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LUBRICANT STUDY IN ULTRAHIGH VACUUM AND IN VARIOUS GAS ENVIRONMENTS

By P. H. Bowen, D. J. Boes, K. W. Grossett, and E. S. Bober

Final Report
26 January 1965 - 15 March 1966

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Prepared under Contract NAS 9-3815 by
WESTINGHOUSE RESEARCH LABORATORIES
Pittsburgh, Pennsylvania

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MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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PREFACE

This program was conducted under NASA Contract NAS 9-3815 for the Mechanical and Landing Systems Branch, Structures and Mechanics Division, NASA Manned Spacecraft Center, with Mr. J. H. Kimzey as technical project monitor.

At the Westinghouse Research Laboratories, the program was directed by Mr. E. S. Bober, Manager, Lubricants and Electrochemical Technology R&D, Inorganic Materials-Science & Technology R&D. Mr. D. J. Boes was responsible for the initial rolling tests. Mr. K. W. Grossett conducted the literature survey. Mr. P. H. Bowen was responsible for the initial sliding tests and later assumed project responsibility for both sliding and rolling tests. Dr. W. J. Lange, Messrs. W. M. Hickam and R. K. Matta contributed valuable consultation on the vacuum technology and surface analysis aspects of the study program. Technical assistance was rendered by A. F. Berringer, G. R. Kelecava and H. R. Wilkinson.

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Westinghouse Research Laboratories

SUMMARY

Wear and friction characteristics of lubricated and unlubricated hardened Type 440C stainless steel couples in sliding and rolling contact were studied first in an ultrahigh vacuum environment and then in an UHV environment degraded by introducing certain outgassing products known to exist in spacecraft and related service modules. The 3 lubricants used in the study represented the fluid, laminar film and solid composite types. The UHV environments were degraded by introduction of high purity CO_2, O_2 and H_2O vapor. Evaluation tests of 100 hour duration were made on a total of 320 test specimens in 32 different lubricant-environmental combinations with 5 specimens tested under continuous operation and a second 5 specimens under intermittent operation. Extended tests of 300 hour duration were made on the 3 lubricants in the environment (H_2O vapor) that proved to be most beneficial to effective lubrication in the 100 hour tests.

The sliding contact tests were made using a disk and rider assembly operated at a rubbing velocity of 32 ft./min. under a load of 150 psi. The rolling contact tests were made using ball thrust bearings operated at a speed of 150 rpm under a load of 2 pounds. Tests were not started until the chamber pressure was in the 10^{-10} torr range. In the simulated outgassing environment tests, the pressure was increased to an operating range of 10^{-2} to 10^{-5} torr by admission of the high purity gas.

The results of the investigation are compiled and presented in graphic form. The degree of lubrication effectiveness is first presented by a comparison of the measured friction values and second by a comparison of the wear rates of the metal components. An analysis was made of selected wear surfaces using various laboratory techniques. Both an optical microscope and scanning electron microscope were used to study wear phenomena of the metal and lubricant surfaces after test. X-ray fluoresence and emission spectrographic analysis was made of the wear track on one disk. An O^{18} isotope of O^2 was used as a tracer in the H_2O vapor to analyze the rider surface by

means of a spark source mass spectograph microprobe.

The best overall lubrication was obtained with the Na_2SiO_3 bonded WSe_2 laminar film whose film thickness averaged 0.002 to 0.005 in. The next best lubricant was the chlorophenyl methyl silicone oil except in the pure ultrahigh vacuum environment. The self-lubricating composite wiper material provided satisfactory to marginal lubrication and appeared to be more effective on rolling surfaces than on sliding contact surfaces. The H_2O vapor degraded UHV environment provided the most overall beneficial effect to lubricants but in varying degrees. The composite lubricated surfaces received the least benefit and in several tests the effect was slightly detrimental.

I. INTRODUCTION

Proper lubrication of moving equipment is a potential problem area in the design of current and future NASA Manned Spacecraft. Exposure of load bearing surfaces to a space environment complicates the lubrication problem considerably because of the environment's effect on both the lubricant through evaporation or chemical decomposition; and the generation of metal surfaces devoid of any protective oxides or adsorbed films. In addition any outgassing materials in the vicinity of the lubricated equipment may be deleterious to the function of the lubricants. The result is a substantial increase in friction between moving parts with a possibility of seizure due to galling or excessive metal transfer.

The degree of galling or metal transfer which can occur in any system is not only dependent on the lubricant but also on the load and relative sliding or rolling velocity of the two surfaces. Thus, a careful analysis must be made for any applications in the Apollo program to establish limits and life of effective lubrication.

The program reported herein was conducted to study and evaluate the performance of unlubricated and lubricated bearing surfaces operating in an ultrahigh vacuum (10^{-10} torr) with those operating in the same system and altered only by having the vacuum degraded to $> 5 \times 10^{-5}$ torr by the presence of gases simulating outgassing of selected materials. The coefficient of friction and wear were determined along with an analysis of surface deterioration for one unlubricated and three lubricated conditions. The gases simulating outgassing were high purity CO_2, O_2 and H_2O vapor. The lubricant systems used represented the fluids, bonded solid laminar films and solid composite lubrication types. The combination of lubricant and environment providing the best performance was rerun in a 300 hour test to determine if the effective lubrication existed for extended periods of time simulating that of an Apollo mission.

The specific tasks undertaken to meet the objectives of the program consisted of a literature survey and an experimental program. The literature survey consisted of reviewing the scientific literature and research programs concerning space and controlled environmental lubrication, outgassing investigations and related surface studies of wear and friction. Results of the literature survey are given in Appendix A.

The experimental program consisted of adapting three test chambers and conducting both wear and friction tests on sliding and rolling surfaces of hardened Type 440C stainless steel. The rolling tests were conducted on 905 size ball thrust bearings at a speed of 150 rpm and a load of 2 lb. (900 gram). The sliding surfaces moved with a relative velocity of 32 ft./min. under a load of 150 psi. The ultrahigh vacuum runs were made at pressures in the range of 10^{-10} torr. In the controlled environment runs gases simulating outgassing were admitted to the ultrahigh vacuum to raise the pressure to a range of 10^{-2} to 10^{-5} torr. Every effort was made to maintain vacuum levels by keeping the chamber leakage to a minimum rather than increase pumping capacity to prevent contamination of the test specimens. Details of the equipment and test procedures are given in Section V.

For purposes of brevity the test environments created by degrading the ultrahigh vacuum environment to $> 5 \times 10^{-5}$ torr by introduction of pure CO_2, O_2 or H_2O vapor to simulate outgassing from materials will be referred to in the remainder of the report as simply the CO_2, O_2 or H_2O vapor environment.

II. EXPERIMENTAL RESULTS

Coefficient of friction measurements were continuously monitored during each 100 hour test run. Data was obtained on 5 slider specimens or bearings for each test condition. Wear data was obtained by pre and post test measurement of the specimens. The information reported herein is a summary of the individual specimen test data reported in each of the monthly letter reports. Two test runs on 10 specimens were made at each test condition: one set of specimens operated continuously and the other set operated intermittently with equal dynamic and static cycles. The cycle for the sliding tests was 4 hours and for the rolling tests was 3 hours.

Results of the extended life tests of 300 hours duration are included and consist of both individual test and summary data.

A photograph of the sliding specimens and bearings is shown in Fig. 1. A detailed description of these items are found in Section V. A summary description of the lubricants and test conditions is shown in Fig. 2. The sliding and rolling test data presented in this report were arranged in the same sequence and using the same test designation number as the detailed test data presented in the monthly letter reports. The first test series number of each number pair in Fig. 2 is the continuous run series and the second number, the intermittent run series under the same lubricant-environment test condition.

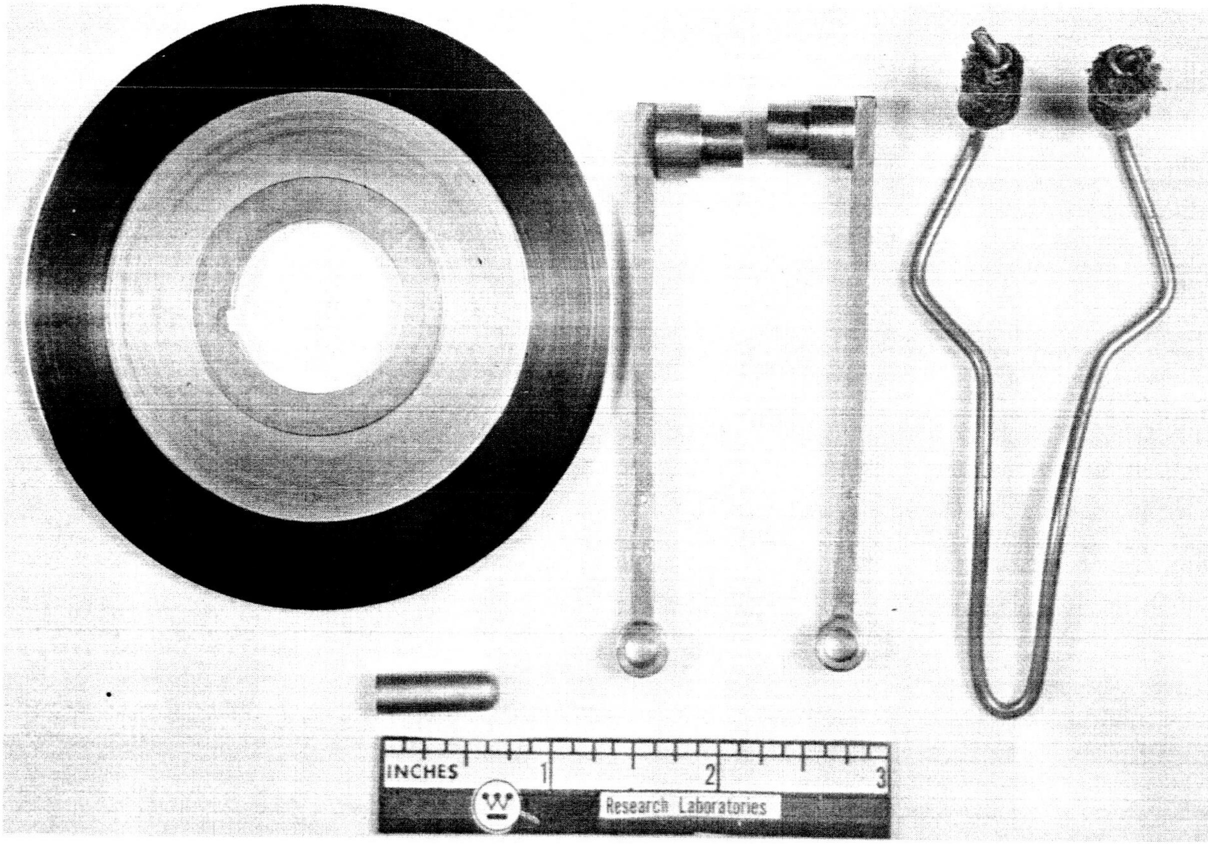
A. Metal Surfaces in Sliding Contact

1. Friction in 100 hour tests.

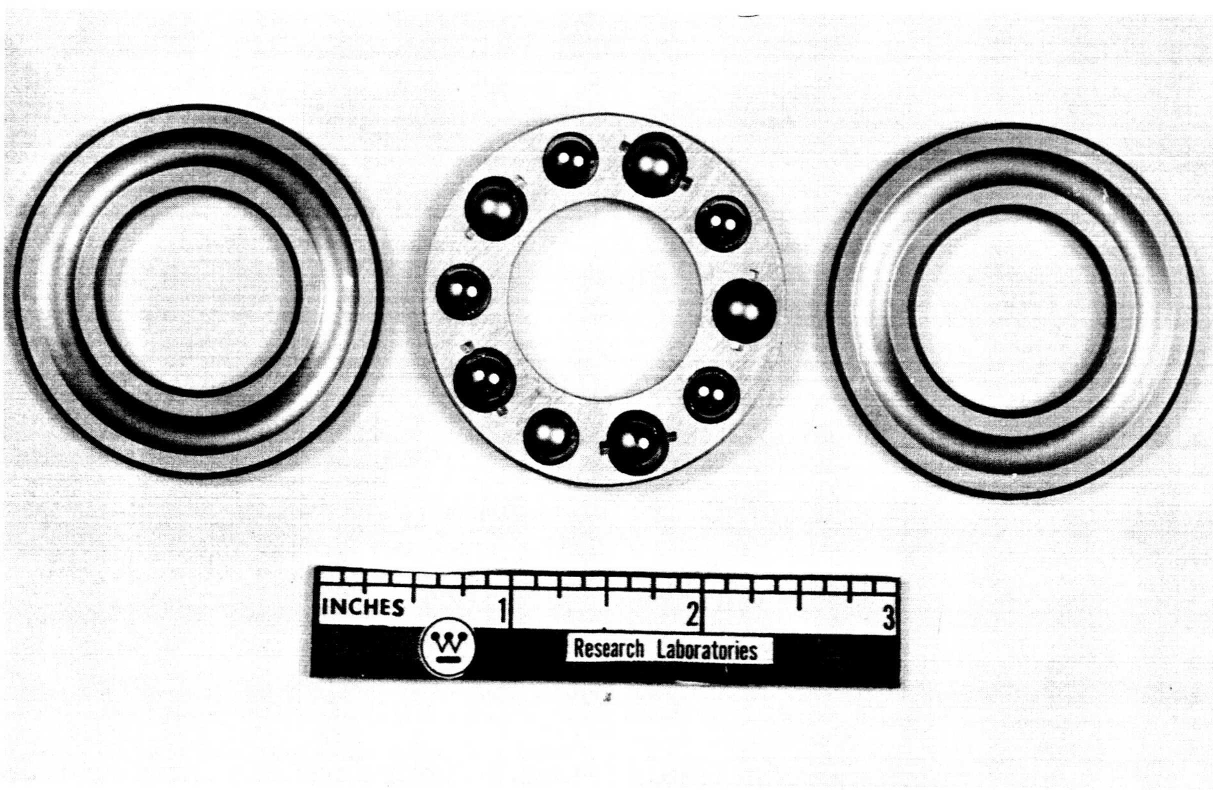
The coefficient of friction determined for each test was used as an indication of effectiveness of lubrication in the sliding 100 hour tests. These friction values varied from 0.02 to 1.20. At the higher frictional values, considerable "stick-slip" motion occurred which resulted in an audible vibration of the rider load arm. The type of operation, continuous or intermittent, made little or no difference on the measured coefficient of friction of the rubbing specimens. The values of both test groups were similar within laboratory measurement error.

The test results presented in graph form are shown in Fig. 3. The coefficient of friction of unlubricated specimens were approximately 1.0 or greater for tests in the UHV environment as well as CO_2, O_2 and H_2O vapor environments.

The coefficients of friction for the sodium silicate bonded tungsten diselenide film specimens were the lowest of the lubricated specimens and ranged from 0.02 to 0.17. Some difference in friction values for the



Disk and Rider
With Composite Idler and Fluid Wick



Ball Bearing Showing
Method of Holding Balls in Retainer

Fig. 1 - Sliding Specimens and Bearings for
Lubricant and Environmental Tests

LUBRICANTS

1. Fluid - A General Electric silicone oil F-50. This is a chlorophenyl methyl silicone and is reported to have better lubricating characteristics than most silicone oils.

2. Composite - A Westinghouse material made of 70% WSe_2 and 30% GaIn. It has a compressive strength of 25,000 psi.

3. Laminar Film - A Westinghouse material made of 60% Na_2SiO_3 and 40% WSe_2. The average thickness of coating was 0.003 to 0.005 in.

TEST CONDITIONS

Sliding: Speed of 32 ft./min. under a load of 150 psi.
Rolling: Speed of 150 rpm under a load of 2 lb.

1. The intermittent runs were made immediately following the respective continuous run. Other conditions and remarks of the 100 hr. tests are noted below.

Sliding No.	Rolling No.	Type of Lubricant	Chamber Envir.	Avg. Pr. torr Starting[1]	Avg. Pr. torr Operating[1]
1-2	1-2	None	Vac.	S-10^{-10}:R-10^{-10}	S-10^{-10}:R-10^{-9}
3-4	5-6	Fluid	Vac.	S-10^{-9} :R-10^{-8}	S-10^{-8} :R-10^{-8}
5-6	7-8	Film	Vac.	S-10^{-9} :R-10^{-10}	S-10^{-9} :R-10^{-8}
7-8	3-4	Composite	Vac.	S-10^{-10}:R-10^{-10}	S-10^{-9} :R-10^{-9}
9-10	9-10	None	CO_2	S-10^{-9} :R-10^{-8}	S-10^{-4} :R-10^{-5}
21-22	11-12	Fluid	CO_2	S-10^{-9} :R-10^{-8}	S-10^{-2} :R-10^{-5}
17-18	15-16	Film	CO_2	S-10^{-9} :R-10^{-8}	S-10^{-3} :R-10^{-5}
23-24	13-14	Composite	CO_2	S-10^{-8} :R-10^{-8}	S-10^{-2} :R-10^{-5}
27-28	17-18	None	O_2	S-10^{-9} :R-10^{-8}	S-10^{-2} :R-10^{-5}
25-26	21-22	Fluid	O_2	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}
31-32	23-24	Film	O_2	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}
29-30	19-20	Composite	O_2	S-10^{-9} :R-10^{-8}	S-10^{-2} :R-10^{-5}
11-12	25-26	None	H_2O[2]	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}
13-14	27-28	Fluid	H_2O	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}
15-16	31-32	Film	H_2O	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}
19-20	29-30	Composite	H_2O	S-10^{-9} :R-10^{-9}	S-10^{-2} :R-10^{-5}

2. The three extended life continuous 300 hr. test conditions are noted below.

Sliding No.	Rolling No.	Type of Lubricant	Chamber Envir.	Avg. Pr. Starting	Avg. Pr. Operating
33S	33R	Fluid	H_2O[1]	S-10^{-8} :R-10^{-8}	S-10^{-2} :R-10^{-5}
34S	34R	Film	H_2O	S-10^{-10}:R-10^{-10}	S-10^{-2} :R-10^{-5}
35S	35R	Composite	H_2O	S-10^{-10}:R-10^{-10}	S-10^{-2} :R-10^{-5}

[1] Pressure of sliding tests S:Those of rolling tests R.
[2] Water vapor.

Fig. 2 - Summary of Lubricants and Environmental Test Conditions

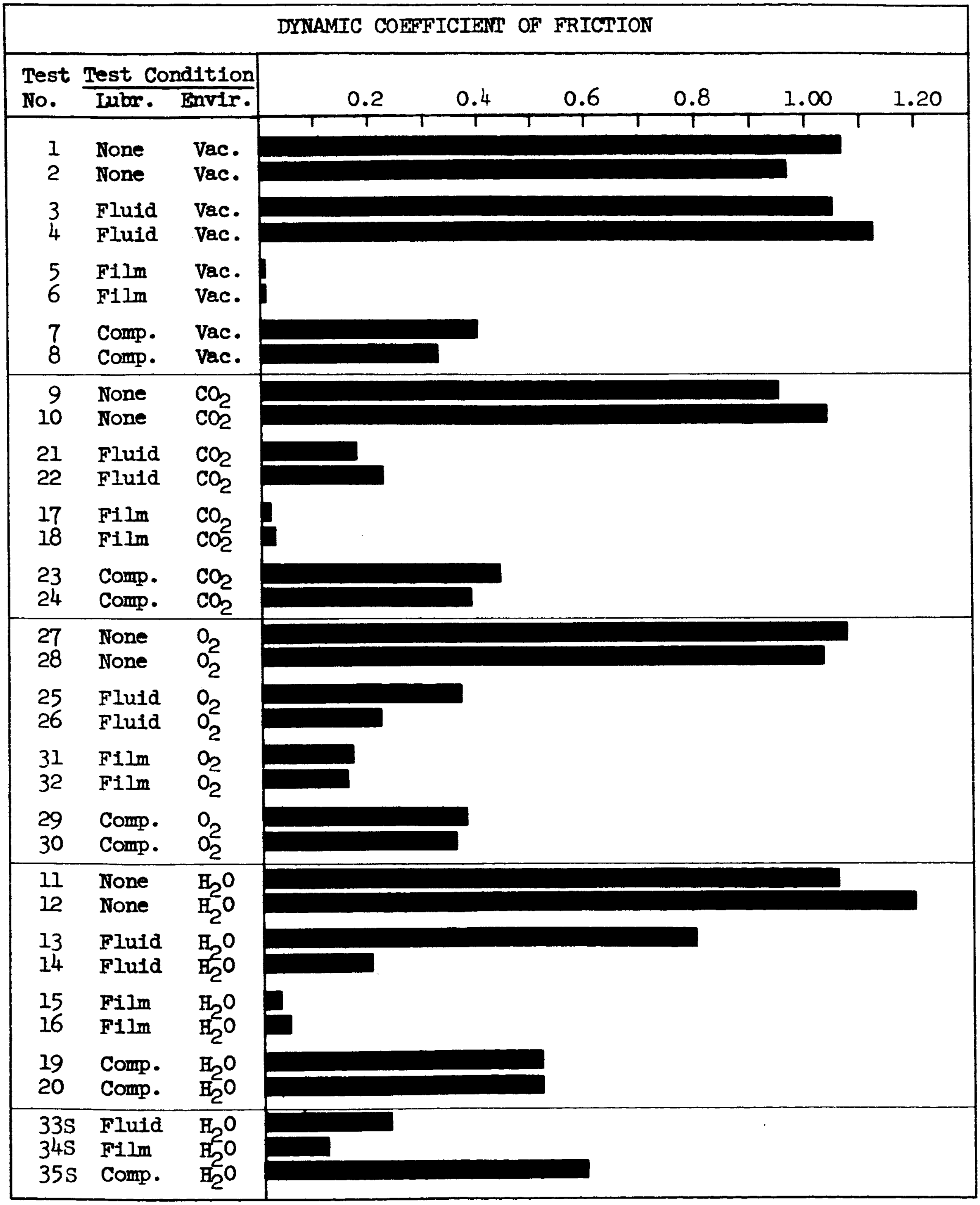


Fig. 3 - Tabulation of Coefficient of Sliding Friction Without and With Lubricants in Various Environments

laminar film lubricated specimens was noted in the various environments with the lowest friction values being obtained in the ultrahigh vacuum atmosphere.

The composite wiper lubricated specimens exhibited average friction values which ranged from 0.40 to 0.53. Results of individual tests varied over a greater range than the above average but the friction values of individual rubbing specimens appeared to be constant for any one test in a specific environment.

Friction values for the silicone oil lubricated specimens varied from 0.15 to 1.10. F-50 silicone oil did not lubricate the sliding surfaces in the UHV environment as evidenced by the extremely high coefficient of friction.

2. Wear rates in 100 hour tests.

The summarized results of weight loss by the disks and riders are shown graphically in Fig. 4 and Fig. 5. The wear values obtained on the various lubricated samples had significantly different ratings. In all the laminar film tests the weight loss occurred solely on the film on the disk in the rubbing track. No wear was observed on the metal surface of the disk. In all the other lubricated and non-lubricated tests the weight loss measurements represented actual metallic loss of the specimens. Where a weight gain was observed, the gain could be either or both that of lubricant and metal.

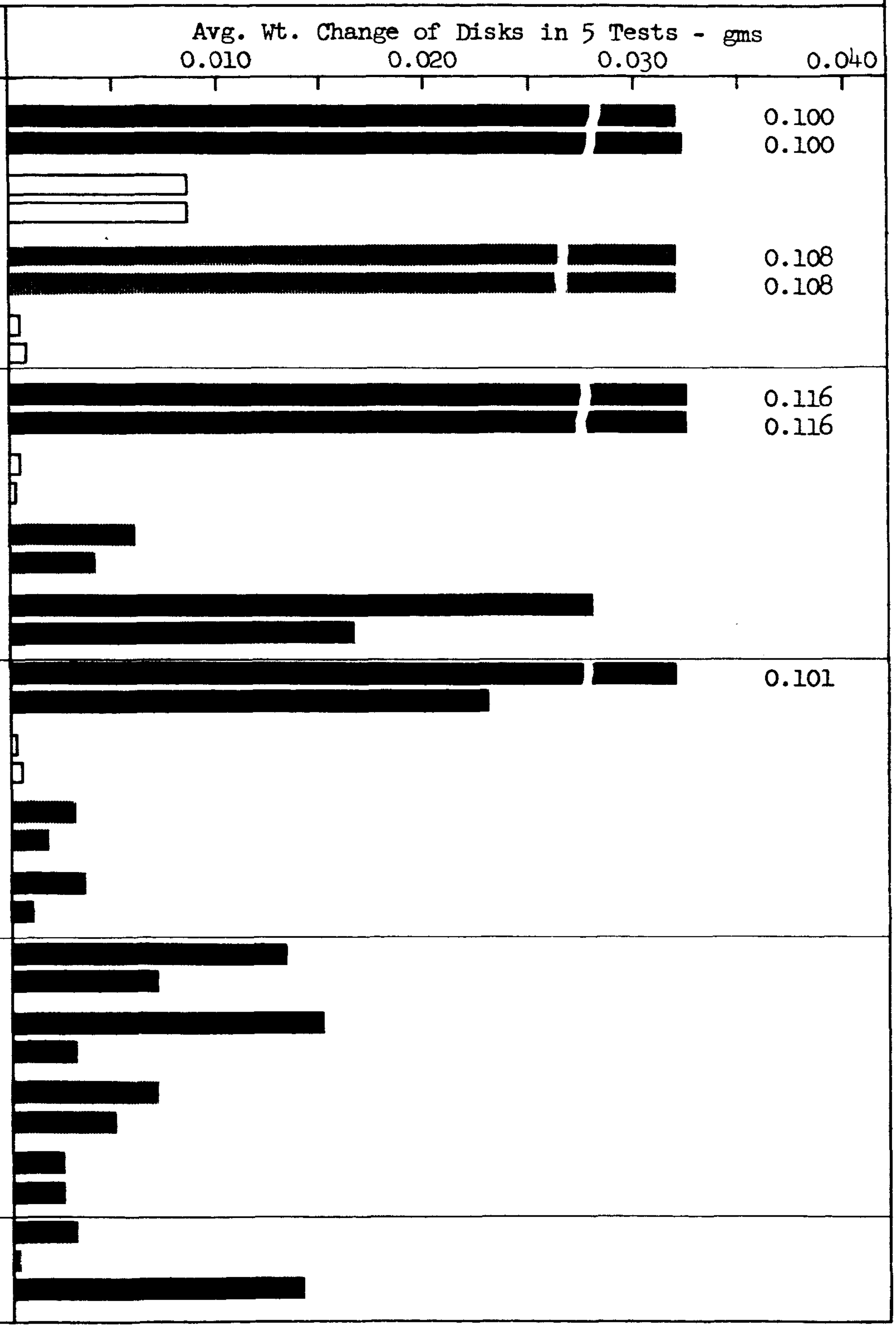
The disk weight loss data obtained in the first 10 tests included only the total weight loss for both the continuous and intermittent runs. These values are shown in the figure as an average weight change of both runs. In the later tests separate values were measured for each of the continuous and intermittent test runs.

In general, the greatest weight loss occurred on the disk and rider sets where the highest coefficient of friction was measured. The one exception was wear occurring on the silicone oil lubricated specimens. The wear debris in this case did not fall from the rubbing area but was held on the surface of the disk.

The best overall lubrication, considering all 3 lubricants, occurred in the H_2O vapor atmosphere. The one minor exception was the high rider wear rate when lubricated with the composite wiper as noted in Fig. 5. However, the unlubricated results in the H_2O vapor environment were similar to that experienced with unlubricated specimens in all of the other environments.

SLIDING WEAR OF DISKS - PER 100 HRS.

Test No.	Test Condition Lubr.	Test Condition Envir.	Avg. Wt. Change of Disks in 5 Tests - gms
1	None[1]	Vac.	0.100
2	None	Vac.	0.100
3	Fluid[1][2]	Vac.	
4	Fluid[1]	Vac.	
5	Film[1][3]	Vac.	0.108
6	Film[1]	Vac.	0.108
7	Comp.[1]	Vac.	
8	Comp.[1]	Vac.	
9	None[1]	CO_2	0.116
10	None[1]	CO_2	0.116
21	Fluid	CO_2	
22	Fluid	CO_2	
17	Film	CO_2	
18	Film	CO_2	
23	Comp.	CO_2	
24	Comp.	CO_2	
27	None	O_2	0.101
28	None	O_2	
25	Fluid	O_2	
26	Fluid	O_2	
31	Film	O_2	
32	Film	O_2	
29	Comp.	O_2	
30	Comp.	O_2	
11	None	H_2O	
12	None	H_2O	
13	Fluid	H_2O	
14	Fluid	H_2O	
15	Film[3]	H_2O	
16	Film[3]	H_2O	
19	Comp.	H_2O	
20	Comp.	H_2O	
33[4]	Fluid	H_2O	
34[4]	Film	H_2O	
35[4]	Comp.	H_2O	



[1] Average of total wear for both continuous and intermittent tests.

[2] Open bar signifies a weight gain.

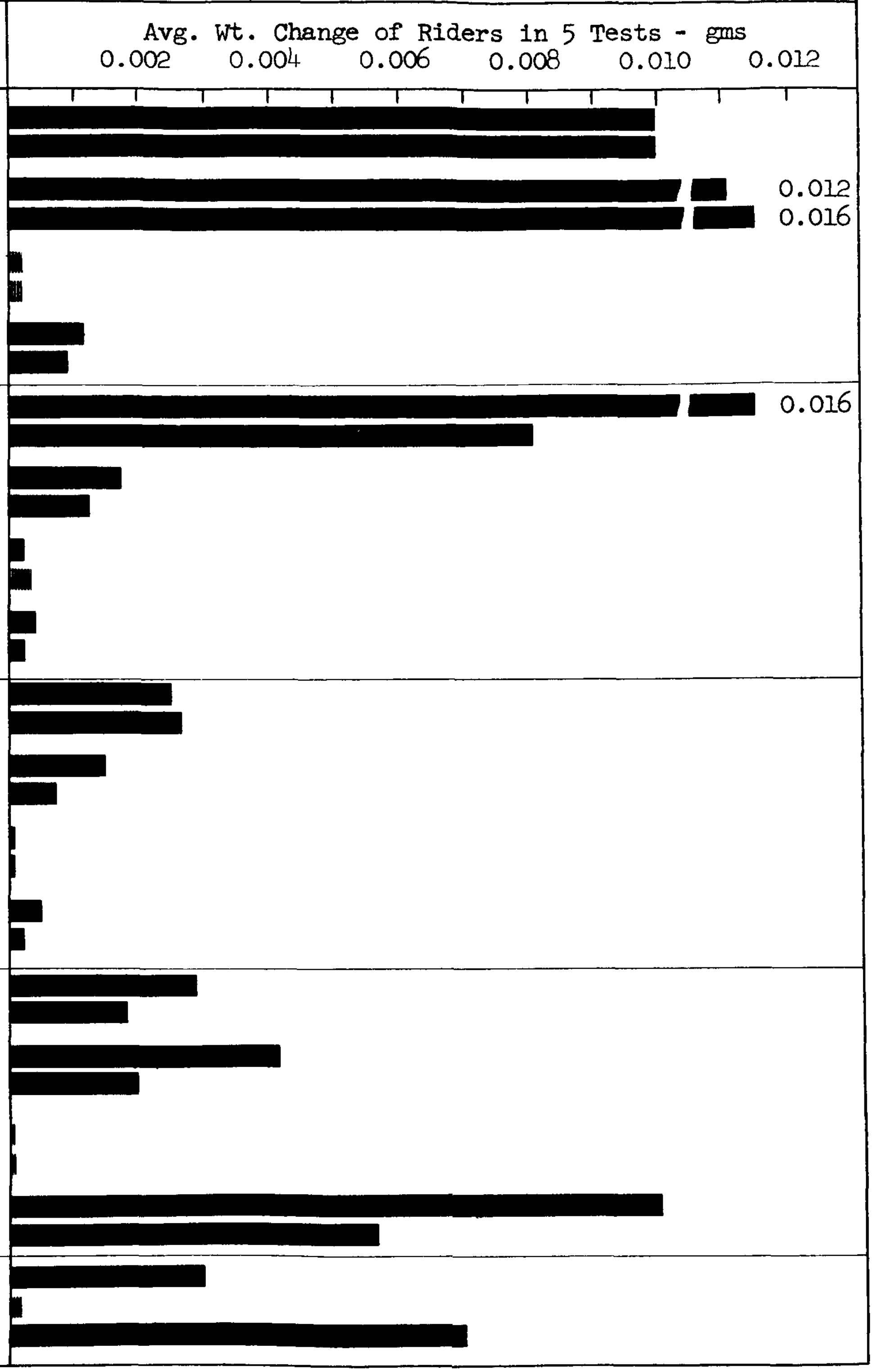
[3] Vertical marked bar signifies weight loss of lubricant with no loss of metal.

[4] Weight loss, gm./100 hrs. for 300 hour test.

Fig. 4 - Tabulation of Weight Change of Sliding Disks
Without and With Lubricants in Various Environments

SLIDING WEAR OF RIDERS - PER 100 HRS.

Test No.	Test Condition Lubr.	Test Condition Envir.
1	None	Vac.
2	None	Vac.
3	Fluid	Vac.
4	Fluid	Vac.
5(1)	Film	Vac.
6	Film	Vac.
7	Comp.	Vac.
8	Comp.	Vac.
9	None	CO_2
10	None	CO_2
21	Fluid	CO_2
22	Fluid	CO_2
17	Film	CO_2
18	Film	CO_2
23	Comp.	CO_2
24	Comp.	CO_2
27	None	O_2
28	None	O_2
25	Fluid	O_2
26	Fluid	O_2
31	Film	O_2
32	Film	O_2
29	Comp.	O_2
30	Comp.	O_2
11	None	H_2O
12	None	H_2O
13	Fluid	H_2O
14	Fluid	H_2O
15	Film	H_2O
16	Film	H_2O
19	Comp.	H_2O
20	Comp.	H_2O
33(2)	Fluid	H_2O
34(2)	Film	H_2O
35(2)	Comp.	H_2O



(1) Vertical marked bar signifies weight loss of lubricant with no loss of metal.
(2) Weight loss, gm./100 hrs. for 300 hr. test.

Fig. 5 - Tabulation of Weight Change of Sliding Riders Without and With Lubricants in Various Environments

The laminar film lubricant surfaces exhibited the lowest wear rate with all weight loss occurring in the film. Even the riders appeared to gain weight as a result of lubricant transfer from the film on the disks.

3. Friction and wear in 300 hour tests.

Three lubricated tests were made using each type of lubricant in an H_2O vapor environment for 300 hours. The H_2O environment was chosen because it provided the most effective overall aid in lubrication during the 100 hour tests and would be most likely to be present as an outgassing product of insulation, plastics, wiring or other materials found in the power section of the Apollo spacecraft.

The results of these extended duration tests are noted in Tables I and II with summary information in Figures 2 through 5.

The coefficient of friction for the sliding test No. 33S varied from 0.16 to 0.27 for the 5 individual rider and disk specimens. This variation was somewhat greater than that experienced in the 100 hour tests. It was noted, however, that the friction decreased during the test. The average decrease was 33% of the starting friction value. A weight loss on each disk and rider set occurred except with disk 48A where a weight gain was noted even though the rider was not in contact with the disk during that particular test run. The overall friction values and average wear rate of both rider and disk in the 300 hour runs was slightly lower than that of the 100 hour test.

The film lubricated sliding surfaces of tests No. 34S and 35S exhibited similar friction values and wear rates as those of the 100 hour duration runs in the H_2O vapor environment. Approximately 50 hours of operation was required for the coefficient of friction to reach the stable operating value, and it then remained relatively constant for the remainder of the tests. The composite and film lubricated tests were completed simultaneously in the same chamber.

B. Metal Surfaces in Rolling Contact

1. Friction in 100 hour tests.

The friction values measured in the rolling contact tests are presented as graphs in Fig. 6. Average coefficients of friction between

TABLE I
TEST 33S

SLIDING RIDERS AND DISKS WITH OIL LUBRICANT IN H_2O VAPOR ENVIRONMENT
300 HRS-32FT/MIN - 150 PSI LOAD.

Disk, Rider and Wick Data, gms.

Initial Weight					Weight Change		
Disk		Rider		Wick	Disk	Rider	Wick
No.	Weight	No.	Weight	Weight	Weight	Weight	Weight
44A	181.8467	141	4.1505	14.4323	-0.0032	-0.0050	-0.1433
45A	180.1446	142	4.1646	14.5359	-0.0036	-0.0041	-0.2064
46A	178.6667	143	4.1698	14.3407	-0.0055	-0.0061	-0.2252
47A	181.5218	144	4.1802	14.7372	-0.0040	-0.0032	-0.2688
48A	180.4311	145	4.1293	14.3402	+0.0005	--	-0.1952

FRICTION COEFFICIENT

Time	Disk No. 44A	45A	46A	47A	48A
Start	0.26	0.25	0.26	0.27	Rider
10	0.26	0.25	0.26	0.26	
20	0.25	0.25	0.27	0.26	became
30	0.24	0.24	0.28	0.25	
40	0.24	0.24	0.28	0.28	loose
50	0.25	0.24	0.26	0.27	
60	0.26	0.24	0.26	0.27	at
70	0.23	0.23	0.26	0.27	
80	0.23	0.23	0.25	0.27	start
90	0.24	0.23	0.23	0.26	
100	0.23	0.22	0.25	0.26	of
110	0.23	0.22	0.25	0.25	
120	0.22	0.18	0.25	0.24	test.
130	0.19	0.21	0.25	0.23	
140	0.22	0.21	0.25	0.24	No
150	0.21	0.21	0.26	0.25	
160	0.21	0.21	0.25	0.25	data
170	0.22	0.22	0.25	0.27	
180	0.21	0.21	0.25	0.26	obtained.
190	0.20	0.21	0.25	0.25	
200	0.19	0.19	0.24	0.25	
210	0.18	0.18	0.21	0.23	
220	0.18	0.19	0.19	0.23	
230	0.19	0.18	0.20	0.23	
240	0.17	0.17	0.20	0.23	
250	0.17	0.19	0.21	0.23	
260	0.20	0.20	0.21	0.22	
270	0.19	0.20	0.21	0.21	
280	0.17	0.19	0.21	0.19	
290	0.20	0.19	0.21	0.19	
300	0.16	0.16	0.19	0.17	

PRESSURE

The initial pressure before test was 10^{-9} torr. After admission of H_2O vapor pressure was maintained at 10^{-2} torr.

TABLE II
Test 34S and 35S

SLIDING RIDERS AND DISKS WITH SOLID LUBRICANTS IN H_2O VAPOR ENVIRONMENT
300 HRS. - 32 FT./MIN. - 150 PSI LOAD

Disk and Rider Data, gms.

Initial Weight				Lubricant Type	Weight Change	
Disk		Rider			Disk	Rider
No.	Weight	No.	Weight		Weight	Weight
57A	181.2998	158	4.2040	Film(1)	-0.0349	-0.0049
59A	178.1877	159	4.1682	Film	-0.0351	-0.0045
61A	184.3068	160	4.1808	Film	-0.0372	-0.0050
51A	181.7488	156	4.1795	Composite(2)	-0.0184	-0.0221
77A	180.6072	157	4.1850	Composite	-0.0229	-0.0183

FRICTION COEFFICIENT

Time	Disk No. 57A	59A	61A	51A	77A
Start	0.08	0.08	0.10	0.71	0.63
10	0.05	0.04	0.07	0.73	0.59
20	0.09	0.09	0.07	0.72	0.45
30	0.12	0.09	0.11	0.64	0.48
40	0.15	0.13	0.14	0.64	0.52
50	0.09	0.17	0.13	0.54	0.45
60	0.12	0.20	0.21	0.60	0.52
70	0.17	0.20	0.20	0.52	0.48
80	0.09	0.20	0.21	0.52	0.46
90	0.12	0.24	0.24	0.52	0.44
100	0.12	0.22	0.20	0.61	0.40
110	0.16	0.20	0.28	0.60	0.43
120	0.14	0.22	0.24	0.61	0.52
130	0.12	0.20	0.19	0.61	0.55
140	0.17	0.18	0.14	0.60	0.53
150	0.14	0.20	0.14	0.61	0.48
160	0.10	0.20	0.12	0.61	0.51
170	0.10	0.16	0.12	0.60	0.44
180	0.08	0.04	0.07	0.61	0.48
190	0.07	0.07	0.08	0.50	0.45
200	0.06	0.07	0.04	0.48	0.49
210	0.09	0.11	0.04	0.46	0.43
220	0.12	0.08	0.06	0.48	0.49
230	0.12	0.09	0.09	0.50	0.43
240	0.14	0.08	0.06	0.46	0.45
250	0.16	0.09	0.06	0.46	0.40
260	0.16	0.10	0.08	0.48	0.43
270	0.16	0.11	0.11	0.53	0.40
280	0.16	0.09	0.12	0.46	0.34
290	0.17	0.18	0.12	0.48	0.43
300	0.14	0.19	0.12	0.48	0.40

PRESSURE

The initial pressure before test was 10^{-9} torr. After admission of H_2O vapor, the pressure was maintained at 10^{-2} torr.

(1) Test 34
(2) Test 35

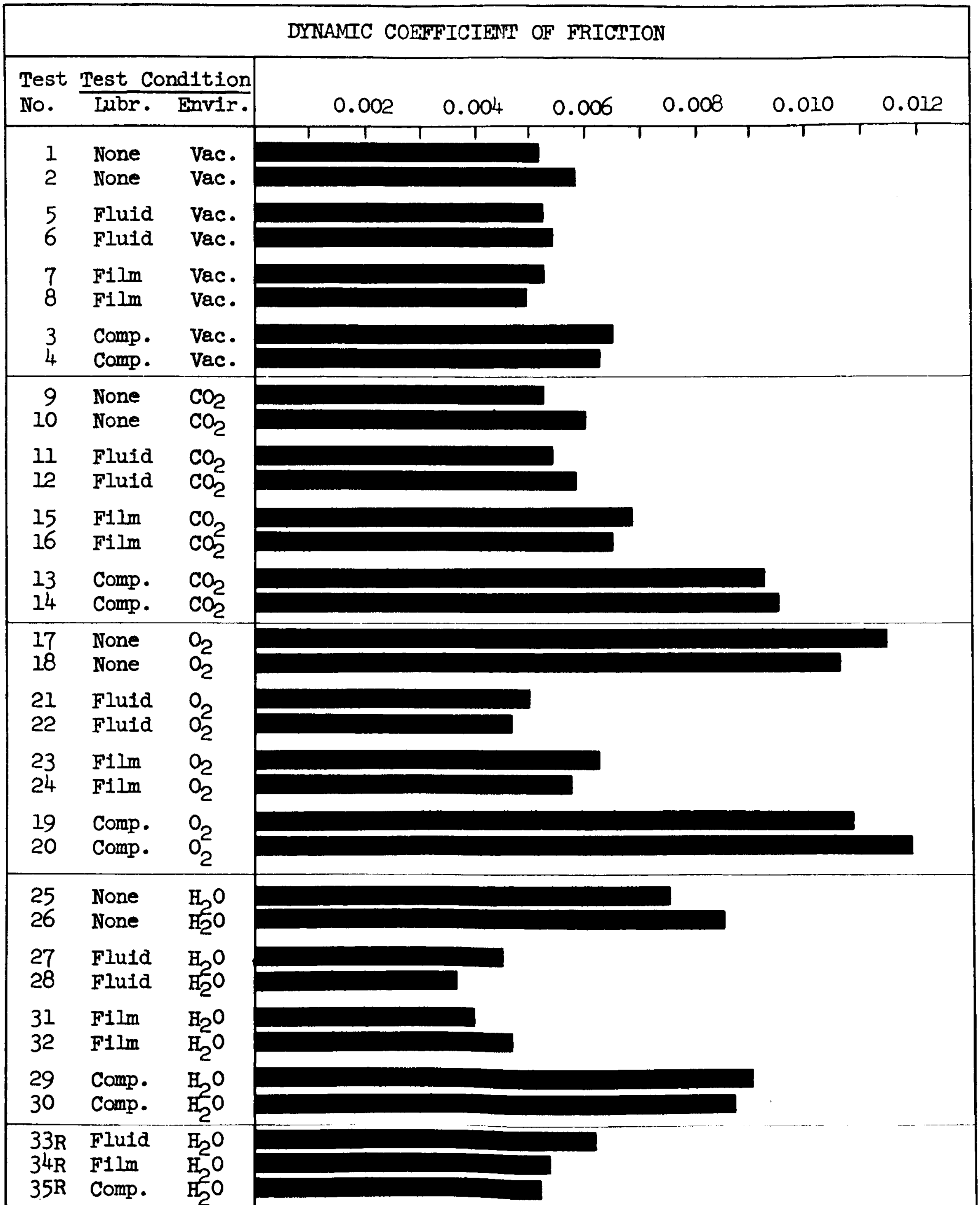


Fig. 6 - Tabulation of Coefficient of Rolling Friction
Without and With Lubricants
in Various Environments

individual test sets of each test varied from 0.004 to 0.012. The coefficient of friction measured for the unlubricated bearings was similar in value to that measured for one or more of the lubricated bearings in the same environment. For the UHV environment coefficient of friction ranged from 0.005 to 0.006 for the unlubricated bearings; and from 0.005 to 0.007 for the fluid, laminar film or composite retainer lubricated bearings.

In the CO_2 environmental tests, frictional values were the same as those measured in the UHV environment except for the composite retainer lubricated bearings which had a higher coefficient of friction.

The friction of both unlubricated bearings and composite retainer lubricated bearings were high in an O_2 atmosphere. These coefficient of friction values of 0.010 to 0.012 were the highest of all of the bearings tested.

Bearing operation in the H_2O vapor environment was similar to that of the O_2 atmosphere except the friction values were proportionately lower. Both fluid and laminar film lubricated bearings exhibited the lowest friction of all the bearing tests.

2. Wear rates in 100 hour tests.

A summary of the wear data of the bearing tests is presented in graphic form. Wear of the bearing races is noted in Fig. 7. A transfer of material occurred in every test. The races of the laminar film lubricated bearings had no metallic wear but lost only film lubricant. This loss was the greatest for the CO_2 and vacuum environment.

The metallic weight loss of the races in the other tests was extremely small. The measured losses for the unlubricated tests were lower than most of the other tests; however, in the 7 tests covering all the various environments, a transfer of metal from the brass retainer was evident as shown by a weight gain of the races. The weight change of the balls is shown in Fig. 8.

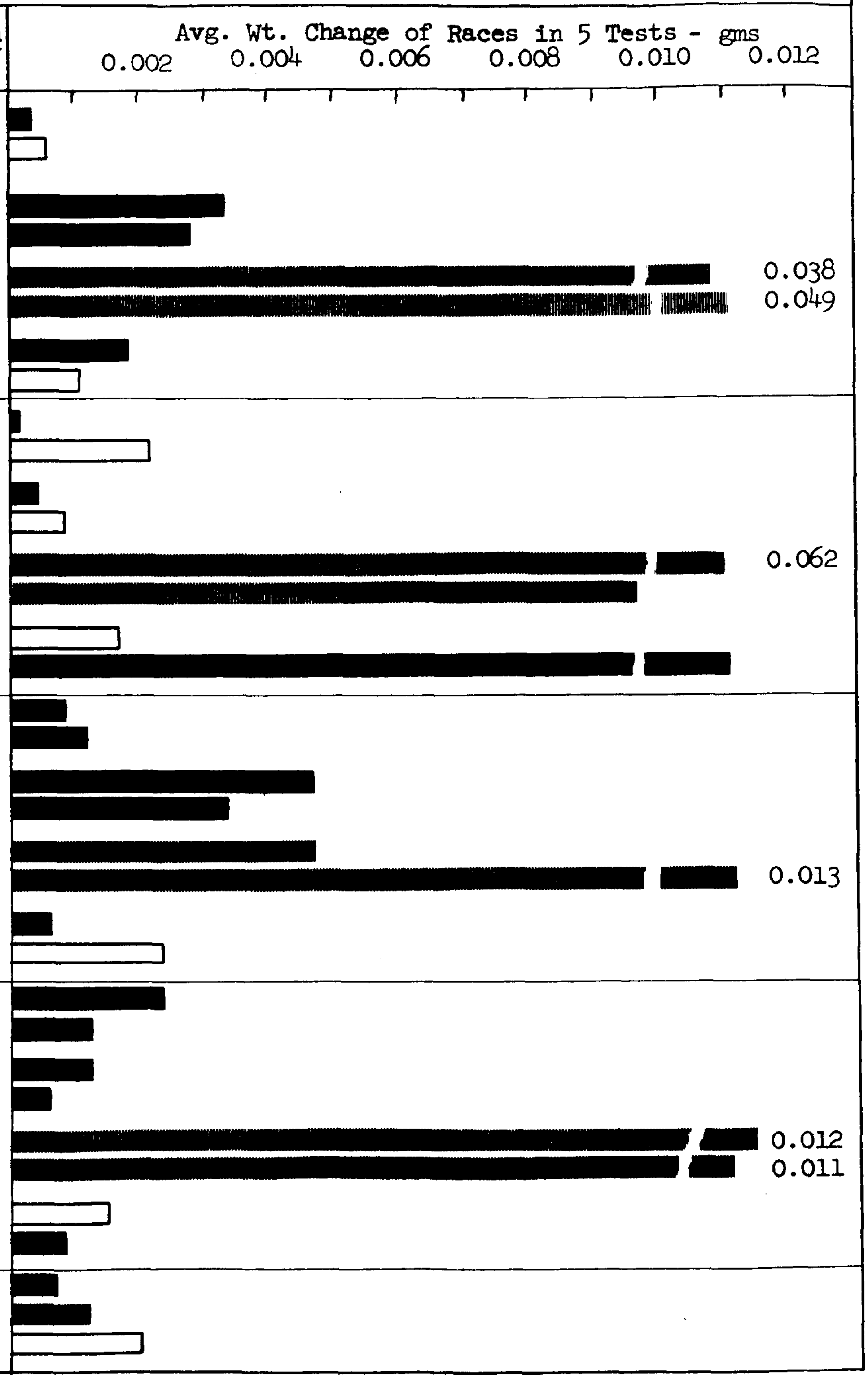
In general, the lowest metal weight loss was observed for the races in the lubricated tests in the H_2O vapor environment.

3. Friction and wear in 300 hour tests.

Friction characteristics of the extended tests in an H_2O vapor environment were similar to the corresponding results of the 100 hour tests

ROLLING WEAR OF BEARINGS - PER 100 HRS.

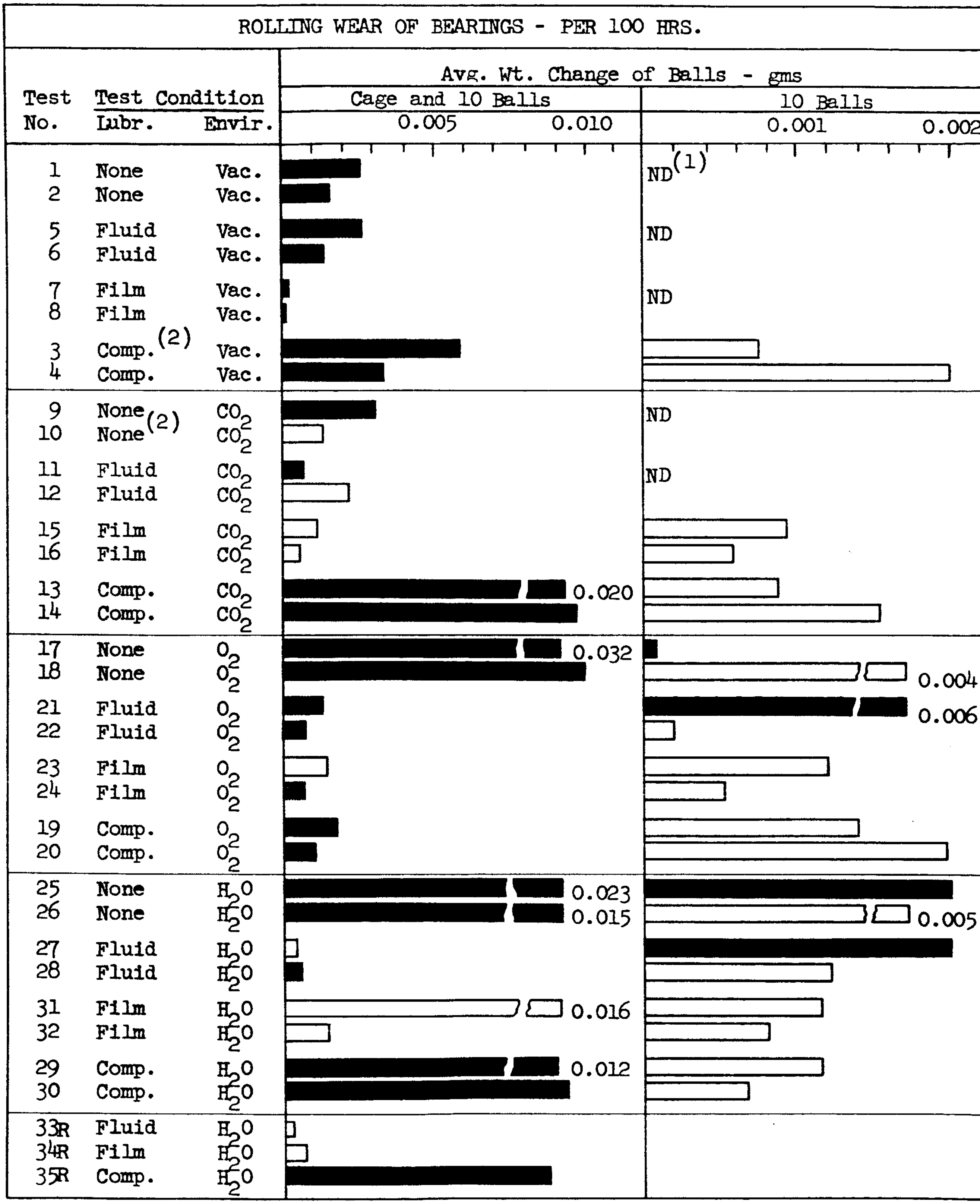
Test No.	Test Condition Lubr.	Envir.
1	None	Vac.
2	None(1)	Vac.
5	Fluid	Vac.
6	Fluid	Vac.
7	Film(2)	Vac.
8	Film(2)	Vac.
3	Comp.	Vac.
4	Comp.	Vac.
9	None	CO_2
10	None	CO_2
11	Fluid	CO_2
12	Fluid	CO_2
15	Film	CO_2
16	Film	CO_2
13	Comp.	CO_2
14	Comp.	CO_2
17	None	O_2
18	None	O_2
21	Fluid	O_2
22	Fluid	O_2
23	Film	O_2
24	Film	O_2
19	Comp.	O_2
20	Comp.	O_2
25	None	H_2O
26	None	H_2O
27	Fluid	H_2O
28	Fluid	H_2O
31	Film	H_2O
32	Film	H_2O
29	Comp.	H_2O
30	Comp.	H_2O
33R	Fluid	H_2O
34R	Film	H_2O
35R	Comp.	H_2O



(1) Open bar signifies a weight gain.

(2) Vertical marked bar signifies weight loss of film lubricant with no loss of meta

Fig. 7 - Tabulation of Weight Change of Bearing Races
Without and With Lubricants
in Various Environments



(1)Not determined.

(2)Open bar signifies a weight gain.

Fig. 8 - Tabulation of Weight Change of Bearing Cage and Balls Without and With Lubricants in Various Environments

TABLE III

TEST 33R

ROLLING BEARINGS WITH OIL LUBRICANT IN H_2O VAPOR ENVIRONMENT
300 HRS. - 150 RPM - 2 LB. LOAD

Bearing Weight Data - gms

	Initial Weight				Weight Change			
	Races				Races			
Brg.	Upper	Lower	Balls	Cage	Upper	Lower	Balls	Cage
189	48.842	42.338		48.9748	-0.002	NC		+0.001
190	42.252	42.241	10.0039	38.8771	-0.001	-0.001	-0.0001	+0.001
191	42.500	42.550		49.1936	-0.002	-0.001		+0.001
192	42.507	42.412	10.0021	38.8039	-0.002	-0.002	-0.0001	+0.001
193	42.520	42.432		49.0433	-0.001	-0.002		+0.001

FRICTION COEFFICIENT

Time	Bearing Number 189	190	191	192	193
Start	0.0054	0.0070	0.0040	0.0042	Brg.
10	0.0052	0.0069	0.0036	0.0046	
12	0.0054	0.0072	0.0038	0.0044	operated
30	0.0054	0.0060	0.0032	0.0048	
40	0.0054	0.0066	0.0034	0.0042	but
50	0.0054	0.0064	0.0034	0.0044	
60	0.0057	0.0064	0.0038	0.0040	no
70	0.0054	0.0061	0.0038	0.0042	
80	0.0058	0.0072	0.0038	0.0044	data
90	0.0058	0.0072	0.0039	0.0046	
110	0.0054	0.0078	0.0040	0.0046	obtained
110	0.0054	0.0084	0.0040	0.0046	
120	0.0054	0.0082	0.0038	0.0048	because
130	0.0054	0.0082	0.0038	0.0048	
140	0.0056	0.0080	0.0038	0.0048	of
150	0.0054	0.0084	0.0040	0.0050	
160	0.0056	0.0084	0.0040	0.0052	strain
170	0.0056	0.0088	0.0040	0.0052	
180	0.0056	0.0090	0.0040	0.0054	gage
190	0.0058	0.0094	0.0040	0.0054	
200	0.0058	0.0096	0.0042	0.0056	circuitry
210	0.0060	0.0096	0.0042	0.0058	
220	0.0062	0.0096	0.0044	0.0058	failure
230	0.0064	0.0096	0.0040	0.0058	
240	0.0066	0.0096	0.0046	0.0060	
250	0.0072	0.0096	0.0044	0.0060	
260	0.0074	0.0096	0.0046	0.0060	
270	0.0074	0.0098	0.0046	0.0060	
280	0.0074	0.0098	0.0048	0.0062	
290	0.0074	0.0098	0.0048	0.0062	
300	0.0074	0.0098	0.0048	0.0062	

PRESSURE

The initial pressure before test was 10^{-9} torr. After admission of H_2O vapor, the pressure during test was maintained at 10^{-5} torr.

TABLE IV
Test 34R and 35R

ROLLING BEARINGS WITH SOLID LUBRICANTS IN H_2O VAPOR ENVIRONMENT
300 HRS. - 150 RPM - 2 LB. LOAD

Bearing Weight Data - gms.

	Initial Weight					Weight Change			
	Races					Races			
Brg.	Upper	Lower	Balls	Cage		Upper	Lower	Balls	Cage
194	42.5096	42.0027	9.9991	38.9254	A(1)	-0.0021	-0.0020	+0.0009	+0.0025
195	41.9146	42.0883	9.9980	38.9407	A	-0.0034	-0.0014	+0.0020	+0.0015
186	42.3761	42.8559	9.9996	41.2475	B(2)	+0.0025	+0.0025	+0.0033	-0.0120
187	42.7379	42.1907	10.0006	41.9333	B	+0.0036	+0.0026	+0.0024	-0.0212
188	42.4017	42.4926	10.0011	41.2721	B	+0.0039	+0.0023	+0.0031	-0.0469

FRICTION COEFFICIENT

	Bearing Number				
Time	194	195	186	187	188
Start	0.0083	0.0052	0.0061	0.0077	0.0043
10	0.0079	0.0051	0.0061	0.0076	0.0037
20	0.0071	0.0052	0.0060	0.0071	0.0035
30	0.0080	0.0060	0.0067	0.0077	0.0030
40	0.0063	0.0058	0.0065	0.0068	0.0028
50	0.0056	0.0055	0.0069	0.0068	0.0028
60	0.0065	0.0056	0.0057	0.0068	0.0028
70	0.0068	0.0051	0.0067	0.0070	0.0029
80	0.0069	0.0051	0.0071	0.0077	0.0031
90	0.0069	0.0050	0.0072	0.0073	0.0032
100	0.0070	0.0050	0.0071	0.0073	0.0031
110	0.0068	0.0048	0.0070	0.0072	0.0030
120	0.0062	0.0048	0.0065	0.0066	0.0032
130	0.0062	0.0048	0.0064	0.0060	0.0034
140	0.0066	0.0056	0.0064	0.0064	0.0034
150	0.0060	0.0057	0.0064	0.0064	0.0048
160	0.0060	0.0053	0.0064	0.0060	0.0037
170	0.0060	0.0054	0.0064	0.0058	0.0042
180	0.0065	0.0053	0.0068	0.0056	0.0040
190	0.0066	0.0057	0.0062	0.0058	0.0041
200	0.0062	0.0059	0.0060	0.0052	0.0036
210	0.0048	0.0056	0.0054	0.0053	0.0032
220	0.0042	0.0056	0.0060	0.0054	0.0032
230	0.0047	0.0054	0.0048	0.0050	0.0038
240	0.0052	0.0053	0.0048	0.0053	0.0039
250	0.0046	0.0058	0.0046	0.0055	0.0031
260	0.0046	0.0059	0.0040	0.0050	0.0038
270	0.0042	0.0057	0.0040	0.0050	0.0038
280	0.0042	0.0052	0.0040	0.0050	0.0036
290	0.0040	0.0055	0.0040	0.0050	0.0038
300	0.0040	0.0052	0.0040	0.0044	0.0037

PRESSURE

The initial pressure before test was 10^{-9} torr. After admission of H_2O vapor, the pressure during test was maintained at 10^{-5} torr.

(1) Test 34 Film Lubr.
(2) Test 35 Composite Lubr.

although the absolute values were lower for the longer operation. Most effective lubrication was provided by the laminar film lubricant. Friction of the fluid lubricant gradually increased during test which was the result of formation of a grease like material on the bearing races. This material apparently was the result of cleavage of the halophenyl group to produce a waxy type stable silanol or an unstable silanol which would crosslink with other silanol groups. The composite retainer lubricated bearing exhibited slightly lower friction values and appeared to have a slightly improved film transfer from the cage. Reference is made to Tables III and IV and Fig. 6.

A significant difference was noted in the wear rates of the bearing components during the 300 hour tests as compared to the previous 100 hour tests. The laminar film loss from the races was much smaller for the 300 hour tests with a correspondingly thinner film deposited on the balls. The composite retainer lubricated bearings exhibited the same weight gain on the races but showed a marked decrease in metal loss from the balls. This may indicate the film forming tendency of the composite is slow in the initial operation of a bearing and that a run-in treatment may be effective in promoting longer bearing life. The fluid lubricated bearing exhibited the same wear rates as the noted rates in the 100 hour tests, see Figures 7 and 8.

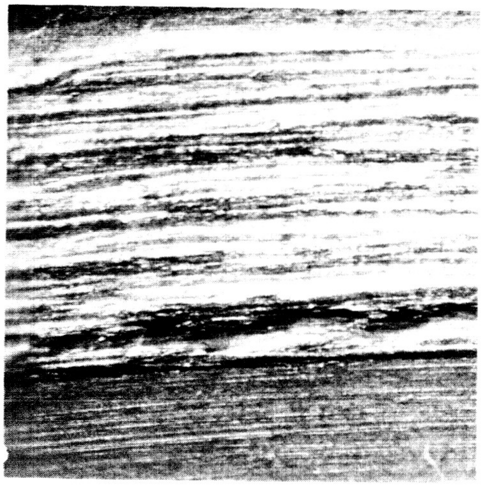
III. ANALYSIS OF WEAR OF SURFACES AFTER TEST

The measured parameters of friction and wear reveal considerable information regarding the degree of lubrication effectiveness. Further insight also can be gathered from actual study of the rubbing or rolling surfaces.

A. Optical inspection of sliding disks.

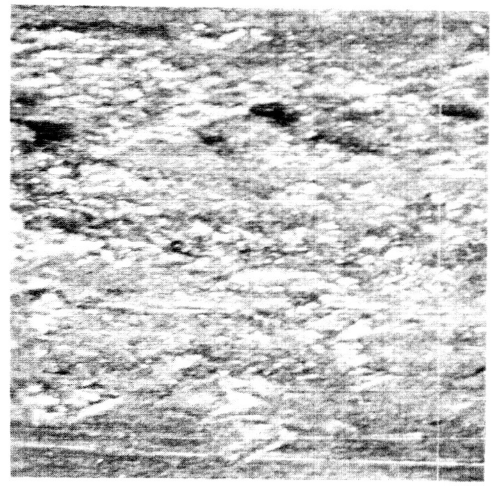
Disks from the sliding tests were viewed under broad angle optical microscope to examine the wear patterns and note the method of lubricant transfer. Photographs of selected disks at 24 x magnification are included as Figures 9 through 13.

Representative wear surfaces from the unlubricated and lubricated tests in the ultrahigh vacuum environment are shown in Fig. 9. The smooth area in the lower portion of test No. 1 is representative of the new or unrubbed surfaces on all the disks. The severe metal transfer (galling) can be observed in the unlubricated test. The surface lubricated by the silicone oil



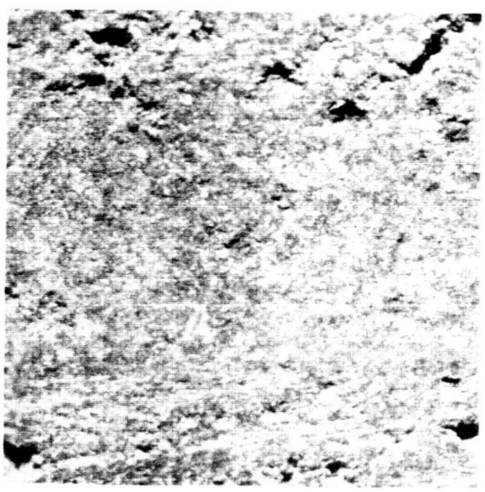
Test No. 1 24X

No Lubricant



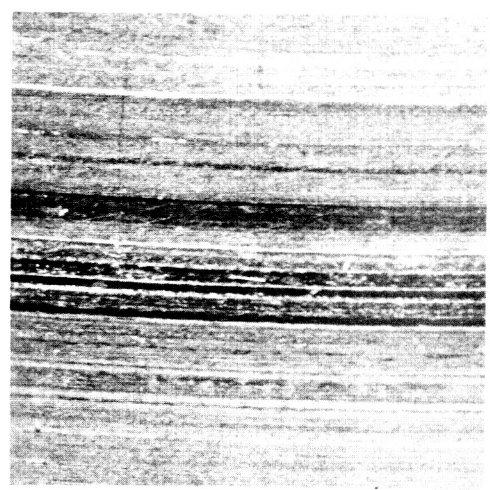
Test No. 3 24X

Fluid Lubricant



Test No. 5 24X

Film Lubricant



Test No. 7 24X

Composite Lubricant

Fig. 9 - Disk Surfaces After 100 Hrs. Test Without and With Various Lubricants in a 10^{-9} Torr Vacuum Environment

oil also exhibited severe metal transfer but the track was more polished making the effective area of contact larger.

In test No. 5 both the wear track and virgin surfaces of the laminar film are shown. The thickness of the laminar film used in these first test series was sufficiently thick (over 0.030 in.) to insure that no film wear-through resulting in metal transfer of the disk would occur. The holes or voids in this film were the result of baking the coating prior to the sliding test. Later tests were made on disks with film thicknesses in the order of 0.003 to 0.005 inches.

Actual wear of the laminar film in the wear track was less than that expected and the thinner films were found to be satisfactory.

Wear of the composite wiper and disk continued in the lubricated tests even though transfer of the composite to the disk to establish a lubricating film had been established. For effective lubrication higher composite transfer rates are needed to cover the remaining rubbing area and possibly provide a thicker lubricating film.

A photograph of the wear track of a disk surface from the CO_2 environment is shown in Fig. 10. The mechanism of wear for the laminar film lubricated surfaces appeared to be similar to that in the ultrahigh vacuum environment. The wear track of the fluid lubricated specimens was narrower and smoother than that of the UHV which indicated transfer of smaller metal particles. In the composite wiper lubricated disk, incomplete lubrication existed although the film was thicker but not as continuous as that of the fluid.

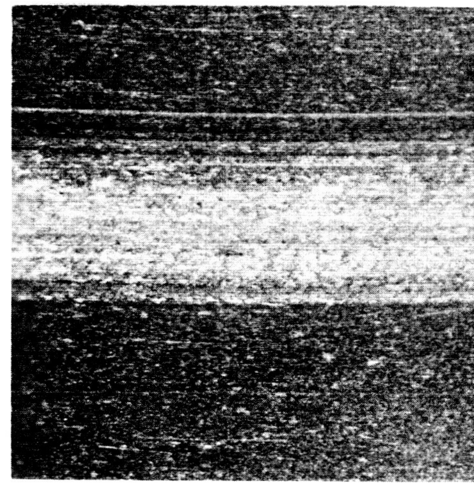
Surface damage resulting on specimens sliding in an O_2 environment is shown in Fig. 11. In general, the wear pattern appears similar to that obtained in a CO_2 environment. Even though the laminar film was reduced to 0.005 in thickness, no metallic wear occurred.

The results of disk wear in the H_2O vapor environment are shown in Fig. 12. The wear tracks of the unlubricated and fluid lubricated disks were less severe than those obtained in a vacuum environment. A different type of metal transfer was noted for the film lubricated disk. Wear debris remained in the rubbing area and was of lower density than the virgin material.

The wear of the lubricated surfaces for the 300 hour tests are shown in Fig. 13. More wear was evident in both the film and composite wiper lubricated disk surfaces. A low density, laminar film wear debris was formed and was similar to that observed in the 100 hour H_2O vapor environment test.

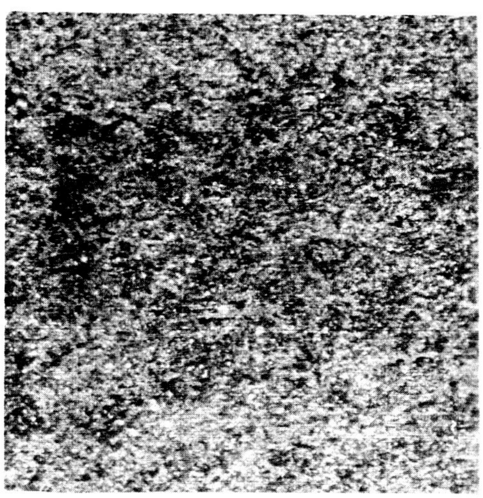
Test No. 9 24X

No Lubricant



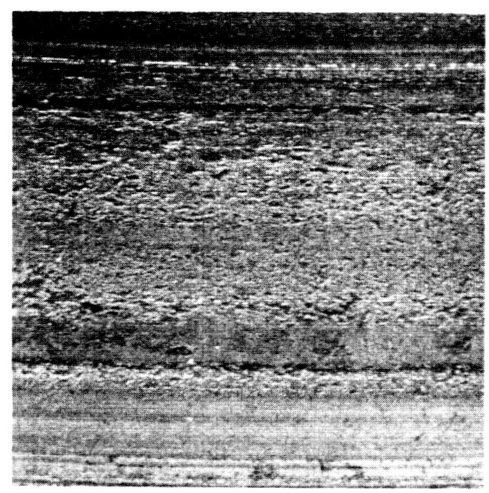
Test No. 21 24X

Fluid Lubricant



Test No. 17 24X

Film Lubricant



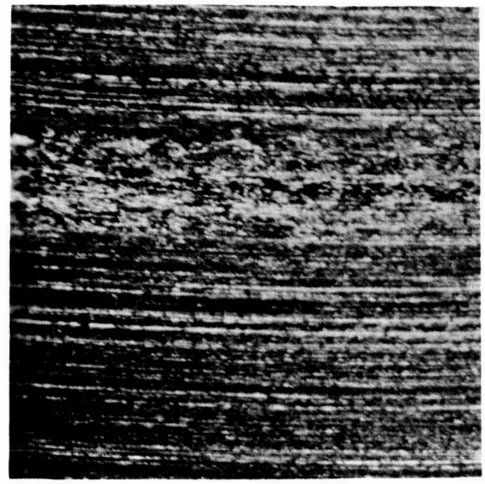
Test No. 23 24X

Composite Lubricant

Fig. 10 - Disk Surfaces After 100 Hrs. Test Without and With Various Lubricants in a Clean 10^{-2} Torr CO_2 Environment

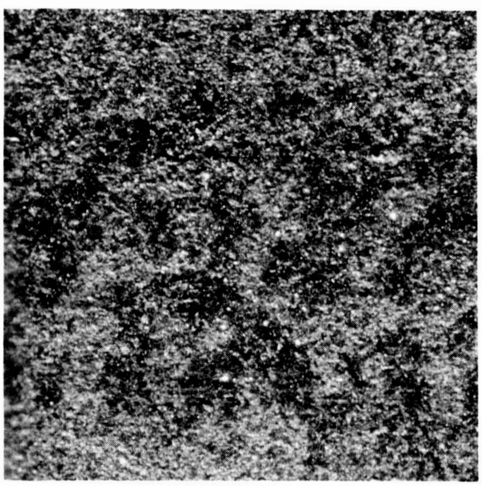
Test No. 27 24X

No Lubricant



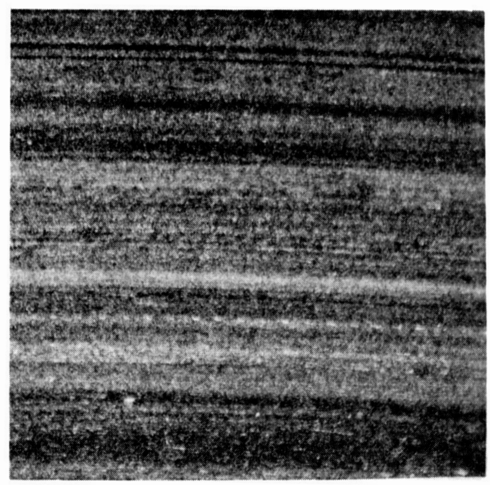
Test No. 25 24X

Fluid Lubricant



Test No. 31 24X

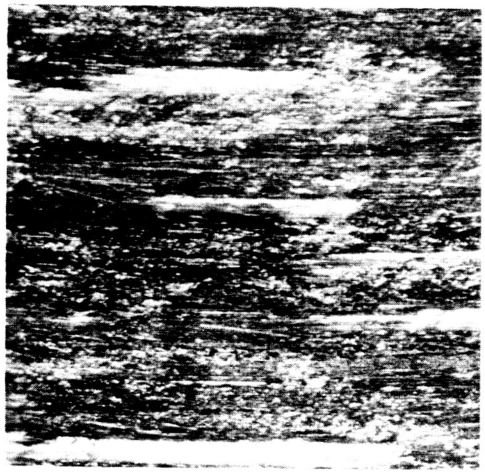
Film Lubricant



Test No. 29 24X

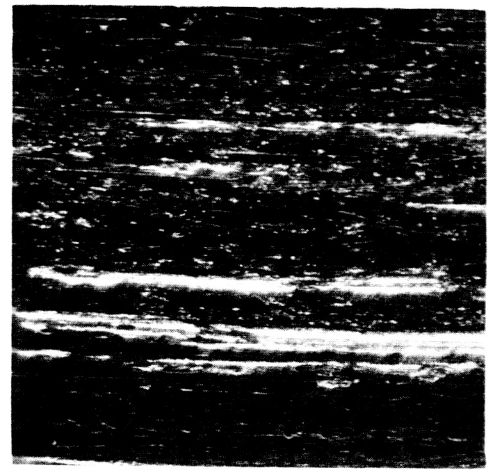
Composite Lubricant

Fig. 11 - Disk Surfaces After 100 Hrs. Test Without and With Various Lubricants in a Clean 10^{-2} Torr O_2 Environment



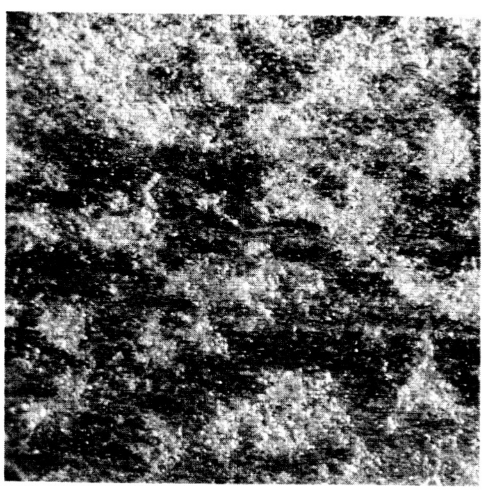
Test No. 11 24X

No Lubricant



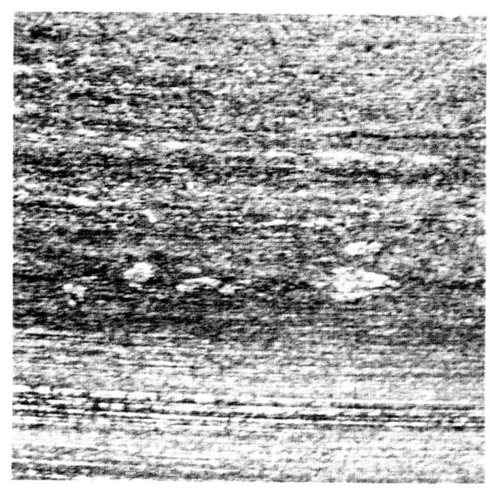
Test No. 13 24X

Fluid Lubricant



Test No. 15 24X

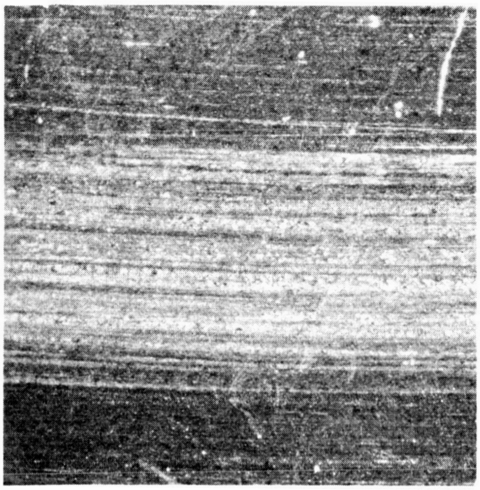
Film Lubricant



Test No. 19 24X

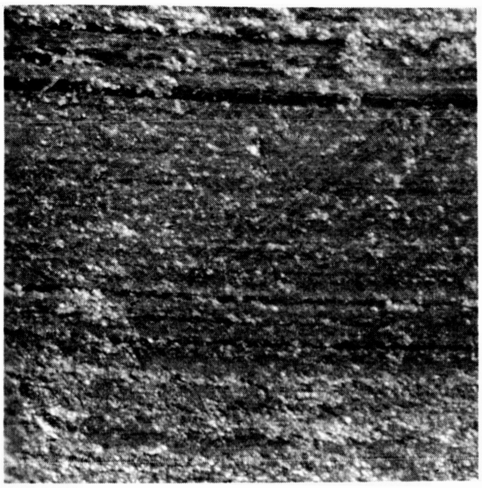
Composite Lubricant

Fig. 12 - Disk Surfaces After 100 Hrs. Test Without and With Various Lubricants in a Clean 10^{-2} Torr H_2O Vapor Environment



Test No. 33 24X

Fluid Lubricant



Test No. 34 24X

Film Lubricant

Test No. 35 24X

Composite Lubricant

Fig. 13 - Disk Surfaces After 300 Hrs. Test
With Various Lubricants
in a Clean 10^{-2} Torr
H_2O Vapor Environment

B. Electron microscope inspection of bearing races.

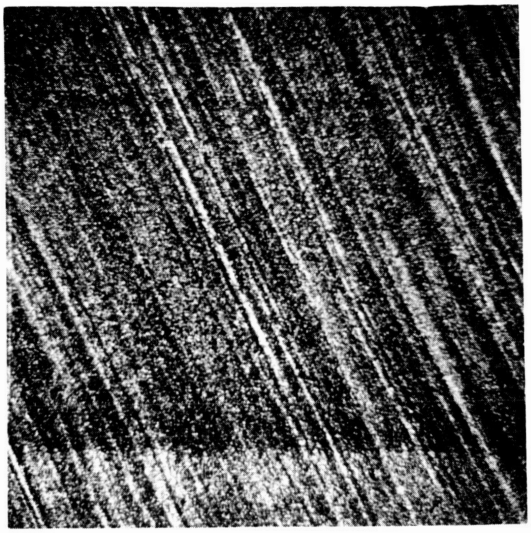
Preliminary examination of the bearing race grooves were made in a visual microscope and only the faintest wear scars could be detected even under large magnification. Most information was obtained after viewing the components in a scanning electron beam microscope. Photographs were taken of the cathode tube image of the surface contour of the bearing races and are shown as Figures 14 through 21. The resolution of the microscope is equivalent to a camera with an aperture of 400. This provides a great depth of focus and a vertical distance of 2 mils can be obtained at a magnification of 500X. The depressions in the target surface are shown as dark areas and the elevated surfaces as light areas. The white areas are materials of different density than that of the main surface. Two different image tubes were used in this program to produce photographs of considerable different contrast and texture. The same information can be obtained from either photograph. In general magnifications of 250X, 500X and 750X provided most information for visual analysis.

The ball path of a new bearing race is shown in Fig. 14. The lap marks which produced a 4 rms finish on the ball path are noted. The same level of light color indicated a good level of uniformity in the lapping operation.

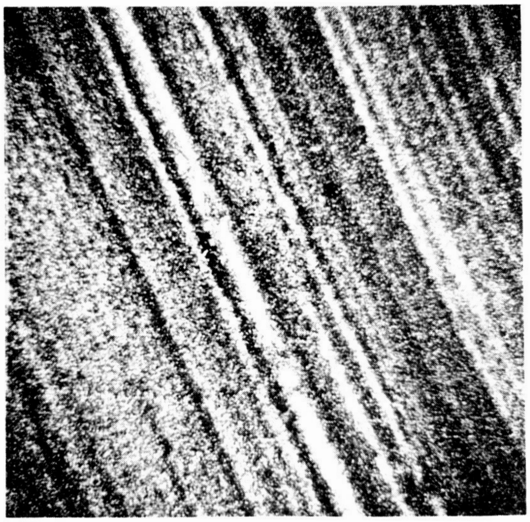
The wear track of an unlubricated bearing operated in a vacuum is shown in Fig. 15. The amount of ploughing or galling was extremely light as verified by weight loss measurements and friction determinations. Only small pockets of race material have been removed from the ball path in the photograph. A greater bearing load or higher speed would have resulted in a greater energy transfer and thus more surface damage. Although not noticeable in black and white photographs, post test examination revealed that some balls had a distinct difference in surface color that indicated the presence of a lubricating or contaminate coating. Most noticeable film buildup on the balls occurred in the composite cage lubricated tests. However, only 3 or 4 of the 10 balls were coated in each test bearing.

Photographs of an unlubricated bearing operated in a clean, 10^{-5} torr, CO_2 environment are shown in Fig. 16. No physical change was observed in components of the various bearings lubricated in the CO_2 environment except a slight darkening of all the balls in the unlubricated tests and some of the balls in the composite and film lubricated tests.

Ball Path 250X

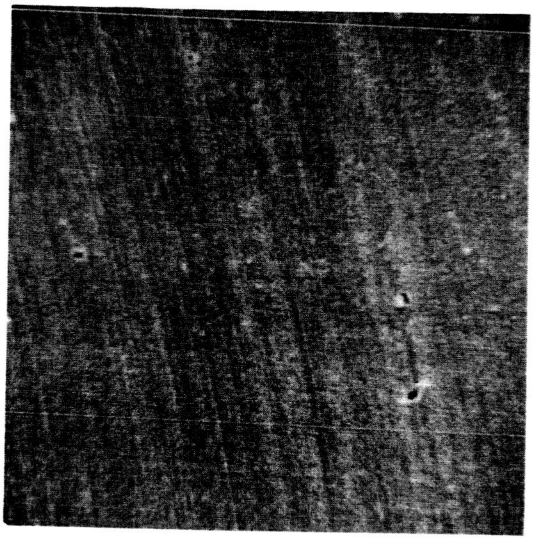


Ball Path 500X



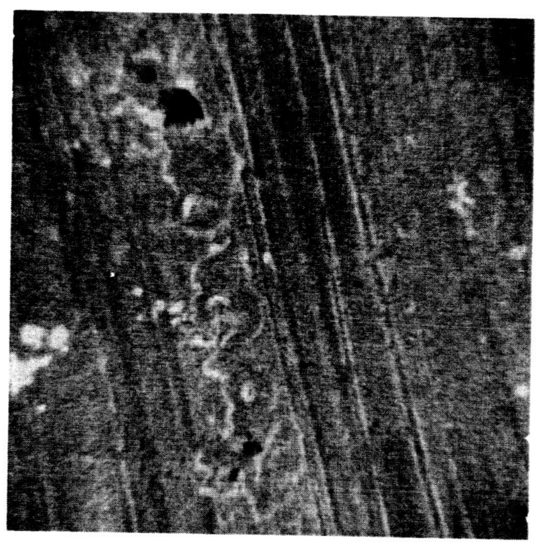
Ball Path 750X

Fig. 14 - Ball Bearing Race Groove of New Bearing Before Test



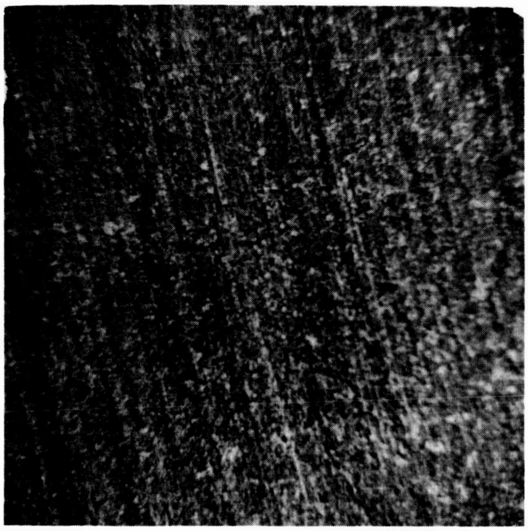
Ball Path 250X

Ball Path 500X

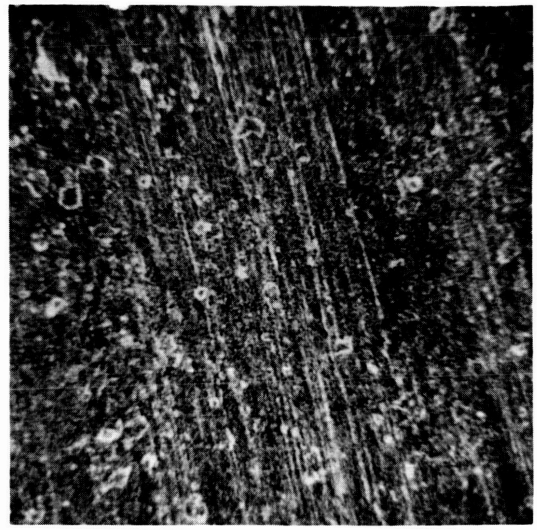


Ball Path 750X

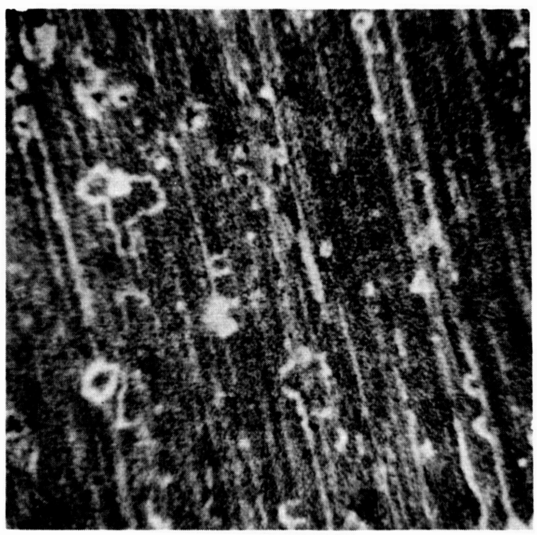
Fig. 15 - Ball Bearing Race Groove After 100 Hrs. in Test No. 1 Without a Lubricant in a Clean 10^{-9} Torr Vacuum Environment



Ball Path 250X



Ball Path 500X



Ball Path 750X

Fig. 16 - Ball Bearing Race Groove After 100 Hrs. in Test No. 10 Without a Lubricant in a Clean 10^{-5} Torr CO_2 Environment

Representative results of unlubricated rolling wear in an O_2 environment is shown in Fig. 17. The formation of a film of low density material is evident, more so than that obtained in the CO_2 environment. However, the coating is still sparse and consists of particles approximately 150 microns in diameter. The balls also had a coating as noted by the dark color. A black ring was observed in the rubbing area of the ball pockets. With the exception of the film buildup on the composite lubricated balls, the components of these bearings did not exhibit any change from that of unused bearings.

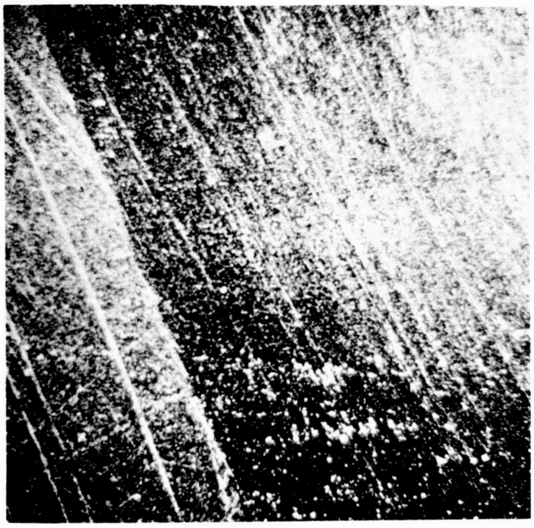
The results of bearing wear in an H_2O vapor atmosphere are shown in Fig. 18. A pronounced change in the surface has occurred, much greater than that noted in the unlubricated ultrahigh vacuum or by gas environments. However, this film did not cause a significant change in friction or wear characteristics.

The results of the 300 hour lubricated extended duration rolling tests are shown in the photographs of Figures 19 through 21. In Fig. 19, the ball path of the race groove lubricated with the silicone oil lubricant shows a relatively heavy film of a material less dense than the steel but more dense than the silicone oil. A further examination of the surface revealed a waxy material had formed and covered the ball path. The film shown in the photograph has a higher density than the wax and must be the result of a reaction between the steel and H_2O vapor.

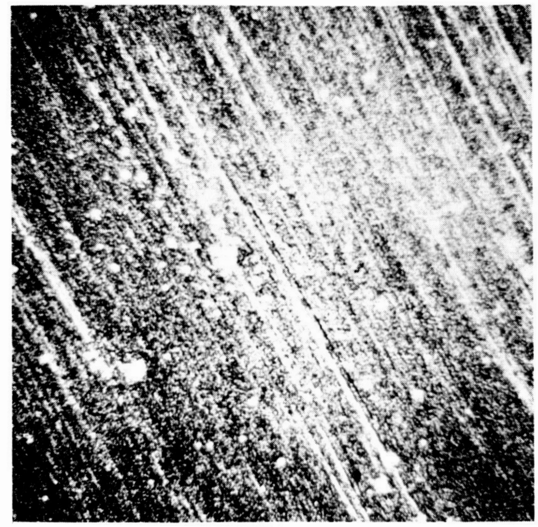
The laminar film lubricated surface is shown in the photograph of Fig. 20. The surface is the lubricant film and is similar to that seen in the optical microscope. The light colored area is the less dense coating and is probably wear debris. The composite lubricated surface is shown in Fig. 21. A film is visible in the surface but it is extremely thin and was deposited in the lap mark grooves of the bearing. Even though wear has occurred in the race sufficient virgin metal remains to show the contour of the grinding or lapp marks.

C. Special analysis of disk and rider.

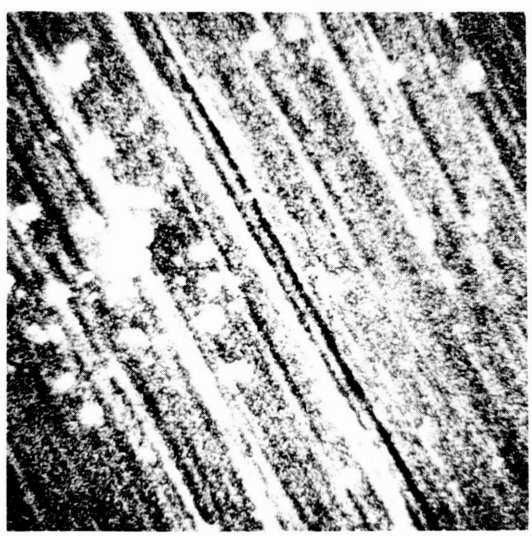
One special test was run on the sliding wear and friction apparatus in which unlubricated disk and rider couples were operated in an ultrahigh vacuum. Prior to the test a small amount of WSe_2 composite with



Ball Path 250X

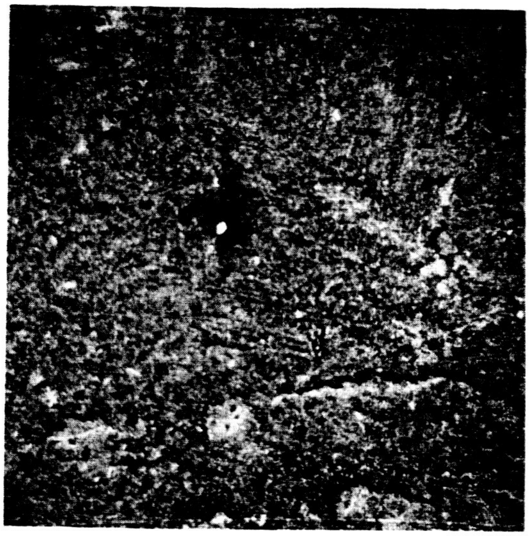


Ball Path 500X



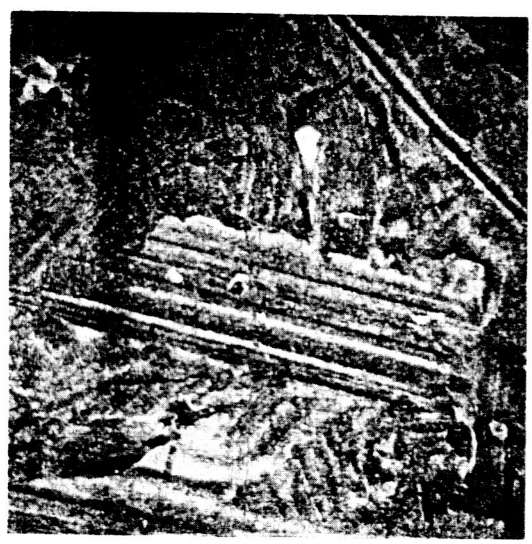
Ball Path 750X

Fig. 17 - Ball Bearing Race Groove After 100 Hrs. in Test No. 17 Without a Lubricant in a Clean 10^{-5} Torr O_2 Environment



Ball Path 250X

Ball Path 500X

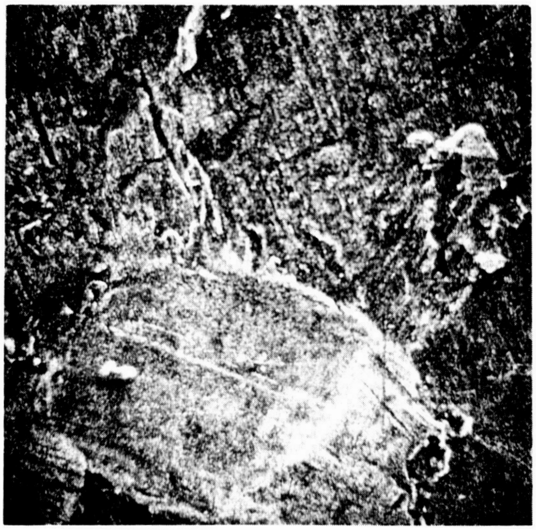


Ball Path 750X

Fig. 18 - Ball Bearing Race Groove After 100 Hrs. in Test No. 25 Without a Lubricant in a Clean 10-5 H_2O Vapor Environment

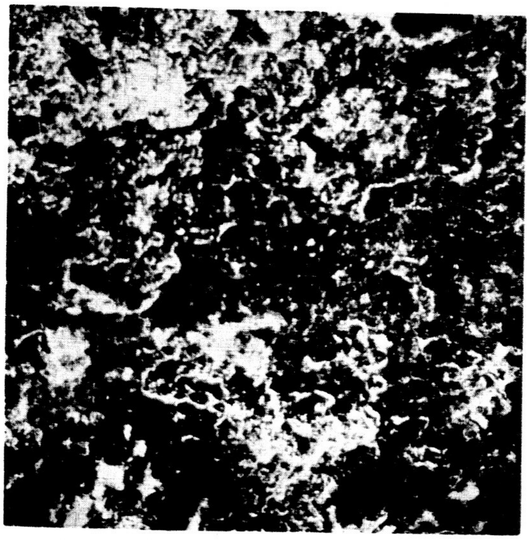
Ball Path 250X

Ball Path 500X



Ball Path 750X

Fig. 19 - Ball Bearing Race Groove After 300 Hrs. in Test No. 33 With an Oil Lubricant in a Clean 10^{-5} Torr H_2O Vapor Environment

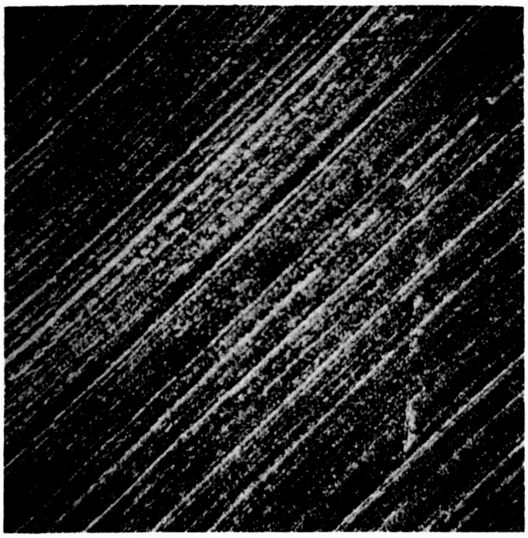


Ball Path 250X

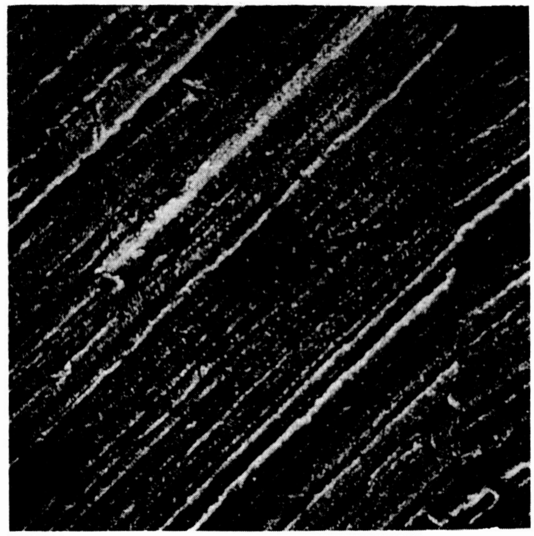
Ball Path 500X

Ball Path 750X

Fig. 20 - Ball Bearing Race Groove After 300 Hrs. in Test No. 34 With a Laminar Film Lubricant in a Clean 10^{-5} Torr H_2O Vapor Environment



Ball Path 500X



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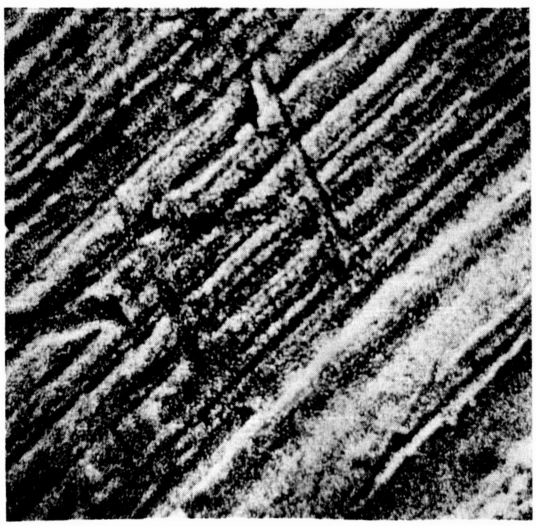

Ball Path 1000X

Fig. 21 - Ball Bearing Race Groove After 300 Hrs. in Test No. 35 With a Composite Lubricant in a Clean 10^{-5} Torr H_2O Vapor Environment

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an excess of selenium was located in the chamber between the diffusion pump and liquid N_2 baffle. During the test the composite was heated to ambient temperature in an effort to transfer material to the disk and rider. A post inspection of the disk surface was made using the X-ray fluorescence technique in which the disk was bombarded with a polychromatic X-ray in the wave length range of 0.2A°to 10A°. No evidence of tungsten or selenium in the range of 1% or greater was found on the disk surface.

The disk was then submitted to emission spectrograph analysis to look for trace amounts of lubricants. No selenium or tungsten was detected. Beryllium was found in the wear area. Calcium and magnesium were detected on the surface with the concentration being higher in the wear and hub area than in the area adjacent to wear track. Silicon was found in all three areas. Both the silicon and magnesium are elements found in the stainless alloy. It is more probable that these materials may be surface contamination from handling. The beryllium may have come from the machining or grinding operation.

Another technique was used to study the unlubricated sliding metal surfaces after operation in the water vapor environment. A scanning microprobe in conjunction with a double-focusing mass spectrograph of the Mattauck type was used to study the surface of the rider. The rider surface was ionized by a radio-frequency spark and thermal source with the ion spectra recorded electrically. The isotope O^{18} of oxygen was used as an aid in identifying any lubricant or environment reaction on the rider surface. The water used in the test was made from the O^{18} isotope of O_2. Approximately 0.025 grams of water were used for each of the 100 hour continuous and 100 hour intermittent tests.

The results of the analysis revealed that Cr, Fe and Si were present. These materials are elements found in the stainless steel alloy. None of the O^{18} isotope of O_2 was found in the rider in either the virgin or wear track surfaces of the sample.

IV. DISCUSSIONS OF RESULTS

Mechanical devices that require lubrication are common to all spacecraft. The information on lubrication in vacuum environments that is available to mechanical designers concerned with space is inadequate. An appreciation of the scope of present and anticipated lubrication problems is important to the planning for future space applications.

This study program covers parameters anticipated in the Apollo mission. This data is primarily of value in applications where **rotating** surface velocities are relatively low, loads are light and the temperature remains near ambient. The data should not be used as the basis for general lubricant selection without first carefully considering the internal geometry of the bearings or the tangential vector forces involved in relative motion of the disk and rider assembly.

In setting up the test program, careful consideration was given both the lubricants and outgassing environments. One lubricant was chosen from each of three major types of lubrication. The outgassing environment selection was made on the basis of past experience.[1] Both thermoset and thermoplastics are used in power conversion equipment, control communications and navigation accessories, thermal insulation and many other functions. Plastics,as a material,are second only to metals in usage for spacecraft design. Table 5 shows the results of outgassing characteristics of some of the most used plastics. From the data observed in the range of 10^{-6} torr both CO_2 and H_2O vapor are released in a vacuum even at high temperatures. The O_2 gas was chosen for the program to represent an active environment since it is required to sustain life and would therefore be present as a supply item in any spacecraft.

Work by Buckley and Johnson[2] gave the evaporation rates for various lubricants and organic solids. Their work covered polyphenyl ethers, silicones, polytetrafluorethylene, polychlorotrifluoroethylene and phthalocyanines. They noted that differences in molecular weight were found to influence markedly the evaporation rates of the lubricants.

Additional work by Solitario, Bialecki and Laubach[3] have investigated the problem of trace contamination in and around spacecrafts and covered contamination of a wide variety of organic materials. They believed that trace contamination was inherent to any closed or semiclosed ecological system. Contamination can be by thermal degradation of the various organic components such as heat sensitive plastics, polymers in electronics and electrical systems. It was concluded that those materials exhibiting relatively high weight loss in vacuums are particularly suspect as sources of atmospheric contaminants. Pyrolytic and thermal degradation studies would provide specific data on outgassing products as well as the mechanisms of degradation.

TABLE V

OUTGASSING CHARACTERISTICS OF PLASTICS

No.	Material	Wt. of Sample Grams	Temp. °F	Mol % of Gases Evolved: H_2O	CO	CO_2	SO_2	N_2	O_2	CO and/or N_2	SiF_4	Unidentified*	Miscellaneous	Vol.** of Gases Evolved CC/gm.
1	Nylon	0.6421	160	97.19	-	-	-	-	-	2.81	-	-	-	0.0175
			360	97.21	-	1.82	-	-	-	0.97	-	-	-	1.0723
			460	96.99	-	1.96	-	-	-	1.05	-	-	-	0.4513
2	Nylasint 2G	0.8023	160	87.33	-	-	-	9.49	3.18	-	-	-	-	0.0289
			360	98.30	-	1.13	-	0.57	-	-	-	-	-	1.5216
			560	93.96	-	5.54	-	-	-	-	-	0.50	-	0.9098
			760	-	-	84.17	-	-	-	-	-	2.00	13.82a	41.3285
3	PTFE	0.9010	160	12.07	-	-	-	62.51	25.42	-	-	-	-	0.0067
			360	14.10	-	-	-	64.64	21.26	-	-	-	-	0.0164
			560	6.28	-	1.78	-	72.88	19.06	-	-	-	-	0.0172
			760	64.37	-	14.14	-	-	-	21.49	-	-	-	0.0052
			960	1.36	-	12.19	-	-	-	4.85	-	81.60	-	0.0672
			1060	-	-	0.87	-	-	-	0.40	-	98.73	-	2.0262
4	PTFE - mica filler	0.8613	160	99.99	-	-	-	-	-	-	-	-	-	0.0056
			360	96.76	0.96	1.49	-	-	-	-	-	-	0.79b	0.0615
			460	92.27	2.03	4.18	-	-	-	-	-	-	1.52b	0.0262
			560	81.06	3.84	10.52	-	-	-	-	-	-	4.58b	0.0199
			560***	80.32	4.32	10.03	-	-	-	-	-	-	5.33b	0.0199
			760	42.76	10.16	29.39	-	-	-	-	-	1.00	16.69b	0.0178
			860	20.91	9.73	27.40	-	-	-	-	-	10.00	31.96b	0.0388
			960	7.28	6.98	13.94	-	-	-	-	-	23.45	48.35b	0.1172
			1060	0.93	4.78	5.34	-	-	-	-	-	60.02	28.93b	2.1769

*Gases were unidentified hydrocarbons
**Total volume of gases was measured at STP
***PTFE - mica filled material heated for additional 90 min. @ 560°F

a - NH_3 b - C_6H_6

Initial work has been accomplished to see if specific volatile compounds would provide vapor lubrication. Devine, Lamson, Stallings and Gilmore[4] used environments of air O, N_2, CO_2, A and He and added various organic gaseous compounds. Materials such as aromatic halogens and amines were considered and evaluated. Specific compounds such as naphtalene, durene, camphene, p-toluidine and certain dithiocarbamates provided effective lubrication.

The friction and wear results of this study are in agreement with general data observed by other investigators. In basic studies Bowden and Tabor[5] found that unlubricated sliding friction of pure iron surfaces in an ultrahigh vacuum was over 1.0. If the surfaces were degassed at 1000°C the friction coefficient was 3.5. It was observed that H_2, O_2 or air did not reduce friction of clean metals to a low value. Water vapor did reduce friction somewhat and in some cases a finite delay was observed before the effect was complete. The effect of water vapor was different for various metal combinations. In oscillating sleeve bearing tests operating in a vacuum, Brown, Burton and Ku[6] have shown that friction values from 0.6 to 1.4 have been obtained over a temperature range of 200° to 900°F when Cr-Mo alloys were rubbed against an oxide,bonded cermet. In other tests at temperatures from -200 to 100°F friction values of 0.5 to 1.0 were obtained. These tests were made at low sliding velocities under heavy load conditions. The loads reached values as high as 4400 psi for the self-aligning bearings.

Some friction measurements were made on sliding surfaces both in the laboratory vacuum and in a satellite by Rittenhouse, Jaffe, Nagler and Martens.[7] Flat disks of metal alloys were rotated at a speed of 0.7 to 1.3 ft./min. against 0.125 in. diameter riders. For unlubricated steel surfaces, the coefficient of friction ranged from 0.2 to 1.0. It was noted that high friction usually occurred where high mutual solid solubility of the metals was prevelant. Values of friction for lubricated metal surfaces using powder type lubricants was in the range of 0.04 to 0.10. In general, the coefficients of friction in space and in a laboratory vacuum simulating space were not significantly different.

V. EXPERIMENTAL PROGRAM

The experimental program consisted of the modification of the vacuum chambers, cleaning and specimen preparation procedure, test operation and post test specimen inspection. The test program and results have been discussed in Section II.

A. Sliding Tests

1. Equipment

The equipment consisted of a 2 cu. ft. type 304 stainless steel vacuum chamber and related pumping systems, wear and friction apparatus, load and torque measuring assembly and control and data recording console. An external view of the equipment is shown in Fig. 22.

(1) Vacuum system. The chamber pumping arrangement included both diffusion and cryogenic pumping systems. The diffusion pumps consisted of a 6 in. unit in series with a 2 in. unit and backed with a gas ballast mechanical roughing pump. A liquid N_2 baffle and liner of approximately 30 sq. in. and 420 sq. in. respectively were used inside the chamber. A liquid He shield finger probe was available but not used. The liquid N_2 cryo-panels pumped water vapor and CO_2. However, most of the water vapor was removed from the system by baking the chamber for 36 hours at a temperature of 450°F during the pump-down cycle. All flange seals used either gold "O" rings or copper crush washers. Oil "back-streaming" during "bake out" was prevented by the use of a liquid N_2 cooled trap; a separate Freon refrigerated external baffle on the diffusion pump elbow, and an internal water cooled "foot-ball" trap located in the elbow just above the pump. A hot cathode ionization gage was used to measure pressure in the chamber. The chamber was capable of reaching a pressure of 1×10^{-10} torr.

(2) Wear and friction apparatus. An externally located magnetic diaphragm drive motor was used to rotate the wear and friction rider and disk apparatus in the chamber. All rotating components of the apparatus were located inside the chamber and supported from the removable lid as shown in Fig. 23. Five individual test stations using external loading systems were located on one shaft. The shaft was supported by two composite retainer lubricating ball bearings. Each load and torque arm held two stationary riders, which rubbed on two rotating disks. The disk specimens were 4 in. in diameter and the rider specimens were 0.25 in. in diameter

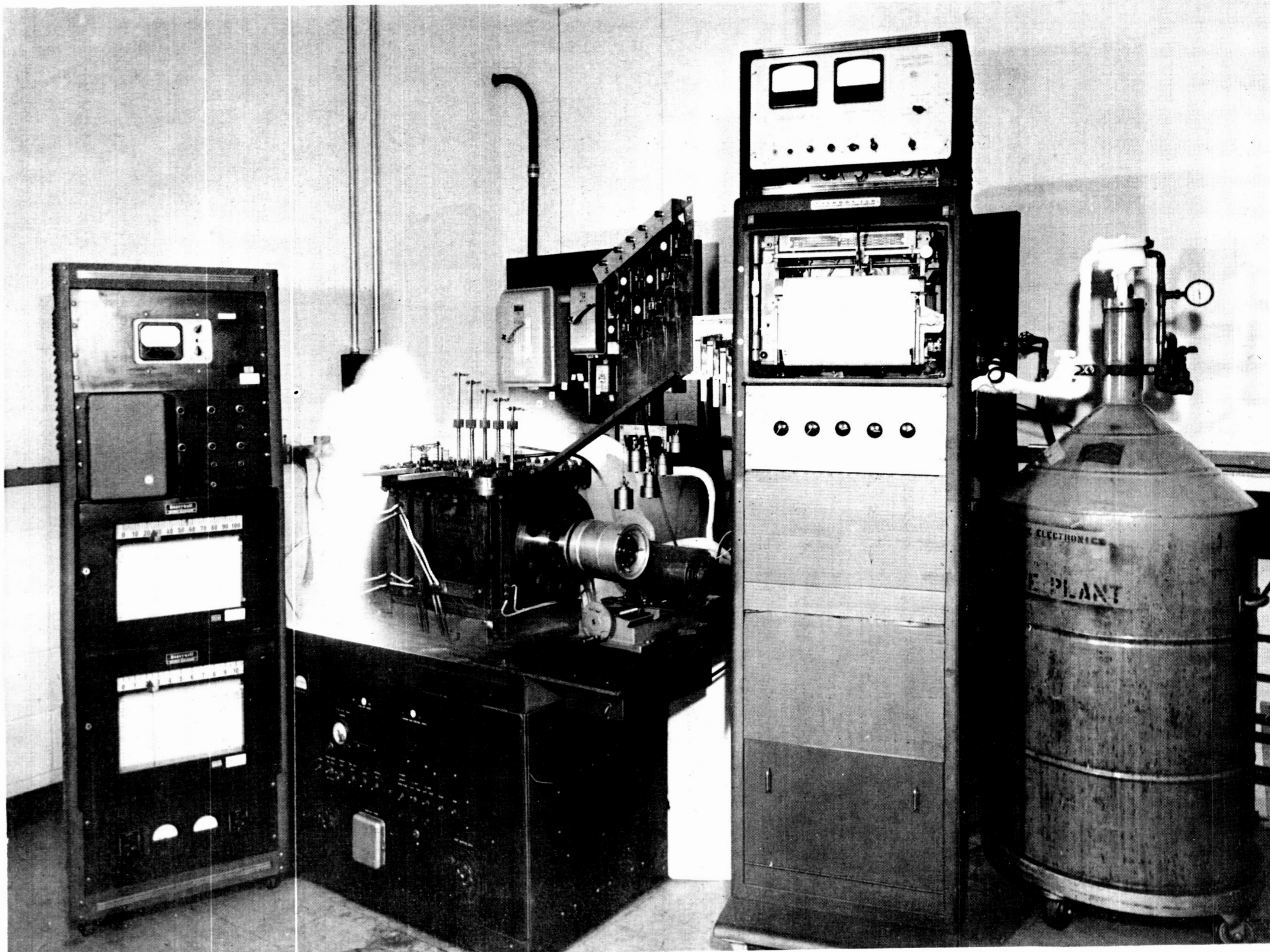

Fig. 22 - Vacuum Chamber Facilities for Sliding Tests

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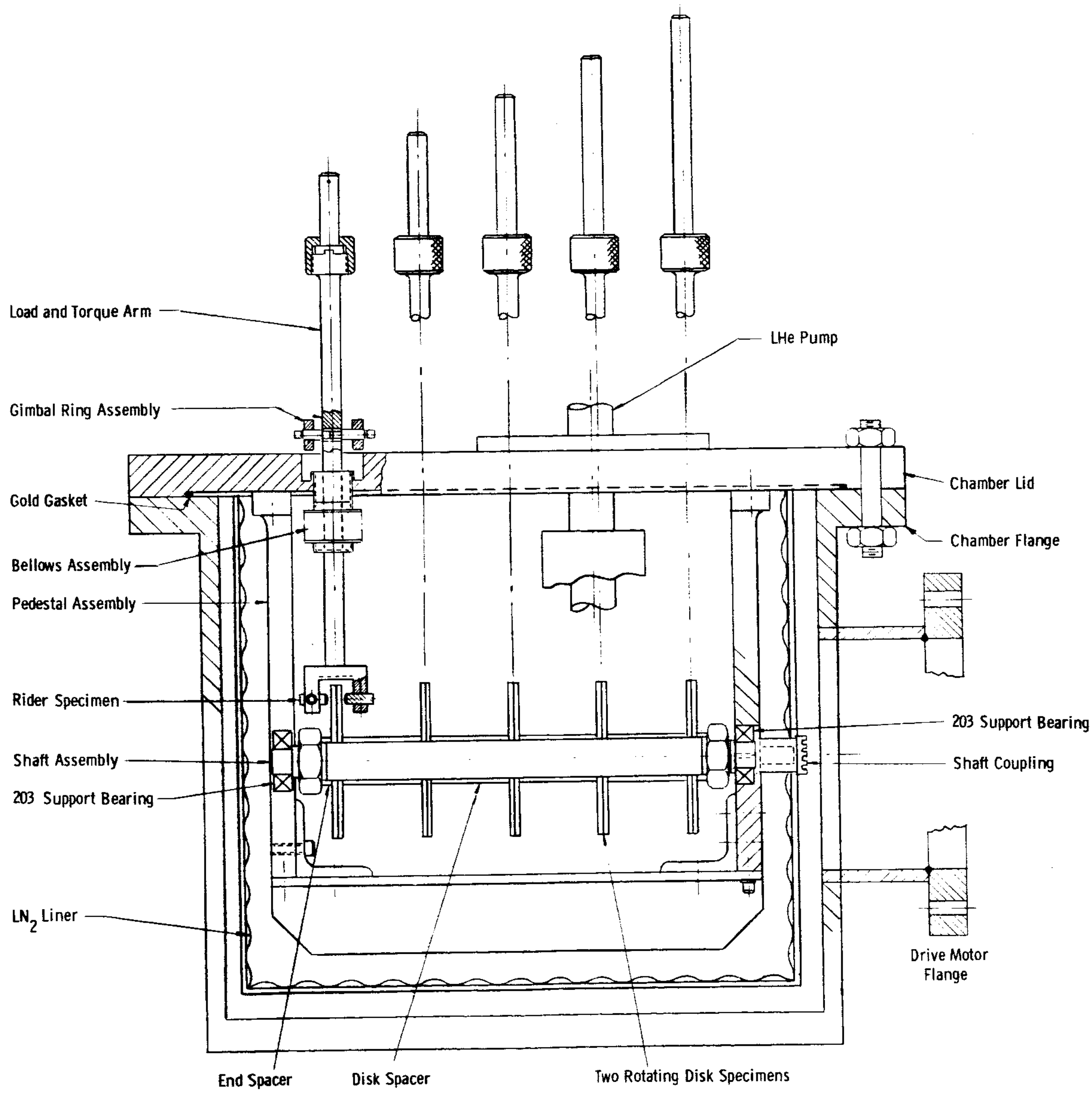

Fig. 23 - Vacuum Chamber Detail for Sliding Tests

with a hemispherical end. A flat of 0.0625 in. diameter was found on the hemispherical end to insure a relative constant area of contact during rubbing. The radius of the contact area on the disk was 1.487 in. Ten rider and disk specimens were used in the 5 stations so that both continuous and intermittent tests could be completed in the same environment.

(3) Load and torque measurements. The load and torque arm holding the riders was supported at the chamber lid by a gimbal ring and flexible bellows. This freedom of movement permitted the use of external load weights with a corresponding accurate measurement of rubbing friction.

The load on each station was applied in a horizontal direction by using individual weights and compensating for the difference in length of the load arm. The load frame assembly was moved from one side of the chamber to the other for completing both the continuous and intermittent tests. The force of rubbing friction was restrained by a wire attached to a cantilivered beam. Movement of the beam was detected by a strain gage and when calibrated was used to continuously observe the friction during tests.

(4) Instrument console. The control for heating the chamber, operating the diffusion pumps, recording friction and temperature and motor operation can be seen in Fig. 22. Insulating blankets were used to bake the chamber during the pump down cycle. Both the Freon and water traps were on during "bakeout" and pump down as well as during normal operation. The drive motor was controlled for 100 hours in the continuous tests and operated on a 4 hour "on and off" cycle during the intermittent tests. Temperature of the 5 continuous riders were recorded along with the frictional data of each rider-disk combination.

2. Specimen and preparation.

The disks and rider specimens were machined from Type 440C steel which had the following composition:

C - .95 to 1.20%
Mn - 1% max.
S - 1% max.
Cr - 16 to 18%
Mg - .75%
Fe - balance

The specimens were heat treated and ground to provide a surface of 4 rms. Hardness values after heat treatment and grinding varied from 57 to 58 Rockwell "C" for the disks and 53 to 58 Rockwell "C" for the riders.

The specimen preparation procedure was as follows:

1. Soak and rinse in Stoddard solvent.
2. Ultrasonic cleaning in Stoddard solvent for 2 minutes.
3. Rinse in absolute ethyl alcohol. (Several rinses used)
4. Air dry.

The specimens were stored in a desiccator until ready for assembly in the test apparatus. Just before assembly the specimens were weighed. All handling was done with lint free nylon gloves.

3. Application of lubricants.

The method of applying the various lubricants differed. The F-50 silicone fluid was transmitted to the rubbing area from stationary asbestos wicks that rubbed continuously against the disk. An extra wick that did not rub a disk was used as a control sample.

The composite lubricant was transmitted from stationary sliders as wipers that rubbed against the disk. The slider was 0.250 in. in diameter and rubbed with a constant force of 0.30 psi.

The laminar film was applied using 60% (wt.) of sodium silicate and 40% (wt.) of tungsten diselenide. The components were blended into a thin slurry and sprayed under pressure on the disk surface. The disk was air dried for 1 hour and baked in a vacuum furnace for 15 hours at 200°C. Film thickness ranged between 0.002 and 0.005 in.

B. Rolling Tests

1. Equipment

The equipment consists of 2 complete chambers, pumping systems, wear and friction apparatus, load and torque measuring assemblies, and control and data recording consoles as shown on Fig. 24. Each vertical vacuum chamber is 0.4 cu. ft. in volume and is surrounded by a LN_2 jacket and outer vacuum shell. A cross section view of the chamber and related test components is

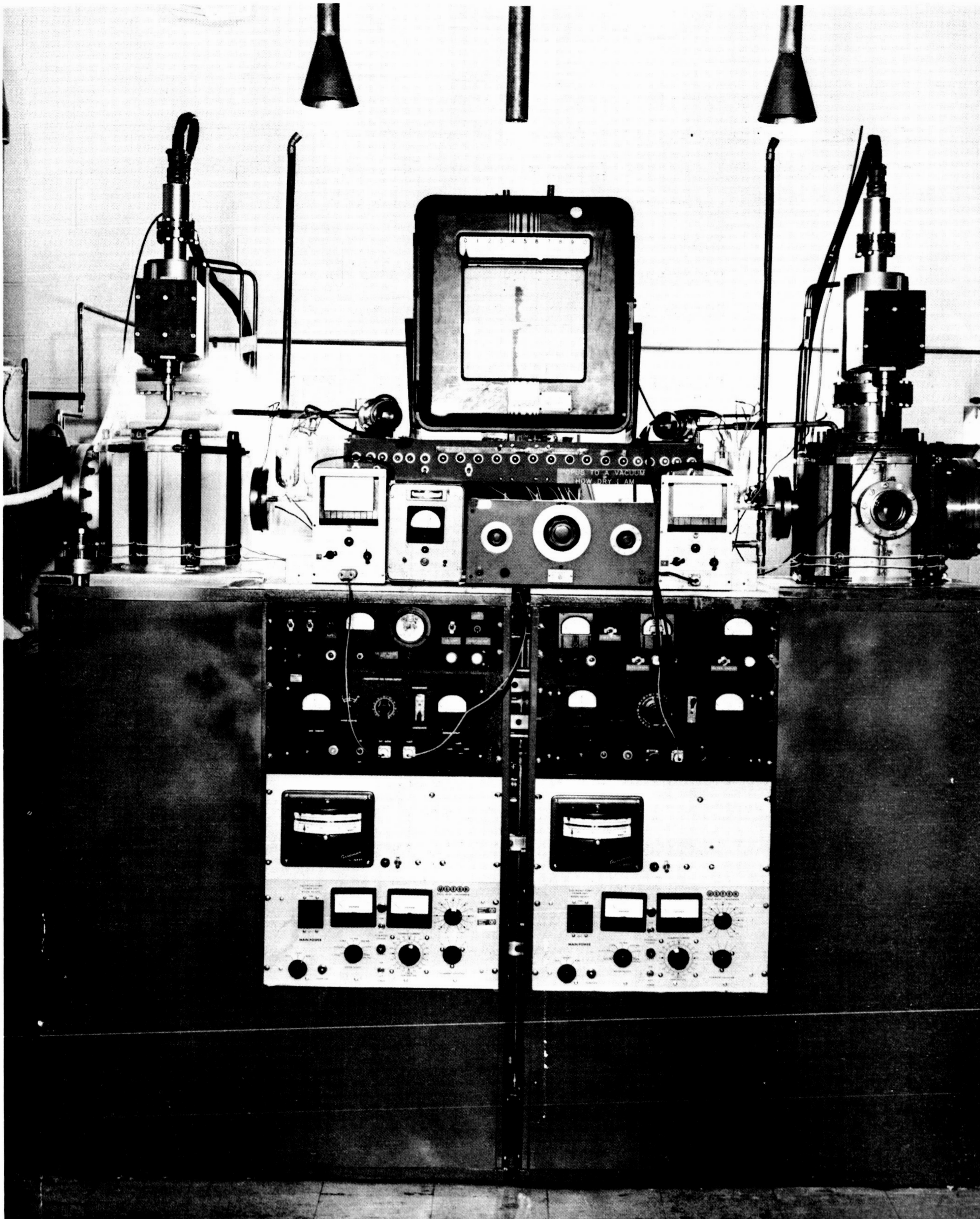

Fig. 24 - Vacuum Chamber Facilities for Rolling Tests

shown in Fig. 25. The chamber was loaded from the bottom.

(1) Vacuum system. The pumping system utilizes a 2 in. diffusion pump in series with a mechanical roughing pump in conjunction with a 25L/Sec. ion pump. In addition a Titanium sublimation pump was used intermittently when an ultrahigh vacuum was required. Oil back streaming was prevented with a LN_2 trap located between the diffusion pump and chamber. The chamber was baked out at $450^{o}F$ for 24 hours to remove most of the water vapor. In addition the LN_2 jacket was used to trap water vapor and CO_2 during the ultrahigh vacuum tests. All flange seals were either copper gaskets or gold "O" rings.

(2) Bearing test apparatus. The bearing test apparatus was located in a vertical position in the chamber and mounted on the lower chamber flange as shown in Fig. 25. The tester is rotated by a belt driven magnetic drive. The two support bearings were located at the bottom and lubricated by using composite retainers. Each of the thrust bearings was loaded with a dead weight of 2 pounds.

(3) Bearing torque measurements. The friction force of the bearings was measured in the chamber using a torque sensing beam with strain gages. Each beam was mounted on a vertical rod and allowed to pivot. The beam was held in position on the bearing by a magnet. If torque became excessive or the bearing seized, movement of the housing swept past the beam allowing the outward end to drop and not interfere with rotation of the housing. The bearings and strain gages were checked for maximum and minimum deflection prior to test and calibrated after test. The bearing test assembly after being removed from the chamber is being prepared for a calibration check as shown in Fig. 26. The signals from the strain gages were switched to one amplifier and output recorder circuit, recording each test bearing torque for a period of 6 minutes of each hour.

2. Bearing preparation.

The bearings were conventional 440C stainless steel 905 R/4 thrust bearings with free machining brass retainers. Composition of the

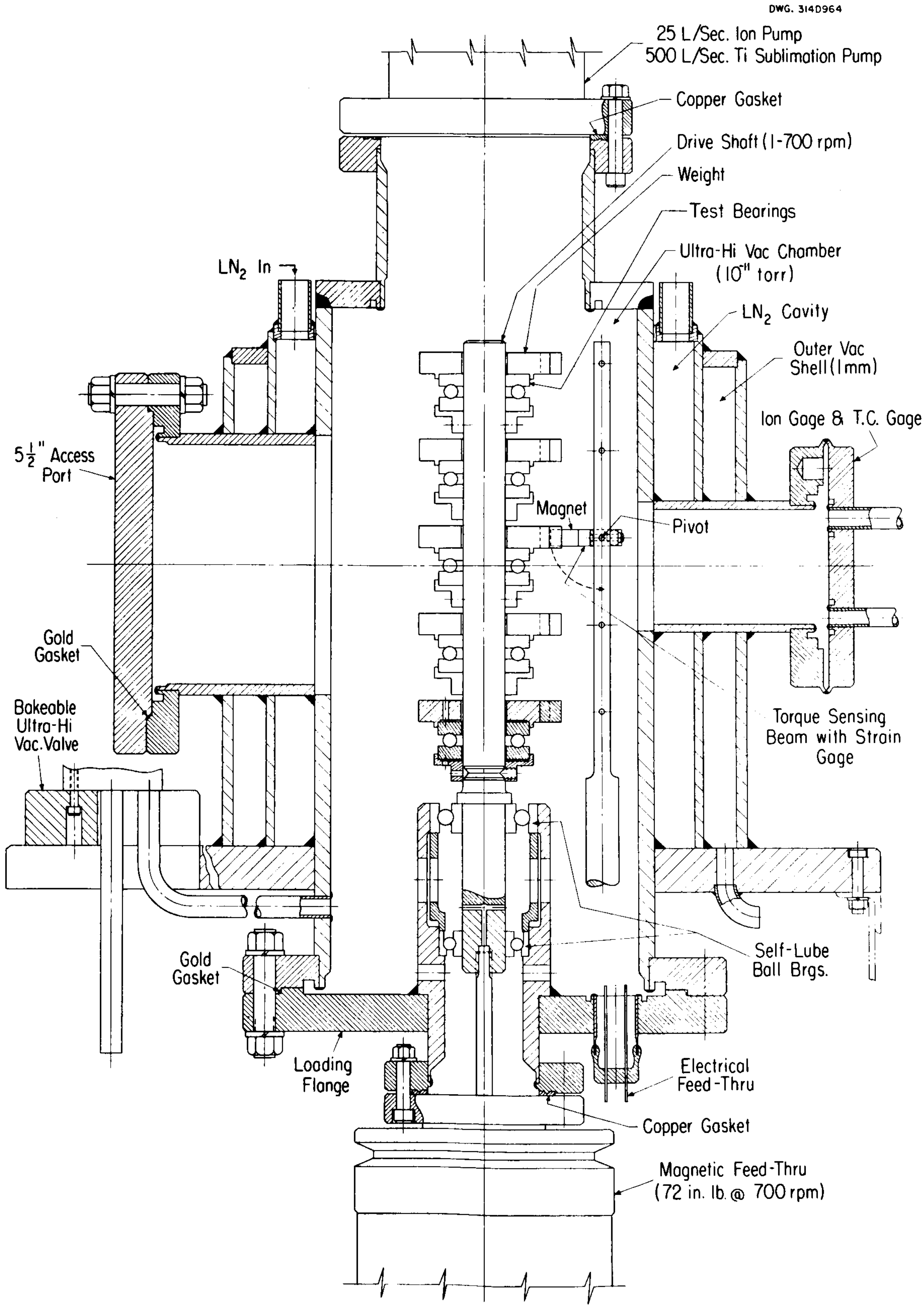

Fig. 25 - Vacuum Chamber Detail for Rolling Tests

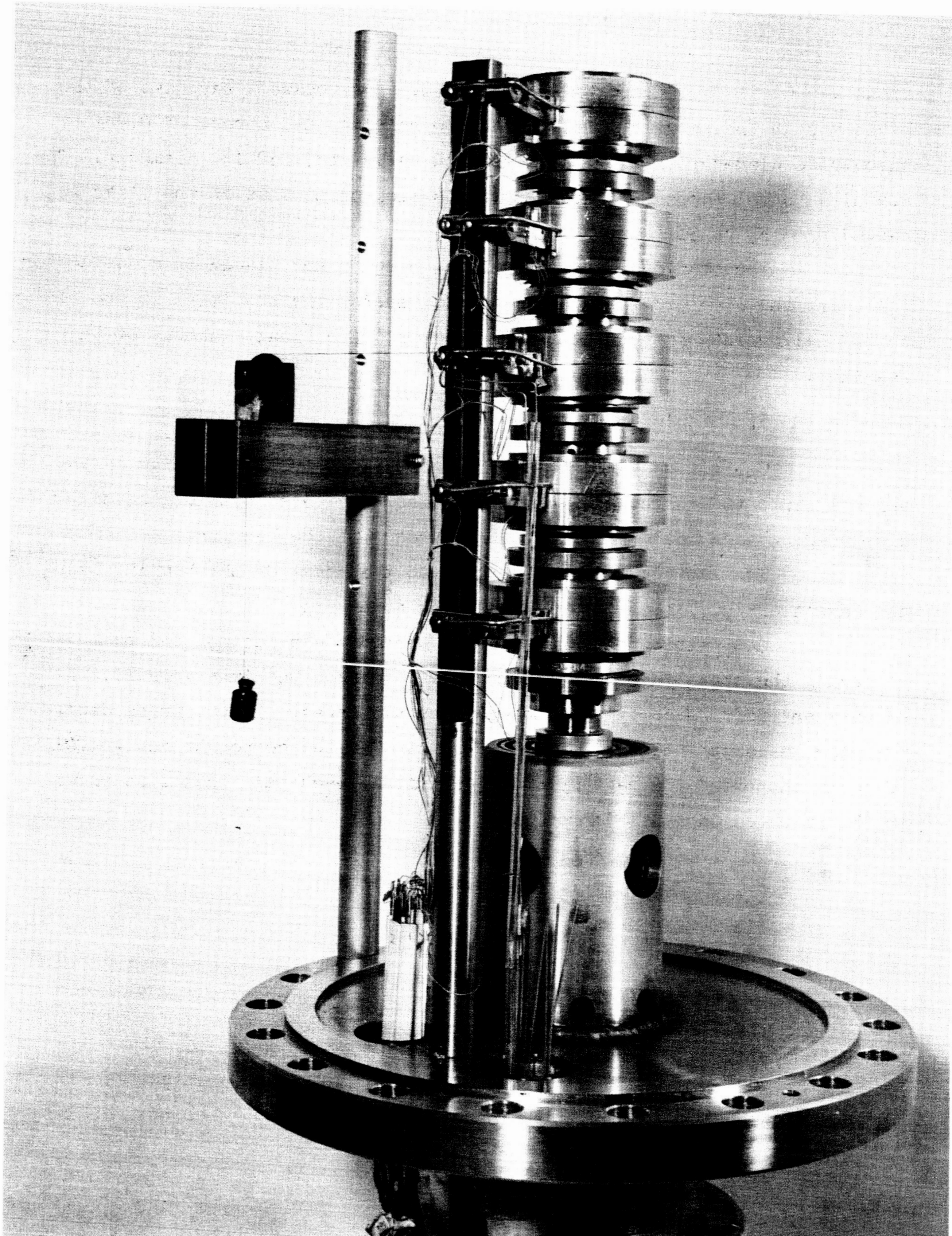

Fig. 26 - Bearing Test Apparatus and Calibration Weights

brass was 61.5% Cu, 35.25% Zn and 3.25% Pb. The rockwell hardness of the brass was in the range of 68-70 "B". The bearings had a bore of 0.984 in., an outside diameter of 1.890 in., with 10 balls of 0.250 in. diameter. The stainless steel races had hardness values similar to that of the disks and ranged from 57 to 58 "C".

The bearings were identified, cleaned and placed in a desiccator following the same procedure as that outlined for the specimens in the sliding tests. All weight measurements were made prior to final assembly of the bearings.

3. Application of Lubricants.

The silicone oil lubricant was applied to the bearings during assembly into the chamber. Each bearing was lubricated with 0.1 cc oil dispersed on each ball and in each ball pocket of the bearing.

The laminar film was applied to the races of the bearing using the same technique as that for the sliding specimens.

Composite lubrication of the bearings was accomplised by replacing the brass cage with a composite cage as noted in Figure 27. A significant difference existed between the two cages. In the brass design, the cage was supported by 5 of the 10 balls. In the composite design, all 10 balls supported the cage by a conical lip in each ball pocket as shown in the inverted cage of Figure 27.

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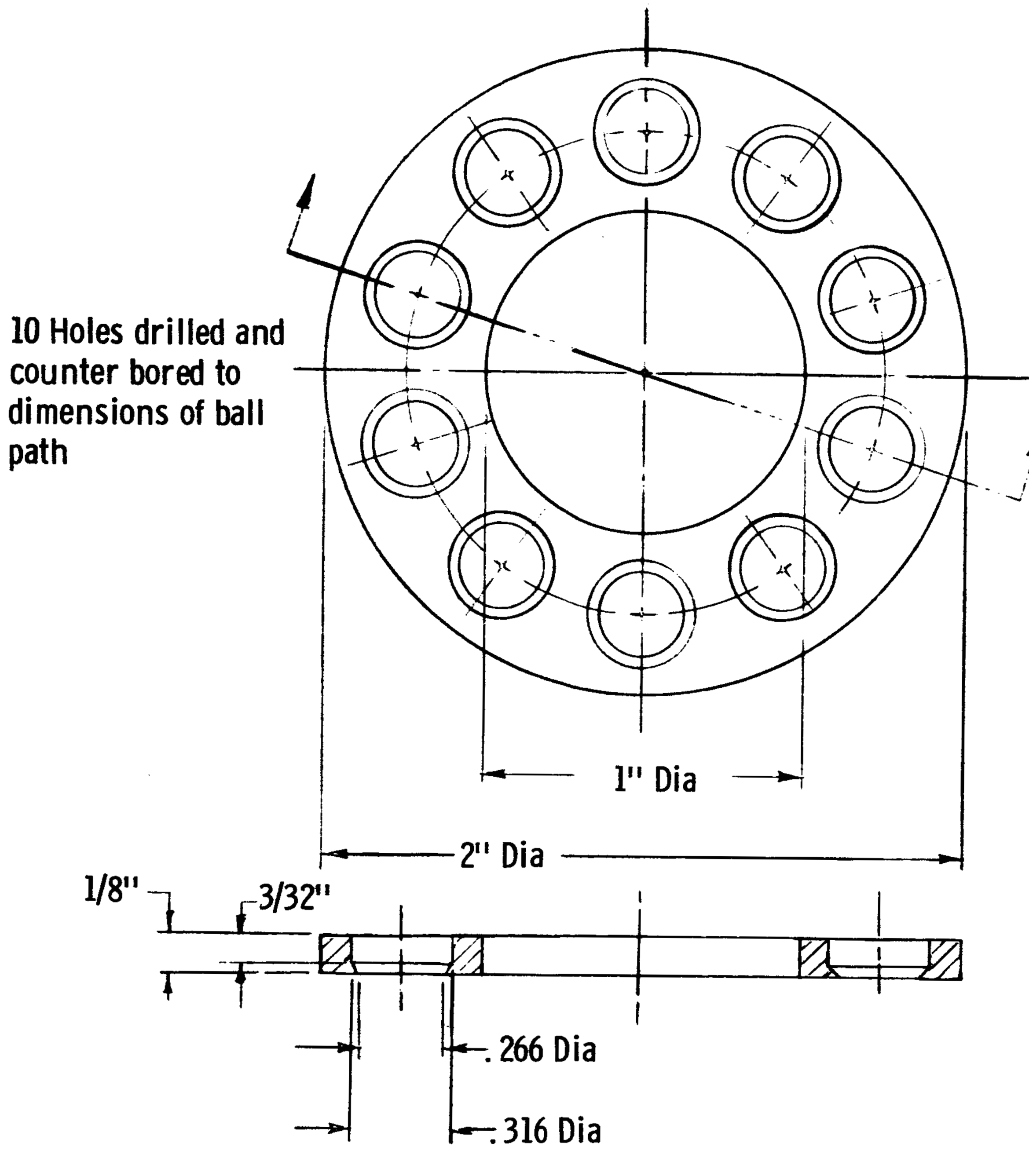

Fig. 27 - Composite Cage Used in Test Bearings

VI. CONCLUSIONS AND RECOMMENDATIONS

Based on the results of this study the following conclusions were drawn:

1. Very little correlation was found between coefficient of friction and rate of wear.

2. Friction was a more consistent method than wear in determining the degree of lubrication effectiveness.

3. Best overall lubrication was provided by the sodium silicate-tungsten diselenide laminar film (0.002--0.005 in. thick).

4. No one environment provided beneficial lubrication to all of the three types of lubricants: but in general H_2O vapor was the most beneficial.

5. Maximum friction values for sliding were approximately one order of magnitude greater than that of rolling.

6. Rolling friction exhibited less variation than sliding friction between various lubricant and environment combinations.

These conclusions coupled with general observations made during the study, lead to the following recommendations:

1. The variation of ambient temperature should be included as a test parameter and cover the range expected in deep space exploration.

2. Heavier loads should be explored for rolling friction. This extension should cover loads expected in relatively large unbalanced high speed rotatory equipment.

3. Additional studies should be conducted on other candidate lubricants selected from each of the three basic types now used in space applications.

BIBLIOGRAPHY

1. Bowen, P. H., "Analytical and Experimental Study of Adapting Bearings for Use in an Ultra-High Vacuum Environment," AEDC-TDR-62-51, February 1962.

2. Buckley, D. H., and Johnson, R. L., Evaporation Rates for Various Organic Liquid and Solid Lubricants in Vacuum to 10^{-8} mm. of Hg at 55° to 1100°F," NASA TN D-2081, December 1963.

3. Solitario, W. A., Bialecki, A., and Laubach, G. E., "An Approach to Trace Contaminant Control for a Spacecraft Atmosphere," A.I.Ch.E. Symposium Series 52, 60, 1964.

4. Devine, M. J., Lamson, E. R., Stallings, L., and Gilmore, L. P., "Lubrication of Ball Bearings with Volatile Organic Compounds," ASLE Paper 65LC-24, presented at the ASLE-ASME Conference, October 18-20, 1965.

5. Bowden, F. P., and Tabor, D., "The Friction and Lubrication of Solids, Part II," Oxford University Press, 1964.

6. Brown, R. D., Burton, R. A., and Ku, P. M., "Evaluation of Oscillating Bearings for High-Temperature and High-Vacuum Operation," ASLE Trans., 6, 1963.

7. Rittenhouse, J. B., Jaffe, L. D., Nagler, R. G., and Martens, H. E., "Friction Measurements on a Low Earth Satellite, ASLE Trans., 6, 1963.

Appendix A

A REVIEW OF LITERATURE PERTINENT TO EFFECTS OF OUTGASSING ON LUBRICATION IN ULTRAHIGH VACUUM

ABSTRACT

This selective compilation of 183 annotated references from a survey of approximately 500 publications provides a coverage of the literature pertinent to establishing the effects of outgassing of materials on spacecraft environment and component lubrication from 1958 through 1965. The material is divided into five parts: (1) ultrahigh vacuum, (2) space environmental effect, (3) manned spacecraft atmosphere, (4) outgassing source and effects, and (5) influence of gases on friction and wear. Subject, author, and corporate source indexes and abstracts are included.

PREFACE

The following review was prepared under NASA Contract NAS 9-3815, "Study of Outgassing Materials Effects on Performance of Ultra-High Vacuum Lubricants". The grouping of literature references in the discussion portion of the review is designed to establish the technical aspects of outgassing in ultrahigh vacuum, to identify specific contaminating gases which occur in spacecraft where possible, and finally to estimate the possible beneficial or detrimental effects these outgassing products have on friction and wear. The ultimate purpose of the contracted effort is to establish data on material outgassing effects on friction and wear in ultrahigh vacuum through laboratory investigation.

The form in which the material is presented was chosen as one that would give the most possible aid to related investigations.

OBSERVATIONS AND TRENDS SECTION

The subjects of vacuum and ultrahigh vacuum, gas chromatography, and friction and wear have received much attention by investigators for many years and reporting has been extensive. The specific subject of outgassing of materials in vacuum has been treated primarily as a problem area in the pursuit of other investigations, however, and outgassing studies of materials for space application are relatively recent. As a consequence, it was necessary to conduct the search on the basis of some forty keywords to accomplish effective selection of material pertinent to the contract problem.

The phenomena of material outgassing in space applications has been well established, as has been the deteriorative effects outgassing of a material has on the original material capabilities. The possible effect on other components and processes of emitted gases produced by outgassing, however, has not been well established. Contaminant gases in spacecraft operation have been found to include primarily water, carbon dioxide, oxygen, and nitrogen with lesser amounts of carbon monoxide, methane and hydrogen. A variety of trace contaminants have also been identified, but the significance of trace contamination was not obvious.

The origin of spacecraft cabin atmosphere contaminating gases includes outgassing of materials plus gases arising from crew metabolic processes, cabin leakage and repressurization or process leakage. The biological requirements of gas contaminant level limits for man have been anticipated for increasing flight endurance times, but no significant attempts to evaluate gas contamination effects on mechanical operation of spacecraft components were apparent in the review. Two notable failures which occurred during manned flight were traced to electronic circuit failure due to water vapor in one case, and over-lubrication of a control valve in another case, which illustrates the real problem area that exists with gas contamination control in spacecraft.

It has been shown that certain lamellar solids exhibit no evidence of improvement in sliding behavior by the presence of gas or vapors. Nitrogen and hydrogen gases offer no reduction of friction of clean surfaces in vacuum, while oxygen does improve frictional behavior under the same conditions. The development of practical, correlated data will depend on present and future investigations of the effect and control of outgassing in spacecraft operation which appear mandatory if extended flight missions are to be successful.

I. INTRODUCTION

The monumental amount of lubrication and vacuum literature required rather severe selection to acquire correlation of outgassing of materials in a vacuum and its effect on load bearing surfaces. It was readily apparent that outgassing studies performed were primarily in the pursuit of other evaluation problems and it was therefore necessary to employ a total of forty index keywords in the search. Actually, most indexes do not consider the word outgassing.

It also became apparent that little significant investigation of outgassing of materials, as it applies to this contract, was conducted before 1958 or even before 1960. Prior to that time much of the space-oriented literature was theoretical or speculative. It was not until after 1960 that space materials and applications became the target of concentrated investigation.

The literature has therefore been separated into five phases for the purposes of this search.

1. The technical aspects of ultrahigh vacuum.
2. The effects of space environment on materials and lubrication.
3. Manned spacecraft and identification of atmospheres and contaminants.
4. Gas sources and effects.
5. Influence of gases on friction and wear.

With this alignment of available literature it is possible to obtain basic information on the problems of materials, vacuums and outgassing through (1) and (2), establish the specific gases that might be considered pertinent to the contract (3), and finally estimate the effects of specific gases on friction and wear. Full abstracting of the references are included as Appendix I.

II. ULTRAHIGH VACUUM

An insight into the activity on space environment effect on materials is provided by the vast amount of information available on the techniques and limitations of producing and measuring ultrahigh vacuum. This element of space environment reproduction has necessarily predominated the material effect evaluations conducted by various investigators and has permitted much classification of suitability of materials and processes. Dushman and Lafferty(1) have contributed an accepted classic on vacuum techniques and gas interaction. Sections appropriate to the purpose of this review include treatment of the sorption of gases and vapors by solids, gas-metal interactions and of vapor pressures and rates of evaporation.

Alpert(2) summarized the recent history of ultrahigh vacuum technology and, in a later work(3), reviewed low-pressure measurement devices and instruments for producing high vacuums. In this work the study of the physical and chemical processes occurring at 10^{-11} torr is summarized. Vacuum techniques, particle interaction at surfaces and residual gases in an ultrahigh vacuum system are discussed by Feldman, Lange, Rabinowitz, Singleton and Zollweg(4). A study of the variables affecting cryotrapping of helium and hydrogen was conducted by Hemstreet, Webster, Ruttenbur, Wirth and Hamilton(5) who show that carbon dioxide has a rather large capacity for hydrogen and consider its use for the pumping of hydrogen in a space chamber. A complete bibliography and index on vacuum and low pressure measurements containing 1538 references was prepared by Brombacher(6). Included in the bibliography are references on vacuum technology including adsorption, degassing and controlled gas leaks.

Measurement of pressure in an ultrahigh vacuum and the usefulness of a nude gage for all measurements is demonstrated by Heimburg, Huang, Jackson, Mueller and Soo(7).

III. (a). EFFECTS OF SPACE ENVIRONMENT ON MATERIALS

With the background information on earth facilities which reproduce the vacuums of space, and the obvious ability to inject other space considerations into that environment, it has been possible for investigators to effectively evaluate a multitude of materials for spacecraft construction and implementation. The necessity for such evaluations and the impact of space technology on research and development was presented before a North Atlantic Treaty Organization Conference in 1958 by Rhode and Houbolt[8]. Apparently this period signalled the beginning of a concentrated effort by governmental and outside investigators to develop specific application information for space vehicle application. The literature prior to 1958, and in fact, prior to 1960, was not factual to the point of experimental verification. Many opinions and problem approaches were advanced prior to 1960 which were not pertinent to this review. The effects of space environment on materials were significantly discussed by Aikins, et al[9] in 1960. Wohl and Robinson[10] described experimental studies conducted to determine the effects of heat, low pressure, and radiation on plastics and elastomeric materials. Kerlin[11] measured the combined effects of nuclear radiation and vacuum on a group of non-metallic materials considered for use in nuclear-powered space vehicles. A bibliography by Landrock[12] lists 202 selected references on the various space environmental factors, natural and induced, and discusses their effects on plastics and related materials. An abstract and summary of literature on the subject of space environments with particular emphasis on the effects of the environment on the reliability of materials, components and equipment contained in aerospace systems was presented by Maguire[16].

Wood and Deem[13] defined and discussed emittance, emissivity, absorptance, reflectance, and transmittance, their usual prefixes, and the relationships among them. Definitive studies of the effects of space environment on polymeric materials such as teflons, vitons, mylars, polyamides and silicone rubbers were conducted by Chamberlain, et al[14]. Further environmental effects on thermosetting and thermoplastic materials are discussed by Ringwood[15] Space environmental effects on reliability of materials, components and equipment in aerospace systems, as presented in the literature was summarized by Maguire[16]. Initial mechanical, physical, chemical and miscellaneous properties of many unpublished materials specific to the space program were given by McDonnell Aircraft[17] while Gayle, Caruso and Egger[18] reported final effects of vacuum and elevated temperature on 54 solid materials. Some correlation may be possible. Parker, Gloria, and Lohr [19], in studies of the effects of space environment on the physical integrity of plastics concluded that there were two sequential mechanisms for weight-loss processes. The first was believed to be the sublimation of the inorganic solid exposed at the surface of a composite, and the second was sublimation, sorption and diffusion of sublimate through the encapsulating polymer film which was found to be a function of the concentration of sublimate, the polymer type, the temperature and sample geometry.

Methods of determining the extra-terrestial solar absorptance specifically of spacecraft materials were suggested by Gaumer, Streed and Vajta[20] while the gross effects of space environment on typical materials for spacecraft applications are discussed by Mauri[21] who included useful material-effect tables listing information on lubricants and thermal control materials. Jaffe and Rittenhouse[22] in a rather complete study attempted to synthesize the best of the information on the behavior of materials in outer space up to 1961 while discarding that which was no longer applicable. The compatibility of materials with storable propellants was investigated by Berman[23]. An interesting comment on lubricants states that solid film lubricants must be used almost exclusively for equipment subject to possible contact with propellants, provided they do not contain organic materials. Organic lubricants are generally attached by both oxidizer and fuel. Some of the highly fluorinated hydrocarbon oils and greases, while they are not attacked, tend to wash out, providing no lubricity thereafter. Even the solid film lubricants have a tendency to wash out. However, the use of a proprietary chrome treatment before solid-film application, followed by steel wool polishing of the film, has resulted in a lubricating surface capable of many exposures to propellants without appreciable damage to the film or change in the coefficient of friction. Sodium silicate based films were used.

The most complete and comprehensive study of space environmental effects on materials and components appears to be the work of Broadway, King and Palinchak contained in references 24, 25, 26, 27, 28, 29, 30, 31, 32 and 33. Included in the work is a compilation of fifty-eight tables giving detailed information on elastomers including such aspects as outgassing rates, weight loss in vacuum, physical properties, exposure to high temperatures and other considerations.

III.(b). LUBRICATION IN THE SPACE ENVIRONMENT

The effect of space environment on lubrication has been a subject receiving much attention. This is particularly true in the literature dating from 1960 when the problems involving space lubrication began to crystallize. Typical of the trend toward investigations of specific problem areas was the work of Freundlich and Jagodowski[(34)] whose objective was to determine vapor pressures and evaporation rates of four experimental high-temperature fluids in a high-vacuum environment over a wide range of temperatures. In another program[(35)] the selection and development of bearing configurations for high speeds typical of space turbomachinery (35,000 rpm) was the objective. The problem of lubrication of guidance, control and instrument type bearings in space was comprehensively studied by Demorest[(36)]. Experimental details and results on the effect of high vacuum and operating conditions on oils, greases, and dry-film lubricants for bearings are presented by Mauri[(37)]. Molybdenum disulfide grease corrosion studies by Calhoun[38], and selected oil and grease application studies by Clauss[39] further typify the concentration of effort by investigators.

The state of the art in 1962 is presented by Adamczack, et al[40] and a survey of firms conducting research into problems of lubrication at that time was presented by Brooks[41]. The results of over 100 tests conducted on bearing lubrication, with variations in bearing type, lubricant, temperature, and radiation level are summarized by Parcel et al[42].

In 1963, Johnson and Anderson[43] prepared a cross section of the information available on lubrication in vacuum. The Aerospace Lubrication Research Survey reported in December 1962 by the Lubricants Group for the Office of the Director of Defense Research and Engineering[44] provided a convenient tabulation of research projects. The role of liquid metal lubrication, specific spacecraft applications, solid film lubrication, high-temperature fluids, chemical composition of metals, and grease research are selectively treated in references 45, 46, 47, 48, 49, and 50. Results of screening tests of plastics, powders, and composites, along with the use of new dry powders and composites, as dry lubricants in ball bearings and gears operating in an ultrahigh vacuum environment are presented by Bowen[51] and Pinson and McRae[52].

Vacuum lubrication programs in eight laboratories during 1963 were reviewed by Kingsbury and McKannan[53] and a second survey and compilation of 189 annotated references on gears and bearings and lubricants and lubrication techniques was conducted by Abbott[54].

A rather severe selection of the literature after 1963 was necessary to avoid redundancy and to affect isolation of original investigations. General discussions of the problems of aerospace lubrication, surveys of requirements, bearings and systems were presented in references 55, 56, 57, 58, 59, 60 and 62. Those references considered specific to other phases of the subject of this review are considered later.

IV. MANNED SPACECRAFT

The selection of literature reviewed to this point indicates the vast amount of information available on the general problems of space environment and the concentrated efforts of investigators to define specific problems. In the conduct of investigations relating to space experiences such basic information is valuable, but actually contributes to only a small part of the actual solution of the problem area. The following references on manned spacecraft provide information on the identification of contamination in manned spacecraft.

(a) Cabin Contamination: Materials and Processes

The problem of atmospheric trace contamination, as reported by Solitario et al[63], is inherent to any closed or semi-closed ecological system. Every spacecraft system, including the man, constitutes a latent source of contaminant vapors and particulate matter. Determination of the exact composition of the contaminants and their concentration is necessarily the first step in any atmospheric contaminant program.

Solitario lists contaminant sources under three main headings: (1) Material generated contaminants refers to those atmospheric contaminants which are outgassed from materials of construction (or equipment) exposed to the internal spacecraft atmosphere, (2) Process generated contaminants include those atmospheric contaminants resulting from the operating of some spacecraft systems, (3) Man-generated contaminants include those directly originating from the man as well as any originating from a hygienic process.

In five recent simulated space capsule flights, McKee et al[64] monitored space cabin atmosphere trace contaminants and identified them as acetaldehyde, acetone, methanol, ethanol, Freon-11, Freon-12, Freon-22, methyl chloride and dimethyl sulfide. Through the use of microtechniques, Saunders[65] identified and summarized twenty-seven organic contaminants from several spacecraft atmosphere activated charcoal filters. These, of course, represent trace contaminants within the spacecraft cabin.

Efforts to extrapolate industrial TLV* data to space conditions were unsuccessful according to Thomas and Back[66]. The inherent difficulties in assaying trace constituents in a space-cabin simulator are further explored by Weber[67].

Anderson and Saunders[68] disclosed the results of analyses of nuclear submarine and spacecraft atmospheres conducted during actual manned operations and have tabulated trace contaminants and the suspected source when known. A review of published data on the effects of deteriorative environments on materials and equipment in closed ecological systems was conducted by Wessel[69] who notes the possible deteriorative effect of water, oxygen and moderate heat fluxes. The maximum use temperatures that have been established for non-metallic materials to be used in the inhabited area of spacecraft are presented by Pickaux and Spruill[70] who also include reports on the contaminants recovered from capsule atmosphere of Mercury flights. A report on spacecraft materials reliability is presented by Matthews and Finch[71] while Cordaro et al[72] discuss deliberate contamination of materials and components during manufacture to develop sterilization procedures.

Possible methods and systems for environmental control in manned space vehicles are suggested by Ivanov[73] and reference 74.

The Mercury Project Summary of 1963[75] reports that strong evidence exists that free water existed in the spacecraft cabin during the MA-9 flight.

A rather complete treatise of manned spacecraft life support systems and engineering design and operation is provided by Smylie and Reumont[76]. It would appear from the literature that the major atmospheric contaminants within the spacecraft consist of water, carbon dioxide, oxygen and nitrogen with lesser amounts of carbon monoxide, methane and hydrogen and trace amounts of various gases. These contaminants arise probably from outgassing of materials used in the spacecraft,

* Tolerable limits for air contamination control.

leakage of stored gases, leakage from material processing equipment and metabolic processes of the crew.

(b) Contamination and Man

The requirements of man in a spacecraft cabin environment are effectively reviewed by Broglio[77] and later by Roth[78] and the Space Science Board of the National Research Council[79]. Further considerations on the principles of formation of artificial habitat in space ship cabins are offered by Zefel'd[80], Genin[81] and Hendler[82]. Gaseous activity products and microbiological contaminants of man in closed ecological systems are discussed by Gorban et al[83] and Irvine[84].

Design considerations and atmospheric control systems are discussed by Landas, et al[85] and references 86 and 87. Saunders[88] discusses the relatively high content of toluene in a charcoal filter of the MA-9 flight.

It was interesting to note, in light of the literature available, one embarrassing account given by reference 89 which illustrates the effectiveness of gaseous contamination in closed systems. In this case, a complete integrated life support system capable of providing life support for five men for thirty days was developed, designed, fabricated and installed inside a variable altitude chamber for test. The first test ended after 4 1/2 days because of crew illness and a catastrophic equipment failure. Prior to resumption of the second test, trace contaminant studies were made resulting in the substitution of many equipment fabrication materials and mechanical adjustments were made which permitted a successful second attempt. All information on the occurrence is included.

A recommended general reference on spacecraft environments, the physiological aspects of the spaceman and associated logistics was compiled by Brown and Ely[90] in book form.

(c) Contamination in Space-exposed Areas

Within the limits of this review, no apparent attempt has been made in the literature to isolate information which specifically considers contamination as the result of outgassing of materials in spacecraft areas exposed to the space environment. The literature on the behavior of materials in the space environment is vast. The effect outgassed products of specific materials had on other components in close proximity to the outgassing material in the space environment was not established.

V. GASES: SOURCE AND EFFECT

The contamination of closed ecological systems by gases and the control of cabin atmosphere contamination are critical areas in spacecraft development, and much attention has been given to these subjects in the literature. The identification of gas sources and possible gas-surface interactions have been an integral part of these investigations. Unfortunately, correlation between the gaseous contaminant sources and the gaseous contaminant effect on other materials was not immediately evident from the literature.

(a) Outgassing

A rather complete reference book on the subject of Materials for Missiles and Spacecraft has been compiled by Parker[91]. The information serves as an aid in understanding the problems involved in the use of available materials. Specific information on materials and outgassing is found in other sources.

A study of the outgassing and evaporation products of a group of materials upon exposure to vacuum was conducted by Caruso and Looney[92]. It was interesting to note that all of the materials investigated released absorbed moisture. Vanderschmidt and Simons[93] found that phenolics, for example, emitted considerable gas (air, water and CO_2) and showed physical degradation in vacuum. Jones[94] reviewed the effects of gas in multilayer thermal insulation considered for applications at cryogenic temperatures and recommended investigation of pre-launch degassing procedures. A complete study of the evolution of gases from electron tubes and materials was conducted by Grubbs and Snider[95, 96, 97, 98, 99]. Although this work was directed toward development of electron tubes, the identification of hydrogen as a major outgassing product from this source is interesting.

Bolstad[100] in the AIAA, 2nd Manned Spaceflight Meeting described an experimental program which would determine the relative outgassing and flammability characteristics of over one hundred materials. The outgassing characteristics of graphite were determined by Overholser and Blakely[101], and similar work by Holshauser and Bennett[102] and Henry[103] on metals was reported.

The detection and measurement of sorption, vaporization and emittance of materials in space environments were reported by various investigators, (see references 104, 105, 106, 107 and 108) and partially attest to the activity in this area.

Dakin and Works[109] explored the gas discharge situation which exposed energized electrical systems will encounter as they pass from atmospheric pressure to the vacuum of outer space and found it would be necessary to completely enclose the electrical system in a sealed capsule.

Outgassing characteristics of various materials determined by Santeler[110] and by Schrank et al[111] provide extensive data on a limited number of materials. Similar investigations on evaporation rates of various organic lubricants by Buckley et al[112] showed that variations in molecular weight influenced the evaporation rate markedly. Lange and Singleton[113] found that at higher temperatures pyrex glass vacuum systems release considerable quantities of carbon dioxide.

Some of the lubricants examined were polyphenyl ethers, polyalkylene glycols, silicones, fluorocarbon polymers, polytetrafluoroethylene, polychlorotrifluoroethylene, and phthalocyanines. Differences in molecular weight were found to influence markedly the evaporation rates of lubricants. With a polyalkylene glycol fluid having a molecular weight of 13,500, the evaporation rate was approximately 10^{-6} g/sq cm/sec at 550°F. This same evaporation rate was achieved with a 660-molecular-weight fluid at a temperature of 55°F. The results obtained with a series of polyalkylene glycol fluids of different composition but having equivalent molecular weights (1000) indicated that the evaporation rate of the series over a range of temperatures could be represented by a single curve. The solids polytetrafluoroethylene, polycholorotrifluoroethylene, and fluorocarbon polymers were also found to exhibit evaporation rates with a molecular weight dependence. For one of the polyphenyl ethers, good agreement was found with data in the literature.

The outgassing characteristics of dry lubricant materials in vacuum were investigated by Bowen and Hickam[114] who have recorded outgassing data on a volume basis for certain plastics, dry powders and metal composites.

A practical application of the outgassing or subliming characteristics of camphor, napthalene and biphenyl was studied by Fischell and Wilson[115] who discussed the principle use of such materials in actuating electrical switches with a predetermined time delay.

(b) Gas-Surface Phenomena

The fact that materials experience outgassing in vacuum is of questionable significance in lubrication unless some insight to the effect of gas-surface phenomena is provided. Rogers[116] emphasizes the need for research specifically oriented toward determining the dynamics of gas-solid interactions.

Frisch[117], in heat of adsorption studies with metal powders, found clear discrepancies between the surface values found by the water vapor adsorption and those obtained by the nitrogen adsorption. This may have correlation with lubrication phenomena. Up to date 1962 data on potentials of adsorption and chemisorption and activation energies of various surfaces for gases is presented by Huang[118]. The literature on the gas adsorption studies on solid surfaces is extensive and provides some possible clue to the phenomena which might affect friction and wear determinations in vacuum.

Rechlin[119] was unsuccessful in measuring adsorption on the surface of HMX using N_2 and CO with the continuous flow modification of the BET (Brunaver-Emmett-Teller) gas adsorption technique. Glebov[120] was successful in measuring sorption of gases by niobium and tantalum. Obviously this is a very difficult field to study experimentally, and Luzzi[121] presented a quantitative and semi-quantitative description of physical adsorption of gases and liquids on solid surfaces. Physical adsorption is described from the macroscopic or thermodynamic viewpoint and the molecular viewpoint. Inouye[122] measured the contamination of various refractory metals resulting from exposure to residual gases in high vacuums, and Husmann et al[123] investigated surface effects caused by individual hydrocarbons in ultrahigh vacuum. Results in the latter work, where changes in work function and critical temperature for cesium ionization were investigated, indicate that small amounts of hydrocarbons as well as carbon monoxide and carbon dioxide reduce the work function and increase the critical temperature for surface ionization. The kinetics of gas adsorption, the role of water vapor and the laws governing physical adsorption as they apply to obtaining ultrahigh vacuums experimentally are discussed by Hobson et al[124], Holland[125], Ptushinskiy and Chuykov[126], and Goldstein[127]. References 128 through 134 report findings of Florio, Baird, Bliven, and Polanyi in a complete study of adsorn of gases on solids in the high vacuum range. Details of equipment development and experimental data is provided.

The flammability characteristics of gases, liquids and vapors as affected by atmospheric environment are reported by the Lovelace

Foundation[135] and affords some speculation on the flammability of lubricant and fuel outgassed products.

The transition from pure gas-surface interaction studies to investigations of gas-interaction phenomena with lubricants is discernible in the literature. Bliven[136] describes an ultrahigh vacuum system which was designed to perform surface adsorption studies in the region of extremely low pressures. Provision was made for the controllable admission of gases into the system and subsequent study instrumentation was provided. Cornelius and Roberts[137] investigated the friction and wear of metals in vacuum and gaseous environments up to 600°C. The gas CF_2 Cl-CF_2Cl was reported by Buckley and Johnson[138] to be effective in providing lubrication for Pyroceram 9608 on various cobalt-base alloys to 1000°F. Feng and Chalk[139] discovered that the effect of vacuum removal of dissolved oxygen on the wear of cast iron in sliding contact was a phenomenal increase in wear. Another investigation by Beerbower and Greene[140] completely eliminated surface interaction evaluations and studied the interactions of five gases (helium, hydrogen, nitrogen, argon and carbon dioxide) with mineral and synthetic lubricating oils on the basis of physical characteristics and performance.

VI. INFLUENCE OF GASES ON FRICTION AND WEAR

Investigations of the friction and wear of materials in contact have been conducted for many years and literature is both abundant and somewhat redundant. Severe selection of pertinent information was necessary to allow exploration of the specific area of how gases affect friction and wear. Preliminary consideration of clean metals and adhesion was considered important to final consideration of frictional behavior.

(a) Clean Metals and Adhesion

As theorized by Bowden and Rowe[141], who investigated the adhesion between surfaces of hard metals cleaned by heating in a vacuum, low initial adhesion is due to released elastic stresses when load is removed, and application of tangential force in addition to load increases adhesion. Such investigations were also conducted by Semenov[142] and Brueschke and Suess[143], the latter of whom discuss the conditions under which seizure of degassed metallic surfaces in ultrahigh vacuum will occur and present methods of preventing seizure.

Examinations of material cleaning techniques for metal surfaces studies are included in the work of Vos[144], Schram[145] and Moll[146]. Associated approaches to clean surface studies are presented by Feng[147], Bryant et al[148], and Dillon[149].

Considerable recent investigation and publication of information is provided by Keller et al, (see references 150, 151, 152, 153, 154 and 155). While there is some repetition in the literature, the observation is made that the mechanisms of metallic adhesion (microwelding) are made because in high or ultrahigh vacuum applications most lubricants lose their effectiveness in preventing bonding of metallic atoms of one surface to the atoms of a second surface.

Also contained in six separate reports is the work of Ham, (references 156, 157, 158, 159, 160 and 161) who used the fracture-rejoin technique to investigate cold-welding in ultrahigh vacuum. Goodzeit[162] provided tables giving information needed to select pairs of bearing metals that will not form strong welded juctions during operation. Further evaluations of the adhesion and cohesion of metal couples was performed by Winslow et al[163]. Ford and Nichols[164] found that Bis (2-ethylhexyl) sebacate synthetic oil and silicone greases were promising materials in resistance to displacement by water through several icing-deicing cycles in which clean and lubricated surfaces were studied. Further information on the influence of moisture on the friction and surface damage of clean metals was provided by Daniels and West[165].

An important facet of such studies is contained in a statement by Kern and Jackson(166) to the effect that the obtaining and maintaining of atomically clean surfaces is a necessary basic step in the study of well characterized surfaces.

(b) Friction and Wear

An insight into the role of gases and vapors in frictional phenomena is contained in information by Bowden and Young(167) who conducted an experimental study of the frictional behavior of thoroughly degassed metal surfaces. They state: "Various gases and vapors have been adsorbed onto the clean specimens and their influences on friction determined. These specific contaminants are most effective as lubricants where they can react with the metal to form a solid and chemically-attached film which is several molecular layers in thickness. Otherwise, friction remains very high".

Probably the most outstanding reference on friction and wear is a two-part publication by Bowden and Tabor(168, 169). An associate, Rowe(170) reported on the vapor lubrication and friction of clean surfaces as early as 1957.

Coffin(171) found that alloying ability serves as a qualitative criterion for local seizure and surface damage, while Buckley and Johnson(172) determined the effects of crystal structure and crystalline phase changes on the friction, wear, and metal transfer characteristics of rare-earth metals in vacuum. These authors(173) also established that some impregnants were beneficial in reducing friction and wear of carbon in vacuum while others were not. Similar investigations are reported by Reichenbach et al(174) and Flom et al(175) extended this type of investigation to include five lamellar solids: molybdenum disulfide, tungsten sulfide, cadmium iodide, bismuth iodide, and phthalocyanine. Flom et al, found no evidence that the sliding behavior of any of these materials is improved by the presence of gas or vapors. Lubrication with lamellar solids also were investigated by Bryant(176) who proposes a stress-etch mechanism to explain the effect of atmospheric gases upon the lubrication properties of lamellar solids. Lavik and Clow[177] considered ceramic-bonded solid lubricant films in an investigation in air and in vacuum, while Hopkins and Gaddis[178] evaluated solid films versus gold in vacuum.

An early program by Hansen et al[179] was directed toward the study of surface friction under conditions of high vacuum and established two modes of contact: one of pure sliding, and a second of areas undergoing shear. The low friction, low wear examples appeared to be special cases wherein almost all contact areas were of the first type. Boyd, Rollins and Thomas[180] examined the temperature profile between surfaces in sliding contact, and Jackson[181], in a review of space lubrication, notes the poor thermal conductivity resulting from the absence of gas conduction. Other investigators have similarly devoted their efforts toward establishing the phenomena of friction and wear. The current design trend, however, appears to concentrate on establishing friction, wear and evaporation data on lubricating materials for specific evaluation in spacecraft. Buckley et al[182] recently completed a study of the evaporation of soft metals, lubricating inorganic compounds and various reference materials in vacuums of 10^{-9} torr. In addition to evaporation, the friction, wear and decomposition mechanisms of the materials were investigated.

It is considered highly desirable that future space missions include in-flight friction and wear measurements much as was reported by Rittenhouse et al[183] on an initial attempt on a low earth satellite.

This experiment established that for unlubricated metals sliding on metals the friction coefficient averaged about 0.5; for some combinations of metals, it occasionally exceeded 1.0. Lower values were observed with lubricants of grease or gold-plate and for ceramics sliding against metals. In general it was found that the coefficients in space and in a laboratory vacuum of 5×10^{-6} mm Hg were not systematically different. No further references were found to confirm this. No specific literature reference was found on the possible beneficial effects of outgassing products of complement materials on apparatus operations.

Appendix I

REFERENCES

1. Dushman, S., and Lafferty, J. M., Scientific Foundations of Vacuum Technique, John Wiley and Sons, Inc., 1962.

In this treatise the writer has not dealt specially with experimental procedures for using vacuum technique in the same manner as in Strong's book, Procedures in Experimental Physics, or the more recent work by Bachman, Techniques in Experimental Electronics. He has attempted to present a survey of fundamental ideas in physics, chemistry, and (to a smaller extent) metallurgy, which will be found useful to both scientists and engineers in dealing with problems in the production and measurement of high vacua.

2. Alpert, Daniel, Ultrahigh Vacuum: A Survey, Illinois U., Phys. Today, Am. Phys. Soc., January 1963.

The recent history of ultra-high-vacuum technology is summarized. Methods for producing low pressures have caught up with the means of measuring them. Since the study of physical and chemical phenomena can only be carried out by using the best ultra-high-vacuum techniques, there is a merging of the scientific and technological motivations. These include: (1) the kinetics of gas-surface interactions at the interface: (2) the interaction of atomic particles, electrons, and photons with surfaces: and (3) the nature of the electronic bonds between adsorbed molecules and surfaces.

3. Alpert, Daniel, Ultrahigh Vacuum: A Survey, Illinois U., Coordinated Science Lab, April 1963.

Low-pressure measurement devices and instruments for producing high vacuums are reviewed and it is found that these two types of instrument systems are approximately equivalent to pressures down to 10^{-10} Torr. Two new classes of ionization instruments, sensitive to 10^{-11} Torr, for the measurement of total pressures and for the mass analysis of partial constituents as low as 10^{-16} Torr, are explained. The study of the physical and chemical processes occurring at 10^{-11} Torr is summarized and includes: the kinetics of gas surface interactions at the interface, the interaction of atomic particles, electrons and photons, with surfaces, and the nature of electronic bonds between adsorbed molecules and surfaces.

4. Feldman, D. W., Lange, W. J., Rabinowitz, M., Singleton, J. H., and Zollweg, R. J., Ultrahigh Vacuum Techniques, Res. Rept. 64-928-441-R2, Westinghouse Electric Corporation, December 1963.

The following topics are presented: "Development of Components and Techniques"--electron sources, high-sensitivity mass spectrometers, and Teflon wall coatings for ultra-high-vacuum systems: "Particle Interaction at Surfaces"--photo-desorption, thermal desorption, the electron reflection at metal surfaces, and the ineleastic collisions of electrons at surfaces; "Basic Phenomena Limiting the Attainment of Ultrahigh Vacuum"--the residual gases in an ultrahigh-vacuum system, and the evolution of carbon monoxide from tungsten.

5. Hemstreet, R. A., Webster, D. J., Ruttenbur, D. M. Wirth, W. J., and Hamilton, J. R., Research Study of the Cryotrapping of Helium and Hydrogen During 20°K Condensation of Gases - Phases I and II, Linde Co. Div. of Union Carbide Corp., Arnold Engineering Development Center, May 1963.

A study of the variables affecting cryotrapping of helium and hydrogen during 20°K condensation of oxygen and nitrogen is presented. The mechanism of helium trapping appears to involve burying helium atoms in the solid oxygen or nitrogen. The process is most efficient at high condensation rates, but is not likely to find application for the removal of helium in a large space chamber. Experimental results indicate that hydrogen trapping occurs by adsorption of hydrogen molecules on the surface of the solid oxygen or nitrogen, and is most efficient at low condensation rates and low heat flux to the solid surface. These conditions indicate that hydrogen trapping may be applicable for hydrogen removal in a large space chamber. The trapping of hydrogen by nitrogen condensed on a 20°K surface has been studied under conditions where the surface was shielded from ambient-temperature radiation. The process is shown to be an inefficient means for hydrogen pumping, and is likely to have value only as a bonus in the operation of a large space chamber. Hydrogen trapping by methane, some simple fluorocarbons, and carbon dioxide condensed on a 20°K surface not shielded from ambient-temperature radiation has been studied. CCl_2F_2 and carbon dioxide show rather large capacities for hydrogen and may be useful for the pumping of hydrogen in a space chamber and in special applications.

6. Brombacher, W. G., Bibliography and Index on Vacuum and Low Pressure Measurement, National Bureau of Standards, November 1961.

The bibliography contains 1538 references, of which 52 are on books. About 550 of the periodical references are specifically on pressure measurement, including both vacuum gages and micro-manometers. The balance are on vacuum technology, including adsorption, degassing, vacuum pumps, controlled gas leaks, valves, seals, and vacuum systems, all of which bear on the technique of vacuum measurement. The indexes consist of an author index and an index of the subject matter of the listed references.

7. Heimburg, R. L., Huang, A. B., Jackson, E. A., Mueller, T. J. and Soo, S. L., Measurement of Pressure in an Ultra-High Vacuum, Illinois U., Urbana, Arnold Engineering Development Center, March 1963.

   Measurement of pressure in an ultrahigh vacuum environment, including the effect of adsorption, multigage operation, and streaming was studied. The theory of the Bayard-Alpert gage was further explored. The concept of adsorption was further generalized. Response of a gage was studied. An experimental system has been devised capable of substantiating these points, as well as comparing a number of different ionization gages and determining the interaction of gages. Generalization of results permits rational gage interpretation in various environments. The usefulness of a nude gage for all measurements is demonstrated.

8. Rhode, Richard V., and Houbolt, John C., The Impact of Space Technology on Research and Development - Structures and Materials, NASA, 1958.

   A broad discussion is given of the structures and materials problems that are involved in the design of space-flight vehicles. Problem areas are outlined and attention is focused on those areas which require increased research activity. The point of view taken is that space technology is a natural extension of aeronautical technology and that it is the environment, mission, and configuration which set the structural problems. The nature of the space-flight environment and the general trends in construction are therefore discussed, and this is followed by a detailed consideration of the loads, structural design, and materials problems. Some specific examples illustrating the severity of the loads and structures problems are given.

9. Atkins, J. H., Bisplinghoff, R. L., Ham, J. L., Jackson, E. G. and Simons, J. C., Jr., Effects of Space Environments on Materials, WADD TR60-721, 1960.

   The purpose of this report is to provide materials research engineers, designers, and fabricators with information regarding the effects that space environment will have on the performance of materials, thus assisting them in the selection of materials for space applications. Since radiation, high vacuum, and their combined effects are considered to be among the major factors that influence the behavior of materials under space conditions, considerable attention is given in this report to the current knowledge in this area and to the problem of simulating these conditions in the laboratory.

10 Wahl, Norman E., and Robinson, John V., The Effects of High Vacuum and Radiation on Polymeric Materials, Bell Aerosystems Co., Aerospace Materials and Process Engr. National Symp. on Effects of Space Environment on Materials, May 1962.

Data on the influence of combined radiation, heat and high vacuum on the physical properties of organic materials that might be used in space vehicles on equipment is deficient. This paper describes experimental studies that were conducted to determine the effects of heat, low pressure, and radiation on plastics and elastomeric materials.

11. Kerlin, E. E., Investigation of Combined Effects of Radiation and Vacuum and of Radiation and Cryotemperatures on Engineering Materials. Vol. 1: Radiation-Vacuum Tests, General Dynamics/Fort Worth, Nuclear Aerospace Research Facility, January 1963.

A series of tests were performed to measure the combined effects of nuclear radiation and vacuum on a group of nonmetallic materials that are considered for use in nuclear-powered space vehicles. This group consisted of materials classified as adhesives, seals, thermal insulations, electrical insulations, potting compounds, dielectric materials, lubricants, structural laminates, and thermal-control coatings. Typical tests performed on material specimens included lap-shear strength, ultimate tensile strength, ultimate elongation, stress-strain characteristics, compressive strength, weight loss lubricity, color changes, and spectral reflectivity. Two vacuum systems having pumping speeds in excess of 3000 l/sec at 10^{-6} torr were designed and built for use in these irradiations. Special dynamic test equipment was built for testing materials in vacuum after irradiation. Measured properties of the materials as a function of integrated neutron flux and gamma dose are reported, and recommendations for use of the various materials in nuclear-powered spacecraft are made.

12. Landrock, Arthur H., Effects of the Space Environment on Plastics: A Summary with Annotated Bibliography, Picatinny Arsenal, Plastics Technical Evaluation Center, Dover, N. J., July 1962

A brief summary outlines the various space environmental factors, natural and induced, and discusses their effects on plastics and related materials. These factors are: ultraviolet radiation, high-vacuum environment, temperature extremes, high-energy radiation and high-energy particles, sputtering, and micrometeorite erosion. Structural plastics, coatings, and elastomeric materials are considered. The bibliography lists 202 selected references. In the annotations, plastic materials covered in the references are listed, and results and conclusions are outlined when feasible. The arrangement is alphabetical by author. An index in depth is provided, covering both materials and subjects. This index is supplemented with additional indexes listing personal and corporate authors, military contract numbers, ASTIA AD numbers, report numbers, and technical conferences.

13. Wood, Webster, D., and Deem, Herbert W., Considerations of Emittance and Absorptance in Coatings for Space Applications, Battelle Memorial Institute, Aerospace Material, and Process Engr. National Symp. on Effects of Space Environment on Materials, May 1962.

Emittance, emissivity, absorptance, reflectance, and transmittance, their usual prefixes, and the relationships among them are defined and discussed. Variations in radiative properties are discussed generally and examples given. Precautions necessary to practical use of the data found in the literature are discussed. The need for a faster and more thorough system of reporting is pointed out, and a suggestion for such a system is mentioned.

14. Chamberlain, D. L., et al, Space Environment Effects on Polymeric Materials, Stanford Research Inst., Interim Technical Report No 1, Oct. 1962--June 1963.

Work was conducted to provide a definitive study of the effect of high vacuum (pressures greater than 10^{-8}mm of mercury) and temperatures in the range of 400° to 550°K on polymeric materials which are suitable for use in spacecraft. Included were studies of (1) polymer degradation by mass spectrometry, (2) volatile condensable materials, and (3) polymer syntheses and degradation. Materials under study include laboratory prepared polymers and commercial polymers, such as teflons, vitons, mylars, polyamides, and silicone rubbers.

15. Ringwood, A. F., The Behaviour of Plastic Materials in the Space Environments, General Electric Co., Valley Forge Space Technology Center, March 1963.

Space consists of a number of environments, of which several are rather easily simulated on earth by artificial means. These environments are vacuum, thermal-vacuum, ultraviolet, and particle radiation. Since space vehicles depend on the functioning of electronic equipment for the fulfillment of their missions, the effects of the space environments on the electrical properties of insulating materials are treated separately. The effects of the environments on some properties of plastic materials, both thermosetting and thermoplastic, are discussed.

16. Maguire, E. T., Reliability in Space Environment, Avco Corp., Wilmington, Massachusetts, Jan. 1963.

An abstract and summary are presented of literature on the subject of space environments with particular emphasis on the effects of the environment on the reliability of materials, components, and equipment contained in aerospace systems, the environment of space is discussed in the following areas: magnetic fields, gravitational fields, vacuum, micrometeorites and radiation.

17. Unpublished Materials - Research and Development Programs, First Semiannual Summary Report, McDonnell Aircraft Corp., December 1963.

Abstracts of the following test programs are presented: (1) mechanical, physical, chemical, and miscellaneous properties of the light metals, low and ultra high-strength steels, austenitic stainless steels, nickel chromium steels, titanium alloys, nickel base alloys, and refractory metals; (2) mechanical, physical, and miscellaneous properties of plastic materials such as epoxys, phenolics, polyethylene, urethanes, and vinyls; (3) mechanical, physical, and miscellaneous properties of silicone rubber materials; (4) chemical and miscellaneous properties of organic finishes, inorganic finishes, surface conditioning treatments, and chemical finishes when exposed to a corrosive environment; (5) effects of inorganic finishes on the mechanical, physical, and chemical properties of refractory metals; (6) chemical and miscellaneous properties of lubricants; and (7) physical and chemical properties of heat-transfer fluids.

18. Gayle, J. B., Caruso, S. V., and Egger, C. T., Vacuum Compatibility of Engineering Materials (Solids), National Aeronautics and Space Administration, Marshall Space Flight Center, September 1963

The effects of vacuum and elevated temperature on 54 solid materials are reported. Other preliminary results indicate that weight regains on exposure to air subsequent to vacuum testing are small for most materials and are not influenced by the temperature used for the vacuum test. Good correlation of total weight loss generally was noted for results with continuous weighing in standard vacuum systems and those for screening tests utilizing before-and-after-weighing from a vacuum oven.

19. Parker, John A., Gloria, Hermilo R., Lohr, Jerome J., Some Effects of the Space Environment on the Physical Integrity of Plastics, National Aeronautics and Space Administration, Ames Research Center, Moffett Field, Calif., 5th Ann. Structures and Mater. Conf., 1964.

The weight-loss phenomenon of heterogeneous solids in vacuum has been investigated. Specifically, composites of a sublimable inorganic solid, ammonium fluoroborate, and cross-linked polymer systems, which included a cast elastomer and an epoxy plastic, have been studied under programed and constant temperature conditions. Quantitative isothermal experiments were conducted in a chamber with liquid-nitrogen cooled walls at a pressure of 1×10^{-6} torr. Examination of the vapor phase chromatography of outgassed material and comparison of the weight-loss processes, by means of thermograms, with those of composites of known constitution have established that the principal component lost under these conditions was the inorganic solid. Analysis of the rates of weight loss of the sublimable component showed two sequential mechanisms for the weight-loss processes. The first, the most rapid, is believed to be the sublimation of the inorganic solid exposed at the surface of the composite. The second part of the weight-loss process, sublimation, sorption, and diffusion of sublimate through the encapsulating polymer film, has been found to be a function of the concentration of sublimate, the polymer type, the temperature, and the sample geometry.

20. Gaumer, R. E., Streed, E. R., and Vajta, T. F. Methods for Experimental Determination of the Extra-Terrestrial Solar Absorptance of Spacecraft Materials, Lockheed Missiles and Space Co., Palo Alto Calif., In NASA Measurement of Thermal Radiation Properties of Solids, 1963.

Two basic methods of experimentally determining solar absorptance are described. Spectral diffuse reflectance and total simulated solar absorptance measurements are compared in terms of accuracy, instrumentation, sample requirements, and data reduction. The use of spectral data during material development to optimize desirable optical characteristics is shown. Typical data obtained by each method are included.

21. Mauri, R. E., Performance of Lubricants and Thermal Control Materials Under Simulated Space Conditions, Lockheed Missiles and Space Co., May 1962.

The gross effects of space environment on typical materials for spacecraft applications are briefly discussed. Equipment and experimental procedures used at LMSC for testing and selecting materials in support of a typical high-reliability satellite hardware program are described. Principal material problem areas associated with this program are lubricants for mechanisms and thermal control materials. Experimental details and results on the effect of high vacuum and operating conditions on oils, greases and dry-film lubricants for bearings are presented. Also discussed are applications of thermal control materials and results of environmental testing of solar reflectors such as white paints in the presence of intense ultraviolet radiation in vacuum.

22. Jaffee, L. D., and Rittenhouse, J. B., Behavior of Materials in Space Environment, Technical Report No. 32-150, Jet Propulsion Lab., 1961

The quantitative effects of the environments encountered in various regions of space upon several kinds of engineering materials are discussed. In the vacuum of space, magnesium sublimes appreciably at elevated service temperatures; zinc and cadmium sublime at ordinary temperatures. Most other engineering metals will be unaffected by vacuum except for a slight surface roughening. Among the organics, polysulfides, cellulosics, acrylics, polyvinyl chloride, neoprene, and some nylons, polyesters, epoxys, polyurethanes, and alkyds break down at rather low temperatures in vacuum. Polyethylene, polypropylene, most fluorocarbons, and silicone resins do not decompose significantly in vacuum below 250°C. Except for plasticized materials, significant loss of engineering properties in vacuum is unlikely without appreciable accompanying sublimation or decomposition. Also, escape of gases through walls which are gas-tight at 1 atmosphere will not be of concern.

23. Berman, L. D., Compatibility of Materials with Storable Propellants, Martin Co., Denver, Colorado, Proceedings of the Fourth National Sampe Symposium, Hollywood Calif., Aerospace Div. of Martin-Marietta Corp. November 1962.

A comprehensive summary of the compatibility of materials with amine fuels and nitrogen tetraoxide is presented. This paper discusses the development of criteria and environments, formulation of test procedures for long-and short-term exposure, decontamination procedures, and data

applicable to the compatibility of metals, nonmetallics, finishes, lubricants, and sealing systems for both airborne and ground equipment. Some of the mechanics of corrosion of aluminum in the amine fuels are also discussed.

24. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, (Batelle Memorial Institute,) Huntsville Ala. April 1964, RSIC-150 Vol. 1: AD 603364.

This volume covers the following elastomeric and plastic materials: potting (embedding and encapsulating) compounds (polyurethane, epoxy, silicone); insulation, wire (teflon, polyolefins, silicones, PVC, natural resins); sealants: elastomers lubricants, and coatings (paints, lacquers anodizing).

25. Broadway, N. J., King R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix A: Elastomers, Battelle Memorial Inst., Columbus, Ohio, April 1964, AD 603365.

This is a compilation of 58 tables giving detailed information on elastomers, including such aspects as outgassing rates, weight loss in vacuum, physical properties, exposure to high temperature and other considerations.

26. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix B: Plastics, Battelle Memorial Inst., AMC, April, 1964.

A wide range of environmental tests are reported for plastics in a series of charts and tables. Such items as thermal irradiation, UV exposure and weight loss rates are included.

27. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix C: Coatings, Battelle Memorial Inst., AMC, April, 1964.

Various tests, analyses and examinations of coatings are presented in tabular forms. Composition, exposure to radiation, weight losses, and vacuum thermal effects are considered.

28. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix D: Structural Adhesives, Battelle Memorial Inst., AMC, April 1964.

The effect of vacuum and elevated temperatures on various structural adhesives is given in tables, along with conditions and results of UV exposure, static tests and other examinations.

29. Broadway N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix E: Electrical Insulation, Battelle Memorial Inst., AMC, April 1964.

This volume covers the following elastomeric and plastic materials: potting (embedding and encapsulating) compounds (polyurethane, epoxy, silicone); insulation, wire (teflon, polyolefins, silicones, PVC, natural resins); sealants; elastomers: lubricants: and coatings (paints lacquers, anodizing) Further work is covered by appendices to this volume one.

30. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix F: Laminates, Battelle Memorial Inst., AMC, April 1964.

Laminates are discussed in terms of flexural and compressive strength, exposure to UV radiation and high vacuum, and low- and high- force dynamic tests: tables, charts, and graphs related to laminates are also included.

31. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix G: Potting Compounds, Battelle Memorial Inst., AMC, April 1964.

Potting compounds are tabulated to give information on encapsulating materials, weight loss rates, test environment and results of static tests, effect of nuclear radiation in vacuum, and effect of high vacuum and elevated temperature on physical and electrical properties of typical plastic potting compounds.

32. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix H: Seals, O-Rings, and Gaskets, Battelle Memorial Inst., AMC, April 1964.

Test results on Buna N O-rings and Neoprene O-rings, as well as on some seals and gaskets, are presented in tabular and graphic form. Stress-strain curves and low force dynamic test results are among the data included.

33. Broadway, N. J., King, R. W., and Palinchak, S., Space Environmental Effects on Materials and Components. Vol. I - Elastomeric and Plastic Materials, Appendix I: Radiation at Cryogenic Temperatures, Battelle Memorial Inst., AMC, April 1964.

Radiation at cryogenic temperatures is presented in a series of tables and charts as it relates to various coatings, laminates, insulations, seals, and adhesives.

34. Freundlich, Martin M. and Jagodowski, Stanley J., Lubricant for High-Vacuum Environment. Part II, Technical Documentary Report, Airborne Instruments Lab., Div. of Cutler-Hammer, Inc., Wright-Patterson AFB, February 1962.

The objective of this work was to determine vapor pressures and evaporation rates of four experimental high-temperature fluids in a high-vacuum environment over a wide range of temperatures. The vacuum microscale developed in this investigation was improved and the measurement method refined. The microscale was checked with n-heptadecane, and the results showed good agreement with published values. The following four fluids were supplied by ASD; and their evaporation-rate and vapor-pressure curves are given: (1) hexaphenyl ether, (2) Siloxane, (3) silicone fluid QF 6-7040, and (4) silicone fluid F 6-7024.

35. Low Viscosity Bearing Stability Investigation, General Electric Co, Flight Propulsion Lab. Dept., Cincinnati, Ohio, February 1962.

The program objective is to select and develop bearing configurations that promise stable operation up to the high speeds typical of space turbomachinery (35,000 r.p.m.). A high-speed test rig, which is precision made for interchangeability of a large variety of bearing configurations and rotors, will be used to record rotor and bearing motions, as well as other parameters affecting bearing operation. The testing will be carried out at close to room temperature with lubricants which simulate the low viscosity and lubricity of liquid metals at operating temperatures. The experimental testing will be supplemented by analytical studies necessary to select the most promising bearing configuration, and to reduce test results to dimensionless parameters.

36. Demorest, K. E., Vacuum Lubrication, NASA, Marshall Space Flight Center, January 1962.

The problem of lubrication of guidance, control and instrument type bearings in space is under comprehensive study. This report describes the apparatus

used in the study, the environment in which evaluations of inorganic dry film lubricants are being made, and a mathematical model designed to describe the failure mode observed in actual testing. The method of total problem solution is described and the status of current work is discussed in detail.

37. Mauri, R. E., Performance of Lubricants and Thermal Control Materials Under Simulated Space Conditions, Lockheed Missiles and Space Co., Palo Alto, Calif., Society of Aerospace Mater. and Process Engr. National Symp. on Effects of Space Environment on Materials, May 1962.

The gross effects of space environment on typical materials for spacecraft applications are briefly discussed. Equipment and experimental procedures used for testing and selecting materials in support of a typical high-reliability satellite hardware program are described. Experimental details and results on the effect of high vacuum and operating conditions on oils, greases, and dry-film lubricants for bearings are presented. Also discussed are applications of thermal control materials and results of environmental testing of solar reflectors, such as white paints, in the presence of intense ultraviolet radiation in vacuum.

38. Calhoun, S. Fred, Wear and Corrosion Tendencies of Molybdenum Disulfide Containing Greases, Rock Island Arsenal Lab., August 1962.

The tendency of molybdenum disulfide to increase the wear of greases is shown by results of laboratory tests. The extreme pressure properties of greases were increased by the addition of the molybdenum disulfide. It also promotes rusting of ferrous metals when added to grease.

39. Clauss, Francis J., Lubrication Under Space/Vacuum Conditions, Lockheed Missiles and Space Co., October 1962.

The effects of space environment on friction, wear, and the selection of lubricants and self-lubricating materials for spacecraft mechanisms are discussed, with special emphasis on the ultrahigh vacuum of space. Experimental studies have demonstrated the feasibility of using selected oils and greases to lubricate loaded ball bearings without replenishment for periods of over one year under the following conditions of operation: speeds of 8000 rpm, temperatures of 160° to 200°F, and vacuum of 10^{-8} torr. Over one-half year of successful operation has been achieved under similar operating conditions with self-lubricating retainers of reinforced Teflon, provided that the loads were light. Bonded films of molybdenum disulfide have given shorter lifetimes and poor reproducibility. Metal-to-metal slip-ring contacts introduce excessive electrical noise (as well as the friction and wear) can be markedly reduced by providing a small amount of oil vapor, sufficient to maintain a pressure on the order of 10^{-6} torr, or by incorporating molybdenum disulfide into the brush material.

40. Adamczak, R. L., Benzing, R. J., and Schwenker, H., Lubrication in Space Environments, Aerospace Mater. and Process Engr. National Symp. on Effects of Space Environment on Materials, May 1962.

Solid, semisolid and liquid lubricants, hydraulic fluids, heat transfer fluids, and novel lubrication techniques are discussed with respect to the current state-of-the-art and the future capabilities of these various materials and/or their application. The severe environmental conditions of space are compared against both the current and future state-of-the-art in the field of lubrication and energy-transfer media.

41. Brooks, D. B., Aerospace Lubrication Research Survey, Defense Dept., Wash, D. C., December 1962. Ad 439678.

The results of a survey of firms conducting research into the problems of lubrication at extreme altitudes and in space are presented. Types of lubrication included in the survey were lubrication in high vacuum, gas bearing lubrication, solid film lubrication lubricants for use in contact with liquid fuels and oxidants, and lubrication with closed-cycle turbine working fluids. Information presented includes the name of firm doing the work, environmental test range and publications.

42. Parcel, R. W., Clauss, F. J., O'Hara, C. F., and Young, W. C., Lubrication and Wear in Space Systems, Lockheed Missiles and Space Co., Palo Alto, California.

With the increasing sophistication of space missions, lubrication for bearings, slip rings and other moving parts must remain reliable for long periods in the hostile environment of space. This paper reports lubrication studies in antifriction bearings and sliding electrical contacts in simulated aerospace environments. In a series of over 100 tests, bearings are shown to perform successfully for up to two years with a single application of certain oils and greases. In tests involving 43 combinations of materials and lubricants, some slip rings are shown to operate up to one year without developing excessive noise, provided that either solid lubricants, such as MoS_2, are incorporated into the metal contacts or a low pressure of oil is main-

tained. Problems in the operation of moving parts, resulting from space environment, are discussed and the advantages of various lubrication techniques are reviewed.

43. Johnson, R. L. and Anderson, W. J., Summary of Lubrication Problems in Vacuum Environment, Lewis Research Center, NASA, April 1963.

A cross section of the information available on lubrication in vacuum is presented to illustrate the problems and characteristics associated with various mechanical devices and materials. Lubrication problems of mechanical devices operating in space are considered to result primarily from low pressure and oxygen deficiency of the environment. Lubricant films will evaporate, and, when the underlying oxide films (on metals) are worn away, the nascent metals will weld. Metal transfer that results is so severe as to destroy operating tolerances in bearings and gears. Devices run at higher temperatures as a result of the vacuum environment than they do in air, since the heat dissipation problem is more difficult.

Special design considerations are required, in many cases, for the satisfactory use of mechanical components in vacuum. Friction, wear, and adhesion problems are common to bearings, gears, electric contacts, and seals. Much fundamental information is being gained.

44. Office of the Director, Aerospace Lubrication Research Survey, Defense Research and Engrg., The Pentagon, December 1962.

This publication presents a tabulation of research projects concerning aerospace lubrication in progress or completed at the time of publication. The publication is useful in establishing identity and field of interest of current investigators.

45. Morris, J. L., Review of Liquid Metal Lubrication Research Programs, Aeronautical Systems Div., Air Force Systems Command, Wright-Patterson AFB, 1963 USAF Aerospace Fluids and Lubricants Conf., Session 11-B, April 1963.

Simplicity and minimum weight are maintained in space power-conversion systems by using the liquid-metal working fluids as hydrodynamic bearing lubricants. This concept has been proven feasible by a number of experiments at expected system conditions.

46. Thompson, R. P., Space Lubrication Problems at JPL, Jet Propulsion Lab., "Spacecraft Lubrication Problems with Specific Applications to Ranger, Mariner and Surveyor Programs", California Institute of Technology, September 1963.

The general approach of the Jet Propulsion Laboratory to spacecraft lubrication problems is presented. Several specific applications on the Ranger, Mariner and Surveyor programs are discussed. A prediction of future lubrication problems on projects such as Voyager is made.

47. Hopkins, Vern, and Gaddis, Donald, Development of Solid Film Lubricants for use in Space Environments, Midwest Research Inst., USAF Aerospace Fluids and Lubricants Con., April 1963.

This research program is concerned with the development of inorganic solid film lubricants suitable for service in space environments. Friction coefficients are given for many potential lubricants subjected to a light load and temperatures from 80° to 400°F in both a normal air atmosphere and in a vacuum of 10^{-6} torr. The main criterion for judging the performance of a potential lubricant film was the friction coefficient, which must be less than that obtained for a 0.001-in-thick film of gold. The following lubricant films exhibited lower overall friction coefficients than a 0.001-in-thick gold film: MoS_2 + graphite + bismuth-sodium silicate; MoS_2 + graphite + gold-sodium silicate; MoS_2 + graphite + molybdenum-sodium silicate; MoS_2 + graphite-sodium silicate; and MoS_2 + graphite-sodium phosphate.

48. Dunham, M. P., Fluids for High-Temperature Applications, Wright-Patterson AFB, AGARD Combustion and Propulsion, 1963.

A review is given of the source and nature of high-temperature fuels, lubricants, hydraulic fluids and electronic coolants problems, and the limitations of the more conventional fluids are discussed. Recent information on the types of advances high-temperature fuels, lubricants, hydraulic fluids and electronic coolants and data on their properties are included.

49. Devine, M. J., Lamson, E. R., and Bowen, J. H., Jr., The Effect of the Chemical Composition of Metals in Solid Lubrication, Naval Air Experimental Station, Aeronautical Materials Lab., 1963 USAF Aerospace Fluids and Lubricants Conf. Session V-B, San Antonio, Texas, April 1963.

The relationship of alloy constituents and chemical composition of lubricating solids in the processes of lubrication have been explored to establish basic concepts.

The lubrication characteristics displayed by metallic sulfides as a class of compounds for molybdenum metal, and the significance of metal composition for surfaces having sliding contact in bearings operating 10,000 rpm and 750°F is described. Experimental results for a bonded solid-film lubricant under these conditions of speed and temperature provided 1100 hours of wear life. A description of a vacuum system designed to operate at pressures in the range of 1×10^{-6} mm Hg, and at temperatures as high as 1000°F is shown, as well as results of studies conducted under the combined vacuum and temperature environment.

50. Christian, John B., Air Force Grease Research Programs, Aeronautical Systems Div., Air Force Systems Command, Wright-Patterson AFB, 1963 USAF Aerospace Fluids and Lubricants Conf. Session IV-A, San Antonio, Texas, April 1963.

The Air Force is conducting research leading to new and improved grease-like materials capable of providing lubrication under those environments and probable operating conditions imposed upon Air Force aerospace vehicles. Some of those environments and probable operation conditions being considered are high temperatures, low temperatures, high speeds, heavy loads, high pressures, deep vacuums, and extremely long periods of operation without lubrication.

51. Bowen, Paul H., Lubrication of Bearings and Gears in Aerospace Environmental Facilities, Westinghouse Electric Corp. Research Labs., Arnold Air Force Station, Arnold Eng. Develop. Center, July 1963.

This report presents results of screening tests of plastics, powders, and composites, as dry lubricants in ball bearings and gears operating in an ultrahigh-vacuum environment. Conclusions are drawn with regard to concepts of dry lubrication, lubrication techniques, and desirable composite materials in adapting bearings and gears for use in handling equipment of environmental space chambers.

52. Pinson, J. D., and McRae, W. F., Lubrication Requirements for Space Environments, Arnold Engineering Development Center, Arnold Air Force Station, October 1963.

This paper presents a detailed description of research in this area with special emphasis on results of tests related to operating gears and bearings in a simulated space environment.

53. Kingsbury, J. E., and McKannan, E. C., A Survey of Vacuum Lubrication Developments, Report from Proc. of the 1963 Annual Technical Meeting of the Inst. of Environmental Sciences, April 1963.

Current vacuum lubrication programs in eight laboratories are reviewed for several purposes, such as: (1) collecting available information in one reference and up-dating a previous effort toward this end, (2) determining the degree of coverage of probable applications and requirements by current development programs, and (3) comparing test methods and conclusions from different programs to increase the reliability in selection of specific materials and components. Some generalized conclusions have been made where there has been sufficient agreement among the programs reviewed.

54. Abbott, Helen M., Gears, Bearings and Lubricants for Aerospace Applications: An Annotated Bibliography, Lockhead Missiles and Space Co., Sunnyvale, California, August 1963.

This compilation of 189 annotated references is divided into two parts: (1) gears and bearings, and (2) lubricants and lubrication techniques. This material provides a coverage of the literature from October 1961 through August 1963. Subject, author, and corporate source indexes are included.

55. Flom, D. G., Survey of Aerospace Requirements for Bearings and Lubricants, General Electric Company, Space Sciences Laboratory, Philadelphia, Pennsylvania, May 1964.

This is a survey of the requirements for bearings and lubricants by the aerospace industry. For convenience, the conditions are separated into natural environments associated with space and induced environments associated with specific vehicles and missions. Natural environments include low pressures, temperature extremes, meteoroid impact, electromagnetic and particulate radiation, and low gravitational forces. Temperature extremes, nuclear radiation effects, and acceleration, shock, and vibration loading make up induced environments.

56. Bisson, Edmond E., Friction and Bearing Problems in the Vacuum and Radiation Environments of Space, National Aeronautics and Space Administration, Lewis Research Center, Cleveland, Ohio, 1964.

A general discussion is given of the friction and bearing problems that result from the exposure of mechanisms to the vacuum or radiation environments of space. Some of the problems can be eliminated by design techniques, such as the use of hermetically sealed systems, but this solution is not always possible because of its complexity and weight disadvantages. The discussion concerns finding better solutions involving self-lubricating materials or limited-life lubricants.

57. Prevention of Corrosion When Using Molybdenum Disulfide Lubricants, Alpha Molykote Corporation, Stamford, Connecticut, 1964.

Several factors were found that must be considered in the formulation of MoS_2-based, extreme-pressure greases and oils if the material is to have assured corrosion-preventive properties. First, the purity of the powder must be carefully controlled and then the factor of particle size must be evaluated. Finally, when required, the proper corrosion inhibitor or other additives must be selected and blended with the lubricant in the required proportions and compounded, not only so that the essential qualities of the lubricant are preserved but also so that the functional properties of the molybdenum disulfide are not impaired but, rather, are enhanced. Investigation of the merits of p-nonyl phenoxy acetic acid as a rust inhibitor was conducted. A low-concentration, fine-powder MoS_2 grease was selected as the subject of a corrosion test. One sample was blended with 1% of the inhibitor, and the other was used as a test control. The bearing lubricated with the inhibited grease showed no evidence of rusting, whereas the control bearing was partially corroded. It was, therefore, possible to nullify completely any rust-inducing tendencies of MoS_2 greases.

58. Johnson, J. H., and Irwin, A. S., Survey of Frictional Problems in Spacecraft, Final Report - Marlin Rockwell Corporation, Jamestown, New York, February 1964.

A survey of frictional problems in spacecraft mechanisms conducted to determine the degree of research and development effort that is required to solve the problems introduced by the space environment is discussed. The survey covered bearings, gears, and seals. It is concluded that research should concentrate on implementing design decisions, developing new mechanical design concepts, and basic investigations to develop materials and lubricants for the future. It is also concluded that more emphasis on lubrication is warranted.

59. Wellons, F. W., State of the Art Appraisal USAF-SwRI, Aerospace Bearing Conference, San Antonio, Texas, March 1964.

Discussed is work carried out in studying the mutual dependence of lubrication and construction on bearing life in the space environment. Bearings made of air-and vacuum-melt steel are compared. Also discussed are the contribution of improved materials to bearing reliability and methods of endurance testing of bearings.

60. Calhoun, S. Fred, and Fisher, Max T., Surface Chemistry of Some Lubricant Additives, Rock Island Arsenal Lab., Ill., January 1964.

Eleven compounds or combinations of compounds were studied in this investigation. They were added to white mineral oil and evaluated for their effect upon the lubricative properties of the oil. The results were a positive but varied improvement for all additives. Six of them were tritiated, and their absorption on bearing steel specimens were studied by radioactive counting. An increase in temperature and humidity resulted in variable increases in absorption. It was observed that on static storage some of the additives apparently settled in the lubricant without forming a precipitate. Others formed a visible precipitate. In either case, their effect upon the lubricant was appreciably diminished. Degreasing with trichloroethylene seemed to eliminate the lubricative ability of the additive even though radioactive counting disclosed some still to be present on the degreased test specimen.

61. Johnson, Robert L., and Buckley, Donald H., Lubricants and Mechanical Components of Lubrication Systems for a Space Environment, National Aeronautics and Space Administration, Presented at the Am. Soc. of Lubricating Engr. Aerospace Council Meeting, Chicago, Ill., May 1964.

This report concerns: (1) design criteria for rolling-contact bearings, sliding bearings, gears, and dynamic seals; (2) component designs for various types of bearings and gears; (3) materials for bearings surfaces; (4) lubrication methods and materials; (5) proof testing of lubricated components; (6) the survey and determination of vacuum evaporation characteristics for lubricated materials; and (7) a review of the state-of-the-art of lubricants and mechanical components of lubrication systems for a space environment.

62. McConnell, B. D., Air Force Materials Laboratory Solid Film Lubrication Research, AFSC, Wright Patterson AFB, Ohio, April 1964.

This report outlines the general range of bearing lubrication requirements of present aerospace vehicles, and briefly describes the range of requirements anticipated for future Air Force weapons systems. This report covers only those programs concerned with solid film lubrication, and contains discussion of both development-type programs and related basic or fundamental-type programs. Program objectives, approaches to the problems, data obtained to date, and future work are discussed for each program.

63. Solitario, W. A., Bialecki, A., and Laubach, G. E., An Approach to Trace Contaminant Control for a Spacecraft Atmosphere, Chemical Engineering Progress, Symposium Series Volume 60, 1964.

The problem of atmospheric trace contamination is inherent to any closed or semiclosed ecological system. Every spacecraft system, including the man, constitutes a latent source of contaminant vapors and particulate matter. Determination of the exact composition of the contaminants and their concentration is necessarily the first step in any atmospheric contaminant program. Removal and detection systems based on control levels must then be designed to effectively eliminate and monitor specific contaminants.

To discuss the problem, it is necessary at the onset to define the term "atmospheric trace contamination". Reference to this term will imply any and all trace vapors, odors, and particulate matter which, if allowed to accumulate in the spacecraft's life support atmosphere, would be detrimental to man's performance. The possible detrimental effects of trace contaminants on operative equipment are excluded from this discussion.

64. McKee, Herbert C., Rhoades, John W., Wheeler, Ralph J., Burchfield, H. P., Gas Chromatographic Measurement of Trace Contaminants in a Simulated Space Cabin, National Aeronautics and Space Administration, March 1963.

Methods have been developed for sampling the air in a simulated space cabin and analyzing it for trace contaminants by gas chromatography. Compounds which were identified during five simulated flights include acetaldehyde, acetone, methanol, ethanol, Freon-11, Freon-12, Freon-22, methyl chloride, and dimethyl sulfide. The presence of Freon-114, isoprene, acetylene, ethylene oxide, carbon tetrachloride, methyl ethyl ketone, benzene, and toluene is also suspected, although identity has not been confirmed unequivocally. Several additional unidentified compounds were also present. A number of unidentified peaks appeared transiently during the malfunction of a waste disposal unit. Thus, gas chromatography has great potential value for monitoring the atmosphere within space capsules for metabolic products as well as for other contaminants introduced accidentially. Chemical tests were made for the presence of inorganic compounds in the atmosphere during two additional simulated flights. The presence of sulfate ion, chloride ion, chlorine, sulfur dioxide, ammonia, and ozone in trace amounts was confirmed.

65. Saunders, R. A., Atmospheric Contamination in the Space Cabin, Naval Research Lab., Washington, D.C., January 1963.

Organic contaminants dispersed in the atmospheres of Mercury spacecraft are adsorbed by activated charcoal in the environmental control system. The contaminants are later recovered from the charcoal in the form of a complex mixture by a process of vacuum desorption. The small volume of the space cabin and the low concentration of the various contaminants result in the recovery of very small quantities of contaminant mixture. The identification of the components in this mixture and the determination of their concentration in the original atmosphere require the use of microtechniques. The contaminant mixture is separated into its components by means of an analytical gas chromatograph. The individual components are recovered from the effluent stream of the chromatograph with a novel fraction collecting system and their identity established by means of infrared and mass spectral techniques. A summary is given of 27 organic contaminants recovered from several spacecraft atmospheres.

66. Thomas, A. A., and Back, K. C., The Environmental Toxicity of Space Cabin Atmospheres, Aerospace Medical Division, Aerospace Medical Research Labs, (6570th), Wright-Patterson AFB, A symp. on Toxicity in the Closed Ecol. System, Lockheed Missiles and Space Company, Palo Alto, California, 1963.

Although spacecraft cabin materials that produce noxious gases and vapors will probably not be much different from those found in submarines, the closed environment of the space cabin poses different problems, such as the management of chemical, algal, bacterial, and perhaps fungal subsystems; cabin operating pressures that will increase the boiloff from common substances; zero-gravity and the delayed settling of particulate matter; radiation decomposition products; and power limitations. To test the validty of extrapolation of industrial TLV's to space conditions, a series of animal experiments were run using a group of metabolic products and a group of propellants. The results indicate that the industrial TLV cannot be used for long-term exposure criteria, and that there are physiological actions and interactions between various contaminants that can be classed as additive, synergistic, or antagonistic. It is suggested that biological evaluations be begun on materials scheduled to be used in research prototype space cabins, so that toxicological data will parallel the developmental schedule.

67. Weber, Thomas B., Atmosphere Monitoring in the Space Cabin Simulator, Beckman Instruments, Inc., A symposium on Toxicity in the Closed Ecol. System, Lockheed Missiles and Space Company, Palo Alto, Calif., 1963.

Inherent difficulties in assaying trace constituents in a space-cabin simulator include accurate collection and assay of a representative sample. Not only is it difficult to quantitatively isolate trace constituent, but transporting and introducing it into suitable instrumentation is an intricate process. Maintaining meaningful gas standards is also difficult. Three principal steps must be followed to resolve problems concerned with closed environment atmospheres: (1) the presentation of an adequate definition of the problem; (2) the development of suitable instrumentation for the continuous monitoring of low-level constituents; and (3) the eradication and control of the undesirable contaminants.

68. Anderson, W. L., and Saunders, R. A., Evolution of Materials in the Closed System, Naval Research Lab., A symp. on Toxicity in the Closed Ecol. System, Lockheed Missiles and Space Co., Palo Alto.,Calif. 1963.

The results of analyses of nuclear submarine and spacecraft atmospheres conducted during actual manned operations are discussed. The trace contaminants that have been identified are tabulated, and the suspected source is indicated if known. In the smaller volume of the Mercury spacecraft the contamination problem is even more acute, since a contaminant can reach the maximum allowable concentration more quickly from a small amount of material. It is important that the exact concentration of each contaminant or group of contaminants be established so that toxic effects and maximum allowable limits can be established by toxicologists.

69. Wessel, Carl J., Harmful Effects on Materials and Equipment, National Academy of Sciences, A Symp. on Toxicity in the Closed Ecol. System, Lockheed Missiles and Space Co., Palo Alto, Calif., 1963.

A review of published data on the effects of deteriorative environments on materials and equipment is presented. The factors discussed are limited to those that exist in closed ecological systems such as submarines and space cabins and include the following: water vapor (humidity), liquid water (condensates), moderate heat fluxes, salts, acids, alkalies, oxygen ozone, sulfur dioxide, nitrogen dioxide, miscellaneous gases and aerosols, and fungi and bacteria. All of these factors can be controlled; however, in the cases of water, oxygen, and moderate heat fluxes, conditions nearly optimum for man are in ranges that could cause low-order deterioration reactions of minor importance over long time periods.

70. Pickaux, M. E., and Spruill, Howard, Physical Properties of Non-Metallic Materials for Manned Space Vehicles, McDonnell Aircraft Corp., St. Louis, Mo., January 1964. Rept. 6792

The maximum use temperatures that have been established for nonmetallic materials to be used in the inhabited area of spacecraft are presented. The indicated temperature limits are based upon laboratory tests using 100% oxygen atmosphere at 5 psi absolute for 3 to 24 hours continuously without producing irritating or obnoxious odors. The charts are guides for design engineers concerned with the selection of nonmetallic or nonceramic materials. Also included are reports on the contaminants recovered from capsule atmosphere of Mercury flights, and fabrication and housekeeping policies applicable to Models 133 and 133P capsules.

71. Matthews, C. O. and Finch, W. L., Report on the LMSC Spacecraft Materials Reliability Program, Lockheed Missiles and Space Co., Research Labs., Soc. of Aerospace Mater, and Process Engr. National Symp. on Effects of Space Environment on Materials, May 1962.

Information is summarized on the applicable spacecraft environment, spacecraft materials requirements, the evaluation of environmental effects on materials, and the selection of promising materials. A spectrum of materials is covered, including surface coatings and finishes, optics and filters, lubricants, sliding electrical contacts, adhesives, seals, electronics component materials, antennas, solar cells, and infrared detectors.

72. Cordaro, Joseph T., Buchanan, Henry, Mann, Bruce, and Miller, A. K., Controlled Contamination: A Practical Approach for Developing Sterilization Procedures for Sealed Components of Spacecraft, School of Aerospace Medicine, Brooks AFB, Texas, September 1963.

Deliberate contamination of components during manufacture appears both practical and feasible for developing sterilization procedures for spacecraft components. Thus, it is possible to determine whether normal manufacturing procedures are sufficient to sterilize or whether the sterilization procedures required (e.g., temperature--time intervals for dry heat) to sterilize can be accomplished without component damage. Methods are presented for controlled contamination with bacterial spores highly resistant to dry heat and bacteriologic recovery of such spores. Impregnated (e.g. with polybutylene) capacitors were rendered sterile during manufacture; nonimpregnated capacitors were not. Any damaging effects of heat sterilization might be increased if the components were subjected to further heating when installed in circuits of spacecraft instrumentations.

73. Ivanov, Yuriy, Atmosphere of the Space Ship, Air Force Systems Command, Wright-Patterson AFB., Ohio, Foreign Technology Division, Sov. Latviya (Moscow), August 1962 Ad 290833

Comparisons made are of three possible methods of regulating the gaseous content of the atmosphere in the cabin of a spaceship: the control of cabin temperature is discussed. Particular emphasis is placed on an automatic system of controlling the gaseous composition of the air by employing sensitive elements that detect the deviation in the content of oxygen, carbon dioxide, and moisture, and a regulator that controls the rate of corresponding reactions in the regenerator. For temperatu e control, attention is directed toward a system of shutters on the spaceship that makes it possible to change the radiation capacity, increase the effectiveness of the heat regulation, and ensure high precision in holding a given temperature for the cabin.

74. Environmental Control Systems Selection for Manned Space Vehicles, North American Aviation, Inc., Los Angeles, Wright-Patterson AFB., Aeronautical Systems Division, December 1961. ASD-TR-61-240.

This is one of seven reports summarizing the first phase of work on a study of thermal and atmospheric control systems for manned and unmanned space vehicles. In this report, realistic requirements for these systems are developed based upon actual preliminary designs of a series of manned orbital space vehicles having mission durations from 36 hours to 6 weeks. In addition to variations in mission duration, the vehicles cover a range of crew size, equipment heat load, re-entry weight, and re-entry wing loading. The report is divided into two volumes, with Volume II (Secret) containing the detailed missions and roles data for the vehicles.

Based upon these vehicles, a series of active and semi-passive thermal and atmospheric control systems are developed and analyzed. Integration of these systems with associated systems such as life support and secondary power is discussed. A promising system using hydrogen fuel as a heat sink has been analyzed in detail, and the results are presented.

75. Mercury Project Summary Including Results of the Fourth Manned Orbital Flight, NASA Manned Spacecraft Center, Project Mercury, May 1963.

Throughout the Mercury development and flight programs, quality control and rigid manufacturing standards were found to be absolutely mandatory if incidental flight failures and discrepancies were to be avoided. Continuing attention to engineering detail was an important reason for the success of the Mercury flight program, particularly the manned sub-orbital and orbital missions. Malfunctions which still occurred are discussed and their causes established. Contamination remained as a major concern.

76. Smylie, R. E., and Reumont, M. R., Life Support Systems, Manned Spacecraft Engineering Design and Operation - Purser Faget and Smith, 1964.

The primary sources of trace contaminants anticipated in spacecraft atmosphere are:

1. Non-metallic materials used in spacecraft.
2. Leakage of stored gases (Hg etc)
3. Leakage from material processing equipment (O_2, reclamation system, etc)
4. Metabolic processes of the crew.

77. Broglio, L., Current Research in Astronautical Sciences, Pergammon Press, London, Proceedings of the Rome Seminar on Astronautics sponsored by AGARD-N.A.T.O., 1961.

This reports deals primarily with the spacecraft cabin environment as it affects human compatibility. Considerations in atmospheric pressure, oxygen provisioning, recycling methods, pressure suits, toxic gases and temperature and humidity variants are discussed.

78. Roth, E. M., Space Cabin Atmospheres, Lovelace Foundation for Medical Education on Research, NASA Proc. of the 4th Nat'l Conf. on the Peaceful Uses of Space, 1964.

In selecting a space-cabin atmosphere, a complex interaction between human physiology, the gaseous environment, the machine and the mission must be considered. Outlined are the major reasons for uncertainty and the problems of optimizing the man-machine system in this respect. The physical variables include total pressure, oxygen pressure, carbon dioxide pressure, inert gas pressure, water-vapor pressure, gaseous trace contaminants, thermal properties of gas, circulation and temperature of gas, leakage rate of gas, duration of exposure and gravitational level. The physiological, physical, and pathological variables on which these environmental variables may act include alertness and performance, decompression syndromes, radiation sensitivity, fire and blast hazards, bacterial flora changes and infections, water physiology, respiratory physiology, oxygen toxicity syndrome and thermal control problems. Project Mercury successfully used 100% oxygen at 5 psi for simplicity of control engineering and minimization of weight, but Cooper's 34 hour flight was apparently just under the wire for oxygen toxicity.

79. Working Group on Gaseous Environment for Manned Spacecraft Summary Report, National Academy of Sciences - National Research Council,

This report describes the results of discussions of the physiological criteria that are important in the selection of the cabin atmosphere in manned spacecraft and discussions, experimental procedures, and investigations that should both precede and accompany preparations for the further development of manned space flight.

80. Zefel'd, V. V., The Setting of the Spaceship Cabin, Joint Publications Research Service, Washington D. C., in Problems of Space Biol., June 1964.

The objects and space in either the cabin or orbital station represent an integral part of the environment of the crew. This part of the medium must contain characteristic elements of the everyday surroundings of their life on earth, which are related to important moments in the psychic life of the crew prior to the flight. This approach makes it possible to stimulate the normalization of the psychic and physical tonus of the cosmonauts through associations and thus to help the organisms resist the injurious action of monotonous flight rhythm and the sharp decrease in stimuli and impressions.

81. Genin, A. M., Some Principles in the Formation of an Artificial Habitat in Space Ship Cabins, Joint Publications Research Service, Washington, D. C., in Problems of Space Biol., June 1964.

When creating experimental manned spacecraft there should necessarily be made a compromise between the requirements for maximal confort for the crew and possibilities provided by modern techniques. However, the increase of the duration of space flight does not allow for a reduction of hygienic requirements for the artificial medium, and at the same time it complicates its conditioning. Several criteria for an artificial medium and methods of its attainment during flights of various duration are considered.

82. Hendler, Edwin, Determination of Respiratory Requirements for Gas Mixtures in Manned Space Capsules, Naval Air Engineering Center, Phila., Pa., Aerospace Crew Equipment Lab., March 1964.

Requirements for artificial atmospheres in manned space vehicles are expressed in graphic form, and take into account varying proportions of oxygen and nitrogen in the respired gaseous mixture, as well as initial pressure (before decompression) and final pressure (after decompression). Criteria used in the determination of artificial atmosphere requirements include avoidance of both hypoxia and decompression sickness due to pressure changes.

83. Gorban'. G. M., Kondrat'yeva, I. I., and Poddubnaya, L. T., Gaseous Activity Products Execreted by Man when in an Air-Tight Chamber, Joint Publications Research Service, June 1964.

Experimental studies have shown that a human being in the process of his life activity liberates a number of toxic gaseous products into the surrounding medium. After man has stayed in a sealed cabin for 24 hours the following amounts of the substances have been accumulated there: ammonium, 297 mg; Co for nonsmokers, 278 mg; and for smokers, 417 mg; hydrocarbons, 504 mg; aldehydes, 0.6 mg; ketons, 232 mg; mercaptanes and hydrogen sulphides, 5 mg; fatty acids 89 mg. Permanent constituents of the air in the cabin were carbon dioxide, hydrocarbons, aldehydes and ammonium, the first two being thereby found in the gaseous phase only while the others were contained both in the air and in the condensate. The data presented indicate the necessity to develop effective means of purifying air and to work out the grounds of admissible limits for the concentration of toxic substances in a sealed cabin.

84. Irvine, Laurence, Microbiological Contamination and Its Effects in the Closed Ecological System, School of Aerospace Medicine, Brooks AFB., A Symp. on Toxicity in the Closed Ecol. System, Lockheed Missile & Space Co., Palo Alto, California, 1963.

Problems associated with microbiological contamination of manned and unmanned spacecraft are considered as follows: (1) the danger of spacecraft failure due to microorganism-caused corrosion or stoppage in secondary or stabilizing fuel lines, (2) the possibility of mutual contamination between two or more alien planets with organisms harmful to man, animals, agriculture, or atmosphere, (3) the danger of culturing pathogens or facultative pathogens as part of the waste regeneration system, and (4) the possible buildup of toxic byproducts and noxious gases from microorganisms within the cabin.

85. Landes, R. A., Neveril, R. B., and Tomsic, C. M., Design of an Internal Environmental Simulator for a Man-Machine System, Final Report General American Transportation Corp., Niles, Ill., October 1963.

This report summarizes the state of the art of operational equipment for providing a life supporting internal environment in a vehicle operating in a hostile external environment. Physiological requirements were determined for support of a three-man crew in a closed compartment on a 2-week mission in a hostile environment in order to design water recovery, oxygen regeneration and cabin gas-conditioning systems.

86. Rowlands, G. F., Maslen, K. R., A Theoretical Investigation Into the Circulation Needed to Control the Carbon Dioxide Concentration in a Space Capsule Cabin, Royal Aircraft Establishment, Farnborough, Gt. Brit.

The minimum ratio of purifying circulation flow to breathing flow needed to obtain an acceptable CO_2 concentration in the breathing atmosphere of a space capsule has been calculated. Equations have been derived for the main gas constituents and for the three possible systems, namely, open circuit (no mask), part-closed circuit (mask with either the inhalation port or the exhalation port open to the cabin, the other piped through the purification circuit) and closed circuit (mask with both inhalate and exhalate piped into the purification circuit). The equations give the time constant of the extraction process and the steady state conditions achieved.

87. Smylie, J. W., The Evaluation and Application of Chemically Regenerative Atmospheric Systems, June 1964. SSD-TDR-64-45

This report presents a survey and analysis of carbon dioxide reduction, atmospheric regeneration systems. The two most promising systems, methanization and carbonization (both using hydrogen reduction of carbon dioxide into water and subsequent electrolysis of the water) were analyzed in detail and compared with other inorganic regeneration, biological, and open cycle systems. A set of penalty curves were derived showing the effects on take off weight of changes in the power penalty, leakage rate, water recovery system efficiency, and use of by-products from the carbon dioxide regeneration system.

88. Saunders, R. A., Analysis of Atmospheric Contaminant Recovered from MA-9 (Faith VII) Preliminary Results, Naval Res.Lab, Washington, D.C, Oct. 1963

A Chromatogram was made of the charcoal filter contents from the environmental control system of the spacecraft. The relative high content of 101 mg toluene in the desorbate is pointed out and discussed.

89. Manned Environmental System Assessment, Boeing Company, [illegible], Washington NASA, November 1964. NASA-CR-134

A complete integrated life support system capable of providing life support for 5 men for 30 days, was developed, designed, fabricated and installed inside a variable altitude chamber for test. The first test attempt ended after 4 1/2 days because of crew illness and a catastrophic equipment failure. Prior to resumption of the second attempt all subsystems were reviewed for performance and modified as required to insure reliable mechanical operation. Trace contaminant studies were made resulting in the substitution of many equipment fabrication materials, additional filtration and increased capacity air catalytic oxidation. The second attempt was successful. Discussed are all aspects of the program including systems, technology, behavioral, and medical and clinical. Individual development, subsystem and system tests, results analyses, conclusions and recommendations are included.

90. Brown, K., Space Logistics Engineering, University of California Engineering and Physical Sciences Extension Series, John Wiley and Sons, 1962.

A general introduction to the way logistic considerations affect the design of components and subsystems of space vehicles is provided. This is followed by a discussion of space environment and the spaceman and his requirements. From these requirements, which establish the parameters to be considered in space vehicle design and logistics, the technical disciplines are presented. These include astrodynamics, guidance and control systems, propulsion, vehicle design, communications, personnel requirements, and reliability.

91. Parker, E. R., Materials for Missiles and Spacecraft, University of California, McGraw-Hill Book Company, 1963.

This book presents a coordinated analysis of materials problems that confront designers of missiles and spacecraft. It is authoritative because only outstanding experts were selected to participate, and it is comprehensive enough to be of real value to engineers. Materials problems limit progress in this field probably more than in any other manufacturing area at this time. The summary of these problems, as presented in this book, should be of substantial value to all engineers working in the missiles and spacecraft industries.

92. Caruso, S. V., and Looney, W. C., A Study of the Outgassing and Evaporation Products of Some Materials Upon Exposure to Reduced Pressure, Marshall Space Flight Center, April, 1962, NASA TM X-50413

The experimental approach entails collection of the outgassing and vaporization products in a special chamber, then examination of the collected vapors with a mass spectrometer. Since the time of collection can be extended indefinitely, even materials with extremely low vapor pressures and/or outgassing rates can be studied. The outgassing and evaporation products of two pure materials (glycerine and dibutyl phthalate), two lubricants (Fluorolube T-45 and Rockwell 950), two solid propellants (normal polybutadiene acrylic acid and Flexadyne, a modified polybutadiene acrylic acid), and seven elastomers (natural rubber, silicone rubber, Buna-N, Viton A, neoprene, butyl rubber, and Kel-F) were collected and analyzed. All of the materials investigated released adsorbed moisture; the adsorption and subsequent release of other atmospheric constituents depend upon the chemical structure of the material. The two pure compounds, the lubricants, the solid propellants, and the natural rubber endured losses in weight from both outgassing and evaporation; the other elastomers examined lost only adsorbed atmospheric constituents. Evaporation rates, determined by continuous weighing of the sample while exposed to reduced pressure, correlate with the results obtained from the mass spectrometric examination of the outgassing and vaporization products.

93. Vanderschmidt, G. F., and Simons, J. C. Jr., Material Sublimation and Surface Effects in High Vacuum, National Research Corp., Cambridge Mass. from: Surface Effects on Spacecraft Materials, by Francis J. Clauss, John Wiley and Sons, Inc. 1960.

Although outgassing of plastics depends principally on purity, it does not necessarily result in a change in mechanical properties. Mass-spectrometer tests indicate that the noncondensable vapor emitted by the cellulose acetate consists largely of water vapor and air: no organic fragments were found to suggest the evolution of plasticizer. Other material (e.g. phenolic) supplies considerable gas (air, water and CO_2 in case of phenolic) and shows mechanical degradation. The possibility that the mechanical properties of some pure materials (high-density polyethylene) are affected by sublimation cannot be eliminated.

94. Jones, Billy P., Gas in Multilayer Thermal Insulation, National Aeronautics and Space Administration, Marshall Space Flight Center, Huntsville, Ala. June 1962. NASA TM X-50156

A review is made of the effects of gas in the multilayer thermal insulation currently considered for applications in cryogenics. Some of the results from A. G. Emslie's analysis are presented and interpreted by comparison with data on outgassing and gas diffusion obtained from various sources. The steady-state pumping of the natural space vacuum is included for the cases of edge pumping of panels of stacked foils and for perforated stacked foils. It is found for these conditions that diffusion of hydrogen through the tank wall is not a problem at temperatures near that of liquid hydrogen. The effects on the diffusion susceptibility of the tank walls after exposure to radiation from on-board nuclear reactors are not considered. Gassing from the foils or other materials imbedded in the foils can be a serious problem. Leaks into the foils cannot be permitted. Procedures for degassing the insulation prior to launch should be investigated, and the transient space pumping problem should be studied.

95. Grubbs, W. J., and Snider, G. H., A Quantitative Study of the Evolution of Gases From Electron Tubes and Materials, Doucette (E. I.) Associates, Inc., Chatham, N. J., April 1962.

Amperex tube type 5894 will be the subject of the initial phase of the study because it is a high quality tube of relative simplicity; a high quality tube whose manufacture is in good control should exhibit similar outgassing from sample to sample. A bakeable, ultra-clean, ultrahigh vacuum system for these experiments is nearing completion. It will incorporate an omegatron mass spectrometer for the purpose of analyzing evolved gases and a novel system of orifices and pressure gauges, which will permit the determination of the quantities of each of various gas types. Pure gases of known types will be injected into the system at known rates for an initial calibration; a simplified version of the same procedure can be used at any later time for a quick check of the overall system performance. To insure data reliability, the apparatus is so designed that each experiment will yield two sets of data from which two separate calculations of the final results can be made. The system's operation, as well as its construction, are described.

96. Grubbs W. J., and Snider, G. H., A Quantitative Study of the Evolution of Gases From Electron Tubes and Materials, Doucette (E.I.) Associates, Inc., Chatham, N. J., July 1962.

The purpose is to achieve a higher degree of reliability in electron tubes through a better understanding of the kinds and quantities of gases which occur in these tubes. A bakeable, ultraclean high vacuum system which incorporates an omegatron mass spectrometer has been constructed; and six ionization gauges and the omegatron mass spectrometer tube have been calibrated. The calibration procedures and the results, which have been obtained, are reported.

97. Grubbs, W. J., Snider, G. H., and Scott, F. I., A Quantitative Study of the Evolution of Gases From Electron Tubes and Materials, Doucette (E.I.) Associates, Inc., Chatham, N. J., October 1962.

This program aims to achieve a higher degree of reliability in electron tubes through a better and more comprehensive understanding of the kinds and quantities of gases which occur in these tubes. A bakeable, ultraclean, high vacuum system which incorporates an omegatron mass spectrometer has been constructed for conducting these investigations. Essentially all of the effort during this report period has been devoted to the construction and calibration of the various orifice systems utilized in the equipment. The results obtained indicate that the objectives of the study can in fact be achieved, and work is currently progressing in this direction. Some preliminary degassing experiments are described.

98. Grubbs, W. J., Snider, G. H., Scott, F. I , A Quantitative Study of Gases From Electron Tubes and Materials, Doucette (E.I.) Associates, Inc., Chatham, N. J., January 1963.

A bakeable, ultra-clean high-vacuum system, which incorporates an omegatron mass spectrometer, has been constructed for conducting these investigations. During this period, several Amperex Type-5894 tubes have been degassed by various schedules. The pumping speed of the ion pump was estimated for methane gas. Several difficulties with heating and operating the tube under test were resolved. The principal gas evolved during d.c. bombardment of this tube is hydrogen.

99. Grubbs, W. J., Snider, G. H., and Scott, F. I., A Quantitative Study of the Evolution of Gases From Electron Tubes and Materials, Doucette (E.I.) Associates, Inc., Chatham, N. J., June 1963.

A continuous quantitative and qualitative gas analysis system has been designed, built and calibrated. The system incorporates an omegatron mass spectrometer, ion pumps, ionization gauges, and precision orifices to measure the flow rate of individual gases. It has been used to examine several processing and materials parameters as they effect the kinds and quantities of gases evolved by electron tubes. CO_2, CO and H_2 in roughly equal amounts comprise about 95% of the gas evolved during cathode conversion and activation.

100. Bolstad, Luther L., Effect of Materials on Atmospheric Contamination in Manned Spacecraft, Minneapolis-Honeywell Regulator Co., Minn., In AIAA 2nd Manned Space Flight Meeting, 1963.

This paper describes an experimental program which will determine the relative outgassing and flammability characteristics of over 100 materials, including surface coatings, wire insulations, tying cords, molding compounds, adhesives and casting compounds. Experimental apparatus and analytical techniques are described. Preliminary results obtained from the experimental testing programs are presented with special emphasis on flammability characteristics of materials in pure oxygen.

101. Overholser, L. G., and Blakely, J. P., Outgassing Characteristics of Various Graphites, Oak Ridge National Lab., Tenn., March 1963.

The outgassing characteristics of various graphites have been determined in vacuo to a maximum temperature of 1000°C using external resistance heating and to 1800°C by induction heating. The graphites examined include commercial and experimental lots of nuclear grades prepared from different sources of raw materials and subjected to varying manufacturing procedures. The ash content of the various grades ranges from 5 to 800 ppm, the calcium content from a few ppm to 340 ppm. Representative data are presented which show marked differences in the composition of the desorbate and the fraction of the total evolved to various temperatures for different grades. The volume-time relationship is satisfactorily expressed as $v = A \log t + B$ for a number of the graphites over extended intervals of time. Marked deviations from this relationship at 600°C are reported for several grades of graphite characterized by a high calcium content. Variations in the CO_2/CO ratio in the desorbate at 600°C appear to be associated with these volume-time relationships observed at 600°C. Data are given which show the differences in the degassing behavior of a group of graphites having ash contents of 30 ppm. These data fail to show any significant effect of either the type of coke or the particle size distribution of the coke used as filler. It appears that the atmosphere present during letdown and the subsequent exposure prior to degassing are responsible for the differences noted. The degassing behavior of samples of graphite from the stock for use in the Experimental Gas-Cooled Reactor is described, including the release of sulfur compounds as a function of temperature and volume-time relationships at various temperatures.

102. Holshouser, W. L., and Bennett, J. A., Gas Evolution from Metal Surfaces During Fatigue Stressing, National Bureau of Standards, Washington, D.C., 1961.

Numerous bubbles were observed to form under transparent pressure-sensitive tape applied to the surface of flat specimens stressed in reversed torsion. The bubbles were produced by hydrogen evolved at the surface of aluminum alloy or carbon steel associated with fatigue damage and crack propagation. Gas evolution started before any fatigue cracks could be detected. The effect was also observed on specimens stressed in reversed bending, but it could not be produced by fluctuating stress smaller than that necessary to produce cracks nor by a single application of load. No gas evolution associated with fatigue damage could be observed on specimens of copper, brass, cadmium, nickel, stainless steel, tin, titanium, or zinc. The presence of the tape retarded the development of fatigue cracks in aluminum alloy and carbon steel specimens.

103. Henry, R. P., Measure du flux de degazage de certains materiaux, Vide-n 18 n 103, Jan-Feb. 1963.

Measurement of outgassing output from some materials: investigation of gas evolution from some materials carried out with method developed earlier: data, dealing particularly with some alloyed metals, and composite sets presented.

104. Lohs, Karlheinz, Detectors for Toxic Gases Vapors and Dusts, Joint Publications Research Service, Washington, D.C., November 1963.

A review of instruments used for detection of gases, vapors, and dust is presented. Instruments of both the Soviet bloc and Allied countries are discussed.

105. Robens, E., Robens, G., and Sandstede, G., Measurement of Sorption, Vaporization and Decomposition of Materials Used in Vacuum Technology by Means of Electromagnetic Microbalance, Vacuum V13, August 1963.

Apparatus by means of which weight change of solid bodies can be measured at different temperatures in different atmospheres and under vacuum: sensitivity is 10^{-6}g: it can be used for study of sorption processes in vacuum technology: it is possible to determine whether loss in weight is caused by emission of sorbed gas, vaporization or decomposition of materials.

106. House, R. D., Lyons, G. J., and Askwyth, W. H., Measurement of Spectral Normal Emittance of Materials Under Simulated Spacecraft Power-Plant Operating Conditions, In NASA Measurement of Thermal Radiation Properties of Solids, 1963.

An apparatus was designed and constructed to determine spectral normal emittance of materials in an environment closely simulating the vacuum of space. The apparatus is capable of measuring spectral emittance of structural materials or coatings over a wavelength range accounting for the major portion of blackbody energy at the temperature at which these measurements are made. The method used is the same as that used by Larrabee and by DeVos, in which comparison is made of the radiant intensity normal from a specimen tube surface to that of a small "blackbody hole" drilled in the tube wall. The ratio of these intensities, at a given wavelength, is a very close approximation to the spectral normal emittance of the specimen surface. A comparison of the data obtained in the apparatus discussed in this paper to those obtained by Larrabee and by DeVos indicates close agreement.

107. Mikk, G., and Askwyth, W. H., Measurement of Total Hemispherical Emittance of Structural Materials and Coatings Under Simulated Spacecraft Conditions, In NASA Measurement of Thermal Radiation Properties of Solids, 1963.

Several test rigs were designed and constructed to measure total hemispherical emittance, over a wide range of temperatures, under conditions which simulate the vacuum of space. The method used in all of the rigs is to compare the electrical power dissipated from an isothermal test section of a resistance-heated specimen to the total emissive power of a blackbody operating at the specimen temperature. Two types of tests are conducted in these rigs--determination of total hemispherical emittance as a function of temperature from approximately 200° to 2200°F, and determination of total hemispherical emittance as a function of time at fixed elevated temperatures (endurance tests). Specimens used for these tests were usually in the form of coated metal strips or coated thin-walled metal tubes. Some typical data presented are comparisons of results of various investigators, and of results obtained in the various rigs used in these tests.

108. Determination of the Emissivity of Materials, Pratt and Whitney Aircraft, Annual Progress Report, December 1963. NASA CR-58054

A screening rig was constructed to enable evaluation of coating behavior at elevated temperatures so that coating volatilization in the emittance rigs could be avoided. Three materials were tested to date--Kennametals K-151A and K-162B, and iron titanate. The Kennametals were found to be stable up to 1,600° F and the iron titanate up to 2,000° F. Emittance values were obtained for several materials and were compared with previously obtained values to determine reproducibility. Tests of four coated radiator segments exposed to temperatures between 650° and 700° F and vacuum for periods ranging from 12,700 to 15,000 hours were completed, and a post test analysis was made. Methods for applying silicon carbide coatings by aluminum phosphate bonding were investigated, but, although some improvement was realized, a satisfactory technique was not developed.

109. Dakin, T. W., and Works, C. N., Gas Discharges in Insulating Systems at Pressures Between Atmospheric and High Vacuum, Westinghouse Electric Corporation, In its Collected Papers of the Dielectrics in Space Symp., Westinghouse Research Labs, June 1963.

A survey is presented of the gas discharge situation which exposed, energized electrical systems will encounter as they pass from atmospheric pressure through the low-pressure regions at high altitudes, and on to the vacuum of outer space. Part of the survey is based on a scrutiny of well-known low-pressures discharge phenomena, as they apply to electrical system environments at high altitude. The discharge behavior of gaps and simple insulation systems in the low-pressure glow discharge region is illustrated by experiments made on such systems. Observations made on discharges with insulating barriers in a vacuum are discussed. Results of this survey indicate that: (1) The complete insulation of conductors at at least one terminal voltage can lead to high dc electric strengths (and with a minimum number of discharges), corresponding to the dc insulation strength throughout the low-pressure range and at high vacuum. With high ac voltage, such an insulation system would have discharges which would reduce the electric strength of the solid. (2) It will be necessary to completely enclose the electrical system in a sealed capsule, or avoid high stresses across solid insulation where series gaps may occur, in order to avoid all discharges.

110. Santeler, D. J., Outgassing Characteristics of Various Materials, Trans., 5th Nat'l Symp. on Vacuum Technology, 1958.

The outgassing process, i.e., the combination of time, temperature, tubulation and pumping equipment, has generally been established by trial and error. The technique of "Vacuum Process Evaluation" was developed to provide an engineering approach to this problem so that the effects of changing conditions could be evaluated and the optimum process could be determined. A variety of different materials were outgassed and the results evaluated by means of vacuum process evaluation. This report summarized the results of this evaluation.

111. Schrank, M. P., Benner, F. C., and Das, D. K., Theoretical Experimental Study to Determine Outgassing Characteristics of Various Materials, Arnold Eng. Develop Center., March 1964. AEDC-TDR-64-53

The report presents the results of experimental studies in outgassing characteristics of materials including both total outgassing rates and analysis of constituents. Two types of experiments were performed: (1) outgassing of structural materials using metal bell jars made of the test material, and (2) outgassing of small test smaples installed in a glass vacuum system. Extensive outgassing data were obtained on stainless steel 304 ELC and aluminum alloy 5083-0 in the bell jar tests at several temperature increments between 100° C and LN_2 temperature (78° K). It was shown that the aluminum alloy 5C830 is an adequate material for vacuum chambers where either no bakeout or temperatures only up to +150° to +200°C are applied among the ceramics tested. Al-Si-Mag 614 and Myealex 400 showed excellent properties for construction materials in vacuum chambers. Very low outgassing rates could also be measured on ceramic-coated copper wire. Teflon No. 7 has low outgassing rates when it is preheated by a soft bakeout.

112. Buckley, D. H. and Johnson, R. L., Evaporation Rates for Various Organic Liquid and Solid Lubricants in Vacuum to 10^{-8} Millimeter of Mercury at 55° to 1100°F, NASA, Washington, D.C., December 1963. NASA TND-2081

The fluids examined were polyphenyl ethers, silicones, and polyalkylene glycols; the solids included fluorocarbon telomers, polytetrafluoroethylene (PTFE), polychlorotrifluoroethylene (PCFE) and two phthalocyanines (metal free and copper). Some greases were also examined. Variations in molecular weight influenced evaporation rate markedly as indicated by the Langmuir equation. With five polyalkylen glycol fluids having different compositions but approximately the same molecular weight (1000) no essential difference in evaporation rates could be measured from 50° to 450°F. A similar dependence of evaporation rate on molecular weight was noted for the solids--telomers PTFE and PCFE.

113. Lange, W. J., and Singleton, J. H., Outgassing Procedures for Glass Ultra High Vacuum Systems - WERL - 2832-14, Scientific Paper 64-9E1-441-P2 Westinghouse Research Labs, Churchill Boro., Pa.

Found that at bakeout temperatures of approximately 400°C Pyrex glass vacuum systems release considerable quantities of carbon dioxide, which accumulate in a liquid nitrogen cold trap. The release of gas from the trap can result in partial pressures of carbon dioxide of the order of 10^{-9} torr.

114. Bowen, P. H., and Hickam, W. H., Outgassing Characteristics of Dry Lubricant Materials in a Vacuum, Westinghouse Electric Corporation, Research Laboratories, Pittsburgh, Pa., Machine Design, Vol. 35, July 1963.

Presentation of experimental data on outgassing properties of certain plastics, dry powders, and metallic composites suitable for lubricants in a hard-vacuum environment. Eleven plastic and carbon compositions, ten powders, and six composites are studied in a vacuum of 10^{-6} mm Hg to determine the amount and composition of gases evolved at various temperatures. These temperatures range from 160°F up to the point of thermal degradation for the plastic material, and from 760° to 1,160°F for the powders and composites. Outgassing data for all materials are recorded on a volume basis and are given as mol % of total gases evolved.

115. Fischell, R. E., and Wilson, L., Spacecraft Application of Subliming Materials, Applied Physics Lab, Johns Hopkins University, Silver Spring, Maryland, August 1964.

Three sublimation materials (camphor, napthalene and biphenyl) have been studied in considerable detail both in the laboratory and on orbiting satellites. A principle use of these materials is to actuate electrical switches with a predetermined time delay after the spacecraft is placed in the vacuum of space. These materials can also be used as a temporary mechanical structure that sublimes away after the spacecraft is launched. A third useful characteristic of these materials is that they can be used for encapsulation of delicate instruments during the severe vibration and acceleration environment encountered during a launching operation. Once in orbit, the encapsulation material gently sublimes away leaving the delicate instrument free to work in the vibrationless, zero-g environment of space.

116. Rogers, Milton, Gas-Surface Phenomena, Johns Hopkins University, Baltimore, Maryland, Based on a transcript on Gas-Surface Phenomena, Air Research & Development, Command Headquarters, Baltimore, March 1956.

The various disciplines (e.g., fluid dynamics, chemistry, and solid state physics) have each developed different ways of looking at the interface between a fluid and a solid body. In attempting to assess the influence of the solid surface on gas-solid interactions it is necessary to relate what the surface looks like to what it does, yet, practically nothing is known about what the surface looks like, and even less about what the layers of adsorbed material and other foreign material look like on the surface. There are no really satisfactory conceptual models of the mechanism of surface structure and adsorption, and there are no completely adequate atomic theories concerning solid bonds or surface energy as related to details of solid or surface structure; furthermore, understanding of adsorption is hampered because the theoretical equations that can be set up are beyond solution. Consequently, one may conclude that as research is continued in many diverse fields the need to define surface structure and its influence on observed natural phenomena will increase. Further advances in surface physics and chemistry will be made only when the nature of the various bonds between solid and gas is better understood. For this reason, research into bonds, specifically oriented toward determining the dynamics of gas-solid interactions, should be emphasized.

117. Frisch, B., Energetischi Vorgange Bei Der Adsorption Und Desorption Von Wasserdampg Un Oxyd- Und Metallpulvern. (Thermal Processes in the Adsorption and Desorption of Water Vapor on Oxide- and Metal Powders), Saarland U. Inst. fur Werkstofftechnologie und Allgemeine Huttenkunde, Saarbrucken W. Germany, Repr. from Ber, deut, Keram, Ges, (Bonn) 1962.

Heat of adsorption of α-Al_2O_3 and tungsten powders was determined as a function of time and the volume adsorbed. The difference between the adsorption and desorption gives the irreversible adsorption whose value is quite considerable with aluminum oxide powders that have been mechanically treated and heated in vacuum. There are clear discrepancies between the surface values found by the water vapor adsorption and those obtained by the nitrogen adsorption. These differences are attributed to both irreversible adsorption and a deposit of foreign gases on the surface. The investigations show a relationship between the molar partial enthalpy and the steam pressure, which reveals the influence of the surface activity, physical adsorption, and capillary condensation.

118. Haung, A. B., Energies of Interaction Between Gases and Various Surfaces, Technical Documentary Report (Oct. 1, 1960 to Mar. 1961), Illinois U., Urbana, Arnold Engineering Development Center, Tenn., Jan. 1962. AEDC-TDR-62-18

This report presents up-to-date data on potentials of adsorption and chemisorption, and activation energies of various surfaces for gases. These data are intended for use in design for space probing and space simulation based on the kinetic theory of ultrahigh vacuum.

119. Rechlin, Philip, Gas Adsorption of an Organic Surface: HMX, Picatinny Arsenal, Dover, N. J., Feltman Research Labs, March 1964. PA-TR-3092

Attempts to measure adsorption on the surface of HMX using N_2 and CO with the continuous flow modification of the BET (Brunauer-Emmett-Teller) gas adsorption technique were unsuccessful. Either (1) no adsorption takes place on the HMX under these conditions, (2) the gas adsorption technique is not sensitive enough to be used to measure the area of a surface as inactive as that of HMX, or (3) the adsorption that actually takes place is masked by effects due to heretofore unobserved polymorphic changes in the crystalline structure of the material. Heating the HMX crystals to about 185°C, well below the melting point, does not activate the surface, but results rather in small amounts of decomposition.

120. Glebov, G. D., Absorption of Gases by Active Metals, Translation into English of a book "Pogloshcheniye Gazov, Aktivnymi Metallami", Moscow Gosenergoiydat 1961.

Sorption of gases (hydrogen, nitrogen and carbon) by niobium and tantalum is discussed.

121. Luzzi, T., A Review of the Physics of Gas Adsorption on Solid Surfaces, Grumman Aircraft Engrg. Corp., Bethpage, N.Y., October 1964.

A qualitative and semi quantitative description of physical adsorption of gases and liquids on solid surfaces is presented. The discussion is limited to those areas that might be most useful to those interested in the study of gas-surface interaction in rarefied gas dynamics. Physical adsorption is described from the macroscopic or thermodynamic viewpoint and the molecular viewpoint. Several physical adsorption theories are reviewed. Analysis indicates that a monolayer of gas molecules "skidding" over the surface in random directions as a two-dimensional gas is a reasonable model of physical adsorption in rarefied gas dynamics.

122. Inouye, H., Contamination of Refractory Metals and Alloys by Residual Gases in High Vacuum Systems, Oak Ridge National Lab., Tennessee, September 1964. ONRL-3674.

The contamination of niobium, molybdenum, tantalum, Nb-1% Zr, FS-85, D-43, cb-752, T2M and T-111 resulting from their extended exposure to the residual gases in high vacuums was measured by chemical analysis. This contamination was characterized in terms of the system pressure, metal temperature, exposure time, metal surface-to-volume ratio and alloy composition. A second phase of the study was concerned with refractory metal envelopes, vapor plated molybdenum, and intentional additions of nitrogen or CH_4 to vacuum atmosphere to counteract the noxious gases.

123. Hushmann, O. K., Jamboa, D. M., and Denison, D. R., The Influence of the Residual Gas Atmosphere in Space Chambers on the Neutral Efflux and Critical Temperature of Tungsten Ionizers, Hughes Research Labs, Malibu, California, AIAA Paper 64-693, Presented at the AIAA 4th Elec. Propulsion Conference Philadelphia, September 1964.

Investigated were changes in work function and critical temperature for cesium ionization caused by hydrocarbons and oxygen: these data are compared with measurements under clean surface conditions in an ultrahigh vacuum system. In addition, an ultrahigh vacuum system has been used for a detailed study of surface effects caused by individual hydrocarbons with mass numbers ranging between 16 and 128:

this range is in accordance with the residual-gas atomic-mass-number range measured in the space chambers. Measurements indicate that a cryopumped space chamber with one of the liners at 22° K, combined with an ion pump, can be equivalent to an ultrahigh vacuum system. Small amounts of hydrocarbons as well as carbon monoxide and carbon dioxide reduce the work function and increase the critical temperature for surface ionization. Experiments with individual hydrocarbons confirmed that excessive amounts of hydrocarbons deposit pyrolytic graphite on the ionizer surface, which results in a greater critical temperature than that of clean tungsten.

124. Hobson, J. P., Armstrong, R. A., Study of Physical Adsorption at Very Low Pressure Using Ultra High Vacuum Techniques, J. Phys., Chem. V. 67, October, 1963.

Laws governing physical adsorption have become of practical importance, since they represent means of achieving very low pressures, ultrahigh vacuum techniques used in measurement of adsorption isotherms of nitrogen and Argon or Pyrex glass. 42 ref.

125. Holland, L., Sources of Surface Contamination in Vacuum Evaporation Systems, Vacuum v13n5, May 1963.

Contamination of clean glass surfaces by organic and silicone vapors in 3 types of kinetic vacuum systems investigated: contaminant vapors were detected by observing effect of their adsorption on hydrophillic surface properties of clean glass and SiO_2 films, and by polymerizing organic films on electron bombarded target.

126. Ptushinskiy, Yu. G., and Chuykov, B. O., Certain Characteristics of Partial Adsorption of Components of Residual Gases at Very High Vacuum II, Air Force Systems Command, Wright-Patterson AFB, Ohio Foreign Technology Div., In its Ukr. J. of Phys. (Selected Articles) April 1964.

The flash method of investigating the kinetics of gas adsorption was used in conjunction with the mass-spectrometric method. Data were obtained on the kinetics of adsorption of components of residual gases and on temperature stability of components of residual gas film adsorbed on the surface of tungsten.

127. Goldstein, R., Preliminary Absolute Intensity Measurements for the 1.38, 1.87 and 2.7μ Bands of Water Vapor Between 125 and 200° C, Guggenheim Jet Propulsion Center, Calif. Inst. of Tech., Pasadena, Aug. 1962.

The absolute intensities of the 1.38, 1.87 and 2.70μ bands of water vapor have been measured in a stainless steel

(variable spacer) absorption cell with sapphire windows using self-broadening. Pressures of 2.29 and 15.34 atm, corresponding to temperatures of 125° to 200° C, and optical depths from 0.348 to 29.18 cm-atm were used. Representative data of the logarithm of the apparent reciprocal fractional transmission as a function of wave number , for the 2.7 region, are shown at 150°C for optical depths ranging from 0.714 cm-atm to 8.95 cm-atm. These data were obtained with a spectral resolution of about 50 cm^{-1}. The resulting estimates for the integrated intensities (α in cm^{-2} $-atm^{-1}$) at the temperatures of the experiments are summarized in tabular form with an estimated accuracy of ± 15%.

128. Florio, J. V., and Baird, D. H., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Scientific Report No. 8, Sept. 1964. AFCRL64-822

The work function of polycrystalline tungsten was measured, using the retarding field technique, as a function of the exposure to a carbon monoxide ambient. The work function was found to vary from 4.4 eV to 5.2 eV in going from an initially clean surface to one saturated with carbon monoxide. The successive adsorption of oxygen on a tungsten surface already saturated with carbon monoxide is inferred from the work-function data. The increase in work function (from 5.2 eV to 6.4 eV) is indicative of possibly a monolayer or more of adsorbed oxygen. The work functions for a clean (111) silicon surface, silicon exposed to 0.000003 torr-sec oxygen, and silicon exposed to 0.000009 torr-sec oxygen were found by the retarding field method to be 4.79 eV, 5.02 eV and 5.07 eV, respectively.

129. Bliven, C. M. and Polanyi, T. G., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Bayside, N. Y., Scientific Report No. 2, Aug. 1962. AFCRL62-773

An ultra-high-vacuum system for gas adsorption measurements at low pressures has been set in operation, and data are reported on the processing of the system and on the composition of the final gas ambient under several operating conditions. When the system is open to the pumps, total pressures of less than 10^{-11} Torr were measured. When the system is isolated from the pumps by means of high-vacuum valves, a linear increase of He partial pressure was measured over a 7-day period up to a pressure of 10^{-6} Torr. For a short time, argon appeared to a pressure of 5×10^{-10} Torr, and later disappeared.

130. Bliven, C. M., and Polanyi, T. G., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Bayside, N. Y., Scientific Report No. 3, December 1962. AFCRL 63-86

An investigation of the interaction of nitrogen with a hot tungsten filament has shown that a chemical pumping effect occurs. The magnitude of this effect and its variation with temperature is discussed. Preliminary results on the study of the effect of adsorbed oxygen on the work function of molybdenum at room temperature have indicated that there are three stages in the adsorption process: during the first two stages, there is a rapid increase in the work function, whereas in the last stage there is a small increase and very slow rate of rise in work function.

131. Bliven, C. M., Florio, J. V., and Polanyi, T. G., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Bayside, N. Y., Scientific Report No. 4, April 1963. AFCRL 63-170

The pumping speed of an omegatron mass spectrometer was determined both in the presence and absence of the ionizing electron beam; when the electron beam is absent, the pumping is attributed to chemical effects taking place at the hot tungsten filament. This chemical pumping speed is 7.5×10^{-6} liter/sec. The difference between the two pumping speeds (2×10^{-6} liter/sec) represents the contribution of electronic pumping to nitrogen removal. These experiments were performed on sealed-off omegatrons; however, similar pumping phenomena are present in any system using hot tungsten filaments, and their relevance increases as the operating pressures in the experiments decrease. Preliminary data were obtained on the interaction between oxygen and the carbon contained in the tungsten filament of the omegatron.

132. Bliven, C. M., Florio, J. V., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Bayside, N. Y., Scientific Report No. 5, August 1963. AFCRL 63-372

Experimental data on the adsorption of nitrogen on tungsten have been obtained. The data have been analyzed, and the sticking probability has been obtained from consideration of the mass-balance relationship in the reaction chamber. The chemical pumping speeds of the omegatron filament and oxide cathode assembly due to reactions with the incoming oxygen were estimated. The sticking probability and number of adsorbed molecules of oxygen on the molybdenum anode were calculated from the pressure-time characteristic.

133. Bliven, C. M, Florio, J. V., and Polanyi, T. G., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Scientific Report No. 6, January 1964. AFCRL 64-113

Adsorption data have been obtained for the tungsten-nitrogen system for a second filament. The lowest surface coverage detectable for which the filament is in quasi-equilibrium with its surrounding is 0.55 of a monolayer. In the study of oxygen adsorption on molybdenum, the carbon monoxide background, resulting from reactions between the incoming oxygen and carbon impurities in the omegatron filament, molybdenum anode, and oxide cathode assembly, has been substantially reduced. The major source of carbon monoxide during oxygen adsorption on the molybdenum anode is replacement of previously adsorbed carbon monoxide by oxygen. Some results on sticking probability and molybdenum work function changes with oxygen coverage are presented.

134. Florio, J. V., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Bayside, N. Y., Scientific Report No. 7, April 1964. AFCRL 64-468

Measurements of the adsorption of nitrogen on a polycrystalline tungsten wire and of carbon monoxide on molybdenum were continued. The saturation coverage of nitrogen on tungsten at room temperature was shown to be a function of the steady-state pressure and varies from 1×10^{-14} to $2.5 \times {}^{14}$ molecules/cm^2 over the pressure range 10^{-9} to 10^{-6} torr. The adsorption of carbon monoxide on molybdenum at room temperature increases the work function of molybdenum over its initial value by 0.1 to o.2 ev at saturation.

135. Effects of Atmospheric Environment on Flammability of Gases, Liquids, and Vapors, Lovelace Foundation for Medical Education and Research, Albuquerque, N. Mexico, In Its Space-Cabin Atmospheres, Pt. II, 1964.

Included in this report are data on the following: (1) the flame speed of methane, acetylene, propane, and hydrogen in varying concentrations of the inert diluents, nitrogen, argon, and helium; (2) the flame temperature of methane, propane, and acetylene in nitrogen, argon, and helium of varying concentrations; (3) the limits of flammability of the fuel gases, methane and hydrogen, in mixtures of 21% oxygen and 79% inert gas (carbon dioxide, nitrogen, helium, neon, and argon); (4) the minimum spontaneous-ignition temperatures of various MLO and MIL-H-5606A hydraulic fluids in oxygen-nitrogen atmospheres at 1 atm pressure, in contact with a Pyrex glass surface, as a function of oxygen concentration; (5) the effect of oxygen partial pressure on the minimum autoignition temperatures of JP-6 fuel mixed with oxygen and nitrogen at various initial pressures; (6) the minimum spontaneous ignition temperatures of the hydraulic fluids of (4) in air at 1 atm pressure, in contact with a Pyrex glass surface, as a function of diesel injector pressure; (7) the ignition temperature at varying oxygen pressures for MIL-0-5606, JP-4, MLO-8200, MIL-H-8446A, and MLO-7117; and (8) the comparative ignition temperatures, at varying altitudes, of the following aircraft fluids: MIL-0-5606, MLO-8200, G.E. #81644 and MIL-H-8446A hydraulic fluids; JP-4 aviation fuel, MIL-O- 7808 lubricating oil; and MLO-7117 naphtenic mineral oil.

136. Bliven, C. M., Study of Adsorption of Gases on Solids in the High Vacuum Range, General Telephone and Electronics Labs, Inc., Bayside, N. Y., First Scientific Report, April 30, 1962. AFCRL 62-372

An ultra-high vacuum system, which was designed to perform surface adsorption studies in the region of extremely low pressures, is described. Provision has been made for the controllable, contamination-free admission of gases into the system and for the measurement of the composition and amount of gas present with an omegatron mass spectrometer. Construction of the system has been initiated, and all concomitant instrumentation has been ordered.

137. Cornelius, D. F., and Roberts, W. H., Friction and Wear of Metals in Gases up to 600°C, ASLE Paper No. 60, October 1960.

A comparison is made of the room temperature behavior of copper, mild steel and brass, rubbed against a hardened tool steel, in four environments: vacuum (10^{-3} mm Hg) dry helium, dry carbon dioxide and dry air. The effect of varying the water vapor content in air is also discussed. Specific wear rates and friction coefficients varied markedly with temperature and values in the ranges 10^{-13} - 10^{-8} cm^3/cm kg and 0.1 - 0.8, respectively were obtained in both dry carbon dioxide and dry helium. Lowest wear rates were observed with nitrided steels. The diverse characteristics observed are discussed on the basis of current theories of adhesive wear.

138. Buckley, D H., and Johnson, R. L., Halogen-Containing Gases as Lubricants for Crystallized-Glass-Ceramic-Metal Combinations of Temperatures to 1500°F, NASA Technical Note D-295, October 1960.

The gases CF_2Cl-CF_2Cl and CF_2Br-CF_2Br were used to provide lubrication for Pyroceram 9608 sliding on various nickel and Cobalt-base alloys. The gas CF_2Br-CF_2Br was an effective lubricating agent for Pyroceram 9608 sliding on Hastelloy R-235 and Inconel X at temperatures up to 1400°F. The gas CF_2Cl-CF_2CL was effective in providing lubrication for Pyroceram 9608 on various cobalt-base alloys at 1000°F.

139. Feng, I-Ming, and Chalk, H., Effect of Gases and Liquids in the Lubricating Fluids on Lubrication and Surface Damage, Wear, Volume 4, 1961.

The nature of surface damage that occurs at the surfaces of solids in sliding contact is highly dependent on the interaction between the surfaces and the environment. This was demonstrated by the experimental results obtained with various amounts of active gases in a liquid lubricant. In particular the effect of vacuum removal of disolved oxygen on the wear of cast iron was phenomenal. A study with various phosphorous compounds added to a liquid environment showed a good correlation between the lubricating effectiveness and their chemical structure.

140. Beerbower, A., and Greene, D. F., The Behavior of Lubricating Oils in Inert Gas Atmospheres, ASLE Paper No. 60, October 1960.

The interactions of five gases (helium, hydrogen nitrogen, argon and carbon dioxide) with mineral and synthetic lubricating oils were studied. The interactions examined included gas solubility, foaming, entrainment, evaporation of oil into gas, stability of oil in presence of gas, and effect of dissolved gas on oil viscosity. Several of the gases showed behavior (appreciably different from that of air) that was not predicted by conventional theories. No importnat differences were found between mineral and synthetic (diester) oils in these respects. The additives used can have appreciable influence on the foaming and entrainment characteristics and evaporation rates of both types of oils.

141. Bowden, F. P., and Rowe, G. W., The Adhesion of Clean Metals, Royal Society Proceedings, V 233 Ser A, January 10, 1956.

Investigation of adhesion between surfaces of hard metals cleaned by heating in a high vacuum. Low initial adhesion is due to released elastic stresses when load is removed. Application of tangential force in addition to load increases adhesion.

142. Semenov, A. P., The Phenomenon of Seisure and Its Investigation, Institute for the Study of Machines, Academy of Sciences of the USSR, Wear, 4, 1961.

The phenomenon of joining metals in the solid state is very common in the friction of machine parts and also in the technological processes of cutting and plastic deformation of metals. It is, in fact, the basis of some technological processes of joining metals. This phenomenon can be divided into two parts: sintering and seizure. Sintering has the nature of a diffusion process. No diffusion takes place in seizure; it is a result of mutual plastic deformation of metals. The influence of different factors on seizure was investigated. In the discussion of results it is assumed that for seizure of metals, not only must there be intimate contact of clean surfaces, but in addition an energy barrier must be overcome.

Other hypotheses of seizure are considered. The influence of chemical composition on seizure is shown to be considerable in the case of copper alloys.

143. Brueschke, E. E. and Suess, R. H., Seizure of Metallic Surfaces in Ultrahigh Vacuum, Hughes Aircraft Co., Culver City, Calif., Technical Memorandum, July 1961.

An experimental study has been made of the seizure of thoroughly degassed metallic surfaces in ultrahigh vacuum. Information compiled from the laboratory investigations and from the literature is presented in this document as an aid to understanding metallic seizure in vacuum. The conditions under which seizure of such surfaces will occur are discussed, and methods of preventing seizure are presented.

144. Vos, G. B., Examination of Cleaning Materials, Techniques, and Evaluation Processes on Various Material Surfaces, SAE paper 749A, for meeting, September 1963.

Study of procedure for cleaning interior surfaces of devices which operate under high vacuum and must be free of volatile hydrocarbon residue and method for determining degree of cleanliness achieved; solvent cleaning, baking, acid immersion, and hydrogen peroxide immersion techniques were tried on glass, ceramic, metal, and plastic surfaces.

145. Schram, A., La Desorption Sous Vide, V 18, N 103, February 1963.

Desorption in vacuum; vacuum below 10^{-7} torr needs low desorbtion rate materials; complexity of desorption phenomenon; limited choice of research proposed; theoretical calculations based on simplified models compared with some experimental results; knowledge of true surface area is found necessary and simple experimental method used to measure this surface described. 23 refs.

146. Moll, J., Zum Problem der Herstellung Reinster Oberflachen in Hoch-Vakuum and Ultrahochvakuum, Vide, V 18, N 105, June 1963.

Obtaining high purity surfaces under molecular vacuum and ultrahigh vacuum; survey of equipment needed for preparation and study of high purity surfaces and films; status of surface physics and needed instruments; further improvement in measurements under vacuum condition; method of dynamic measurements shall be used instead of static experiments. In German and French.

147. Feng, I-Ming, The Influence of Surface Activity on Friction and Surface Damage, Ethyl Corporation, Detroit, Michigan, Wear, 4, 1961.

The adhesion theory and the interaction between the environment and the surface of solids in sliding contact is studied. Surface activity influences on friction and surface damage is discussed.

148. Bryant, Paul J., Gosselin, Charles M., Taylor, Lyle H., Extreme Vacuum Technology (Below 10^{-13} Torr) and Associated Clean Surface Studies, Midwest Research Inst., NASA, July 1964. NASA-CR-84

Experimental results are discussed in the following areas: (1) development of extreme vacuum technology using the vapor-jet mechanism and a helium permeation guard technique (2) determination of the quantities and species of gas above gettering-ion pumps and chemically trapped oil diffusion pumps (3) derivation of a physical adsorption isotherm for inert gases (4) development of a total-pressure gage for readings below 10^{-12} torr, and (5) investigation of the adhesion or cold-welding tendency of metals exposed to vacuum and thermal outgassing.

149. Dillon, J. A., Jr., The Clean Surface Approach to Adsorption Studies, Brown U. Barus Research Lab. of Physics, Providence, R. I., Presented at the American Vacuum Society 8th National Vacuum Symposium, 1962.

Because of the intimate relationship between adsorption properties and the surface condition of a solid, considerable research has been devoted to the preparation of single crystal surfaces which are initially atomically clean. Several high-vacuum techniques which have been used for this purpose and several methods which have been employed to evaluate the degree of surface cleanliness and perfection are discussed and compared. Examples of the types of information provided by such experiments are drawn from the extensive measurements which have been made of the properties of semiconductor crystal surfaces.

150. Keller, Douglas V., Jr., Adhesion Between Atomically Clean Metallic Surfaces, Syracuse Research Inst., Final Report, July 1962. NASA CR 52482

Results are presented of studies of (1) bulk adhesion, (2) determination of the surface energy of silver at -187°C, and (3) determination of the crystal structure of the interface formed in adhesion. In the bulk-adhesion study, the energy of adhesion was found to be a function of the loss of the free surface energy of both free surfaces which in turn is a function of their crystallographic orientation, of the neighbor orientation across the interface, and of the nature and energy of the atomic bond between the two different metals constituting the contacting surface. The couples Fe/Al, Cu/Ag, Ni/Cu, and Ni/Mo all form a sort of intermediate phase with adhesion observed, while the couples Cu/Mo, Ag/Mo, Ag/Fe, Ag/Ni all form immiscible mixtures with no adhesion observed. In the surface energy study, a low temperature, high-vacuum, calorimetric apparatus is being assembled. In the interface study, the deposition of a very thin film of nickel on an atomically clean substrate of aluminum at various temperatures was accomplished, and the metallurgical phases present will be determined by electron diffraction techniques.

151. Keller, D. V., Franklin, W. M., and Hauser, D., Adhesion Between Atomically Pure Metallic Surfaces, Part III: Annual Report (Final), Syracuse U. Research Inst., N. Y., July 1964.

Contents:

1. "Surface Energy of Solid Silver" - W. M. Franklin, 1964.

A new, direct experimental approach to the determination of surface energy of atomically clean surfaces was developed. The technique involves the evaporation in ultra-high vacuum of a solid sample to form a thin film of very large surface area.

2. "Forces of Adhesion Between Clean Metallic Solids, Part II", D. Hauser, July 1964.

An atomistic approach to the problem of solid adhesion suggests a mechanism for metallic adhesion in which the application of either normal or tangential forces is unnecessary, provided the surfaces are atomically clean when they are brought into contact. An analytical balance for measuring adhesion forces between clean surfaces in ultrahigh vacuum was designed, constructed, and tested.

152. Keller, D. V., Adhesion Between Solid Metals, Syracuse University, Syracuse, N. Y., Wear, 6, 1963. NASA TN-D-2228

A broad definition of adhesion between solid metals is proposed and discussed in order to permit a better understanding of the vast amount of metallic adhesion data being published currently. An interesting result of the definition in this paper is that there appears to be a real relationship between adhesion phenomena and the processes of friction, cold-welding, sintering, grain boundaries strength and fatigue. A number of experimental techniques are discussed and analyzed.

153. Keller, Douglas V., Jr., Adhesion Between Atomically Clean Surfaces, Syracuse U. Research Inst., N. Y., February 1962.

Contents:

Part 1. Bulk Adhesion. T. Spalvins. p. 1-12. 24 refs.

Part 2. Determination of the surface energy of silver at -187° C. W. Franklin. p. 13-19. 3 refs.

Part 3. Determination of the structure of the interface formed in adhesion. A. Kerner. P. 20-24. 3 refs.

154. Keller, D. V., Jr., and Spalvins, T., Fretting and Dry Friction under Space Conditions, Syracuse Univ. Research Inst., N. Y., Final Report, 1961.

A system was designed in which the adhesion between atomically clean metal and alloy surfaces could be investigated. The liter cell containing the test pieces was evacuated to 10^{-9} Torr, flooded with high purity argon, bombarded by argon ions and re-evacuated to provide suitable test conditions. Under these conditions, the test pieces were then brought into touch contact without plastic flow of either surface. Adhesion was observed as the lack of ability to remove the test pieces from their touch contact, as well as surface disruptions, by careful micrographic inspection of the polished and etched surfaces. The results, though not exhaustive, indicated that the laws of the formation of a second phase, i.e. the interfacial boundary, strongly influence the ability for one atomically clean surface to adhere to another, the adhering forces being made up of both surface energy terms, as well as atomic bonding or bulk-free energy terms.
Further study of these phenomena is to be continued.

155. Spalvins, T., and Keller, D. V., Adhesion Between Atomically Clean Metallic Surfaces, Part 1 Bulk Adhesion, Syracuse Univ., Research Inst., N. Y., 1961.

The mechanisms of metallic adhesion (microwelding) are investigated because in high or ultrahigh vacuum applications most lubricants lose their effectiveness in preventing bonding of metallic atoms of one surface to the atoms of a second surface. An experiment was designed to bring two clean metallic surfaces into touch contact at a near-zero force and determine if adhesion welding took place. Results showed complete adhesion between the couples Cu-Mo, Ag-Mo, Ag-Fe, Ag-Ni; Ge-Ge (single crystal). These results suggest an adhesion mechanism which depends on the physical chemistry of the surfaces rather than the mechanical aspects of the contact area. It is further stated that "Conclusions indicate that total seizure (welding) should not occur if immiscible pairs of metallic surfaces are selected."

156. Ham, John L., Investigation of Adhesion and Cohesion of Metals in Ultrahigh Vacuum, Nat'l. Research Corp., Cambridge, Massachusetts, Final Report, March 1963.

Apparatus was developed for the measurement of the force necessary to separate small specimens of metal cleaned and joined in ultrahigh vacuum. The fracture-rejoin technique eliminates the surface cleaning problem and permits acquisition of data characteristic of the metal itself; it is not applicable to dissimilar metal pairs. Both similar and dissimilar combinations of the following metals at two hardness levels were studied: copper, copper-beryllium alloy, 1018 steel, 4140 steel, 440 C steel, and titanium. The cleaning method used was wire brushing. Three runs (24 tests) were made with flat specimens and one run (8 tests) with chisel edge specimens. Cohesion occurred only between flat faced soft copper specimens wire brushed in vacuum. The cohesive force varied from 8 to 120 lbs. after a compressive force of 2000 lbs and appeared to depend primarily on the thoroughness of wire brushing.

157. Ham, John L., Investigation of Adhesion and Cohesion of Metals in Ultrahigh Vacuum, National Research Corp., Cambridge, Massachusetts, First Annual Summary Report, June 1961

Techniques were developed for evaluating the cohesion of metals at various temperatures by repeatedly fracturing and rejoining notched tensile specimens in ultrahigh vacuum. Two types of apparatus were used: (1) a differential expansion device and (2) a screw drive device. The latter was found to be the better. The maximum cohesion obtained at room temperature was about 65% for copper, 19% for 1018 steel, and zero percent for hardened 52100 steel. Time in contact appears to be an important factor for copper at 200°C and above. Both 1018 steel and 52100 steel were "self-cleaning" at 500°C; the former showing repeated readings near 100% cohesion, and the latter increasing in percent cohesion with each successive break. Except for steel at 500°C, and copper at 350°C and 400°C, cohesion dropped on each successive test.

158. Ham, John L., Investigation of Adhesion and Cohesion of Metals in Ultrahigh Vacuum, National Research Corp., Cambridge, Massachusetts, Third Quarterly Progress Report, April 1962.

By repeatedly breaking and rejoining notched cylindrical specimens and measuring the true stresses involved, the effects of cohesion of temperature, environmental pressure, time apart, and time in compression were evaluated. Compressive stresses were kept as high as possible without increasing specimen diameter beyond its original value. Type 1018 steel and OFHC copper were studied in the 25°C to 500°C temperature range and in the 10^{-9} to 10^{-6} torr pressure range. Results are presented in the form of graphs relating percent cohesion to the cumulative product of the time apart and the pressure while apart. Temperature, time in contact, and compressive stress are given as parameters. The maximum cohesion obtained at room temperature was about 19% for the steel and about 12% for the copper. About 30% was obtained at 90°C on copper. Time in contact was an important factor for copper at elevated temperature. Exposure at low temperature to residual vacuum system gases, expressed in units of 10^{-7} torr-minutes, reduced cohesion more than exposure at high temperature for both steel and copper. Percent cohesion, with temperature, compressive force and time in contact held nearly constant, continues to decrease from break to break even though time apart and pressure while apart are less than required for formation of a monolayer of adsorbed gas. This is ascribed to surface migration and can probably be prevented by ion bombardment of the specimen surface adjacent to the fractured surfaces.

159. Ham, John L., Investigation of Adhesion and Cohesion of Metals in Ultrahigh Vacuum, National Research Corporation, Cambridge, Massachusetts, Second Quarterly Progress Report, December 1961.

Cohesion tests were made on one specimen of copper at various temperatures (25 to 400°C) and on one specimen of 1018 steel at 500°C by repeatedly breaking and rejoining notched specimens in high vacuum. The effect of time in compression was studied for the copper and the effects of time apart and of pressure were studied for the steel. The copper was broken forty-nine times and the steel, ten times. Cohesive stresses ranged from 10 to 100% of estimated perfect weld values, depending on time in compression, time apart, pressure while apart, and temperature. Compression force was raised momentarily to the estimated "yield point" each time to ensure a perfect fit but was held at only half that value for the "time in compression" studies.

Further tests are planned on these same materials, using a new specimen for each temperature level as in the last test. New side leg heaters and automatic temperature control are being installed to improve timing and temperature control.

Bars of 52100 steel, 440-C and 17-4 P.H. stainless steel, a copperberyllium alloy, and 4140 steel were procured for future tests.

160. Ham, John, L., Investigation of Adhesion and Cohesion in Metals in Ultra-high Vacuum, First Quarterly Progress Report, September 1961, National Research Corp., Cambridge, Massachusetts.

Apparatus for the measurement of cohesion has been modified and calibrated in preparation for initial tests on O.F.H.C. copper by the fracture-rejoin method proposed.

161. Ham, John L., The Influence of Space Phenomena on the Mechanical Properties of Structural Materials (Fatigue of Aluminum in Vacuum), National Research Corp., Cambridge, Massachusetts, Final Report, Presented in part at the ASTM 4th Pacific Area Natl. Meeting, January 1963.

Techniques were developed for evaluating the fatigue life of metals by reverse bending in controlled gaseous environments, including high vacuum, and bombardment. These techniques were applied to electropolished specimens of commercially pure, half-hard rolled aluminum sheet. The fatigue life of aluminum in reverse bending at 125 to 140 cycles per second was found to be about seven times longer in vacuum than in wet air, and about four times longer in vacuum than in dry air. Life is independent of pressure in the range 760 to 10^{-2} torr; increases rapidly in the range 10^{-2} to 10^{-4} torr and is again independent of pressure in the range 10^{-4} to 7×10^{-9} torr. Life under argon bombardment is up to three times longer than in high vacuum. The cyclic strain causes more surface roughening in vacuum than in air. A hypothesis based on adsorption equilibrium and immunization to cracking by work hardening is proposed to explain the step change in life with pressure. The effectiveness of bombardment is ascribed to prevention of crack contamination by migration of mobile surface-gas films.

162. Goodzeit, C. L., Selecting Bearing Materials That Will Not Seize, Materials in Design Engineering, June 1958.

Table gives information needed to select pairs of bearing metals that will not form strong welded junctions during operation.

163. Winslow, P. M., Horwitz, D., and McIntyre, D. V., Study of Adhesion and Cohesion in Vacuum, Hughes Aircraft Co., Culver City, California, Summary Report, July 1964. NASA CR 59488

This is a study of a vacuum chamber and its application for evaluation of the adhesion and cohesion of metal couples. The maximum test criterion was the loading of the materials to 80% of their compressive yield strength at various temperatures for 70,000 seconds. The tensile force required to separate two specimens was then measured to determine the extent of adhesion and cohesion. It was found that copper formed a weak bond to itself at temperatures as low as 300°C, and that the 2014 aluminum alloy showed a tendency to bond to itself, to A286 steel, and René 41 at 300°C. The chromium nickel stainless steels and the high-nickel alloys had no tendency to bond to themselves or to each other.

164. Ford, T. F., and Nichols, O. D., Adhesion-Shear Strength of Ice Frozen to Clean and Lubricated Surfaces, Naval Research Lab., Washington, D. C., Interim Report, August 1962. NRL 5832

The adhesion-shear strength of ice to bulk plastics, plastic films, lubricated plastics, and lubricated metals has been measured at three different temperatures. The bulk plastics used were nylon, polyethylene, and Teflon; the plastic films were Teflon and two polymerizable silicones. The adhesion strength of ice frozen to clean bulk nylon and polyethylene and to clean Teflon films was found to be higher than for ice frozen to bulk Teflon. In most cases the laboratory tests show self-detachment of the ice from bulk Teflon at -1°C and -20°C, but not at -60°C. Thermal-mechanical factors were probably responsible for self-detachment at -20°C, a persistent water film on ice or pressure-liquefaction in the ice/solid interface may be responsible at -1°C. Adhesion of ice to clean bulk plastics and to plastic films is low compared with that to metals, but still too high for ease of separation. Ice was removed easily from lubricated plastics. With some plastic-lubricant systems, as many as 12 zero-adhesion freeze-shear-thaw cycles were obtained in laboratory teste before replenishing the lubricant; on metals, five or six cycles were possible. All experiments indicate that an effective coating must be a fluid or semifluid material on which the ice will slide. (No effective solid coatings have been found.) Fluid or semifluid coatings must be such as will resist displacement by water through several icing-deicing cycles. Bis (2-ethylhexyl) sebacate, one of several available synthetic oils, and silicone greases are promising materials.

165. Daniels, R. O., and West, A. C., The Influence of Moisture on the Friction and Surface Damage of Clean Metals, Presented at ASLE Annual Meeting, April 1955.

A new, controlled atmosphere, low-speed friction apparatus for fundamental boundary lubrication studies is described. The friction of a one-eighth inch diameter hemispherical slider on a flat disk is automatically plotted as a function of the desired operating variable on an "X-Y" type recording potentiometer. An investigation of the effects of moist surrounding atmosphere and bulk water on the kinetic friction of high purity, unlubricated metals is reported and a theory presented which explains the observed behavior in terms of an oxidizing reaction which occurs at the contacting asperities as they deform. The oxidation is accelerated at the freshly exposed metal surfaces by the presence of adsorbed moisture and by any rise in temperature which may occur, with the result that friction and surface damage are reduced.

166. Kern, E. L., and Jackson, A. G., Nature of the Interaction Between Electrons and Well-Defined Surfaces: III. Ultra-High Vacuum System and Sample Outgassing IV. Gas Source for the Ultra-High Vacuum Study of Adsorption of Known-Gas Layers on Clean Surfaces, Aeronautical Research Labs., Wright-Patterson AFB., Ohio - ARL 64-80 - May 1963

The obtaining and maintaining of atomically clean surfaces is a necessary basic step in the study of well characterized surfaces. The initial part of such cleaning is to incorporate the sample and necessary measuring components in an ultrahigh-vacuum system, capable of maintaining a pressure of $1 \cdot 10^{-9}$ torr (1 torr = 1 mm Hg) to $1 \cdot 10^{-10}$ torr. This report describes the means of obtaining these conditions. A double pumping arrangement, using a diffusion pump and a getter pump, with appropriate vapor trapping, valves, and gages, is described. Chamber bakeout and high-frequency heating of metal components are described. Equipment such as liquid nitrogen and oven controllers, which provide around-the-clock maintenance, is also described. Studies of the influence of known-gas layers on a clean surface necessitate an ultrahigh-vacuum gas manifold system. The vacuum pumping, valving, measuring equipment, and gas manifold are described. Ion gages can be calibrated absolutely against a high-vacuum McLeod gage. By this system, capable of 10^{-9} to 10^{-10} torr, partial pressures of gases of the order of 10^{-12} torr can be introduced into the main testing chamber.

167. Bowden, F. P., and Young, J. E., Friction of Clean Metals and the Influence of Adsorbed Gases, Proc. Roy Soc., London, March 1951

An experimental study has been made of the frictional behaviour of thoroughly degassed metal surfaces. An apparatus is described, in which friction can be measured at any desired temperature up to 1200° C or more, either in vacuo or in a particular gas. It is found that when sufficiently clean metals are allowed to touch, even at room temperature, complete seizure occurs. Over the real area of contact the specimens adhere with the bulk strength of the metal, and this area increases greatly with continued sliding or attempted sliding.

Various gases and vapours have been adsorbed on to the clean specimens, and their influences on friction determined. These specific contaminants are most effective as lubricants where they can react with the metal to form a solid and chemically attached film which is several molecular layers in thickness. Otherwise the friction remains very high, although seizure is prevented. It is shown that physical adsorption may occur in addition, with a significant reduction in the friction.

The results support the view that the friction of metals is due mainly to adhesion at the points of real contact, and is governed by the extent to which even the thinnest of surface films can reduce this metallic contact.

168. Bowden, F. P., and Tabor, D., The Friction and Lubrication of Solids Part I, Oxford University Press, London, 1950.

This monograph describes an experimental study of the physical and, to a less extent, of the chemical processes that occur during the sliding of solids - particularly of metals - and an investigation into the mechanism of friction and boundary lubrication. The field covered is somewhat wider than the title might indicate and it deals with a number of the physical properties of solid surfaces. The book deals almost entirely with experimental researches carried out by the writers and their collaborators and colleagues.

169. Bowden, F. P., and Tabor, D., The Friction and Lubrication of Solids Part II, Oxford University Press, London, 1964.

Part II, a sequel to "The Friction and Lubrication of Solids, Part I, describes the subsequent work carried out by the authors and their colleagues. In addition to further work on metals, it discusses the frictional behavior of nonmetallic solids. It is shown that the energy lost by the deformation of the surfaces may constitute a considerable part of the total frictional losses - particularly in rolling friction and in certain types of lubricated sliding. It is possible under these conditions to describe the frictional behavior in

terms of the visco-elastic properties of the solids. In addition to the studies on friction, researches on a number of other physical processes involving the contact and deformation of solids are described.

170. Rowe, G. W., Vapor Lubrication and the Friction of Clean Surfaces, Proc. Conf. on Lubrication and Wear, Institution of Mechanical Engineers, London, 1957.

An experimental study has been made of the friction of metals and hard metals in high vacuum and in the presence of pure vapours. The results demonstrate directly the action of certain boundary and extreme-pressure lubricants.

To produce a repeatable reference surface which approaches as nearly as possible to the ideally pure uncontaminated state, the specimens are heated in a high vacuum (10^{-2} microinches Hg) until an appreciable quantity has evaporated away. When sliding is attempted after the specimens have cooled the friction is always high, even with very hard sliders such as tungsten carbide or sapphire, and many metals (e.g. copper, platinum, silver, nichel, chromium) seize completely.

Very small quantities of vapours can suffice to prevent this seizure. Fatty acid vapours have some influence alone, but in the presence of oxygen and water vapour a chemical attack of the surface occurs which provides a good lubricating film, other films formed "in situ" can give adequate lubrication up to high temperatures.

171. Coffin, L. F., Jr., A Study of the Sliding of Metals, with Particular Reference to Atmosphere, Lubrication Engineering, February 1956.

Comparative friction behavior of 75 couples and the role of atmosphere in the sliding process were investigated. Alloying ability serves as a qualitative criterion for local seizure and surface damage.

172. Buckley, D. H., and Johnson, R. L., Influence of Crystal Structure on Friction Characteristics of Rare-Earth and Related Metals in Vacuum to 10^{-10} mm of Mercury, NASA-Lewis Research Center, Cleveland, Ohio, NASA-TN-D-2513, November 1964.

The friction, wear and metal-transfer characteristics were determined for rare-earth and related metals in vacuum to 10^{-10} mm of mercury. The metals studied were lanthanum, neodymium, praseodymium, cerium, holmium, erbium, gadolinium, dysprosium, samarium, yttrium and thalium. Friction and wear experiments were conducted with the rare-earth or related metals generally sliding against 440 C stainless steel

at sliding velocities to 2000 ft/min and loads to 3000 grams. The rare earth or related metals were the rider specimens (3/16" rad hemisphere) sliding on flat 2 1/2" diameter disk specimens of 440C stainless steel. Factors studies were the effects of crystal structure and crystalline phase changes on the friction, wear, and metal transfer characteristics of these metals in vacuum.

173. Buckley, Donald H., and Johnson, Robert L., Mechanism of Lubrication for Solid Carbon Materials in Vacuum to 10^{-9} Millimeter of Mercury, NASA, Lewis Research Center, American Society of Lubrication Engineers, Lubrication Conference, Rochester, N.Y., October 1963, ASLE Transactions, January 1964.

Determination in vacuum, at ambient pressures from 760 to 10^{-9} mm Hg, of the friction and wear characteristics of various carbon materials sliding on metals and aluminum oxide. The friction and wear experiments were conducted with a hemispherically tipped carbon rider, under a load of 1 kg, sliding on various disks rotating at a speed of 390 ft/min. The results of this investigation are stated to show that additional research on carbon in vacuum is warranted.

Adsorbed surface films present on both carbons and metal, as well as the presence of oxide on metals, appreciably influenced the friction and wear obtained with carbons in vacuum. Some impregnants were beneficial in reducing friction and wear of carbon in vacuum, while others were not.

174. Reichenbach, George S., Shaw, Robert Jr., and Foster, Robert G., Lubricant Behavior in High Vacuum, Massachusetts Institute of Technology, Surface Laboratory, Dept. of Mechanical Engineering, American Society of Lubrication Engineers, Lubrication Conference, Rochester, N.Y., October 1963, ASLE Transactions, January 1964.

Description of pin-on-disk friction tests and crossed-cylinder load-carrying tests run in air and in vacuum. Dry friction behavior was found to be very sensitive to pressure level and previous history of the specimens. It is stated that lubricated friction behavior for the lubricants tested was essentially independent of pressure unless there was selective evaporation of friction-reducing additives in the lubricant. Most of the fluids tested evaporated very slowly in these room-temperature tests. Load-carrying ability was reduced in vacuum by more than 50% for several lubricants tested. This reduction was attributed to the absence of oxygen needed to form EP load-carrying films.

175. Flom, D. G., Haltner, A. J., and Gaulin, C. A., Friction and Cleavage of Lamellar Solids in Ultrahigh Vacuum, General Electric Co., Missile and Space Division, Space Sciences Laboratory, American Society of Lubrication Engineers and American Society of Mechanical Engineers, Lubrication Conference, Washington, D.C., October 1964.

Presentation of results of measurements of sliding friction on copper surfaces at 10^{-6} to 10^{-9} torr for five lamellar solids, namely, molybdenum sulfide, tungsten sulfide, cadmium iodide, bismuth iodide, and phthalocyanine. No evidence is found that the sliding behavior of any of these materials is improved by the presence of gas or vapors. Each is found to evolve considerable quantities of gas during sliding. Molybdenite and surface-nucleated pyrolytic graphite are cleaved in an ultrahigh vacuum apparatus built for this purpose. The graphite specimens are tested in both as-deposited and annealed forms. It is found that the predominant gas given off for the former is methane, while for the latter, it is water vapor. In the cleavage of molybdenite, the primary gas is found to be methane.

176. Bryant, P., Lubrication Studies With Lamellar Solids, Wright-Patterson AFB, Directorate of Materials and Processes, 1962.

A basic research program is being conducted to determine the mechanisms of friction and wear for lamellar solid lubricants. Single crystals of graphite were grown and a UHV ($2 \cdot 10^{-13}$ torr) controlled atmosphere system was perfected. A stress etch mechanism is proposed here to explain the effect of atmospheric gases upon the lubrication properties of lamellar solids. The proposed mechanism describes the observed reduction of cohesive energy (mica was 30 times stronger in vacuum than in air) by an external attack upon the bifurcation line or shearing edge; the mechanism thus depends on the well established processes of surface adsorption and migration without requiring diffusion of air molecules between lamellae.

177. Lavik, M. T., and Clow, W. L., Friction and Wear Characteristics of a Ceramic-Bonded Solid-Lubricant Film, Midwest Research Inst., Presented at the 1963 USAF Aerospace Fluids and Lubricants Conf., Session V-B, April.

This paper summarizes friction and wear studies of the $PbS:MoS_2:B_2O_3$ lubricant system. A review of the film preparation and evaluation techniques used in the investigation is given. The wear-life and friction performance of the films in this system are discussed. In electron micrography of film surfaces, consideration is given surface films rubbed in air

and surface films rubbed in a vacuum. Results of the film performance show that (1) the film wear-life is very good in air over a limited temperature range near 1000° F and friction coefficients remain below 0.20; (2) the films exhibit useful wear and friction properties over the temperature range 80° to 1000° F in both air and vacuum (~ 10^{-6} Torr). The wear-lives are proportional to e^{-ct} and are approximately 300 percent longer in vacuum than in air. Film structure results show that (1) the films rubbed in air at 700° F exhibit much more severe and extensive wear areas than similar films rubbed in vacuum, (2) the wear patterns of film rubbed at 700° F in vacuum are composed of closely spaced rub marks in the film areas still intact; few areas of severe wear are noted, (3) films rubbed at 1250° F in vacuum exhibit diffuse rub marks and relatively large-scale plastic deformation.

178. Hopkins, V., and Gaddis, D., Friction of Solid Film Lubricants Being Developed for Use in Space Environments, Presented at 1964 ASLE Annual Meeting, Chicago, Ill. Preprint No. 64-AM4A2.

This paper describes the evaluation of inorganic solid film lubricants being developed for service in space environments. Friction coefficients are given for many potential lubricants subjected to a light load and temperatures from 80° to 400° F in both a normal air atmosphere and in a vacuum of 10^{-6} Torr.

The main criterion for judging the performance of a potential lubricant film was the friction coefficient, which must be less than that obtained for a 0.001-in thick film of gold.

179. Hansen, S., Jones, W., and Stephenson, A., Research Program on High Vacuum Friction, Litton Industries of Calif., Space Research Laboratories, Final Report, 1959.

In a twelve month program directed towards the study of surface friction under conditions of high vacuum (10^{-5} to 10^{-6} mm Hg) the existance of two modes of contact were established, one of pure sliding and a second of areas undergoing shear. The low friction, low wear examples appear to be special cases wherein almost all contact areas are of the first type.

180. Boyd, K. E., Rollins, C. T., and Thomas, A. D., Mechanisms of Friction and Wear Between Solid Surfaces, Utah Univ., Salt Lake City, Utah, 1962.

A low velocity friction testing machine for surface velocities of from 1.0 ft/sec to 15.0 ft/sec and a high velocity friction testing machine for surface velocities

of from 1.0 ft/sec to 200 ft/sec are designed and used to test a number of pairs of solid materials. Coefficients of friction as a function of several parameters were measured and plotted. It was found that a unique interface temperature between rubbing materials does not exist, but rather a random extremely variable temperature profile of considerable magnitude does exist. Data were obtained which give evidence for deducting the effects of reactivity and solid solubility on the friction process.

181. Jackson, E. G., Lubrication in Space Vehicles, Wear-Usure-Verscheiss, V 5, N 6, December 1962.

Survey of problems, and some of solutions, associated with lubrication of mechanical apparatus in space; space environmental factors; lubrication in vacuum is considered including discussion of volatilization of fluids and solids, condensation of volatiles, lack of reactants and absorbates, and thermal conductivity, recent efforts to solve space lubrication problems, space simulation problems.

182. Buckley, Donald H., Swikert, Max, and Johnson, Robert L., Friction, Wear, and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg, Repr. from ASLE Trans., Presented at the ASLE Lubrication Conf., Chicago, Ill. October 1961.

Evaporation data on soft metals, lubricating inorganic compounds, and various reference materials are reported for temperatures from 75° to 1000° F in vacuum as low as 10^{-7} mm Hg. Observations on modes of vacuum degradation (e.g., evaporation or dissociation) and methods of experimentation are related. Friction and wear data are presented for several unlubricated metals (e.g., type 440-C steel) and metal films in vacuum at ambient pressures between 10^{-6} and 10^{-7} mm Hg.

183. Rittenhouse, J. B., Jaffe, L. B., Nagler, R. G., and Mortens, A. E., Friction Measurements on a Low Earth Satellite, ASLE Paper 63-AM6A1, 1963.

The coefficient of sliding friction for a number of materials was measured during the flight of Ranger 1 spacecraft. Flat disks of materials of interest were rotated at a speed of 8-11 inches per minute while in contact with 1/8 inch diameter hemispherical riders. Because of the low orbit achieved by Ranger 1, the experiment was exposed to vacuum in the range of 3×10^{-6} to 8×10^{-9} mm Hg. For unlubricated metals sliding on metals, the friction coefficient averaged about 0.5; for some combinations of metals, it occasionally exceeded 1.0. Lower values were observed with lubricants of grease or gold-plate and for ceramics sliding against metals. The coefficient of friction was very low, averaging 0.04, for metallic pairs lubricated with molybdenum disulfide and for polytetrafluoroethylene sliding against metals and ceramics. Relatively low friction coefficients were found for metallic materials sliding against unlubricated metallic and ceramic materials when at least one member of the pair was of high hardness. The coefficients observed for unlubricated metal pairs were not inconsistent with the hypothesis that high friction tends to correlate with high mutual solid solubility. In general the coefficients in space and in a laboratory vacuum of 5×10^{-6} mm Hg were not systematically different. For unlubricated metallic materials, friction in vacuum was higher than in air at shorter running times.