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INVESTIGATION OF STATIC AND DYNAMIC
 COEFFICIENT OF FRICTION
 (For Various Combinations of Material)
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ABSTRACT

The low friction of graphite results from a gas film on surface platelets. Therefore, if graphite is one of the materials in a rubbing combination, the coefficient of friction at room temperature in air, hydrogen, or nitrogen will reduce to about 0.2 in a few rubbing cycles for surface pressures within the elastic range.

In hydrogen, graphite combinations have lower friction with increasing temperature. For metal on graphite, the friction decreases with temperature until a surface reaction occurs after which it increases with rising temperature.

Removal of surface films causes an increase in friction. This can be accomplished for graphite by outgassing (heating in a vacuum). Only a partial pressure of hydrogen is necessary, however, to reduce the coefficient to 0.2 at room temperature.

Niobium carbide surfaces have an increase in friction for air, hydrogen, or vacuum with increase in temperature. The coefficient reaches unity at 4000°R.

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I. PURPOSE

It is the purpose of this study to determine the static and dynamic coefficient of friction for various combinations of materials under varying thermal and environmental conditions.

II. INTRODUCTION

The maximum shear loads transmitted between loaded interfaces of unlubricated machine components are a function of the coefficient of friction and the normal surface load. A reliability study of these components must consider these forces in conjunction with the service loading. The WANL friction test program includes the material combinations encountered in the design of components and test fixtures over a range of temperatures, atmospheres, and surface pressures simulating service environments. Wagner ⁽¹⁾ has shown that for graphite combinations, the coefficient of friction varies with surface finish and temperature, but is fairly insensitive to surface pressure. Mordike ⁽²⁾ showed that the coefficient of friction of outgassed graphite decreased with temperature and that the strength of graphite depended on the adsorbed gases. He also showed for graphite-metal combinations that when a temperature was reached where diffusion of carbon into the metal occurs, the coefficient of friction increased with further increase in temperature. In his work on refractory carbides, the friction of carbide initially decreased as the temperature was raised, but then increased rapidly. This was not found to be true for carbide on graphite.

The test results reported herein substantiate the findings described above. The tests included are combinations of different grades of commercial graphite, of unfueled WANL graphite, of niobium carbide, and of metals. Since the interface

¹"The Friction Coefficients of Graphite at Extreme Temperatures" by P. Wagner and A. Driesner, Los Alamos Scientific Laboratory Report. LA-2146, Metallurgy and Ceramics, 1958.

²"The Mechanical Properties and Friction of Carbon and Graphite at High Temperature", by B. L. Mordike, Fourth Carbon Conference. pp 729-739.

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is such an important variable, the following factors were investigated:

1. Roughness
2. Adsorbed and absorbed gases
3. Surface films
4. Strength and distribution of asperities
5. Chemical reaction with mating surface, or wear debris

Temperature and loading pressure influence these factors as a function of time and loading, or sliding rate.

Many of the above investigations are continuing and additional data will be presented in the future. This report, however, will summarize some of the currently significant data and provide data for design.

III. TEST APPARATUS AND PROCEDURE

Most of the data was obtained in two types of friction test apparatus. The high temperature friction test machine and atmosphere chamber are illustrated in Figure 1. The fixed friction-test-specimen rests in a slot machined in a graphite resistance heating tube. The movable test-specimen is inserted into a graphite rod which extends horizontally through the center of the heating tube and out each end where it is loaded by dead weights. This tube is connected to a force bar instrumented with strain gages and is driven by a 1/16 in. eccentric on a 1 rpm motor.

The resistance heating tube has water cooled terminals and is capable of heating the specimens to 5000°R. The extreme temperatures are measured by an optical pyrometer through the sight port in the chamber. Lower temperatures are recorded by a thermocouple which can be retracted from the hot zone.

The surface pressure can be varied by changing the interface area of the specimens or the end weights. Standard pressure used for most of these tests was 4 psi.

The normal test procedure for a varied atmosphere test consisted of runs of about three cycles under the following sequential conditions:

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- (a) Room temperature in air, nitrogen, and hydrogen
- (b) In hydrogen at 500°F intervals from room temperature to maximum selected temperature
- (c) Continuous run in hydrogen; furnace cooling from maximum temperature to near room temperature
- (d) Ambient temperature in hydrogen, nitrogen and air

The friction force is automatically recorded for all runs.

Another apparatus was utilized for out-gassing studies. This was a "nut-cracker" type friction test fixture which could be inserted into a furnace and vacuum chamber, Figure 2. This fixture consisted of two graphite beams which extended through the furnace and were pivoted at one end and dead weight loaded at the other. The test specimens were thus clamped at the furnace center. Two stationary specimens were fastened into these beams and bear on each side of a central moving specimen with a pressure of 4 psi. This central specimen fits in a graphite yoke which is driven up and down through a series force dynamometer at the bottom, the output of which is automatically recorded.

Normal procedure for out-gassing runs consists of three cycles at room temperature in air and vacuum with the following sequence in vacuum:

- (a) At out-gassing temperature of 1000°R
- (b) At ambient temperature
- (c) At out-gassing temperature of 3000°R *
- (d) At ambient temperature

A measured quantity of hydrogen is then admitted and runs made with the partial pressure of hydrogen, after which the hydrogen is pumped out. A final run is then made in air at room temperature to determine the integrated effect of the above environment, and out-gassing.

* For graphite on Nb C specimens; 1500°R for stainless steel; or 1000°R for aluminum or titanium.

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IV. TEST RESULTS

A. Static Coefficient of Friction in Air

The coefficients of static friction at room temperature in air are summarized in Table 1 for the material combinations listed. The value of the coefficient is read at the intersection of the horizontal and vertical columns for the particular material combination. This value is an average of several tests at 4 psi after a run-in of about 3 cycles. The coefficients in hydrogen, or nitrogen for the same conditions were practically equal. The low friction of graphite on any of the materials is attributed to the low shear strength of graphite platelets, the sliding of these platelets on very thin film of adsorbed gas, or the rolling up of these platelets to form miniature roller bearings with a gas film.

B. Coefficient of Friction in Hydrogen

The average coefficient of friction in hydrogen after about three wear-in cycles for surface pressure of 4 psi is listed in Table 2 for material combinations No. 1 and No. 2, for two special surface conditions, and for indicated test temperatures. The surface finish is given as the root-mean-square micro-inch range as obtained with a stylus of 0.0005 in. radius at one gram pressure. ⁽¹⁾

(1) Initial Surface Condition

The "initial condition" refers to "as machined", or "as prepared" samples. The data given are the average of several runs as interpolated from plots of coefficient versus temperature similar to that shown for one test of niobium carbide coated graphite on pyrolytic graphite in hydrogen atmosphere, Figure 3. Both the static ("pull-away") friction and the kinetic ("moving") friction coefficients are given. Where "stick-slip" was encountered, an average value was used for the kinetic coefficient.

¹ Even this low pressure was found to leave a mark on graphite.

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Table 1. AVERAGE COEFFICIENT OF STATIC FRICTION AT
ROOM TEMPERATURE IN AIR FOR MATERIAL COMBINATIONS *

	HLM	ZTA	ATJ	Gr. G	Pyro	Unfueled	Nb C	2024 Al	2219 Al	A110 Ti	304 SS
HLM Graphite		.19		.20	.13	.17	.18	.18	.22		.19
ZTA Graphite	.19	.25			.16						.13
ATJ Graphite			.15		.17			.16	.17		.19
Graphitite "G"	.20			.21							
Pyrolytic Graphite	.13	.16	.17			.13	.19				
Unfueled Graphite	.17				.13	.14	.12	.16			
Nb C over Graphite	.18				.19	.12	.20	.16			
2024 Al	.18		.16			.16	.16				.35
2219-T31 Al	.22		.17						.38	.38	
A110AT Ti									.38	.29	
304 SS	.19	.13	.19					.35			
347 SS	.20										
Inconel-X	.19										
Ni-Span-C										.2	

- * (a) Average value of several tests after at least 3 run-in cycles.
 (b) Surface pressure of 4 psi.
 (c) Surface finish, Graphite $\approx 100\mu$ in., Metal $\approx 32\mu$ in.
 (d) Values approximately same for hydrogen or nitrogen

Table 2. COEFFICIENT OF FRICTION IN HYDROGEN

Materials		Surface Finish(a)		Room Temp.		Initial Condition (b)				At Room Temp. After Outgas(c)			
						1000°R		2000°R		4000°R		After Outgas(c)	
No. 1	No. 2	No. 1	No. 2	μ_s	μ_k	μ_s	μ_k	μ_s	μ_k	μ_s	μ_k	μ_s	μ_k
HLM	ZTA	200/250	250/300	.19	.17	.18	.16	.16	.14	.07	.06	.21	.17
"	Pyrolytic Gr.	50/250	225/250	.13	.10							.11	.08
"	Unfueled Gr.	30/70	35/55	.17	.12							.17	.14
"	Nb C	70/90	60/160	.18	.16							.2	.18
"	2219-T31	150/200	10/20	.22	.17	.15	.14					.18	.14
"	304 SS	220/275	32	.19	.17	.17	.15	.11	.10			.21	.17
ZTA	ZTA	60/100	60/100	.25	.18								
"	Pyrolytic Gr.	60/100	90/120	.16	.13								
"	304 SS	40/50	10	.13	.10							.21	.17
ATJ	Pyrolytic Gr.	115/125	90/100	.17	.14			.14	.10	.12		.18	.15
"	2219-T31 Al	90/115	8/13	.17	.14							.14	.12
"	304 SS	90/200	10/20	.19	.17	.18	.12	.19	.12			.19	.13
Unfueled Gr.	Pyrolytic Gr.	30/45	50/120	.13	.11	.13	.11	.12	.10	.08	.05	.16	.13
"	Unfueled Gr.	30/45	30/45	.14	.10							.15	.10
"	Nb C	30/45	60/75	.12	.11							.16	.15
"	2024 Al	100/110	30/40	.16	.14							.14	.10
Nb C	Pyrolytic Gr.	20/60	60/110	.19	.19		.18		.12		.14	.17	.16
"	Nb C	40/50	50/60	.20	.18	.20	.19	.32	.27	.93	.75	.25	.24
2024 Al	304 SS	20/25	10/15	.35	.32							.55	.53
2219-T31 Al	A110AT Ti	10/20	15/30	.38	.34							.8	.7
2219-T31 Al	2219-T31 Al	10/20	10/25	.38	.32							.85	.79
A11AT Ti	A110A7 Ti	12/15	12/15	.29	.26							.40	.36
Ni-Span-C	A110AT Ti	10/25	15/20	.2	.17							.57	.47

(a) RMS micro-inch readings for 0.0005 in radius stylus at 1 gram pressure.

(b) As prepared, average coefficient after at least 3 cycles at 4 psi.

(c) Outgassing at 3000°R in vacuum for graphite, or Nb C, 1000°R for aluminum, 1500°R for SS

 μ_s = static coefficient; μ_k = kinetic coefficient, surface pressure 4 psi

(2) Out-gassing of Surfaces

The second conditioning is an "out-gassing and run-in" cycle described above for the vacuum friction test apparatus. Typical runs are shown for unfueled graphite on pyrolytic graphite in Figure 4, and for unfueled graphite on niobium carbide in Figure 5.

These runs substantiate the necessity of an adsorbed film of gas for low coefficient of friction. The friction is low during the first three runs at room temperature in air, and the runs in a vacuum (the adsorbed gases continually replace the surface film) before and after heating to 1000°R. However, when pumped at 3000°R, the gas is drawn from the graphite and a slight increase in friction is noted; but, when the specimen was cooled, the diffusion of absorbed gas is stopped and the gas is pumped away. Thereupon, the friction increases to about 0.4. When a partial pressure of hydrogen gas is then introduced to the chamber, the friction drops to a low value, runs starting at No. 20.⁽¹⁾ This can be shown to be an adsorbed film since it can be removed by further pumping with consequent rise in friction. When air is admitted to the system, the film is restored and the friction coefficient again falls to about 0.2.

When the combinations of samples are both metals, the out-gassing removes all surface film and high friction and galling are observed, Table 2.

C. Wear-In

The surface conditioning of graphite results in a wear-in effect on the coefficient of friction. The degree of conditioning depends on the initial surface roughness and its geometry. Tool marks leave hills and valleys and the mating of such surfaces leads to wear, or shearing of the asperities. The roughness is thus reduced as the wear debris fills in the valleys. Since graphite

¹ See Figures 4 and 5

grains are platelets, the surfaces are coated with these, and friction is reduced. This occurs whenever one of the mating surfaces is graphite.

Figure 6 illustrates this wear-in friction of graphite on stainless steel as a function of the number of runs. The top curve is for machined samples and shows that the coefficient of friction decreases gradually and approaches a value of about 0.19 after only 10 cycles. The lower curves are for samples in which one or both surfaces have been machined, ground, or polished to a smoother profile. It is of interest to note that when both surfaces are polished the initial friction is low, but increases with wear-in, and approaches the same coefficient as the rougher samples. This indicates that the surfaces have then become coated with graphite platelets.

D. Niobium Carbide Friction in Air, Hydrogen, and Vacuum

The friction coefficient is extremely dependent upon the surface conditions. For niobium carbide, the surface reactions depend upon the surrounding atmosphere and temperature. Oxidation will occur in air, films will be removed in a vacuum, or hydrogen, and diffusion and bonding will increase with the temperature. The effect of these factors are shown in Figure 7. The coefficient of friction increases with temperature, for all three atmospheres, but is larger for air and hydrogen (reaching a value of about 1). On cooling in hydrogen, the friction returns to nearly the same value as the original, but for air or vacuum, the friction remains higher. For air, this is a result of the surface oxidation, Figure 8. In a vacuum, the surface asperities are bonded by galling. This also occurs in hydrogen, but to a lesser degree, Figure 9.

E. Surface Pressure

As mentioned above, surface pressure has been found to have very little influence on the coefficient of friction in the range where surface distortion is primarily elastic. ⁽¹⁾ Table 3 shows that for niobium carbide surfaces deposited on graphite, the coefficient of friction is about 0.2 for surface pressures of from 4 to 1000 psi at room temperature in air.

¹ cf p. 1, note 1

Table 3. EFFECT OF SURFACE PRESSURE ON COEFFICIENT OF FRICTION
OF NIOBIUM CARBIDE IN AIR AT ROOM TEMPERATURE

Test Temperature	Surface Pressure	Coefficient of Friction		Surface Finish
<u>°R</u>	<u>psi</u>	<u>Static</u>	- <u>Kinetic</u>	<u>10⁻⁶ in.</u>
540	4	.18		40-100
540	4	.19	.13	40-100
540	6	.20	.16	40-100
540	10	.21	.17	40-100
540	20	.21	.17	40-100
540	1000	.18	.15	40-100

Surface pressure is, however, expected to alter the friction characteristics at elevated temperature where diffusion and welding may occur (Figure No. 7), or at extremely high local pressures where cold welding and galling are encountered. High local pressures are found at interfaces that are clamped by bolts, or forced together by the external loading. If relative motion occurs between such surfaces, then wear and/or galling may occur. Galling, or fretting is a function of the surface roughness.

The static coefficients of several metal to metal combinations are given in Table 4 for a surface pressure of 25,000 psi at temperatures of 140 and 960°R.

A comparison of the data for titanium on titanium or titanium on aluminum from Tables 1 and 2 shows that coefficients of friction are obtained at 4 psi at room temperature, which are about the same as the interpolated values from Table 1. The high coefficients which result from the out-gassing treatment, Table 2, indicate that galling can also occur at 4 psi.

V. CONCLUSIONS

The coefficient of static friction of graphite in air at room temperature is low; about 0.2 for many combinations of different grades, or on metals after a run-in of several cycles. The "virgin", or initial pull-away friction is a function of the surface roughness, or interlocking asperities. However, if one member of the combination is graphite, these asperities shear off and the static friction coefficient approaches a constant low value between 0.12 to 0.25 as the graphite platelets slide on a gas film.

For metal on metal, the wear debris causes a galling which gives a higher coefficient of friction. The degree of galling, fretting, and wear increases with temperature, and is more severe for "atmospheres", or environments which clean the surface films.

Table 4. STATIC COEFFICIENT OF FRICTION FOR METAL COMBINATIONS
AT A SURFACE PRESSURE OF 25,000 psi IN HYDROGEN

Materials	Test Temperature °R	Average Coefficient Static Friction (a)	No. of Cycles (b)
Ti (A110 A-T) on Ti	140	.40 → .51	0-15
	140	.59	15-30
	960	.52 → .42	30-45
	960	.45	45-60
Ti (A110 A-T) on Be	140	.45	0-15
		.53	15-30
	960	.64	30-45
	960		45-60
Ti (A110 A-T) on Al (2219-T6)	140	.27	0-15
	140	.30	15-30
	960	.59	30-45
	960	1.1	45-60
Be on Al (2219-T6)	140	.69	0-15
	140	1.55 (c)	15-17

(a) Average, or range during run.

(b) Normal run consists of 15 cycles of 15 mils displacement, rest at temperature for 1 hr. and an additional 15 cycles.

(c) Test stopped on 17th cycle, specimen galling badly.

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Removal of the gas film from graphite by outgassing at 3000°R in a vacuum causes the friction to increase (0.4 to 0.6). However, only a small partial pressure of hydrogen is necessary to replace the absorbed film and reduce the friction to about 0.2.

The coefficient of friction is relatively insensitive to surface pressures that are in the elastic range. Little change was found for graphite materials and carbide up to 1000 psi. For metals, the coefficient was practically constant up to 25,000 psi and 960°R. Galling, however, can occur with wear and cause seizing as was found for a combination of beryllium and aluminum.

The kinetic coefficient of friction is slightly lower than the static one and ranges from 50 to 95% depending upon the debris and "stick-slip" characteristics.

In hydrogen, if one of the material combinations is graphite, the friction reduces with temperature to a point where surface reactions occur, then it increases. For graphite and graphite combinations, the friction increases throughout the temperature range up to 4000°R.

Niobium carbide surfaces in air, hydrogen, or vacuum have a higher coefficient of friction as the temperature is increased and have a value of about unity at 4000°R in air, or hydrogen. This is caused by bonding of the asperities.

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Figure 1 Friction Test High Temperature Furnace

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Figure 2 Vacuum Friction Test Fixture

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Figure 3 Niobium Coated Graphite on Pyrolytic Graphite
in Hydrogen Atmosphere

Figure 4 Vacuum Out-gassing and Hydrogen Runs of Unfueled
on Pyro Graphite

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Figure 5 Vacuum Out-gassing and Hydrogen Runs of Unfueled on Nb C

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Figure 6 Wear-In Effect of HLM Graphite on 304 Stainless Steel at Room Temperature in Air

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Figure 7 Static Friction Coefficient of Nb C on Nb C

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Figure 8

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Figure 9 Niobium Carbide Surfaces After Friction Test
to 4200°R in H₂