperature are 9.4×10^{-3} and 2.1×10^{-2} torr, respectively. The advantage of using polar lubricants in vacuum is further demonstrated by results of LMSC studies on lubricants for ball bearings operating in vacuum, in which halogenated silicone oils have given longer lifetimes in vacuum than either dimethyl or phenylmethyl silicone oils which had lower bulk vapor pressure. These results indicate: (1) oils and greases may be more useful in vacuum than their bulk vapor pressure alone might indicate, and (2) molecules having a high degree of polarity appear preferable to those with low polarity.

Various techniques can be used for replenishing films of lubricant in the vacuum/zero-G environment of space. For example, if the lubricant is a low vapor pressure liquid, the liquid can be impregnated into a porous material and allowed to evaporate slowly so that it maintains a small partial pressure of vapor in the vicinity of the contact area. In this case, the lubricant is applied to the contact area as a vapor, and the rate at which it is released from the reservoir will depend upon such factors as the vapor pressure-temperature relationship of the material, the temperature of the reservoir, the surface area of the reservoir, and the porosity of the reservoir. The porous material should have certain other characteristics; for example, it should be lint free so that it does not otherwise contaminate the system, it should retain the impregnated liquid under high G loads during the launch and ascent, it should have a high pore volume in order to retain the maximum amount of lubricant, and it should have a low density. This technique has been used successfully to operate sliding electrical contacts in vacuum in the studies referred to earlier (Ref. A.7).

A second technique for replenishing a film of liquid lubricant on a surface is by wicking. In this case the lubricant is held in a container that is provided with a wick of appropriate material that contacts the surface requiring lubrication and that draws the lubricant from the reservoir to the surface by means of capillary attraction. This case is distinguished from the former in that the liquid lubricant is applied directly to the contact surface as a liquid rather than as a vapor. This technique is used on some ball bearings by impregnating the lubricating oil into a porous retainer material from which it bleeds out slowly against the balls during operation, and it has proved quite successful in tests at LMSC for lubricating ball bearings operating in vacuum.

If the lubricant is a solid film type, it is possible to renew the film periodically provided that the substrate can be chemically reacted with a gas to form a compound with an appropriate laminar structure. For example, the surface films formed by heating molybdenum in hydrogen sulfide or in carbon-disulfide vapor can give low coefficients of friction, even at high temperatures and in vacuum. If destroyed during rubbing, such films can be reformed by further reaction with the hydrogen sulfide or other gas (Ref. A.9).

Some results reported for the coefficient of friction of MoS_2 formed chemically in situ on sintered molybdenum, using a steel slider and a load of 8820 lb are shown in Table A-1 (Ref. A.10). These data show that the coefficient of friction remains low at temperatures as high as 752°F. The value of this temperature (0.07) is lower than that observed at room temperature with well-lubricated metals. The wear and surface damage of steel sliding on pure molybdenum was heavy; on the sintered molybdenum containing MoS_2, however, the wear was very slight.

Table A-1

COEFFICIENTS OF FRICTION FOR MoS_2 ON SINTERED MOLYBDENUM

Substance	Coefficient of Friction at Room Temperature				
	Initial	After Repeated Sliding			
Sintered molybdenum	0.4	0.45			
Sintered molybdenum containing MoS_2	0.1	0.1			
	Coefficient of Friction at Various Temperatures				
	15°C (59°F)	100°C (212°F)	200°C (392°F)	300°C (572°F)	400°C (752°F)
Sintered molybdenum	0.45	0.5	0.5	0.5	0.55
Sintered molybdenum containing MoS_2	0.1	0.08	0.06	0.06	0.07

In general, any gas can act as a lubricant, provided it reacts with the surface to form a compound with an appropriate laminar structure. For example, one patented procedure for producing such a coating on steel, copper-base, or aluminum-base alloys consists in first electroplating these substrates with tungsten or molybdenum and then causing them to react in an atmosphere containing a sulfide, selenide, or telluride at pressures from 15 to 400 psi, under temperatures from 140 to 257°F, and for periods ranging from 30 to 110 hr (Ref. A. 11).

A film of solid lubricant can be applied directly to a contact surface by means of a "lipstick" type applicator riding against the surface. Such a technique is often used in practice for burnishing a film of molybdenum disulfide onto a surface. The technique is also used with Teflon, as in ball bearings supplied with retainers of a reinforced Teflon composition. In this case a certain amount of Teflon is transferred by rubbing from the retainer to the balls and provides, in turn, a lubricating film between the balls and the bearing retainer. This technique has also provided lubrication in tests conducted at LMSC on ball bearings operating in ultrahigh vacuum.

Since metals can cold weld on earth (as, for example, when the contacting forces are sufficient to break through the surface films) as well as in vacuum, a great deal of research has been conducted to define the conditions under which cold welding is probable and to develop a satisfactory theory of the mechanism by which adhesion takes place between metals. These studies make it clear that the mechanism is a complex one that involves the physical metallurgy of the bodies as well as the physics and chemistry of their surfaces. This is illustrated by the following list, which indicates (1) some of the elements of metal and surface behavior that have been found important in cold welding, and (2) some of the external environments, or service conditions, that affect cold welding through their influence on the behavior of the metals and their surfaces.

Important Elements of Metal and Surface Behavior

1. Metals and metal combinations
2. Metallurgical relations and alloying tendencies of the mating metals
3. Crystal structure and crystallographic orientation at the surfaces

4. Annealing behavior (i.e., recovery, recrystallization, and grain growth of the strained metals)
5. Sintering behavior
6. Strain-hardening characteristics
7. Microstructural stability
8. Diffusion rates and the effects of stress and temperature on them
9. Melting and recrystallization temperatures
10. Vapor pressures of the metals
11. Modulus of elasticity
12. Hardness and yield strength of the metals
13. Reactivity of surfaces and wear debris with the surrounding atmosphere to form oxides, nitrides, etc.
14. Surface cleanliness
15. Stability of surface oxides, nitrides, etc.
16. Cohesive strength and ductility of surface oxides, nitrides, etc.
17. Spalling of surface layers under cyclic stressing
18. Adhesion of monolayers and thicker surface films to the metal substrate
19. Dissociation pressure of surface oxides, nitrides, etc.
20. Abrasiveness of wear debris
21. Surface roughness
22. Surface energy and surface tension

Important External Environments (or Service Conditions)

23. Atmospheric pressure (or vacuum)
24. Atmospheric composition
25. Ambient temperature
26. Type of motion (e.g., rolling, reciprocating, and twisting)
27. Relative velocity of motion
28. Contact load or pressure
29. Hertzian stresses
30. Time duration
31. Passage of electrical current across the interface

Many of the items in the above list, of course, are interrelated and are not mutually exclusive. Some of them are repetitions, in which the same factor may be considered with a slight change in view or emphasis.

Although a complete discussion of these factors and the theories of adhesion and cold welding that have been developed around them would be too lengthy to present here, a few remarks are presented in the following paragraphs to illustrate their importance and significance.

The first three items in the list have been reduced to the general "rule of thumb" to avoid contact between like metals, which has often been used by design engineers as a guide in selecting materials for parts that slide over one another. This dictum has a theoretical basis, and might be stated in metallurgical terms as "avoid combinations of metals that tend to alloy or dissolve into one another, since these combinations tend to have high coefficients of friction against one another and to have high adhesion and wear rates." The importance of the metallurgical relations is illustrated by the following results (Ref. A.12; see also Refs. A.13 and A.14 for similar results and discussion), which indicate combinations of metals that either did or did not adhere to one another when they were brought together in ultrahigh vacuum after carefully cleaning their surfaces:

Adhesion occurred	No adhesion observed
Fe-Al	Cu-Mo
Cu-Ag	Ag-Mo
Ni-Cu	Ag-Fe
Ni-Mo	Ag-Ni

All of the metal combinations for which adhesion occurred form solid solutions and/or intermediate alloy phases, while those for which no adhesion was observed have extremely limited solid solubility in one another.

Metallurgical principles are well enough advanced that it is possible to predict alloying behavior of metals from their basic atomic and crystallographic properties. For example, two metals tend to form solid solution alloys with one another when the following conditions are satisfied: (1) The atoms of both metals are approximately the same size (extensive solubility is favored when the atomic diameters of both metals are within 15 percent of each other); (2) both metals have the same crystal structure (e.g., both are face-centered cubic, as with copper and gold); and (3) both metals have similar chemical reactivities (i.e., they are on the same side of the periodic table) so that they have a minimal tendency to interact and form intermediate phases. Such items as the first three in the list, then, provide one set of considerations for anticipating the behavior of metal combinations.

While the first three items emphasize material relations that are favorable or unfavorable for cold welding to occur, items 4 through 10 place the emphasis more on the atomic rearrangements that occur when metal surfaces are placed into intimate contact and that result in the formation of welded junctions. From a metallurgical point of view, the fact that the contacting metal asperities are in a stress-strain condition (as a result of the load) at an elevated temperature (as a result of frictional heating) places this behavior in the general area of high-temperature metallurgy. An important part of the high-temperature behavior of metals is the annealing that occurs when a strained metal is subjected to high temperature, which in turn can be divided into the more or less distinct stages of recovery, recrystallization and grain growth. The relation between this behavior and cold welding is pointed out in a recent theory of metallic adhesion (Ref. A.15), which is based on the recrystallization and recovery of strain-hardened metals. Applying the basic rate reaction equations of Arrhenius to the process of recrystallization and recovery, the author of this theory derived the following equation for the coefficient of adhesion:

$$\sigma = \sigma_0 e^{-Q'/RT} t^n$$

where

σ = coefficient of adhesion

Q' = activation energy for the process

R = universal gas constant

T = absolute temperature

t = time

and σ_0 and n are constants, equal to the slopes of the plots of $\ln \sigma$ versus 1/T and $\ln \sigma$ versus ln T.

Closely allied to the recovery-recrystallization concept of metal adhesion is the concept of sintering of powder metallurgy compacts, by which pressed or compacted powders of metals are made to weld together at a temperature well below the melting point of the metals or alloy system. Asperities on metal surfaces can be analyzed by procedures similar to those that are used to analyze the sintering of powders.

Both annealing and sintering behavior are, in turn, largely influenced by other factors, such as items 6 through 10 in the list above.

As pointed out earlier in this section, the localized temperatures generated by sliding surfaces can reach the melting point of the metal. Under such a condition, localized fusion welding might occur, and it would not be surprising to find the coefficient of adhesion to correlate with melting point. Such a correlation has, in fact, been obtained (Refs. A. 1 and A. 12), in which adhesion increases as melting point decreases. The correlation is particularly interesting in that the data points for different metals define three curves rather than one, thereby indicating the importance of other facts. The coefficients of adhesion of most of the metals fall along a central curve which represents the normal behavior. Metals which do not form stable oxides, such as gold, palladium, and platinum, show greater adhesion than the normal behavior; whereas metals that crystallize in a close-packed hexagonal structure (e.g., Be, Cd, Zn, and Mg) have lower adhesion than normal.

It is worth noting that the recrystallization temperatures and melting temperatures of metals also correlate with each other, so that a correlation between adhesion and melting temperature also implies a correlation between adhesion and recrystallization temperature. Both recrystallization temperature and melting temperature are, in turn, measures of the effect of temperature on atomic mobility, whereby the atoms of a metal can rearrange themselves into a condition of more nearly perfect crystallinity by processes that take place without melting (i.e., recovery and recrystallization) or with melting (i.e., fusion and resolidification).

Items 12 through 22 have to do with the ability of metal surfaces to come into intimate contact with one another, which is a necessary first condition if they are to cold weld together.

The hardness and yield strength of the metals (item 12) are important in that, together with the applied load and the amount of sliding, they govern the true area of contact and the ability of the substrate to provide a nonyielding surface on which contaminating films (e.g., oxides) are supported. The area of true contact between the metals is given by the equation

$$A = \frac{W}{p}$$

where

- A is the area of true contact
- W is the contact force
- p is the yield pressure

If this equation is combined with the following equation, which is based on the adhesive or cold-welding concept of the origin of the friction force

$$F = sA$$

where

- F = friction force
- s = average shear strength of the welded junctions
- A = true contact area

one obtains

$$F = \frac{sW}{p}$$

or defining the coefficient of friction μ in the usual way

$$\mu = \frac{F}{W} = \frac{s}{p}$$

Surface oxide films are normally more brittle than metals, which means that they are likely to crack and expose underlying metal if the underlying metal is too soft to provide a firm support under load. Thus, the hardness and yield strength are also important in defining the true contact area of contaminated surfaces because of their influence on the mechanical integrity of the contaminating films.

Items 13 through 19 deal with the presence, nature, and stability of surface films on metals that might prevent the metals from coming into intimate contact with one another. In the sense that these surface films reduce the cold welding that would otherwise occur on intimate contact, as illustrated in the experiments discussed above, the surface films are naturally formed lubricating films, and the entire art of lubrication can be said to be an attempt to improve upon the lubricating films that nature otherwise provides in the normal air atmosphere. The presence and nature of these films will depend upon the reactivity of the surfaces with the surrounding atmosphere to form oxides, nitrides, or other compounds that are held by chemical bonds or to form physically adsorbed gas films that are held by weaker van der Waals-type forces. The stability with which the films remain on the surface during sliding friction (item 15) depends upon the mechanical strength of the films and their ability to deform without cracking when the substrate below them is plastically deformed (items 16 and 17), on the adhesion of the film to the substrate (items 17 and 18), and on their thermal stability (item 19).

Research also indicates that friction is related to the work of adhesion of the contacting materials (Ref. A.16), where the work of adhesion is given by the equation

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab}$$

where

W_{ab} = work of adhesion

γ_a = surface free energy of material a

γ_b = surface free energy of material b

γ_{ab} = interface free energy

and all quantities are for a unit or area. High coefficients of friction occur for sliding metals with high values of W_{ab}/p (i.e., high ratios of work of adhesion to hardness).

The last group of items (23 through 31) are the external environments or service conditions under which the metal combinations must operate. These environments affect the degree of cold welding principally by their effects on the intimacy of contact between the mating metals and the temperature of the metal surfaces and asperities. Most of these effects are fairly obvious from the previous discussion. The effect of atmospheric pressure (or vacuum) on the rate at which contaminating films form on freshly exposed surfaces has already been discussed. The type of motion is important in its effects on the rupture and removal of surface films (easier under reciprocating sliding than rolling) and the exclusion of atmospheric contaminants from freshly exposed surfaces (exclusion is more complete with twisting than with rolling or reciprocating sliding). Items 28 and 29 are important in that they determine the true contact area and the extent to which surface films are ruptured. The passage of an electric current results in heating and may also introduce polarity effects with certain types of contaminating films.

The foregoing discussion indicates that although theory is still not adequate to predict quantitatively the adhesion and cold welding tendencies of engineering alloys under specified conditions of application, their qualitiative behavior can be reasonably anticipated and, in some cases, quantitative correlations can be made. Although cold-welding is a complex phenomenon, the important elements of the behavior of metals and surfaces and the effects of the external environment have been identified.

A.3 REFERENCES

A.1 M. E. Sikorski, "Correlation of the Coefficient of Adhesion With Various Physical and Mechanical Properties of Metals," J. Basic Engrg., Trans. ASME, 85 (no. 2), 279 (Jun 1963)

A.2 F. P. Bowden and D. Tabor, The Friction and Lubrication of Solids, Oxford University Press, London, 1954

A.3 F. P. Bowden and T. P. Hughes, "The Friction of Clean Metals and the Influence of Adsorbed Gases: The Temperature Coefficient of Friction," Proc. Royal Soc., London, 172A, 263 (1939)

A.4 F. P. Bowden and J. E. Young, "Friction and Adhesion of Clean Metals," Nature, 164, 1089 (1949)

A.5 D. H. Buckley, M. Swikert, and R. L. Johnson, "Friction, Wear, and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg," ASLE Trans., 5, 8–23 (1962)

A.6 W. E. Campbell, "The Role of Atmospheric Components in Friction, Wear, and Boundary Lubrication," Proc. USAF-SwRI Aerospace Bearing Conference, 29–43, 30 Sep 1964

A.7 Francis J. Clauss, "Lubrication Under Space/Vacuum Conditions," Scientific Lubrication, 15, 180–199, Mar 1963

A.8 H. Gisser and S. Sadjian, "Evaporation of Organic Compounds From Metal Surfaces at High Vacuum," Proc. USAF-SwRI Aerospace Bearing Conference, 20–27, 30 Sep 1964

A.9 F. P. Bowden and G. W. Rowe, "Lubrication With Molybdenum Disulfide Formed From the Gas Phase," Engineer, 204 (no. 5311), 667, 8 Nov 1957

A.10 F. P. Bowden, "Frictional Properties of Porous Metals Containing Molybdenum Disulfide," Research, 3, 383–384, Aug 1950

A.11 J. E. Brophy and R. W. Ingraham, "Application of Solid Lubricant Coatings to Surfaces," U.S. Patent 2,902,417 (assigned to IBM Corp.), 19 Sep 1956

A.12 D. V. Keller, "Adhesion Between Solid Metals," Wear, 6, 353 (1963)

A.13 A. E. Roach, C. L. Goodzeit, and R. P. Hunnicutt, "Scoring Characteristics of Thirty-Eight Different Elemental Metals in High Speed Sliding Contact With Steel," Trans. ASME, 78, 1659 (1956)

A.14 L. F. Coffin, Jr., "A Study of the Sliding of Metals, With Particular Reference to Atmosphere," Lubrication Engineering, 12, 50–59, Jan–Feb 1956

A.15 F. F. Ling, "On the Mechanism of Metal Adhesion," Proc. USAF-SwRI Aerospace Bearing Conference, 5–27, 30 Sep 1964

A.16 E. Rabinowicz, "Influence of Surface Energy on Friction and Wear Phenomena," J. Appl. Phys, 32, 1440 (1961)

Appendix B

PROPRIETARY CODE

OILS TESTED

Code	Proprietary Name	Chemical Type	Manufacturer	Lifetime in Vacuum at Approximately 180° F > 1 Year	< 1 Year
		Petroleum			
O-1	Teresstic V-78	Paraffinic oil plus oxidation inhibitor and load-carrying additive	Humble Oil and Refining Company	X	
O-2	XRM128C	Paraffinic oil	Socony Mobil Oil Company	X	
O-3	XRM141C	Paraffinic oil (Code O-2) with oxidation inhibitor and load carrying additive	Socony Mobil Oil Company	X	
O-4	Apiezon K	Petroleum oil	Associated Electronics Industries, Limited	X	
O-5	Apiezon J	Petroleum oil	Associated Electronics Industries, Limited	X	
O-6	Apiezon C	Petroleum oil	Associated Electronics Industries, Limited	X	
O-7	Apiezon B	Petroleum oil	Associated Electronics Industries, Limited	X	
O-8	Brayco 777	Naphthenic-base oil with hindered-phenol type oxidation inhibitor	Bray Oil Company		X
O-9	Molykote M-55	Colloidal dispersion of molybdenum disulfide in petroleum oil	Alpha-Molykote Corp.		X

Silicone

O-10	Versilube F-50	Chlorophenyl-methyl polysiloxane	General Electric	X	
O-11	Versilube F-50, distilled	Chlorophenyl-methyl polysiloxane (Code O-10) with 50% more volatile fraction removed by distillation	General Electric		X
O-12	None	2/3 by volume chlorophenyl-methyl polysiloxane (Code O-10) and 1/3 molybdenum disulfide (prepared by LMSC)	None		X
O-13	QF-1-0065 (250 centistokes) (present designation FS-1265)	Fluorosilicone oil	Dow Corning	X	
O-14	QF-1-0065 (1000 centistokes) (present designation FS-1265)	Fluorosilicone oil	Dow Corning	X	
O-15	MLO 61-97 (DC 7024)	High-phenyl content polysiloxane oil	Supplied to LMSC by Aeronautical Systems Division, USAF	X	
O-16	SF-96	Dimethyl polysiloxane	General Electric		X
O-17	QF-6-7040	Low-phenyl content polysiloxane stripped of light ends	Dow Corning		X
O-18	DC-704	Medium-phenyl content methylphenyl-polysiloxane	Dow Corning		X
O-19	SF-1017	Methylphenyl-polysiloxane, 35% more volatile fraction stripped	Dow Corning		X
O-20	QF-1-0026	Halogenated phenylmethyl polysiloxane plus organometallic anti-wear additives	Dow Corning		X

OILS TESTED (cont.)

Code	Proprietary Name	Chemical Type	Manufacturer	Lifetime in Vacuum at Approximately 180° F > 1 Year	< 1 Year
		Diester Base			
O-21	Plexol 201	Dioctyl sebacate	Rohm & Haas		X
O-22	Univis P-38	Diester base oil meeting MIL-L-6085	Humble Oil and Refining Company		X
O-23	Ester A	Di-basic acid ester	Custom Lubricants		X
O-24	Dispersion D	Di-basic acid ester (Code O-23) containing molybdenum disulfide dispersion	Custom Lubricants		X
O-25	Ester C	Di-basic acid ester	Custom Lubricants		X
O-26	Dispersion E	Di-basic acid ester (Code O-25) containing molybdenum disulfide dispersion	Custom Lubricants		X
		Other Synthetics			
O-27	FPPN-10802-77	Trifluoromethyl-phenoxy phenoxy phosphonitrile FPPN (10802-77)	E. I. DuPont	X	
O-28	Oronite 8200	Hexa 2-ethyl butoxy disiloxane	Oronite Chemical Co.		X
O-29	Oronite 8515	85% hexa 2-ethyl butoxy disiloxane (Code O-28) plus 15% dioctyl sebacate	Oronite Chemical Co.		X

O-30	Diphenylbis-n-dodecyl-silane	Diphenylbis-n-dodecylsilane	Metals and Thermit Co.	X
O-31	Cellulube 90	Triaryl phosphate	Celanese Corporation of America	X
O-32	Cellulube 220	Triaryl phosphate	Celanese Corporation of America	X
O-33	OS-124	Isomeric 5-ring polyphenyl ether	Monsanto Chemical Co.	X

GREASES TESTED

Code	Proprietary Name	Chemical Type	Manufacturer	Lifetime in Vacuum at Approximately 180°F > 1 Year	< 1 Year
		Petroleum Oil Base			
G-1	Andok C	Petroleum oil with sodium soap thickener	Humble Oil and Refining Company	X	
G-2	Chevron OHT	Petroleum oil with sodium stearate thickener	Standard Oil of California		X
G-3	Chevron Duraplex EP, Heavy	Petroleum oil with complex calcium soap thickeners	Standard Oil of California		X
G-4	Chevron Industrial Grease, Heavy	Petroleum oil with sodium soap thickener	Standard Oil of California		X
		Silicone Oil Base			
G-5	Versilube G-300	Versilube F-50 (Code O-10) with lithium soap thickener	General Electric	X	
G-6	Aeroshell-15	Methylphenyl silicone oil with dye thickener, meets MIL-G-25013 and MIL-G-27343	Shell Oil Company	X	
G-7	Supermil ASU Grease No. 31052	Silicone oil with aryl substituted urea grease, meets MIL-G-25013	American Oil Company	X	
G-8	EG-509	Silicone oil with organic thickener and solid lubricant	Marlin Rockwell Corp.	X	

G-9	MLG 61-92	MLO 61-97 (Code O-15) with aryl substituted urea thickener	Supplied by Aeronautical Systems Division, USAF	X	
G-10	MLG 62-142	MLO 61-97 (Code O-15) with ammeline thickener	Supplied by Aeronautical Systems Division, USAF	X	
G-11	EG-429	Silicone oil with organic thickener and solid lubricant	Marlin-Rockwell Corp.	X	
G-12	QC-5-0010	Fluorosilicone oil with soap thickener	Dow Corning		X
G-13	QC-2-0026	Fluorosilicone base grease	Dow Corning		X
G-14	High vacuum silicone grease		Dow Corning		X
		Di-Ester Oil Base			
G-15	RPM No. 5	Diester oil with lithium soap thickener (met MIL-G-3278)	Standard Oil of California		X

TESTS WITH SPECIAL RETAINERS

Code	Proprietary Name	Description	Manufacturer	Lifetime in Vacuum at 140 – 180° F > 1 Year	Lifetime in Vacuum at 140 – 180° F < 1 Year
R-1	Rulon C	Modified Teflon	Dixon Corporation	X	
R-2	Duroid 5813	60% Teflon, 40% glass fibers with molybdenum disulfide	Rodgers Corporation		X
R-3	Nylasint MS	Sintered nylon containing molybdenum disulfid	The Polymer Corporation		X
R-4	Microporous nylasint impregnated with oil O-10	Microporous sintered nylon impregnated with Versilube F-50 (Code O-10)	The Polymer Corporation		X
R-5	Arguto MP	Porous plastic impregnated with silicone oil	Arguto Oilless Bearing Company		X
R-6	Polymer SP	Aromatic polyimide	Polymer SP from Dupont, retainers fabricated by Miniature Precision Bearings, Inc.		X
R-7	Material M-1	Epoxy-molybdenum disulfide	Material M-1 from Alpha-Molykote, bearings fabricated by Microtech		X
R-8	Graphalloy 4007	Pressed porous graphite impregnated with silver	Graphite Metallizing Company		X
R-9	Sinitex	55% sintered bronze, 27% Teflon and 18% molybdenum disulfide	Booker-Cooper, Inc.		X
R-10	Sinite D-10	50% bronze, 50% Teflon	Booker-Cooper, Inc.		X

TESTS WITH DRY FILM LUBRICANT

Code	Proprietary Name	Description	Manufacturer
S-1	Hi-T-Lube	Coating of molybdenum disulfide applied over silver matrix	General Magnaplate, Inc.
S-2	Everlube 811	Sodium silicate bonded molybdenum disulfide	Everlube Corporation
S-3	Electrofilm 2396	Ceramic bonded molybdenum disulfide	Electrofilm, Inc.
S-4	Teleflex S.W. 16	Molybdenum disulfide bonded by low temperature curing ceramic	Teleflex, Inc.
S-5	Teleflex S.W. 25	Molybdenum disulfide bonded by low temperature curing ceramic	Teleflex, Inc.
S-6	Electrofilm 2007	Silicone bonded molybdenum disulfide	Electrofilm, Inc.
S-7	Polychem	Epoxy bonded molybdenum disulfide	Poly Chem Company
S-8	None	Proprietary coating	Reher-Simmons Co.
S-9	CL6001	Molybdenum disulfide "soft" coating	Lubeco, Inc.
S-10	CL6001A	Molybdenum disulfide "hard" coating	Lubeco, Inc.
S-11	Coating 904	Proprietary molybdenum disulfide coating	Lubeco, Inc.
S-12	Coating E 3C	Plated molybdenum disulfide	Alpha Molykote, Inc.
S-13	Molykote Z	Molybdenum disulfide powder applied by burnishing	Alpha Molykote, Inc. (Powder burnished by LMSC)
S-14	Microseal	Graphite applied by impingement process	Microseal Products
S-15	None	Proprietary coating	Lubrication Services