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ABSTRACT

AN INVESTIGATION INTO THE WEAR AND FRICTION CHARACTERISTICS OF SHIP PROPELLER SHAFT AND SEAL MATERIAL COMBINATIONS

by

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Submitted to the Department of Naval Architecture and Marine Engineering on May 21, 1960, in partial fulfillment of the requirements for the degree of Naval Engineer and the degree of Master of Science in Naval Architecture and Marine Engineering.

The unsatisfactory wear properties of various seal and propeller shaft material combinations on many of our submarines, particularly those of the deep-submergence class and those where the trend is towards the larger shaft diameters, prompted this investigation. While the fault may well lay in design, this paper approaches the problem as one in boundary lubrication; attempting to find the best combination of seal material and mating service in this particular service condition from a wear viewpoint. An additional aim was to attempt some correlation between wear, friction, and the physical properties involved. Results from this latter goal could well find application in the selection of steam turbine seals as well as those employed in the aircraft industry.

The approach used by the authors was first to evaluate potential seal materials from different families in combination with various corrosion-resistant shaft materials. This work was done on the Kinetic Oiliness Testing Machine (KOTM) and the results are presented in Part I of this investigation. The testing involved obtaining friction and wear data on carbons and laminated phenolics, as well as teflon, in combination with chrome, bronze G, and stellite #6. Synthetic sea water was the primary lubricant, although the effect of wetting agents was also checked. Results here conclusively demonstrated the superiority of commercial grade carbon seals, for the wear of the laminated phenolics was excessive, and transition temperature effects were experienced with the straight teflon samples at roughly 250°F ambient temperature.

While successful as a screening tool, the KOTM proved inadequate for wear measurements of carbons; and for this reason the pin on disc geometric configuration was utilized in Part II. This section involved a more extensive analysis of the friction and wear properties of carbons in combination with five potential shaft materials. Twenty-one commercial grade carbons in all were tested, the number representing a

wide cross section in graphite content, hardness, impregnation and other physical properties. The effect of wetting agents, up to 50% by volume, are also presented. Results of this phase conclusively demonstrated the superiority of chrome as a mating surface for carbon, its high heat of reaction and resultant resistance to carbide formation giving reasonably low friction and wear values. Several carbons were grouped close to the top when all were compared from a wear and friction viewpoint, but one, Carbon 1, was shown to be the superior material of those tested in this boundary lubrication problem. The effect of wetting agents contradicted our original assumption, in that concentrations up to 50% by volume gave higher frictional values than that experienced with synthetic sea water.

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Part II - Wear and Friction Characteristics of Carbons on Five Shaft Materials

I. INTRODUCTION

The selection of effective seal materials is, through necessity, one primarily of trial and error; for the problem is enveiled in a shroud of mystery - that of boundary lubrication. While hydrodynamic or "fluid film" lubrication takes place under the maintenance of an oil film of sufficient thickness so that hydrodynamic properties, such as viscosity and relative motion of the two surfaces, are the sole factors; boundary lubrication (sometimes called "non-viscous" or "thin film" lubrication) occurs under high pressures and low sliding velocities, and is characterized by coefficients of friction which are practically independent of viscosity.

The mechanism of boundary lubrication is a complex one and may involve either a chemical or physical surface reaction, with the resultant formation of films of mono- or multimolecular thickness. Darkening this already complex picture is the fact that the wear characteristics of a seal material concern us most, and here there is no empirical law to guide us and define any "wear coefficient." Coulombs first law enables us to define a coefficient of friction, just as Newton's law gives us a coefficient of viscosity and Hooke's law a Young's modulus - but such is not the case with wear, consequently making it impossible to apply dimensional analysis to the problem. [1]

The hardness of the mating surfaces all too often is chosen as the primary guide in selecting seal materials.

Results definitely contradict this. [2, 3] Factors such as porosity, oxide formation, and the like must be considered.

Several investigators have advanced theories regarding this wear problem. Rabinowicz [4] has derived an equation relating wear (to the two-thirds power) to friction, using wear and friction data from his own experiments as well as that of other investigators. While the equation exhibits reasonable validity at low wear rates, considerable divergence from the postulated wear exists under more severe wear conditions. Further work in this field has demonstrated that the wear rate increases exponentially with load at room temperature, with the development of an "apparent critical stress." [5, 6] It is quite obvious, then, that wear occurs not through one process, but through many, and, as the wear rate increases, we find the behavior governed by laws about which we know very little.

Investigators [2, 6, 7, 8, 9, 10, 11, 12] seem to agree that metal transfer and wear occurs primarily at points of actual contact, not as a uniform smear, but as a relatively small number of discrete fragments. A secondary cause of metal transfer is the adhesion or diffusion process which takes place during the breakage. One factor entering this wear process is temperature, one that considerably exceeds the ambient temperature. With carbon sliding on steel, for example, these flash temperatures can reach 2000°F at the contacting asperities. [2, 3] Radioactive tracer techniques have demonstrated that both this adhesion and smearing of one metal surface to the other occurs <u>through</u> the lubricant

film. [2, 8]

While wear is immensely more sensitive to the choice of lubricant than is the coefficient of friction, there is a limiting steady-state condition in which the rate of transferred material increases no longer. [9] Moreover, there is a definite value of load associated with each material combination in which detectable wear ceases. Numerous studies indicate this to be attributed to the formation of lubricant pockets giving rise to local hydrodynamic lift forces whose sum equals the largest load for which no wear could be detected. [10]

Another phenomenon encountered with boundary lubrication is that of "transition temperature." It is arbitrarily defined as the onset of high friction and wear, being caused by the "softening" or "melting" of the absorbed monomolecular films of the lubricants. [14] Below this temperature effective lubrication is provided because the absorbed film is "solid" and capable of keeping the two surfaces apart. [15] Amazingly enough, this abrupt increase in wear rate is on the order of 10^2 to 10^5, increasing the median particle size a thousandfold from micron to millimeter size. The wear surface changes from a scored condition to a severely torn or galled surface. [14] This transition temperature, while associated with the bulk melting point of the lubricant, must also be considered a function of the metal. [16] Investigators have also detected a second as well as this primary transition temperature. [7] Tabor [17] accredits the first to the melting point of the liquid film, while the second deterioration in lubrication

properties corresponds to the desorption of the film. At this point the surface damage and friction is comparable with that observed with unlubricated surfaces. These effects are reversible, corresponding to changes in the state of the lubricant film. The sliding velocity, on this "phenomenon" alone, assumes a more important theoretical role than has heretofore been supposed, for increasing the velocity raises the transition temperature.[13, 15, 18]

There is obviously another factor that must be considered in boundary lubrication problems, and that is the lubricant itself. As far back as 1903, Kingsbury concluded that there was a friction-reducing property in a lubricant under conditions of boundary friction that was separate and distinct from viscosity - this property he termed "oiliness." This is a term signifying differences in friction greater than can be accounted for on the basis of viscosity when comparing different lubricants under identical test conditions.

Since the lubricant utilized in this investigation is far from the ideal long-chain polar boundary lubricants, it was felt that a portion of the work presented should be devoted to checking the effect of oiliness or wetting agents. One qualifying point for these agents, however, was that they be soluble in water, since the net lubricant flow of these submarine seals is out to the surrounding sea. These wetting agents exhibit a strong affinity for metal surfaces and their molecules adjacent to the metal are capable of holding their position and resisting displacing forces to a

marked degree. But while a great majority of compounds will reduce the coefficient of friction for some operating condition, the effectiveness of such compounds on wear may differ in degree, and sometimes in direction, from their effect on friction. [22]

There can be no doubt of the complex nature of boundary lubrication, but the problems should not be deemed insurmountable. The answers lie in the continuing efforts of investigators to accumulate data, and, through its dissemination, so enhance the fundamental knowledge in this field that the mystery may be unfolded at least in part.

This investigation will comprise two distinct steps:

(a) A preliminary survey in which seal materials from different families will be tested from a friction and wear viewpoint, using synthetic sea water as the lubricant.

(b) Based on the results of the first, a more exhaustive study will be made on the more promising family, using a larger number of potential shaft materials, investigating wear and friction, as well as the effect of water-soluble wetting agents.

PART I

Preliminary Material Survey Utilizing the Kinetic Oiliness Testing Machine (KOTM)

II. DESCRIPTION OF TEST APPARATUS AND MATERIALS

The Kinetic Oiliness Testing Machine (Figure I) was used in this preliminary material survey to measure the frictional force between the specially designed sliding surfaces. This machine was designed to minimize fluid film effects (viscosity), in order to investigate lubricants under conditions where boundary lubrication prevails. While designed specifically for frictional measurement of lubricants, it was felt that the machine's ability to duplicate a good portion of the actual service conditions that the material combinations would be exposed to, made this an ideal "screening" method.

As shown in Figure II, the sliding contact surfaces consist of a track, having two flat-topped, sharp-edged concentric rails, and three wear buttons positioned 120° apart on the rails. Fairly uniform surface smoothness of these contact surfaces is maintained during testing by the lapping action produced by the combined rotating and sliding motion of the test buttons. The rails were fabricated from potential shaft materials: bronze G, stellite #6, and chrome; while the wear buttons were machined from possible seal materials, viz, carbons, laminated phenolics, and teflon.

Early models of this machine are described in references [21] and [22]. The current model offers simple and more accurate control of speed, temperature, and load. Speed control of the track is accomplished through a

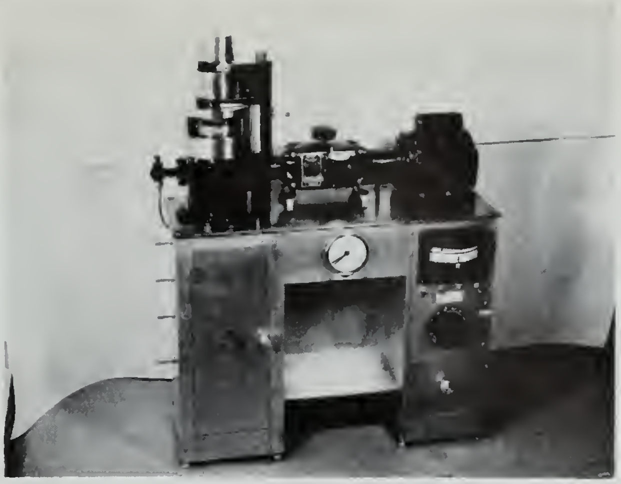


FIGURE 1 - KINETIC OILINESS TESTING MACHINE (KOTM)

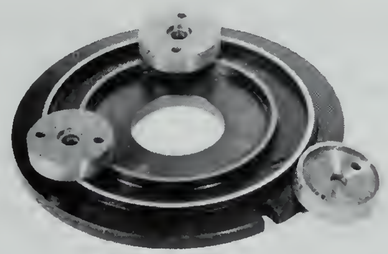


FIGURE 11 - TRACK AND WEAR BUTTONS

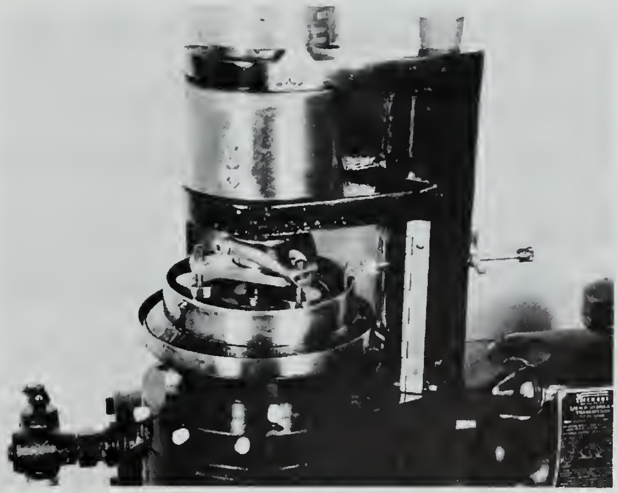


FIGURE 111 - MACHINE ASSEMBLED, SHOWING TORQUE DRUM AND BUTTONS

hydraulic transmission over a range of speeds from 0.5 to 100 RPM. Temperature is automatically controlled by an electronic temperature controller over a range from 50° F to 475° F, employing an electric heater, variable transformer, and relays. Variation in dead loading is possible from 1 to 91 pounds, corresponding to unit loadings in this investigation of approximately 20 to 1900 psi. The application of the dead load is accomplished by selective manipulation of the lever system to rest the weights on the wire suspended carriage, which in turn transmits the load to the tripod plate and buttons. Figure III gives a close-up of this torque drum assembly. By interpreting the drum scale torque reading, a frictional load may be read directly and a coefficient of friction determined.

The eight laminated phenolic bearing materials were selected from data provided in Report 090023 from the U.S. Naval Engineering Experiment Station and were materials appearing on the Qualified Products List. Those materials that did not meet the swelling requirement of less than the design limit of 30 mils per inch were not tested, as they were deemed unsatisfactory as bearing materials; for swelling in service could possibly seize the propeller shaft. The test buttons (Figure II) were fabricated with the laminated layers perpendicular to the wear surface, as the material is usually installed in this manner for minimum wear. Material characteristics and properties are presented in Table I.

TABLE I

Laminated Phenolic Materials

Material Letter I.D.	Hardness (Rockwell m scale)	Laminations per inch	Specific Gravity	Thread Count	Known Additives	Weave
D	95.8	24	1.40	24 x 14	-	Coarse
F	102.0	mat	1.35	mat	moS_2	-
G	101.8	49	1.35	40 x 35	moS_2	medium
K	101.0	61	1.33	38 x 36	-	medium
L	103.9	160	1.33	80 x 80	-	fine
N	89.1	64	1.33	36 x 40	-	medium
W	99.3	mat	1.32	mat	-	-
R	92.5	70	1.37	*46D x 26	-	medium

* D indicates double thread

The four carbons were common grades produced by manufacturers of carbon seals, bearings, and brushes; and were representative of base grades as well as those utilizing phenolic resin fillers. Essential data for this group appears in Table II. For purposes of identification, the carbons have been assigned Nos. 1-4.

TABLE II

Properties of Carbon Samples

Carbon	Hardness (Rockwell m)	Water Absorption %	Graphite Content	Apparent Density gm/cc
1	120.3	0.12	low	1.815
2	103.7	0.14	medium	2.380
3	123.3	1.32	medium	1.739
4	114.75	Analysis Incomplete		

The wear surfaces of the three test rails were bronze G, stellite #6, and chrome. The chrome surface was applied to an old 55100 steel rail with several attempts necessary before the required flat, sharp-edged surfaces were obtained. This was due to the fact that the use of "thiefs" or blanks during the application of the chrome repeatedly resulted in flaking when they were removed. Plating thickness was approximately 0.015 inches. The stellite #6 rail was achieved by welding a 4140 steel rail. Here again, considerable difficulty was encountered, this time with warpage and minute pinholes. Several attempts finally resulted in a fairly homogeneous overlay with minimum pockets that could result in a "quasi-hydrodynamic" effect. Table III gives average hardness values of the three materials.

TABLE III

Hardness Values of Rail Materials

Bronze G	86 Rockwell B	(4.4 Rockwell C)
Stellite #6	40 Rockwell C	
Chrome	1015 Brinell	(>40 Rockwell C)

Hersey and Staples [19] conclude in their work that pure boundary lubrication can be realized and isolated only with surfaces of extraordinary flatness and smoothness, owing to the persistence of hydrodynamic action on a microscopic scale. This requirement is met, as far as practicable, by the use in the Neely KOTM of contact surfaces on the three track materials and carbon buttons

verified to within five microinches by optical flat observations. The phenolic buttons, however, as well as the teflon samples, presented another problem; for here it was not possible to ascertain the surface finish, although the profilometer and millionth-comparator, as well as optical flats were used. This prompted the running-in period of the test procedure to establish a common starting point for friction measurements.

Synthetic sea water (Fed. Spec. VV-L-79e, Method No. 4011.2) was used as the lubricant throughout these tests.

III. PROCEDURE

Each run totaled approximately two hours and was of the format given in Table IV. While basically concerned with wear, friction measurements were taken for comparable purposes. Wear was measured by the weight-loss method, using a Fisher Gram-atic Balance, with a sensitivity of 1/10 mg.

TABLE IV

Test Procedure

Temp. (°F.)	Speed (RPM)	Load (LBS)	Duration (min)
125	100	30	15
125	50	30	15
125	100	30	15
200	100	30	15
225	20	30	15
150	20	30	15
150	10	30	10
125	10	10	10
125	5	10	5
125	5	30	5
125	5	60	1
125	2.5	60	1
125	2.5	90	1

The laminated phenolics presented the biggest problem. Lapped in on a "Lap Master," as well as hand-lapped (dry), there was no way of ascertaining the surface finish of the wear surface. With the laminations perpendicular to the

plane of rotation, attempts at measuring the surface finish with optical flats, millionth comparator, and profilometer all indicated surface finishes far in excess of the desired 5 microinches. Prior to each run, then, the buttons were lapped-in, using iso propyl alcohol for a period of 5 min. (Earlier attempts using mineral oil had been unsuccessful due to the lubricant imbedding itself in the material.) The buttons were then washed in the alcohol and oven-dried at a temperature of 250° F. for one hour. Weight readings were then taken hot and the buttons placed in a dry atmosphere (silica gel), where weight measurements were again taken just prior to the run some 24 hours later. Each test consisted of running the buttons in for 15 minutes at 100 RPM with a 30 pound load (550 surface feet per minute, 630 psi) to achieve a common starting point for friction readings. Noting Table IV, after 30 minutes of testing, the same speed-load combination is again in effect; and, if the friction reading at this point is the same as that at the end of the running-in period, it could be reasonably assumed that the specimens in each run had the same degree of initial preparation as well as a common starting point.

The carbons offered no problem. Lapped in with iso propyl alcohol, the surface finish could be readily checked by optical flats. The specimens then followed the procedure used for the phenolics. The rail materials could likewise be checked by optical flats, receiving their "finish lap" with diesel oil.

It was felt that the hot and cold readings were

necessary for the weight-loss measurements since these figures represented the primary aim of the test. By taking the two readings prior and after the run, the difference in hot readings and the difference in cold readings should offer the same values, thus serving as a check. Moreover, the test room was not one of constant temperature, and the moisture absorption of the laminated phenolics resulted in erratic readings if left in the room air too long.

The testing procedure itself was extremely simple. The machine was assembled and operated with synthetic sea water as a lubricant to study the effect of operating variables such as material combination, load, speed, temperature and duration. With the track held in its circular pan, the salt water charge was filled to slightly above the track rail surfaces and the thermocouple positioned. With no load, the machine was started and run at the desired speed, and the variable transformer and temperature controller was set to give and maintain the desired temperature, after which the selected load was applied. Frictional values were measured at a fixed dead load and at various speeds for the desired duration, using a fixed temperature.

At the conclusion of each experiment on a material combination, the friction components were disassembled and the buttons, track, and adjacent parts thoroughly cleaned with alcohol. No residual or carry-over effect on the next run was evidenced from this cleaning procedure.

IV. RESULTS

Tables V and VI give the essential results regarding the laminated phenolic seal materials; and, for basis of comparison, Table V also gives the order of merit for bearing wear as indicated by reference [26]. Noteworthy is the fact that reference [26] was based on data obtained using an Amsler test set-up, with abrasive wear the primary aim. It can be seen from the data presented that phenolic D offers the least wear of the phenolics, with the phenolic D-stellite #6 combination the best from a wear viewpoint of the three tested material pairs.

Table VII lists the wear of the carbons that occurred during the abbreviated testing, as well as an average friction coefficient. This friction coefficient was arrived at by weighting the coefficient of friction for each speed by the number of revolutions it was in effect, and had as its purpose the possibly "shedding" of new light on the inconclusive carbon wear data.

Figures IV-VII give a breakdown of the frictional values at the various RPM for the different material combinations (the familiar $^{ZN}/p$ curve in a sense).

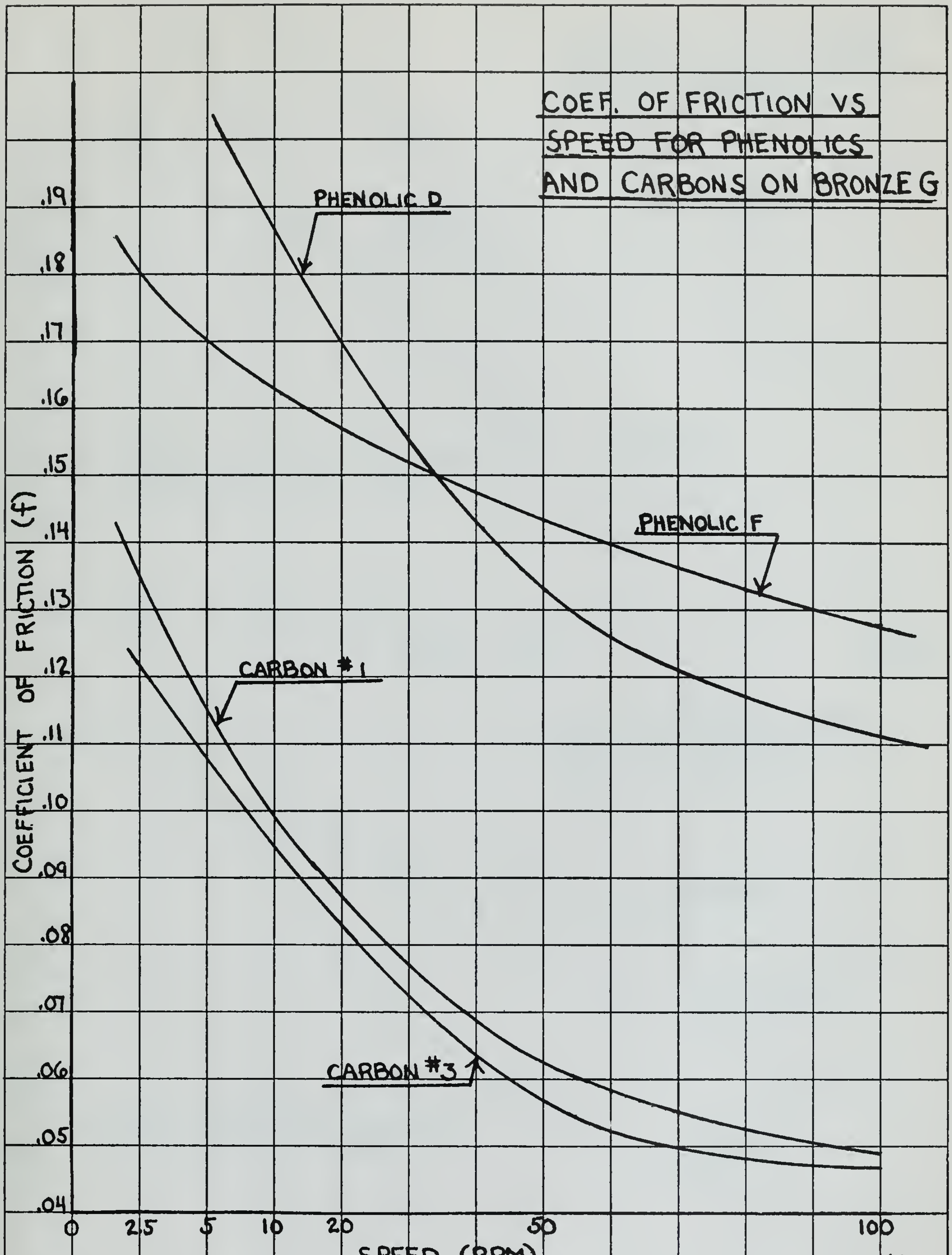

COEF. OF FRICTION VS
SPEED FOR PHENOLICS
AND CARBONS ON BRONZE G
PHENOLIC D
PHENOLIC F
CARBON #1
CARBON #3
COEFFICIENT OF FRICTION (f)
.19
.18
.17
.16
.15
.14
.13
.12
.11
.10
.09
.08
.07
.06
.05
.04
0
2.5
5
10
20
50
100
SPEED (RPM)

FIG. 4

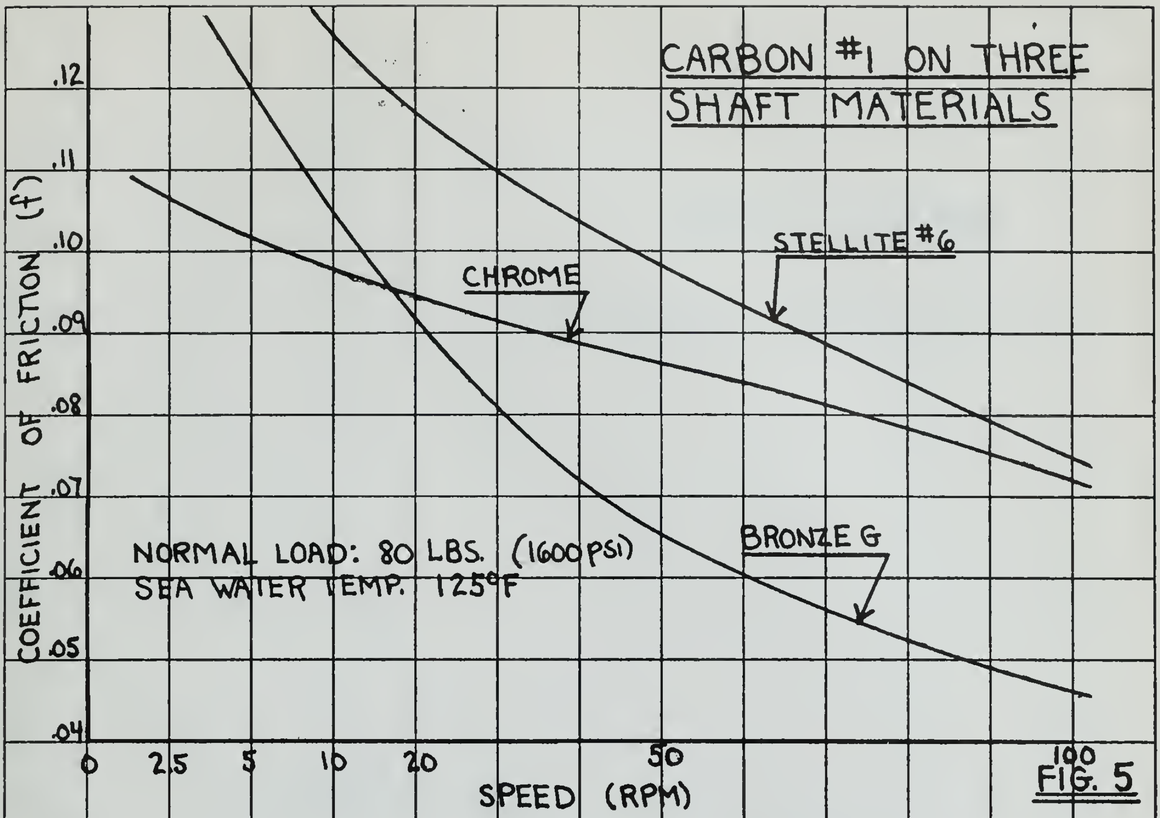

CARBON #1 ON THREE SHAFT MATERIALS

FIG. 5

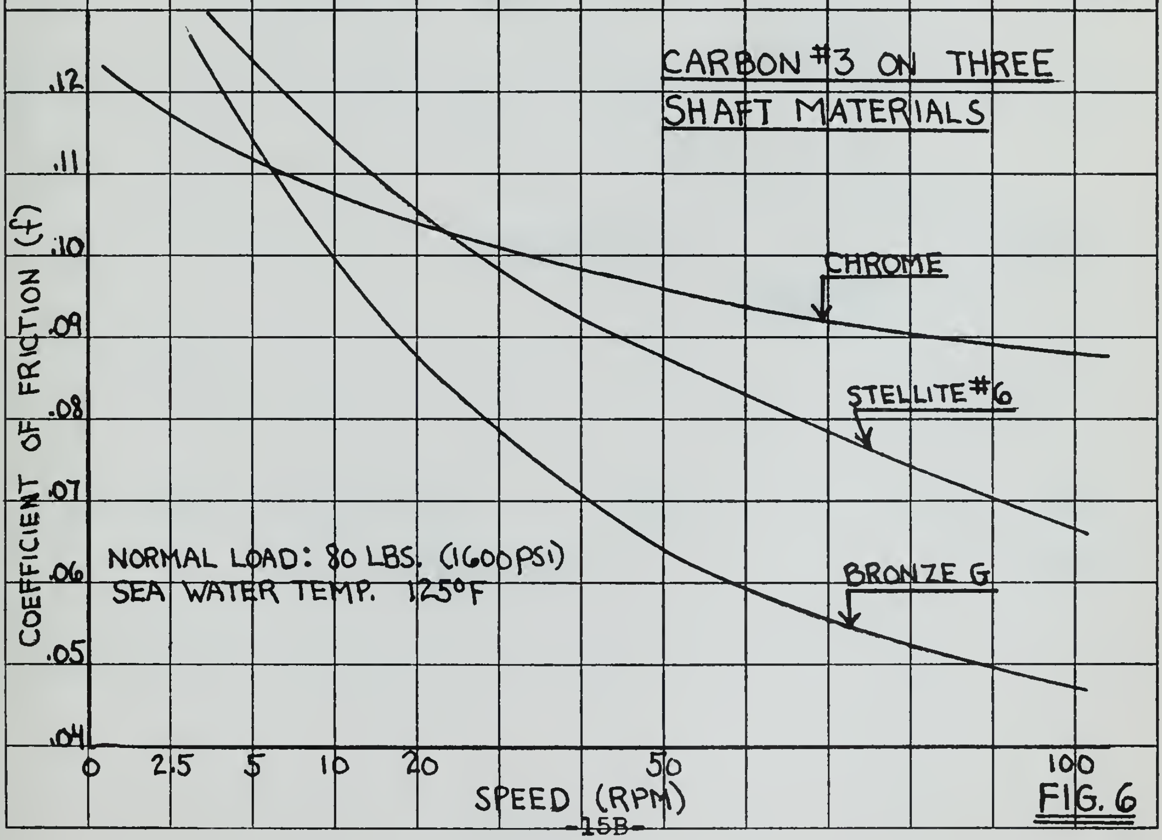
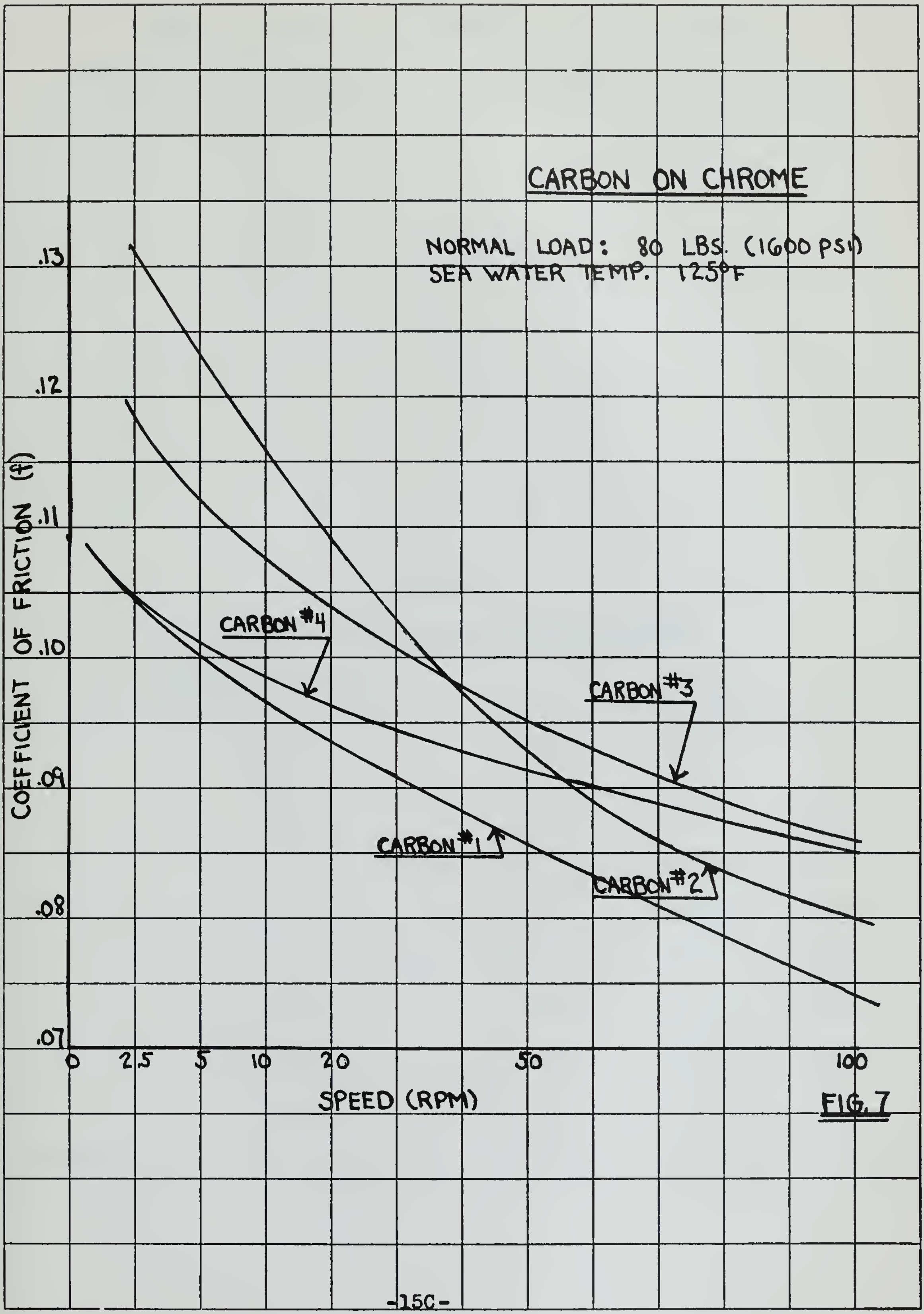

CARBON #3 ON THREE SHAFT MATERIALS

FIG. 6



CARBON ON CHROME

NORMAL LOAD: 80 LBS. (1600 PSI)
SEA WATER TEMP. 125°F

FIG. 7

TABLE V

Order of Merit for Phenolics Based on Wear

Reference 26	Phenolics on Bronze-G	Phenolics on Stellite #6	Phenolics on Chrome
D	D	D	D
L	L	L	K
K	F	K	G
W	G	G	L
R	K	W	F
F	R	F	R
G	W	R	W
N	N	N	N

TABLE VI

Wear of Phenolics in Milligrams

Phenolic	Hardness-Rockwell M Scale (as Recened)	on Bronze G	on Stellite #6	on Chrome
L	103.9	39.2	12.9	21.9
F	102.0	43.1	34.0	25.5
G	101.8	73.8	18.7	18.1
K	101.0	97.7	13.9	16.8
W	99.3	122.7	21.1	45.3
D	95.8	14.3	10.0	13.7
R	92.5	119.6	35.0	43.0
N	89.1	124.2	52.6	45.4
Average wear, all phenolics:		79.33 MG	24.78 MG	28.71 MG

TABLE VII

1. Average Friction Value of Carbons

Carbon	Hardness-Rockwell M	On Bronze G	On Stellite #6	On Chrome
1	120.3	.0753	.1003	.0885
2	103.7	.0742		.0959
3	123.3	.0729	.0942	.0969
4	114.75			.0930

2. Wear of Carbons in Milligrams

Carbon	On Bronze G	On Stellite #6	On Chrome
1	1.27	.43	.44
2	1.21	Specimen Broke	Specimen Broke
3	1.23	.40	.36
4			.58

V. DISCUSSION OF RESULTS

It was found that considerable discrepancy existed in the weight readings unless the one hour drying time was strictly adhered to. Moreover, since the humidity of the room - and temperature - were not constant, the weight readings when dried in silica gel were taken as a second check.

The phenolics experienced considerable "partial" stick-slip [27, 28, 29] whenever the load dropped below 30 pounds (approximately 600 psi), while loads in excess of this resulted in fairly smooth operation. Figure IV shows the general frictional trends in the comparison of phenolics and carbons on bronze G. Under these same test conditions, the wear on the carbons was practically negligible when compared to that of the phenolics; phenolic F showing a wear of 43.1 mg., carbon #1 a weight loss of 1.27 mg.

In an attempt to investigate the effect of "oiliness" [2, 21] on the wear and frictional characteristics of the phenolics and carbons, a run was made on one specimen from each of these two groups, using the synthetic sea water containing 5% by volume of a non-ionic detergent MIL-D-16791C-Type 1 . Little frictional change was noted with the carbon sample, but the phenolic showed as much as a 25% reduction in friction values, with the wear (Phenolic W on stellite #6) dropping from 21.1 to 17.9 mg. No check was made on repeatability. While far from conclusive, it

did indicate a possible trend, and future tests on the more promising carbon group may prove of value.

Two runs were made using unimpregnated teflon buttons in an attempt to evaluate its behavior when exposed to adverse temperature effects. In both tests, one using a bronze G rail and the other a stellite #6 rail, the buttons seized to the rail as the temperature approached 200° F. Originally, it had been planned to use a glass-filled teflon sample, as has been used in practice, but the failure to obtain this material in time prevented it. Load at the time of seizure was 40 pounds (approximately 800 psi) with a speed of 10 rpm.

There was no evidence of any transition temperature effects (the incidence of high friction and high wear) on any of the runs. The maximum temperature reached on any run was 225° F, a temperature exceeding the lubricant's boiling point. It was thought that this might find a parallel in actual service in an instance of restricted sea water flow around the shaft, with the resultant rise in temperature.

Having established the fact that the phenolics were a distant second when compared to the carbons from a wear and friction viewpoint, the test procedure for the carbons was revised to one of high load (80 pounds or approximately 1600 psi) and low speeds (2.5-50 rpm) in hopes of establishing trends within this group. The time alloted to this investigation limited the test duration for each combination to one hour. Wear results were still inconclusive,

as seen from Table VII, although chrome did show the more consistent results as a mating surface.

No check was made on the wear of the rails, although the use of radioactive tracer technique had been considered for use with stellite #6. Time again was the ruling factor. A rough order of comparison could be achieved by checking the surface finish of the rails by optical flats at the completion of the run. With all four carbon materials, the rails could be ranked according to hardness for an order of merit. In other words, the chrome surface appeared untouched, the light bands being practically straight. In sharp contrast to this, the bronze G rail required considerable lapping-in in most instances to restore the surface finish to the desired five micron inches.

From the average friction coefficients tabulated in Table VII, it can be seen that carbons-on-chrome tend to be "bunched" in one group, while those of carbon on bronze G are grouped at the opposite end of the scale at lower values. Contrary to the "high friction - high wear" behavior of the phenolics, in this case the wear of the carbon on bronze group was double that of the chrome group, even though the average friction coefficient was lower. Rabinowicz' [4] wear to the two-thirds power versus friction coefficient relationship would result in considerable "scatter" in any plot. With Rabinowicz' work, however, his plots were for one material combination, using the lubricant as the variable. The discrepancy undoubtedly lies here.

Figures V-VII give the friction values at various speeds for different material combinations. The fact that the curves appear to be leveling out at the higher speeds would justify further investigation in this range, especially since the KOTM's maximum speed of some 550 surface feet per minute is substantially below the maximum anticipated service figure.

As would be expected, the wear values of Table VII cannot be considered all-conclusive. While the dividing line between the bronze G and stellite #6-chrome group is distinctly drawn, the breakdown within this group can only be "legally" justified by more extensive testing. It is noted that the wear and average friction values of the stellite and chrome carbon groups are relatively similar, but it should be mentioned that the behavior of these two material combinations was markedly different within the test itself. The actual operation of the two carbons on stellite was evidenced by considerable partial stick-slip. At times, tiny bubbles could be seen emanating from the stellite rail as if an electrolytic action were in process. Quite probably, since flash temperatures in excess of 2000° F are in effect at the interface of the materials, a reaction is taking place; since, at this temperature, carbon is chemically reactive. It would seem, then, since the stellite mating surface is instrumental in the oxide and carbide formation that persists, the chrome would offer the more chemically resistant mating surface. This would explain the smooth motion of carbon on chrome at all speeds,

a total of four tests exhibiting little, if any, partial stick-slip.

From Figures V and VI, it can be seen that the friction coefficient-RPM curve for carbon on chrome is much flatter than that of the other two material pairs, exhibiting a more or less constant friction coefficient over a wide range of speeds. Analyzing the data and curves, as well as the test behavior of the material combinations, it was felt that the chrome-carbon combination offered the greatest possibilities. Although limited by time again, an evaluation within the carbon group on chrome was sought. Extending the ordinate, as in Figure VII, a good perspective is drawn on the friction characteristics of the carbons. Carbon #1 stands out in this regard, and its average friction coefficient of .0885 adds testimony to the fact that carbons of lower graphite content yield lower friction values.[24] Additional runs, however, must be made to furnish more conclusive wear data.

VI. CONCLUSIONS

This preliminary investigation into the selection of shaft-seal material combinations has led to the following conclusions:

(1) Phenolics place a distant second when compared to carbons from a wear and friction viewpoint when the mating surface is stellite #6, chrome, or bronze G. Toughness and ease of fabrication appear the former's primary assets.

(2) Should it be necessary to use a laminated phenolic as a shaft seal material, phenolic D exhibits the best wear characteristics whether the shaft surface be chrome, bronze G, or stellite #6. Stellite #6 gives the least phenolic wear of the three.

(3) Although the friction values of carbon on bronze G were the smallest, the wear of any carbon on bronze G was more than double what it would be if chrome or stellite #6 were used as a mating surface.

(4) From observation, the metals requiring the maximum heats of reaction appear to offer the best mating surfaces for carbons. Chrome filled this spot in these tests, giving the maximum resistance to oxidation and carbide formation, resulting in smooth test operation.

(5) Test results indicate that the lower the

graphite content of non-impregnated carbons, the lower the friction coefficient.

(6) The Neely KOTM can effectively serve as a screening tool for various material combinations in boundary lubrication problems.

VII. RECOMMENDATIONS

It is recommended that additional carbon wear data, namely low speeds and high loads, be collected in order to completely evaluate the stellite #6 and chrome groups. Supplement carbons already selected with more carbons of base stock and phenol resin impregnated category.

It is recommended that the frictional characteristics of carbons be determined further by exposing the carbons to speeds encountered in service, i.e., in excess of 1000 S.F.M., using the rail surfaces presently tested, as well as Monel K and Silicon Monel.

It is recommended that a series of tests be conducted using various wetting agents to ascertain its effects on the frictional and wear properties of the selected shaft-seal material combinations.

Part II - Wear and Friction Characteristics of Carbons on Five Shaft Materials

VIII. DESCRIPTION OF APPARATUS AND MATERIALS

The same apparatus was used for all tests in the second phase.

The apparatus was arranged to rotate the test shaft material at constant speed under the stationary carbon specimen. The carbon was mounted in a test carriage which was instrumented for measuring the friction force of the contact area. This friction force was recorded by means of a Sanborn Recorder. Lubricants were applied by means of a constant head drip feed with manual control. Wear was measured optically by a calibrated microscope. Detailed description of individual components and test materials follow.

A. Test Stand.

The test stand was a thirty-six inch metal lathe erected on end so that the lathe drive shaft was in a vertical position (Figs.I&II). The drive shaft was rotated by electric motor and a belt drive at a constant speed of 335 RPM. The lathe chuck was replaced by a flat circular plate on which was mounted the shaft material specimen to be tested. A fixed table was attached to the lathe such that the test carriage could be mounted on it adjacent to the rotating head. The drip feed applicator for the salt water and wetting agents was arranged such that the drops fell on the shaft material just ahead of the carbon. This can be readily seen in the photographs.

B. Test Carriage.

The test carriage had the function of positioning the

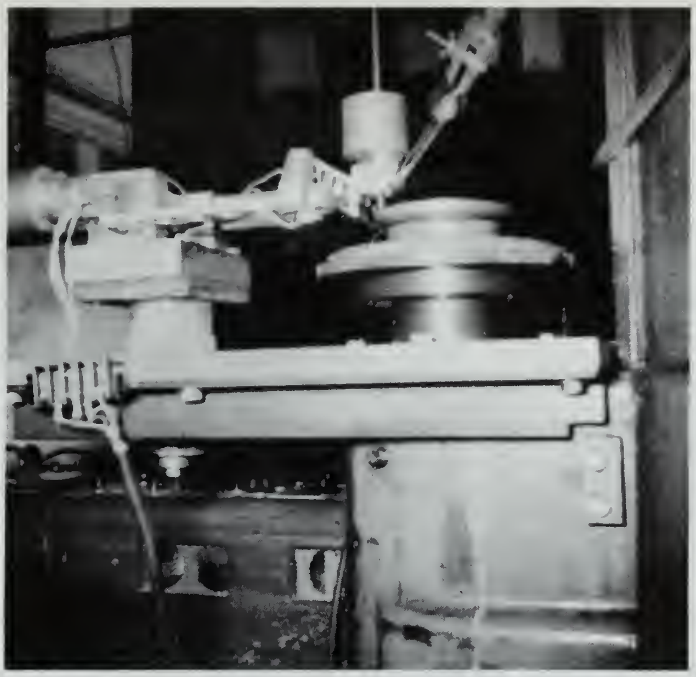


FIGURE I

TEST APPARATUS WITH SPECIMENS IN PLACE.

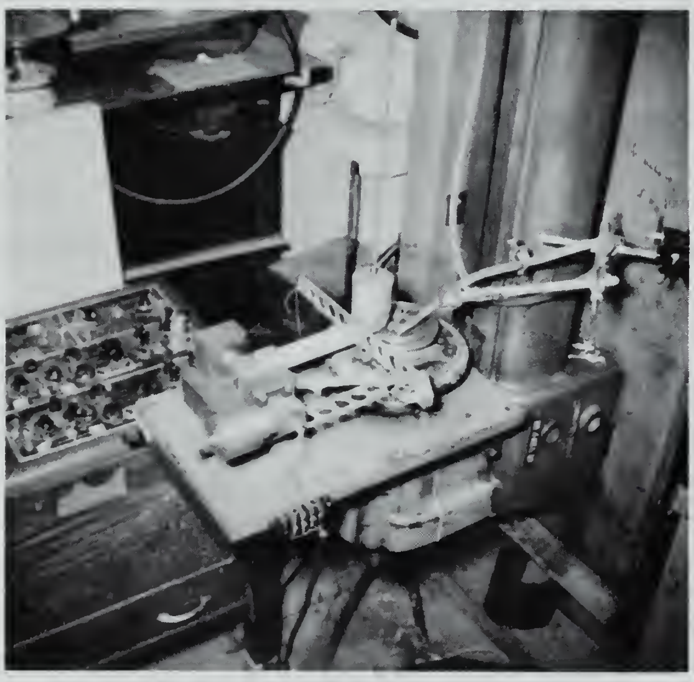


FIGURE II

TEST CARRIAGE AND SANBORN RECORDER

carbon on the shaft material and measuring the friction force of the contact area. The principal features of the test carriage are as follows:

(1) The support shaft is located rigidly and precisely by a pair of face-to-face mounted flush ground bearings at one end, and a spring loaded, precision angular contact bearing at the other end.

(2) The connecting hinge between the support shaft and the tube is flexible in bending in the horizontal plane, but stiff in bending in the vertical plane. This type hinge minimizes errors in the measurement of friction force and permits accurate rematch of mating surfaces if the carbon is lifted from the wearing surface.

(3) The wearing surface is nearly in the horizontal plane formed by the support shaft and the centerline of the tube. This feature minimizes the twisting moment on the hinge due to the friction force.

(4) The strain ring is also nearly in the wearing surface plane for the same reason as (3) above.

(5) All wiring is extremely flexible and is so located that it does not interfere with the loading or cause errors in the measurement of friction force.

(6) The test carriage is counterweighted so that the weight of the carriage does not load the wearing surface.

(7) The center of gravity of the weights used in applying the load to the wearing surface is vertically above the wearing surface.

(8) The strain ring is located such that the point at which the strain ring is loaded forms a line with the contact point of the carbon which is tangent to the contact circle on the shaft material. This feature eliminates the necessity of correcting the friction force measured by the cosine of the angle to the tangent.

C. Sanborn Recorder.

The Sanborn Recorder is a device for recording the friction force on the test carriage. Briefly, this is accomplished by incorporating the two strain gages on the strain ring into an electrical bridge circuit. The bridge circuit is balanced with zero load on the strain ring. Hence when the strain ring is loaded, the bridge is unbalanced, and the resulting currents are amplified and applied to an indicating arm. The deflections of the arm are recorded by passing sensitized paper under the arm at constant speed. The recorder is calibrated by applying known loads on the strain ring and observing the deflections of the indicating arm.

D. Microscope.

The microscope used was the standard laboratory type. The eyepiece had a magnification of x10 and the lens a magnification of 5.6. A scale in the eyepiece of 100 graduations of 0.0247 mm each was used at this magnification.

E. Shaft Materials.

All shaft materials were machined to a ring of four inches outer diameter and polished on a "Lapmaster" with 900 and 400 grit aluminum oxide and finally on a diamond

impregnated ceramic polishing block to a finish of less than 2 rms as measured on a profilometer and 3 micro-inches as measured by optical flats. The materials investigated were:

Aluminum Bronze
Bronze G
Chromium Plate on 55100 Steel Base Plate
Monel K
Silicon Monel
Stellite 6 on 55100 Steel Base Plate

The chemical compositions and hardness readings are tabulated in Appendix F.

F. Carbons.

The carbon-base materials used, with their respective properties, are listed in Appendix E. All are commercial grade carbons recommended by the manufacturer as seal materials. For the most part these carbons are classed in the general category of carbon-graphites, but their compositions and manufacturing processes vary. Generally the carbons are made in the following manner: the basic mix containing such compounds as petroleum coke, lampblack, natural graphite, synthetic graphite, etc., is blended with a binder such as coal-tar pitch. It is then baked at high temperature (up to 2000F). The carbons may then be impregnated and cured at about 350F or higher. If the carbon is impregnated, it is done primarily to reduce porosity and improve other physical properties of the product. The impregnants used may be metals, resins, pitch, inorganic salts, plastics, etc.

One notable exception to the above is Carbon 12 which

contains no graphite. This particular material is a "plastic alloy" containing dry lubricants and impregnated after final machining. It is essentially a highly effective bearing material and was utilized in this phase of the investigation as a comparison tool.

Physical properties of carbons vary with little or no variation in chemical content. This problem in quality control may be caused in part by baking temperature variations which will occur during the baking time of up to six months. In addition, normal methods of chemical analysis will not distinguish between the allotropic forms of carbon in the sample, making it difficult to evaluate the various manufacturing techniques.

Each specimen was machined to a length of one inch, diameter 0.036 inch, with a 10 degree cone on one end. The carbon's diameter and length were directed by the requirements of the test carriage while the cone angle was selected in order to obtain a relatively large change in diameter for a small amount of wear.

G. Salt Water and Wetting Agents.

Salt water was prepared in the laboratory in accordance with ASTM standard for substitute ocean water (Reference 30). This was done in order to insure that the identical solution would be used for all tests (which covered a period of 10 weeks). Reagent type chemicals and distilled water were used in the preparation of each batch. The method of preparation is included in Appendix D for convenience.

Wetting agents used were selected on the basis of water

solubility and similar physical properties. UCON HYDROLUBE is a water and ethylene glycol base material used as a hydraulic fluid. CARBOWAX 300 is a polyethylene glycol used as a water soluble lubricant in the rubber and textile industry. Solutions of wetting agents were prepared with salt water of strengths 10, 25, and 50% by volume wetting agent.

IX. PROCEDURE

The test procedures utilized in this phase of the investigation evolved from a series of trial runs; once developed, they were rigidly adhered to in order to preserve the accuracy of the individual runs, as well as to enhance the possibility of attaining repeatability.

A. Wear Tests.

(1) The shaft material surface was cleaned with iso-propyl alcohol in order to reduce surface contamination to a minimum. No residual or carry-over effect was experienced in any of the runs.

(2) The tip of the carbon specimen was wiped with dry tissue. Specimens were handled and stored carefully at all times.

(3) The mating surfaces of the shaft material ring, support plate, and ring retainer were lapped lightly together to be certain that the ring would not be distorted on clamping in place, as a result of nicks or other damage to the mating surfaces.

(4) The carbon specimen was then run-in dry, i.e., with no lubricant, with a 1,000 gram load until the friction force reading on the Sanborn recorder was constant. The diameter of the tip was then measured, using a calibrated microscope. Readings were taken 90 degrees apart, and were read to the nearest half-unit on the scale, i.e., 0.01235 mm. The average of these two readings was used as the initial diameter.

(5) The carbon specimen was then run for 45 minutes with a 2,000 gram load, using synthetic sea water as the lubricant. The salt water was applied from a dropper arrangement just ahead of the specimen; see Figure I. The rate of 15 drops per minute was determined by trial, and was just sufficient to keep the carbon tip immersed and to keep the track on the shaft material ring wet at all times.

In the case of carbons with very high wear rates, the running time was reduced to 30 or even 15 minutes.

(6) Upon completion, the tip was wiped dry and measured as before. The average of the two readings was used as the final diameter. Knowing the initial and final diameters and the angle of the cone, the volume of the frustrum was then readily computed. (See Appendix C for a sample calculation.) This established a wear rate in cubic millimeters per minute.

(7) The shaft material ring was inspected, cleaned, and refinished. The polishing block readily restored the original 2-5 microinch surface finish. Attempts to determine the wear of the shaft material ring proved unsuccessful, as none of the materials were marked to the extent that a profilometer could detect any track.

B. Friction Tests

(1) The procedure for these tests was identical to that used for the wear tests up to and including obtaining the initial diameter of the carbon tip.

(2) The Sanborn recorder was balanced, checked and calibrated before and after each run, and adjustments made,

if necessary, to preclude the possibility of instrumentation errors affecting the accuracy of the results.

(3) The carbon specimen was then run for a short time with loads of 500, 1,000, 1,500 and 2,000 grams, with the ring rotating at 335 rpm. This represents a linear speed of 5.4 fps. Running time for each of the loads was that required to obtain a constant friction force, usually a matter of less than a minute.

The salt water lubricant (both with and without various wetting agents added) was applied as in the wear tests. The readings from the Sanborn recorder were used to calculate the coefficient of friction in each case.

(4) Upon completion of a run, the carbon tip diameter was measured as before. The average of the initial and final diameters was used in the calculation of normal load, but they were in all cases nearly identical.

(5) The shaft material ring was again inspected, cleaned, and refinished to original flatness.

X. RESULTS

Figure III shows representative curves of friction force versus normal load drawn from data in Table V of Appendix B. Chrome plate is the mating surface, with synthetic sea water as the lubricant. Rather than show all carbons, only sufficient carbons were selected to show the "spread" in plots. Figures IV, V and VI show these same carbons when a mixture of synthetic sea water and a wetting agent (UCON-HYDROLUBE 275 CP), 10%, 25%, and 50%, respectively, is used as a lubricant.

Figures VII through X are similar to Figure III in that they show friction force versus normal load curves of representative carbons, but this time the mating surfaces are silicon monel, monel K, stellite #6, and aluminum bronze respectively. Data for these plots has been taken from Tables I-IV in Appendix B.

Figure XI is a check on repeatability for two carbons with a chrome mating surface, this time showing a plot of friction coefficient versus normal load. Again, while numerous carbons were tested, only representative curves are shown. Figure XII is the now familiar friction force versus normal load plot of carbon 8 on chrome plate, showing the effects of different lubricants, as well as dry operation.

Figure XIII has been drawn to show the effect of different mating surfaces when the same carbon is used.

Figure XIV is a plot of the relative porosity of the carbons versus the wear. Both scales use the order of merit.

The final plot (Figure XV) is an attempt to correlate carbon hardness and carbon wear rate in mm^3/minute. Wear rate is plotted on the ordinate and the Shore Scleroscope hardness on the abscissa.

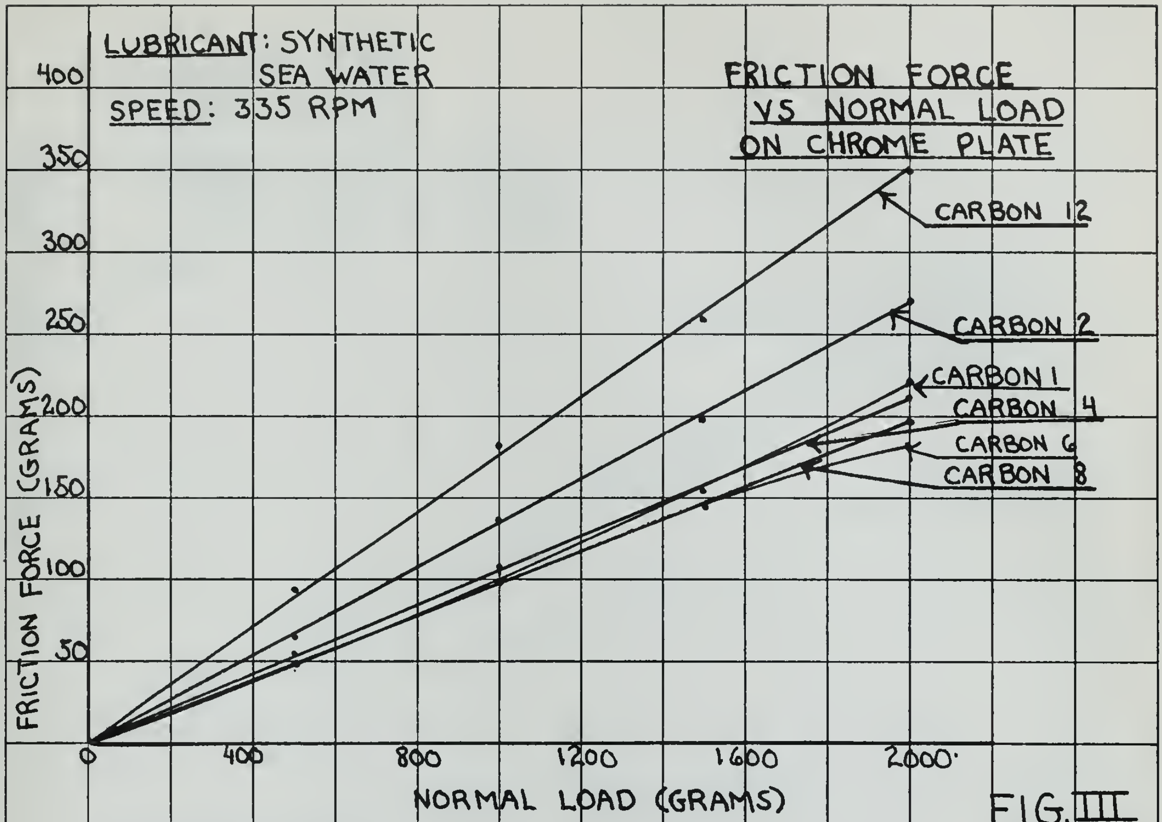


FIG. III

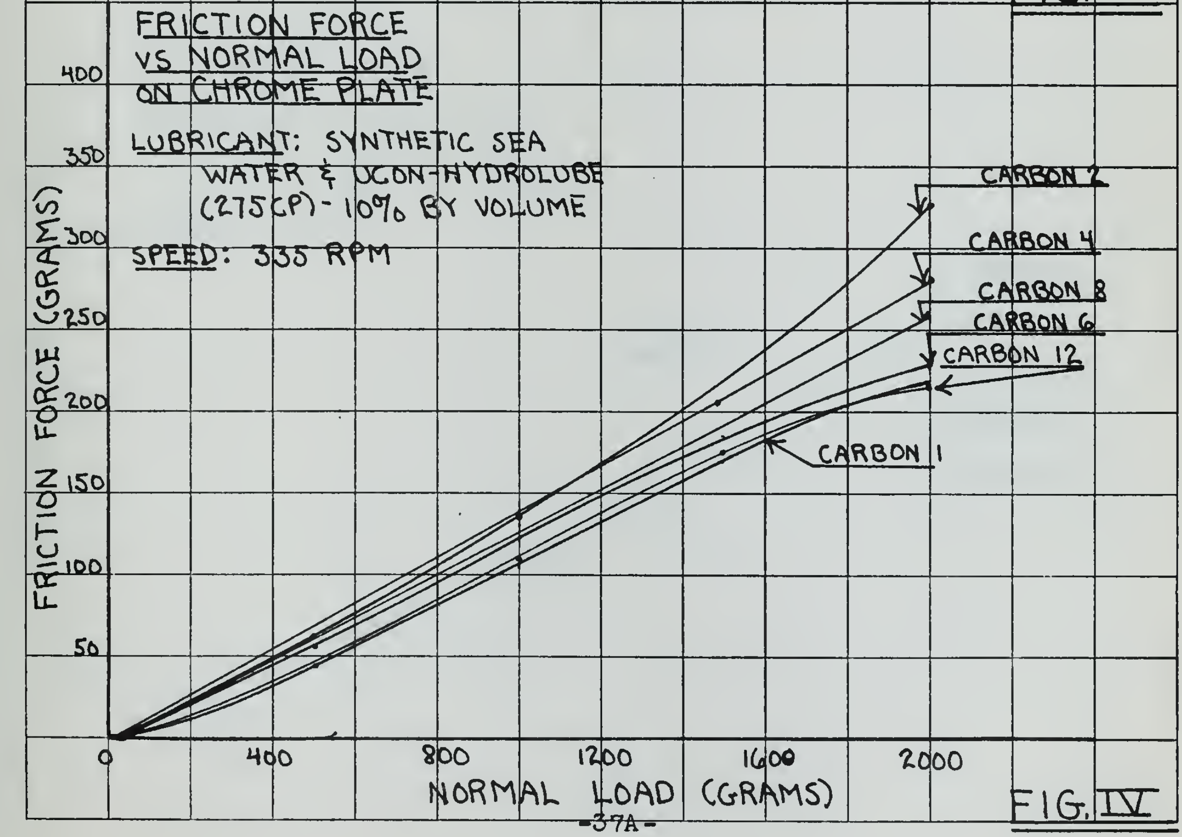


FIG. IV

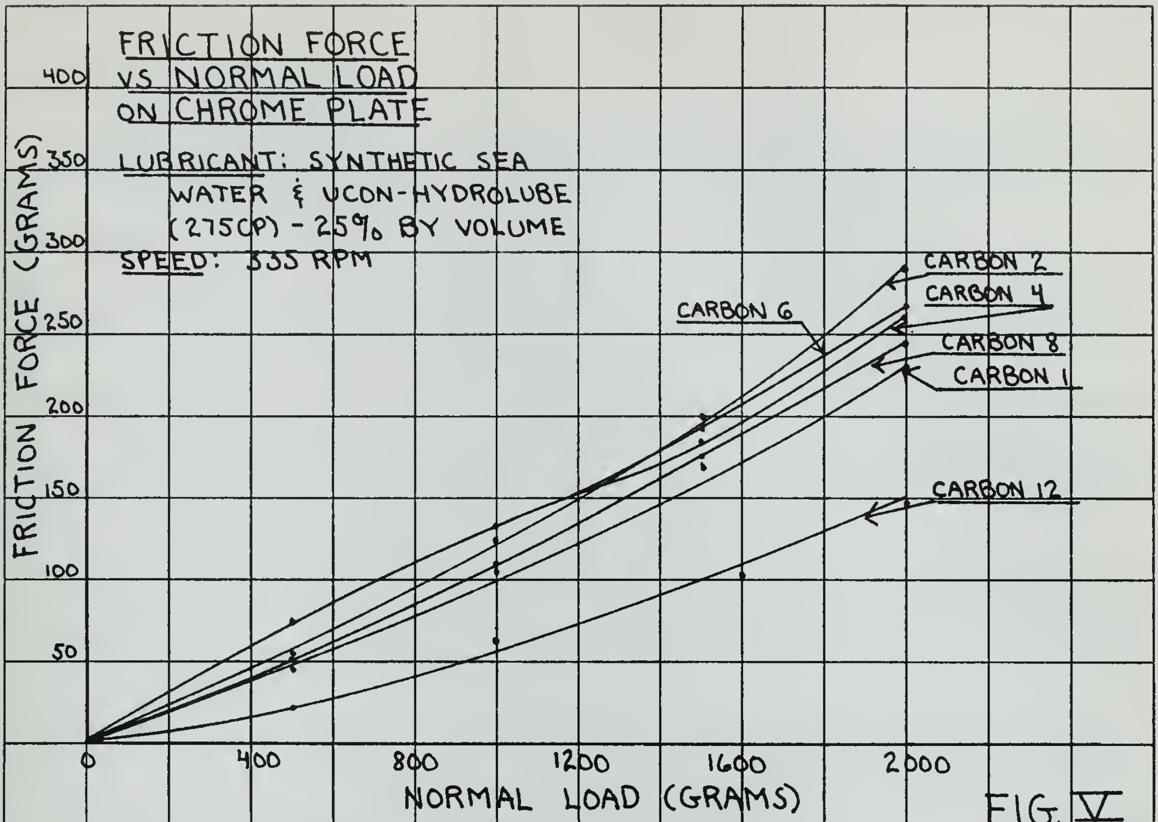

FRICTION FORCE
VS NORMAL LOAD
ON CHROME PLATE
LUBRICANT: SYNTHETIC SEA
WATER & UCON-HYDROLUBE
(275CP) - 25% BY VOLUME
SPEED: 335 RPM
FRICTION FORCE (GRAMS)
400
350
300
250
200
150
100
50
0
400
800
1200
1600
2000
NORMAL LOAD (GRAMS)
CARBON 2
CARBON 4
CARBON 6
CARBON 8
CARBON 1
CARBON 12

FIG. V

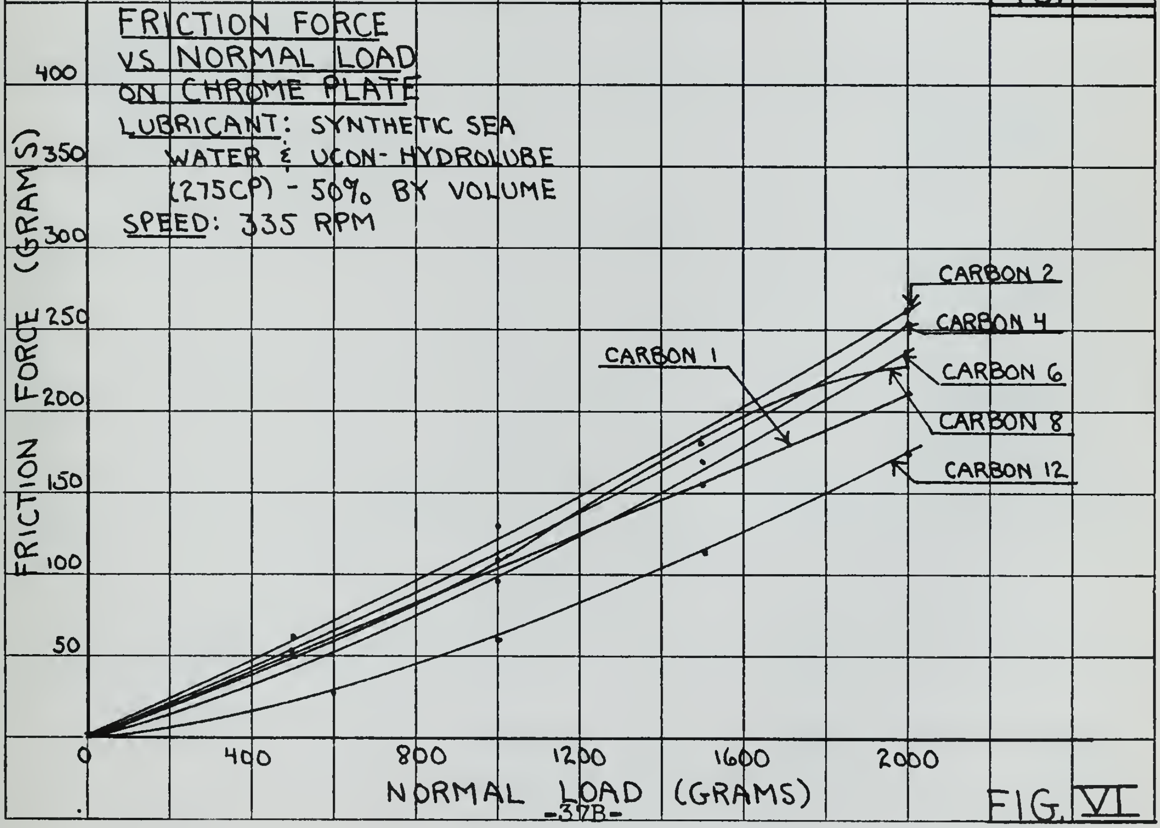

FRICTION FORCE
VS NORMAL LOAD
ON CHROME PLATE
LUBRICANT: SYNTHETIC SEA
WATER & UCON-HYDROLUBE
(275CP) - 50% BY VOLUME
SPEED: 335 RPM
FRICTION FORCE (GRAMS)
400
350
300
250
200
150
100
50
0
400
800
1200
1600
2000
NORMAL LOAD (GRAMS)
CARBON 2
CARBON 4
CARBON 1
CARBON 6
CARBON 8
CARBON 12

FIG. VI

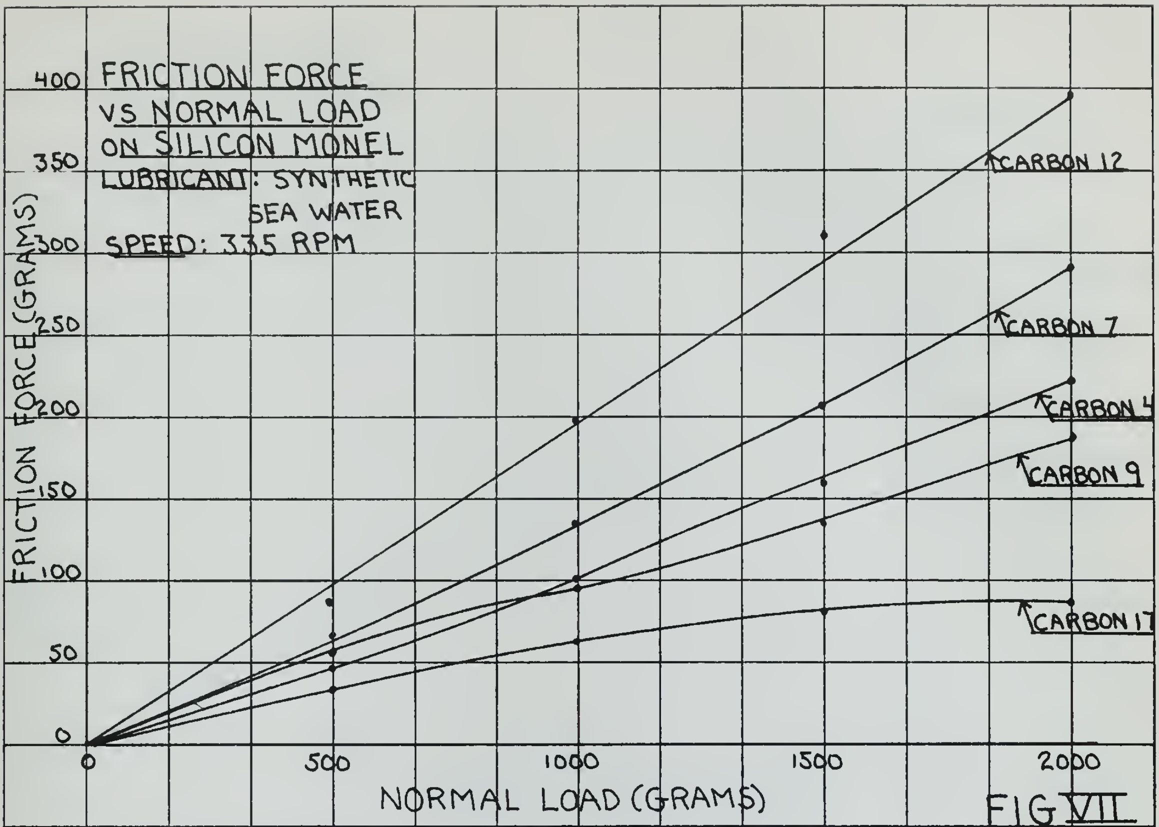


FIG VII

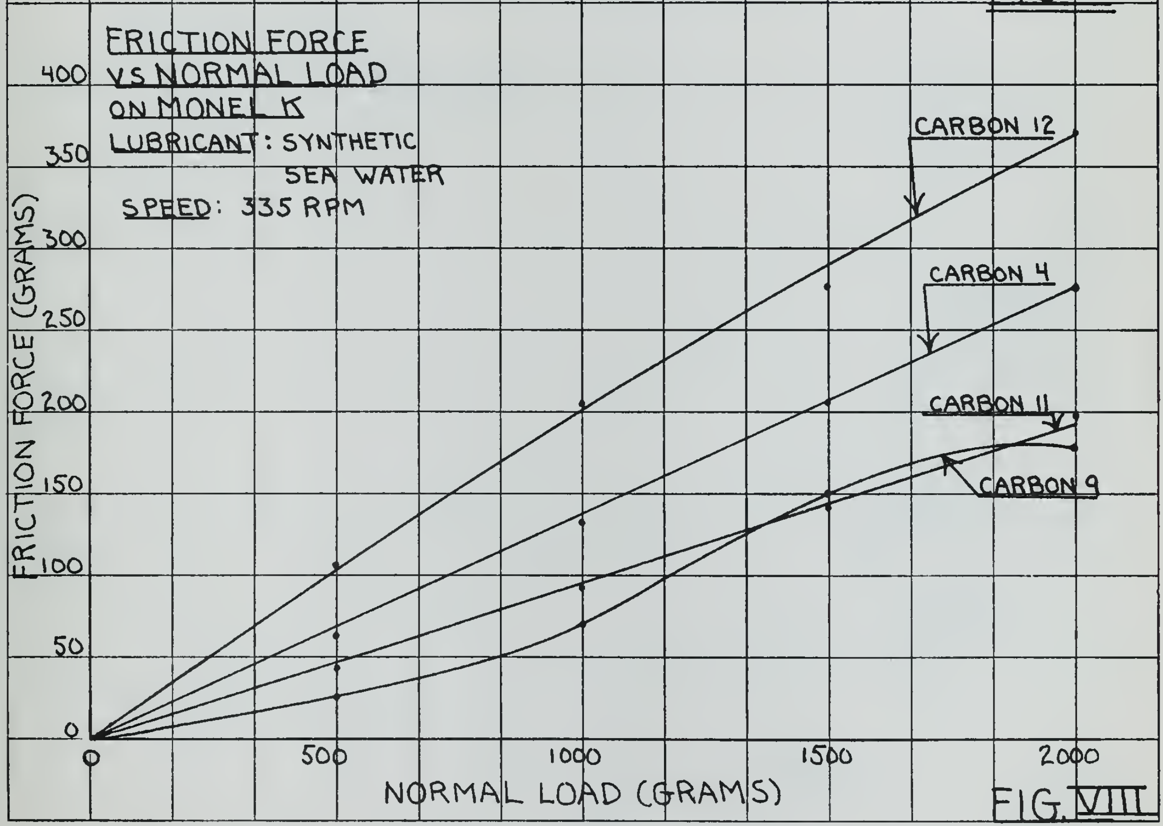


FIG. VIII

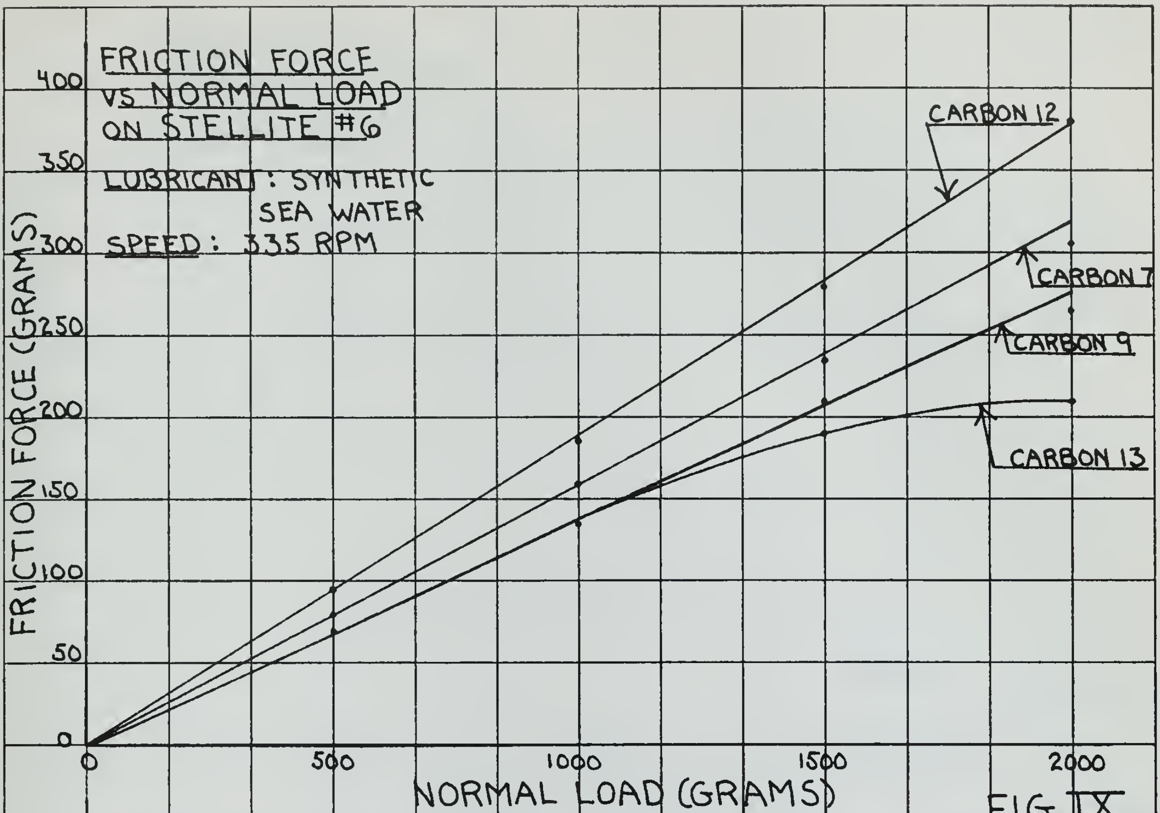

FRICTION FORCE
VS NORMAL LOAD
ON STELLITE #6
LUBRICANT: SYNTHETIC
SEA WATER
SPEED: 335 RPM
FRICTION FORCE (GRAMS)
400
350
300
250
200
150
100
50
0
0
500
1000
1500
2000
NORMAL LOAD (GRAMS)
CARBON 12
CARBON 7
CARBON 9
CARBON 13

FIG. IX

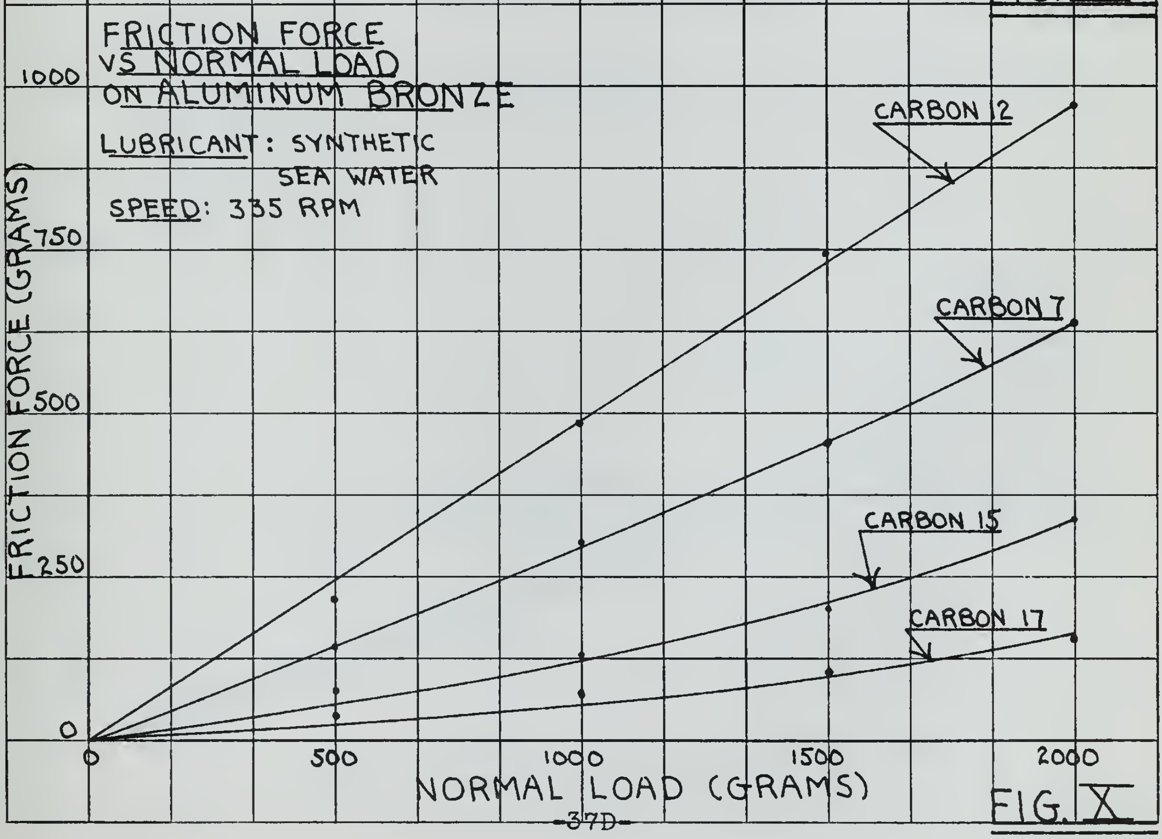

FRICTION FORCE
VS NORMAL LOAD
ON ALUMINUM BRONZE
LUBRICANT: SYNTHETIC
SEA WATER
SPEED: 335 RPM
FRICTION FORCE (GRAMS)
1000
750
500
250
0
0
500
1000
1500
2000
NORMAL LOAD (GRAMS)
CARBON 12
CARBON 7
CARBON 15
CARBON 17

FIG. X

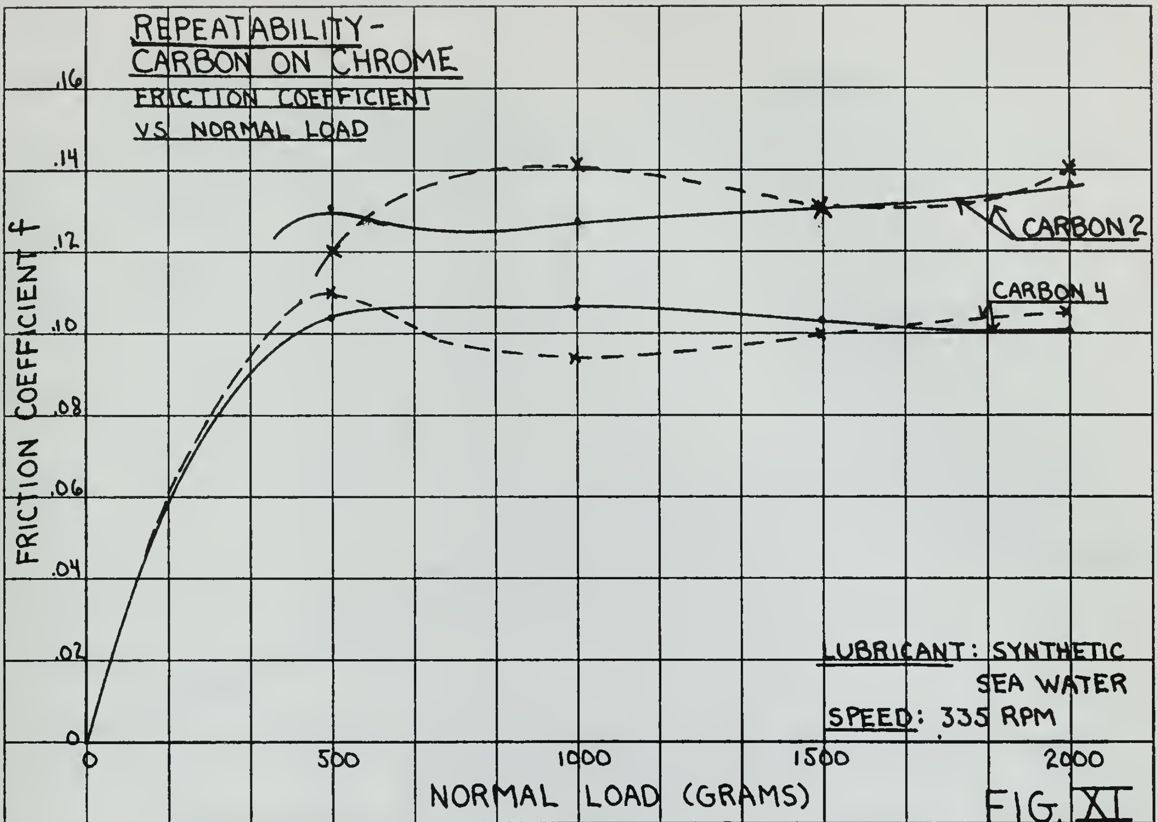


FIG. XI

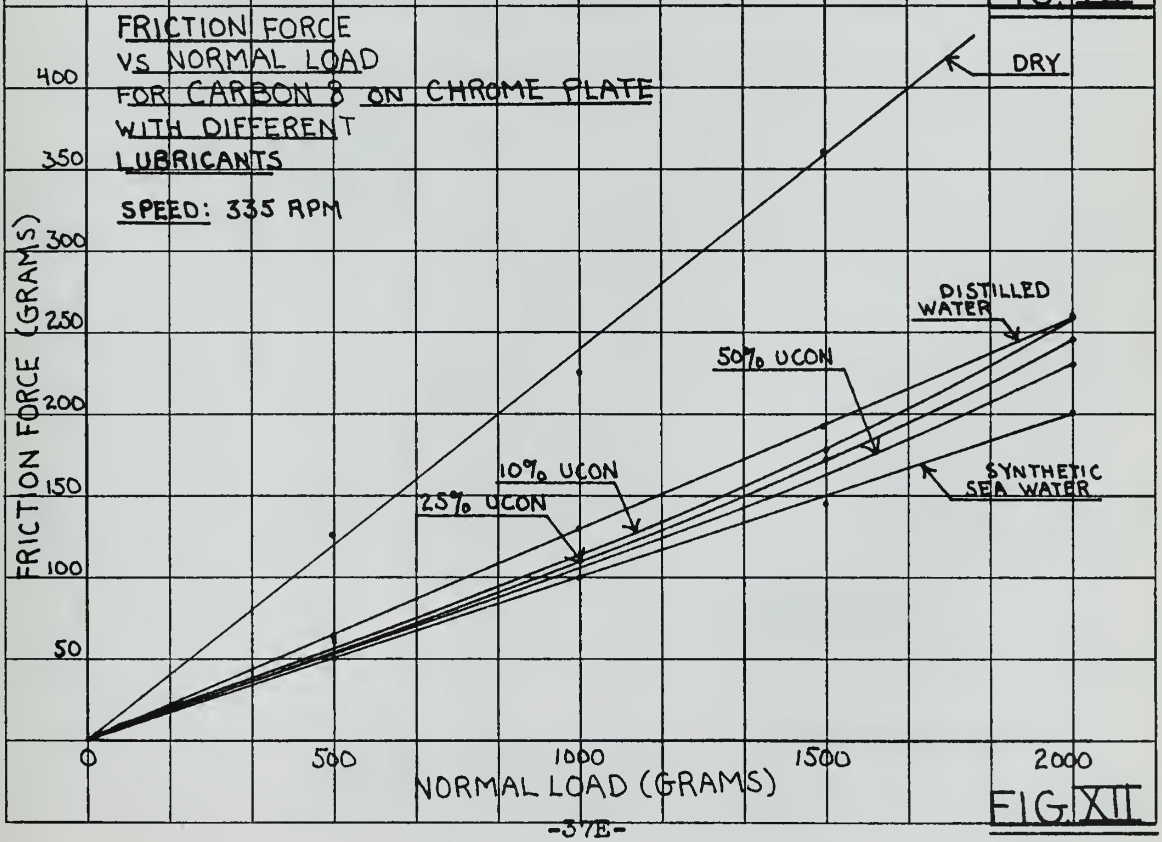


FIG. XII

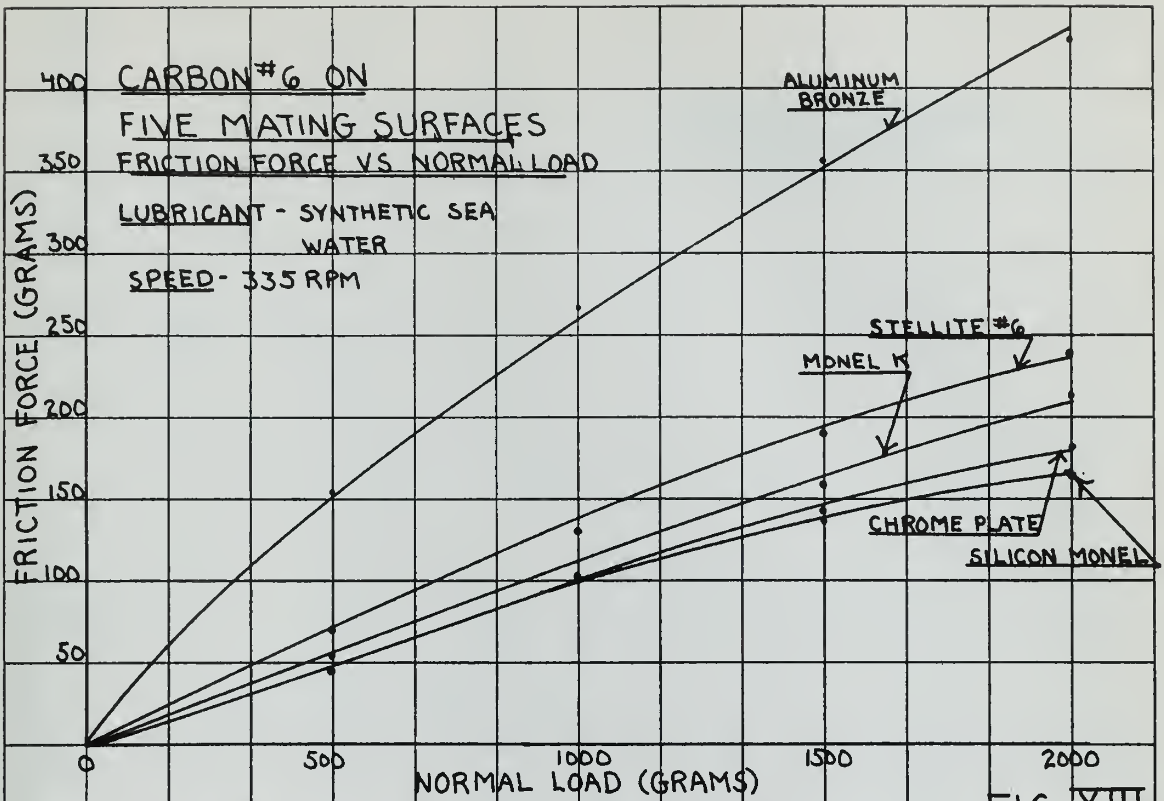


FIG. XIII

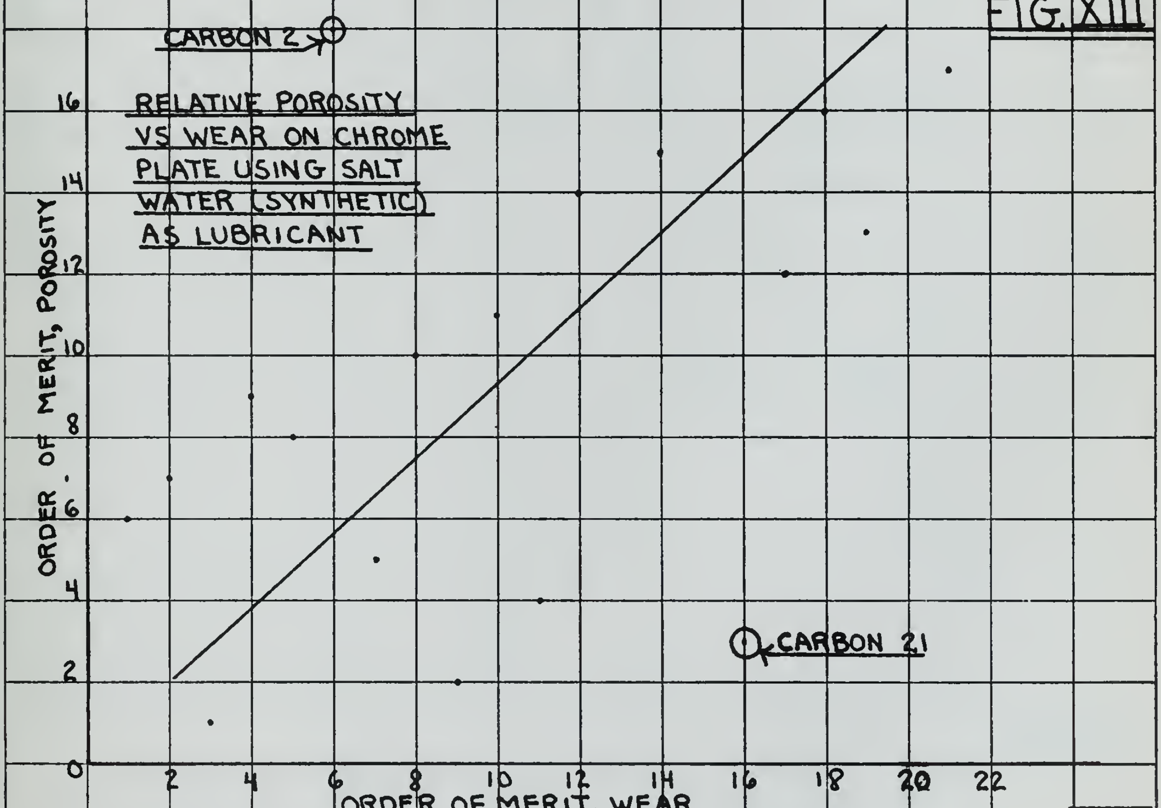
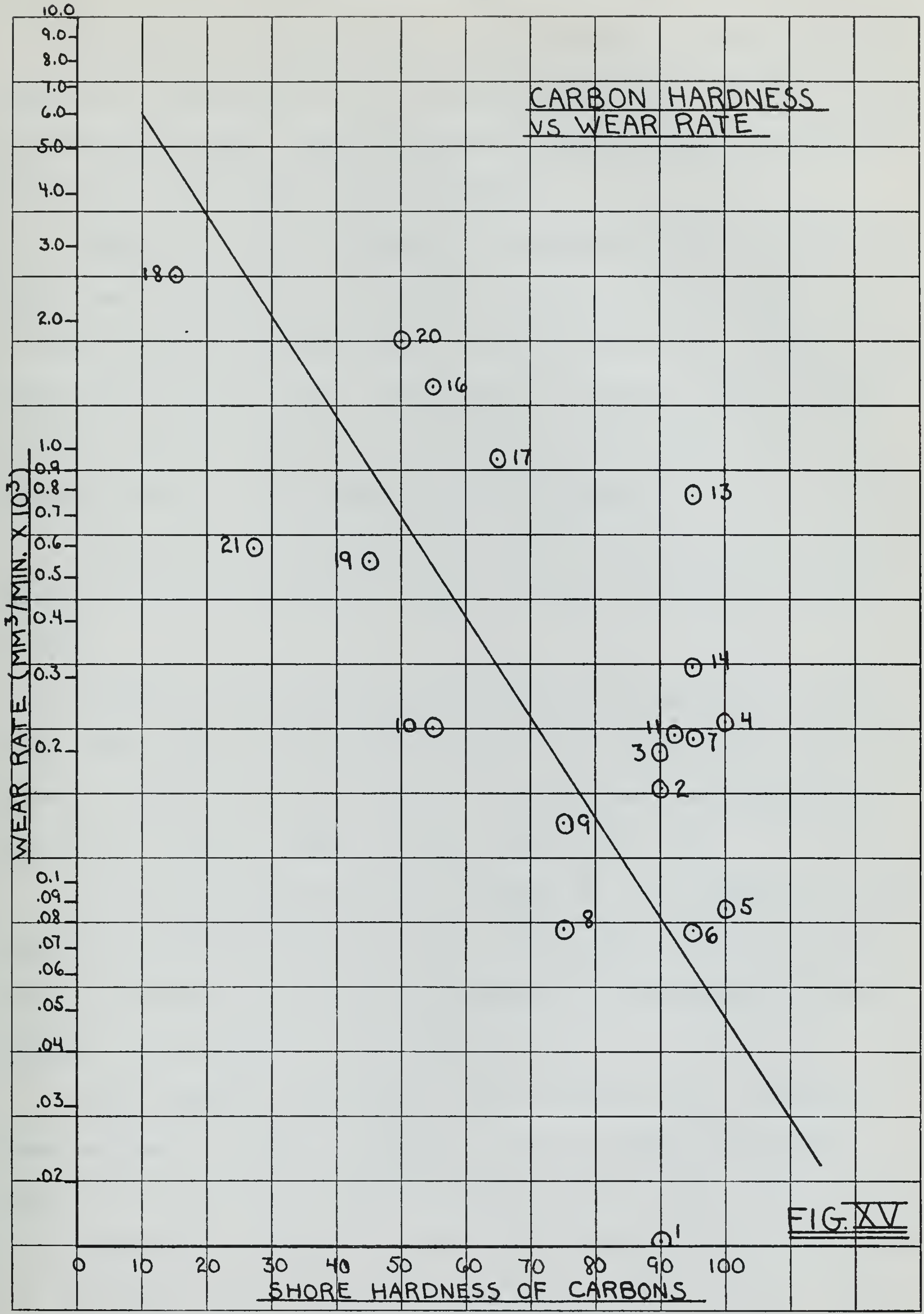


FIG. XIV



CARBON HARDNESS vs WEAR RATE

FIG. XV

XI. DISCUSSION OF RESULTS

The flat, 10-degree-cone shape for the carbon specimen tips was decided upon after investigating the various methods of measuring wear. This geometry affords several advantages over the other techniques considered.

First, the large change in tip diameter for a relatively small wear volume was desirable, because of the large number of wear tests to be made and the resulting short running time available for each test. This fact, together with the high loads applied, allowed us to measure significant wear volumes after a test duration of 45 minutes.

Secondly, the tip diameter could be easily and quickly measured very accurately, using a simple calibrated microscope.

Thirdly, the conical tip could be machined (or ground, when necessary) accurately at low cost. This item, with the first, made the conical tip the choice over the parabolic tip which has been used in some wear tests. [3]

A flat tip was ruled out because of the tendency of the carbon to chip around the edge. Also, the change in length of the specimen could not be measured as accurately as the change in diameter of the conical tip.

This change in geometric shape method (i.e., finding wear volume) is more accurate as well as more meaningful than the weight-loss method generally used. [3] The weight-loss method is subject to error due to absorption of moisture or lubricant, and to metallic transfer to the carbon. This

weight-loss method was used in the initial investigation, but was not satisfactory.

In the actual use of carbon seals, it is the wear of the seal which is important (i.e., the change in clearance), and not the weight of seal material which is lost.

Attempts to determine the wear rates for carbons on the aluminum-bronze ring were unsuccessful. In every case severe galling occurred, and the carbon samples fractured after very short running times. It was impossible to get a constant friction-force reading during the running-in period of any carbon. The very large change in tip diameter during these short runs indicated extremely high wear rates. Several carbons were tried with loads reduced by half, with the same results.

It is believed that the high wear rate and high friction force were caused by the formation of carbides on the carbon tip. This would produce, in effect, an efficient grinding action. The galling is probably a function of the softness and low melting point of the aluminum.

The average wear rate for the carbons tested on monel-K was much higher than for these same carbons on the other four surfaces. Since monel-K contains about 2% aluminum, the higher wear rates can be explained by the formation of aluminum carbides at the interface.

The hardness of the carbon samples used in this investigation varied from 100 to less than 20 on the Shore Scleroscope scale. From Appendix C it can be seen that, in general, the harder carbons gave the better results. However,

no direct correlation between hardness of the carbons and wear rates was found.

The greatest wear rate did occur with the softest carbon, and the smallest wear rate occurred with a hard carbon, but not the hardest. The highest wear rate found in these tests was 55.44 x 10^{-3} mm^3/min, and was the combination of carbon number 18 (hardness less than 20) on the stellite surface. The lowest wear rate was with carbon number 1 (hardness of 90) on the chrome surface, and was 1.34 x 10^{-5} mm^3/min.

Some of the harder carbons did not perform as well as some much less hard. For example, carbon 19, with a hardness of 45, has the best results of all carbons on the silicon-monel surface, although it was followed closely by carbons 1 and 5, having hardness values of 90 and 100, respectively.

Figure XV shows a plot of wear rate vs. carbon hardness for the chrome surface. Although the scatter is very great, the trend toward lower wear rates for high-hardness carbons is evident. The results of all the wear tests plotted in this manner show a similar trend.

The hardness of the shaft material seems to be important, since every carbon had its lowest wear rate on the hardest surface, chrome-plated steel. However, the average wear rates for all the carbons on bronze-G, silicon-monel, and stellite #6 are almost identical, although these materials have hardness values of 25, 62, and 69 respectively on the Rockwell A scale. The average wear rate for the carbons tested on the monel-K ring was significantly higher

than that of the other surfaces, although its hardness was Rockwell A 53.5.

The wear and friction characteristics of carbons on chrome, as seen in Appendix B, Tables V, VI, and VII, and Appendix C, as well as from the curves of the previous section, clearly indicate the superiority of chrome over the other four materials as a mating surface for carbon in this seal investigation.

While a high hardness value all too often is chosen as the primary guide by designers in selecting mating materials to be run against carbon, there are other factors that must be considered. Temperatures of 2000° F or higher appear likely at the contacting asperities [3] , and at this temperature carbon is chemically reactive. Therefore, the possibility of a chemical reaction between the carbon and mating metal (via the oxide film) must be considered. This chemical reaction at the interface can involve (1) a reduction of metallic oxides, (2) direct oxidation of the carbon by the atmosphere, and (3) the formation of metallic carbides. [2, 3, 24] Since the strength of the chemical bond forces between the reacting materials must be considered - for the consequence could well be a mass "pull-out" or spalling of the carbon particles as was evidenced with all carbons on aluminum bronze - metals requiring the maximum heats of reaction should be used. The wear and friction results of all carbons on chrome conclusively bear this out, and its inherent high heat of reaction and subsequent high resistance to carbide formation indicate that this factor

should be a dominating one in selecting seal material combinations.

High hardness, however, is a contributing factor in this interplay of physical properties, for it can usually be related to low wear and friction values by the resultant low real area of contact. Moreover, the hard surface, such as with chrome, can be expected to gall less readily than the softer materials. [27, 32] Also to be considered is that an increase in load quite naturally makes galling more likely, since it increases the possibility of the adsorbed and oxide films being penetrated with a marked increase in naked metal contact. Here again chrome excels, for this increased load would instinctively result in higher flash temperatures, once again focusing our attention on the higher reaction temperature of chrome.

Two different wetting agents, both water soluble, were used in one phase of the investigation in hopes of improving the lubricating properties of synthetic sea water when carbon is mated with a chrome surface. Figure XII shows the effect of three different concentrations (by volume) of one wetting agent (UCON-HYDROLUBE 275 CP) in combination with synthetic sea water. While only carbon 8 is shown in the plot, the same trend is true with the other carbons on a chrome surface (Figures IV, V, and VI). It can be seen that the wetting agent <u>increased</u> the frictional force acting, a value that approached that of distilled water when a 10% solution was used. As the concentration of wetting agent is increased, the friction force decreases; although it does not go below

the value achieved with a straight artificial sea water solution. The same behavior was experienced with the other wetting agent (Polyethylene Glycol) when a chrome mating surface was used.

Probably one of the more interesting facets of this investigation was that concerning graphite content. While the various carbon manufacturers were extremely cooperative in furnishing sample carbons as well as extensive data on their physical properties, they were reluctant to furnish information regarding the graphite content of their specimens. This, in a sense, prompted us to delve into the matter a bit more extensively than originally planned. Graphite content can be classified as one of those "jealously guarded" trade secrets, for, in any one company, only a selected few know the actual graphite content of their various grades. This is prompted by the fact that the quantity contained is unpatentable, and, as far as is presently known, cannot be ascertained accurately by any chemical analysis. It is, however, possible to obtain a relative standing between carbons, but even this is a crude approach. One such method consists of burning the carbon in a crucible at 1200° F. The smaller the percent of material consumed at 1200° F in the presence of oxygen, the smaller the percentage of graphite, for graphite is much less resistant to oxidation at this temperature than is carbon. As mentioned, however, this approach is a crude one, and, limited by time as it were, we decided to rely on information provided by the manufacturers.

The manufacturer of carbons 8, 9, and 10 furnished some

information regarding this matter. He indicated that carbon 10 had the highest graphite content, being 20% higher than carbon 8. Carbon 8, in turn, contained 20% more than carbon 9. The friction results of these carbons on chrome were in agreement with that of Swikert and Johnson [24] in that the friction coefficient increased as the percent graphite increased. At a 500 gram normal load, for example, the friction coefficient went from .097 (carbon 9) to 100 (carbon 8) to .130 (carbon 10). Viewing Appendix E, this could be explained as due to increased softness and friability. Bowden and Tabor [2] explain the friction force as the product of shear area and shear strength. Since the shear strength of the amorphous carbon in the specimens is greater than that of the graphite, it can be said that the shear strength decreases with increasing graphite content. The real area of shear, however, increases more rapidly with increased graphite than the strength, due to the softness and friability; therefore it is to be expected that the friction force would be higher with the higher graphite content specimens.

It can be seen from Appendix C and E that the wear characteristics of electro-graphitized carbons definitely is inferior to that of the graphitic carbons. This can be primarily attributed to their greater softness, although the greater oxidation resistance of graphitic carbons must be considered also. High resistance to oxidation is definitely desired, for, assuming the same mating surface is used, this factor probably contributes more to low wear than

any other. For high oxidation resistance, it is obvious that low porosity is necessary, and this is one of the primary aims of impregnation. At the same time, it reduces the permeability to the fluid being sealed. Viewing the wear values of Appendix C, however, it would appear that the type carbon and the impregnant used has a decidedly lesser effect on wear than the choice of mating surface.

A relative standing was established among the various carbons for porosity. This was accomplished by immersing the samples in a solution of wetting agent and water for two days and measuring the weight gained. Comparison with actual wear values on a given shaft material indicated that no direct correlation was possible. It was noted, however, that porous carbons normally perform poorly in wear, while the better carbons in wear are usually the least porous. This is shown in Figure XIV for the case of all carbons on chrome plate. The results for other shaft materials give plots which are similar to chrome plate. It is realized that the method used for measuring relative porosity is primitive and in certain cases may have given erroneous readings as compared to the actual seal materials. For example, carbons 8, 9, 10, and 11 have impregnated surfaces only 1/16 to 1/8 inch thick; hence, deeply machined specimens or fragments may give erroneous indications of the nature of the working portion of the carbon. A better method of investigating porosity might be measurement of the rate of leakage from a tube sealed by the lapped working surface of the carbon.

Figure XII shows the results of using no lubricant at all and shows the merits also of the synthetic sea water as a lubricant. It is to be realized that the main function of a boundary lubricant is to interpose between the sliding surfaces a film that is able to reduce the amount of metallic interaction, and that is, in itself, easily sheared. Considering the application of these carbons on chrome for submarine seals, since the net flow is to the surrounding sea, the lubricant must be undetectable to the enemy. In other words, should oiliness agents or other substitute lubricants be considered, they must be soluble in sea water. With a carbon on chrome combination, there appears to be no superior lubricant than the surrounding medium itself.

It is readily seen from the various friction force vs. normal load curves that the frictional resistance varies directly with the load. This is in agreement with Amonton's law of friction of solid bodies, in that the coefficient of friction is not influenced by the intensity of loading - further evidence that fluid film effects have been eliminated and that our investigation is in the boundary lubrication region. It is true that there is some deviation from a straight line at the higher loads, but Amonton's law, as generally applied, refers to moderate loads.

Considering the unit loads applied during the wear tests (2000 grams normal load or roughly 5000 psi based on the average diameter) it can be assumed that the wear rates were severe; far more, undoubtedly, than would normally be expected in service. This would explain the extreme divergence

from the postulated wear when Rabinowicz' relationship [4] of wear to the two-thirds power is plotted against friction coefficient on a log-log plot. His equation appears to offer fair agreement at the low wear rates only. Moreover, considering a series of carbons run on chrome plate, carbons 19 and 21 exhibit very low friction coefficients (.074 and .083 respectively), especially when compared with carbon 10's value of .130 on carbon 25 value of .140. In both instances, however, the lower friction coefficients resulted in a wear at least twice as big as that experienced with carbons 2 or 10. In other words, a low friction coefficient does not necessarily mean low wear. A further example can be made by considering the same carbon on different mating surfaces: carbons 9 and 10 both exhibited lower friction coefficients on monel-K than on chrome plate, but the wear of both on monel-K far exceeded that experienced on chrome.

A further statement should possibly be made regarding carbons 19 and 21. Carbon 19 has been impregnated with 35% lead, while carbon 21 contains SAE 11 Babbitt. While both showed very low frictional values but excessive wear when run with a salt water lubricant, it should be mentioned that these grades have proven extremely successful in steam turbine applications. This lends testimony to the fact that amorphous carbons, non-impregnated and of low graphite content, may prove satisfactory with salt water, but that impregnation must be utilized in carbons designed for higher temperature applications if only to reduce the porosity and increase its resistance to oxidation.

Unlike Part I, this phase did not lend itself to detecting stick-slip, primarily due to the geometrical configuration used. While the Sanborn recorder would indicate some needle fluctuation at a constant loading, and from this a comparison drawn, the KOTM arrangement of Part I appears more ideally suited to this type measurement.

In general, the accuracy of the measurement of friction coefficient is limited only by the accuracy of the method of measuring normal and friction forces. In this case, the normal load was applied externally by known weights, so the only source of possible error was in the measurement of friction force. Reference [3] indicates that performance of friction tests were repeatable within 10% of the friction coefficient. Since the test results indicate the same repeatability, the accuracy of measurement is not believed to be a factor since calibration of the Sanborn Recorder was checked before and during each friction run.

In some cases of high wear combinations, incidence of wearing surface generated vibrations were detected. In general, these vibrations did not change in frequency with load, but the amplitudes appeared to be proportional to load. The source of vibration was verified to be the wearing surface by the absence of vibration on certain carbons with the same mating surface. In addition, it was shown that changing the wetting agent caused a change in frequency of vibration. It is believed that these vibrations were caused by the galling action of high wear carbons although this aspect was not proven.

In spite of the lack of correlation with wear, it is obvious that low friction at the wearing surface is desirable if for no other reason than reduction in power transmission losses. Of course, there is the additional consideration of heat generation due to high friction at the mating surface which would cause higher ambient temperatures and temperature gradients.

It was found that friction tests were generally repeatable within ten percent of the friction coefficient. While this variation is in agreement with past work with carbon-metal surfaces, it was noted that friction tests are very sensitive to certain environmental conditions which may have contributed partially to this variation. The feed rate of wetting agent was the most important of these conditions. While this was duplicated as closely as possible for the friction tests, it is pointed out that wetting agent feed was controlled manually with inherent human error. On the other hand, it was found that changing specimens of either or both carbon and shaft material did not produce noticeable departures from the repeatability band of plus or minus 10% as long as the conditions above were duplicated.

Wear tests were found to be less satisfactory from a repeatability standpoint. It was found that while carbons maintained their orders of merit, magnitudes of wear were not repeatable. In addition to wetting agent feed rate mentioned above, it is believed that the difference between carbons and lack of homogeneity within a given carbon were primary factors in this variation. As mentioned before, physical pro-

perties may vary within a carbon independent of chemical composition. Since working areas were only about 0.75 mm in diameter on the average, it is obvious that these local variations could exert their maximum influence on the wear of a particular run.

It is also noted that since there was no compensation in load for wear, the apparent PV factor changed considerably during the course of a 45 minute wear run due to the changes in pressure. Since the magnitudes of wear rates were not repeatable, neither was the spectrum of PV values. It is pointed out also that tests did not start with identical wearing areas, so that apparent PV was not the same even at the start of the wear run. There were several reasons for conducting the tests in this manner. It was known that even if the apparent PV was the same, the number and areas of actual contact points could not be duplicated. It was also apparent that any attempt to duplicate this initial contact area would consume a prohibitive amount of preparation time. Some thought was given to not running in the carbons before a wear test to enable having a common starting point, but it was felt that this would unduly amplify the variations in transverse strength of carbons for such small amounts of wearing volumes. Consequently, it was decided to run in the carbons and not to attempt to control PV factor so long as hydrodynamic conditions at the wearing surface did not occur.

In spite of these limitations, it was readily apparent that the local conditions of loading on the carbon are an im-

portant aspect of wear. Most of the high wear carbons appeared galled on the wearing area at the end of a run, while the low wear specimens were eroded smoothly indicating a larger number of actual contact points. The influence of other factors such as carbon grain structure, geometry, and temperature were recognized to be important factors but were not investigated.

As a result of the above considerations, it is believed that the success in repeating the orders of merit for wear on chrome is indicative that magnitudes of wear may be repeatable if carbon homogeneity can be improved by the manufacturers. This problem is one of quality control in manufacturing primarily, and it is believed that increased effort in this field is warranted.

The ingredient common in all oiliness or wetting agents is some kind of fatty acid occurring in chemical reaction with glycerine or some other high molecular weight alcohol. The action of this acid in reducing friction under boundary conditions is now generally agreed to be one of molecular adherence. [15] The carboxyl molecular groups of the acids attach themselves to the metal surface, and, as a result of the chemical action between the metal and the lubricant, a metallic soap is formed, lowering the frictional force required when this reaction takes place. Chrome, however, much like nickel and glass, can be considered a non-reactive surface, and the desired effect was not realized. The effect of a 10% wetting agent-synthetic sea water solution on chrome was to increase the friction force. This might be explained

by the very nature of a wetting agent in the presence of a non-reactive surface, viz., the addition of the oiliness agent, in a sense, diluted the lubricant. Rather than have some of the contacting surface asperities separated by synthetic sea water, the addition of the agent did as its name implies - it "wetted" the surface, filling in the valleys and exposing more peaks, but, nevertheless, wetting a greater portion of the surface in a thinner but more continuous film. This is all without the formation of a metallic soap. As the concentration of the wetting agent is increased, more and more of the polar groups, much like the pile of a carpet, attach themselves to the surface, "submerging" an increased number of peaks and reducing the friction force. It can be seen from Figure XII that the friction curve of a 50% solution approaches that of synthetic sea water, but whether a 100% wetting agent solution on a non-reactive surface would be better is doubtful.

Time prohibited experimentation with other surfaces, but the semi-reactive nature of Al and Fe, and the reactive characteristics of Cu, Cd, Zn, and Mg would make interesting tests of the other surfaces. The percent composition in each of the other shaft materials (Appendix F) readily indicates the feasibility of testing bronze G should material shortages dictate the use of this material.

While the polar structure of distilled water detracts from its merits as an effective boundary lubricant, synthetic sea water does achieve a portion of non-polar structure, dependent on the quantity of salts present, and it can

generally be stated that friction decreases with the increased chain length of the lubricants [2]. This would explain the superiority of sea water over distilled water in this application.

One comment seems in order regarding Carbon 1, our number one carbon from a wear point of view. Under the action of Cw 300, it was the only carbon tested that did show beneficial results with increasing wetting agent concentration (Appendix B). The reason for this action when it did not occur with any of the other carbons or with oiliness agent 275CP goes unexplained. No check was made on repeatability on this particular behavior.

XII. CONCLUSIONS

1. The heat of reaction of the shaft materials must be considered in the selection of suitable shaft and seal material combinations. This was suggested in Part I but was emphasized in this phase with the action of aluminum bronze with carbons. Chrome plate exhibited the maximum resistance to oxidation and carbide formation, carbons in contact with it showing consistently low wear rates throughout.
2. The hardness of carbons is not a fool-proof guide in selecting efficient seals in this particular application. While the softest carbons generally gave the greatest wear, the hardest carbon did not give the least; although it did rank high in the order of merit.
3. The porosity of the carbons, in general, is a good yardstick for selecting effective seal materials. The carbons with the least porosity tended to have the least wear, probably due to a lower real area of contact.
4. The degree or type of impregnation, as well as the quantity of graphite content in the carbons, appears less important from a wear viewpoint than the selection of mating surface.
5. If concerned primarily with friction, carbons of lower graphite content generally give lower frictional values; but low friction does not necessarily MEAN low wear.
6. While chrome proved to be the superior mating surface with all carbons tested, other material combinations

(Appendix C) showed satisfactory wear values should material shortages dictate their use (carbon 19 on silicon monel, for example).

7. Carbon 1 proved to be the most effective carbon from a wear viewpoint and was fairly close to the top from a frictional viewpoint also. It is to be noted that this same carbon is the one proving so effective in Part I.
8. Aluminum bronze and monel K are unsatisfactory shaft materials in this particular application, being active carbide formers. The common element in both these materials is aluminum, and its low melting point is probably the most contributing factor in this action. Stellite #6 leaves much to be desired, judging from its fairly high wear values. It appears quite probable that an electrolytic action of sorts is taking place when a carbon on stellite in salt water is used. The pitting and bubbling action of Part I has been subsequently verified by full scale tests at the U. S. Naval Experiment Station in Annapolis, Maryland.
9. Shaft hardness should not be used as a guide in selecting materials for such use; for, as mentioned above, chemical composition is much more important.
10. The wetting agents tested indicate that there is no particular advantage in their use, but rather that increased friction values can be expected.
11. Carbons presently appearing on the Qualified Products List (Carbons 16 and 18, for example) had excessive

wear in most instances. This suggests the inadequacy of the present military specifications and the fact that they should be revised. Other carbons demonstrating extremely good wear and friction characteristics, as well as stability, do not appear on this list.

12. This present test arrangement does not permit measurement of shaft wear. Tests of a similar nature but of much longer duration may be desirable in order to accomplish this. A radiochemical technique has been shown feasible [37] and might prove of value here.

13. While friction results proved to be repeatable with 10%, wear values could not be. This can be accredited primarily to quality control and the subsequent lack of homogeneity between carbons even of the same batch. Whereas this apparently has little effect on friction values, it could well cause wear values of the same carbon to fall within a ±20% spectrum vice the desired 10% or less repeatability values. It goes without added emphasis that the rate of lubricant feed must be constant. Also to be considered is the fact that the same initial starting diameter was not used for the repeat run. This would result in varying PV values for each run, since P, in psi, is a function of the normal load and diameter. But it should be emphasized, however, that neither of these factors detracted from the accuracy of the wear order of merit, since the spread between carbon values was sufficiently large and prevented the repeat run from over-lapping the wear value of another carbon.

XIII. RECOMMENDATIONS

1. It is recommended that chrome plated surfaces be used for submarine propeller shafts in way of the shaft seal in combination with carbon 1. Carbons 5, 6, and 8 ranked reasonably close to this and could be used as substitutes.
2. It is recommended that the use of wetting agents be discouraged in this application.
3. It is recommended that the use of aluminum bronze, monel K, and stellite #6 be discouraged in this application.
4. It is recommended that seal wear and friction tests be required in any specification for the use of carbons as seal materials. In this vein, it is recommended that the present military specifications for carbon seals (MIL-P-18493-NAVY) be revised to correct their present inadequacies.

XIV. APPENDIX

APPENDIX A

Identification of Materials Tested

Part I

1. Phenolics

Material Letter Identification	Manufacturer	Material Code
D	J. T. Ryerson & Sons, Inc.	Ryertex Grade SBE-50
F	The Richardson Co.	Insurok Grade XT-883
G	The Richardson Co.	Insurok Grade T-856
K	Farley-Loescher Mfg. Co.	Farlite 5759
L	J. T. Ryerson & Sons, Inc.	Ryertex Grade NLDC (67841)
M	Formica Co.	Formica CN-86
R	American Brakeblok Div., American Brakeshoes Co.	ABK-505
Z	J. T. Ryerson & Sons, Inc.	Ryertex Grade C-1557

2. Carbons

Carbon Specimen Number	Material Code	Manufacturer
1	Graphitar #14	U.S. Graphite Co.
2	Graphitar #30A	U.S. Graphite Co.
3	Graphitar #39	U.S. Graphite Co.
4	Graphitar #84	U.S. Graphite Co.

Part II

1. Carbons

Carbon Specimen Number	Material Code	Manufacturer
1	Graphitar #14	U. S. Graphite Company
2	Graphitar #30A	U. S. Graphite Company
3	Graphitar #35	U. S. Graphite Company
4	Graphitar #39	U. S. Graphite Company
5	Graphitar #47	U. S. Graphite Company
6	Graphitar #86	U. S. Graphite Company
7	Graphitar #88	U. S. Graphite Company
8	P-61-A	Pure Carbon Company, Inc.
9	P-692	Pure Carbon Company, Inc.
10	P-62W2	Pure Carbon Company, Inc.
11	CDJ-72	National Carbon Company
*12	ARGUTO-MP	Arguto Oilless Bearing Company
13	W-1285	The Ohio Carbon Company
14	351	Speer Carbon Company
15	H	Speer Carbon Company
16	EH	Speer Carbon Company
17	E-25	Speer Carbon Company
18	3499	Speer Carbon Company
19	5473	Speer Carbon Company
20	6208	Speer Carbon Company
21	6493	Speer Carbon Company

*This item is not a carbon but rather an alloy of plastics. It was utilized throughout the second part of our investigation as a means of comparing the behavior of seal carbons with a highly effective bearing material.

APPENDIX B

TABLE I

Friction Force and Friction Coefficients of Carbons on Stellite #6 using Synthetic Sea Water

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
6	70	130	190	240	.140	.130	.127	.120
7	75	160	235	305	.150	.160	.157	.152
8	70	120	195	245	.140	.120	.130	.123
9	70	135	210	265	.140	.135	.140	.133
10	75	138	205	265	.150	.138	.137	.133
12	70	185	278	380	.140	.185	.185	.190
13	70	135	190	212	.140	.135	.127	.106
14	60	130	185	243	.120	.130	.123	.122
19	70	150	225	282	.140	.150	.150	.141

TABLE II

Friction Force and Friction Coefficients of Carbons on Monel K using Synthetic Sea Water

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
4	57	112	185	270	.114	.112	.123	.135
6	55	100	157	215	.110	.100	.105	.107
7	57	125	200	235	.114	.125	.133	.118
8	50	105	162	207	.100	.105	.108	.103
9	27	70	150	185	.054	.070	.100	.093
10	57	105	125	220	.114	.105	.083	.110
11	40	92	140	200	.080	.092	.093	.100
12	105	242	277	350	.210	.242	.185	.175

TABLE III

Friction Force and Friction Coefficients of Carbons on Silicon Monel using Synthetic Sea Water

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
3	55	110	125	172	.110	.110	.084	.086
4	42	102	162	220	.084	.102	.108	.110
6	50	75	145	167	.100	.075	.096	.084
7	67	135	202	290	.134	.135	.135	.145
8	75	132	170	230	.150	.132	.113	.115
9	55	92	135	190	.110	.092	.091	.095
10	65	115	167	212	.130	.115	.113	.106
11	62	95	175	205	.124	.095	.117	.103
12	85	197	315	400	.170	.197	.211	.200
13	55	110	177	225	.110	.110	.118	.113
14	72	145	212	255	.144	.145	.141	.128
16	36	77	125	145	.072	.077	.084	.073
17	37	62	80	85	.074	.062	.053	.043
19	32	85	125	85	.064	.085	.084	.043

TABLE IV

Friction Force and Friction Coefficients of Carbons on Aluminum Bronze using Synthetic Sea Water

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
1	52	95	140	180	.104	.095	.103	.090
4	67	115	160	225	.134	.115	.117	.113
5	52	87	135	180	.104	.087	.099	.090
6	60	100	142	202	.120	.100	.104	.101
7	62	122	185	237	.124	.122	.136	.119
8	60	105	160	215	.120	.105	.118	.108
9	52	95	145	180	.104	.095	.106	.090
11	50	90	142	190	.100	.090	.104	.095
12	75	175	240	330	.150	.175	.176	.165
14	60	115	180	245	.120	.115	.132	.123
15	72	135	205	335	.144	.135	.150	.168

TABLE V

Friction Force and Friction Coefficients of Carbons on Chrome using Synthetic Sea Water

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
2	60	147	197	280	.120	.146	.131	.140
3	55	107	172	235	.110	.107	.115	.117
4	55	107	152	212	.110	.107	.101	.106
6	45	100	145	182	.090	.100	.097	.091
7	50	130	202	262	.100	.130	.135	.131
8	50	100	145	200	.100	.100	.097	.100
9	47	107	162	217	.097	.107	.108	.108
10	65	135	197	260	.130	.135	.132	.130
11	52	120	175	225	.104	.120	.117	.113
12	92	182	252	350	.184	.182	.168	.175
13	52	102	142	205	.104	.102	.095	.103
14	60	120	170	220	.120	.120	.113	.110
15	45	85	125	160	.090	.085	.083	.080
16	32	47	70	102	.064	.047	.047	.051
17	45	87	135	157	.090	.087	.090	.079
19	32	72	120	147	.064	.072	.080	.074
21	55	87	132	165	.110	.087	.088	.083
1	55	105	165	220	.110	.105	.110	.110

TABLE VI

Friction Force and Friction Coefficients of Carbons on Chrome (Repeatability)

Normal Load	500	1000	1500	2000	500	1000	1500	2000
Carbon	Friction Force				Friction Coefficient			
2	65	127	197	275	.130	.127	.131	.137
4	52	95	155	202	.104	.095	.103	.101
6	37	80	127	177	.070	.080	.085	.088
8	47	107	162	217	.094	.107	.108	.108
9	57	105	157	212	.104	.105	.105	.106

TABLE VII

Friction Force And Friction Coefficients of Carbons on Chrome with Varying Wetting Agent Concentration (UCON-HYDROLUBE-275CP)

Normal Load		500	1000	1500	2000	500	1000	1500	2000
Carbon		Friction Force				Friction Coefficient			
1	(10%)	47	107	170	230	.094	.107	.113	.115
	(25%)	55	115	160	237	.110	.115	.107	.119
	(50%)	52	112	155	217	.104	.112	.104	.109
2	(10%)	62	137	237	327	.124	.137	.158	.164
	(25%)	62	127	200	290	.124	.127	.134	.145
	(50%)	62	130	180	262	.124	.130	.120	.131
4	(10%)	72	130	205	282	.144	.130	.137	.141
	(25%)	75	130	185	260	.150	.130	.125	.130
	(50%)	52	90	185	252	.104	.090	.125	.126
6	(10%)	62	125	185	235	.124	.125	.125	.118
	(25%)	72	127	192	260	.144	.127	.128	.130
	(50%)	52	95	170	237	.104	.095	.113	.119
8	(10%)	62	115	172	260	.124	.115	.115	.130
	(25%)	52	110	175	245	.104	.110	.117	.123
	(50%)	50	110	185	230	.100	.110	.125	.115
12	(10%)	55	110	175	215	.110	.110	.117	.108
	(25%)	30	70	100	147	.060	.070	.067	.124
	(50%)	20	60	115	175	.040	.060	.077	.138

TABLE VIII

Friction Force of 3 Carbons on Chrome Using Different Lubricants

1. Carbon 1

Normal Load (grams)	500	1000	1500	2000
Dry	105	250	362	500
Distilled Water	62	135	185	237
Syn. Sea Water				
* 10% UCON Sol'n.	47	107	170	230
25% UCON Sol'n.	55	115	160	237
50% UCON Sol'n.	52	112	155	217

2. Carbon 8

Normal Load (grams)	500	1000	1500	2000
Dry	125	225	360	480
Distilled Water	62	130	192	260
Syn. Sea Water	50	100	145	200
10% UCON Sol'n.	62	115	177	260
25% UCON Sol'n.	52	110	175	245
50% UCON Sol'n.	50	110	175	230

3. Carbon 12

Normal Load (grams)	500	1000	1500	2000
Dry	180	390	650	837
Distilled Water	80	207	270	347
Syn. Sea Water	92	182	252	350
10% UCON Sol'n.	55	110	175	215
25% UCON Sol'n.	30	70	100	147
50% UCON Sol'n.	20	60	115	175

* Solution is % by volume of wetting agent + synthetic sea water.

TABLE IX

Friction Force and Friction Coefficients for 3 Carbons on Chrome using Various Concentrations by Volume of Polyethylene Glycol (CW300) with Synthetic Sea Water

		Normal Load				Normal Load			
Carbon		500	1000	1500	2000	500	1000	1500	2000
		Friction Force				Friction Coefficient			
	(10% Sol'n.)	40	102	150	275	.080	.102	.100	.133
1	(25% Sol'n.)	62	110	167	230	.124	.110	.111	.115
	(50% Sol'n.)	40	80	140	207	.080	.080	.093	.103
	(10% Sol'n.)	65	142	210	285	.130	.142	.140	.143
2	(25% Sol'n.)	77	142	207	317	.154	.142	.138	.159
	(50% Sol'n.)	77	150	220	295	.154	.150	.147	.148
	(10% Sol'n.)	37	127	182	262	.074	.127	.121	.131
8	(25% Sol'n.)	70	120	197	267	.140	.120	.131	.129
	(50% Sol'n.)	60	127	200	247	.120	.127	.134	.124

APPENDIX C

Wear Volume and Wear Rate Calculations

and

Tables of Wear Rates

I. Sample Calculation of Wear Volume and Wear Rate

D_1 = Initial Diameter, mm.

D_2 = Final Diameter, mm.

V = Volume of Frustrum, cubic mm.

Basic Formula: $V = \frac{\pi}{24} \tan 10^\circ (D_1^2 + D_1 \times D_2 + D_2^2)(D_2 - D_1)$

10° = Cone Angle

Example: Carbon No. 9 on Chrome-plated Steel

D_1 = .2964

D_2 = .6669

1. D_1^2 = .0879
2. D_2^2 = .4445
3. $D_1 \times D_2$ = .1977
4. $\sum 1,2,3$ = .7301
5. $D_2 - D_1$ = .3705
6. 4 x 5 = .2705
7. $\pi/24 \tan 10^\circ$ = .02308
8. 6 x 7 = .006243 = Volume
9. Running Time = 45 minutes
10. Wear Rate, $mm^3/min \times 10^3$ = 0.139

II. Tables of Wear Rates

TABLE X

Tabulation of Wear Rates

Carbon No.	Wear Rates, $mm^3/min \times 10^3$ Bronze-G	Stellite #6	Chrome	Silicon Monel	Monel-K
1	.586	.276	.0134	.223	-
2	2.731	1.612	.164	4.626	-
3	1.632	2.246	.201	1.906	-
4	.610	1.122	.232	2.732	.781
5	.648	.339	.087	.389	-
6	.494	.962	.077	1.299	1.748
7	.560	.802	.217	1.619	1.492
8	.745	.479	.078	.432	4.708
9	.535	.633	.139	.478	3.184
10	1.488	.776	.227	4.536	6.164
11	.499	1.211	.220	2.100	7.840
12	1.077	.371	.272	1.624	1.061
13	1.589	.308	.798	2.309	-
14	1.157	.494	.318	4.447	-
15	4.943	2.857	.485	7.993	-
16	-	8.215	1.409	12.008	-
17	10.851	8.599	.954	27.655	-
18	28.314	55.440	2.556	4.555	-
19	.967	.340	.558	.203	-
20	4.201	1.026	1.804	4.363	-
21	-	1.549	.589	-	-

APPENDIX D

Preparation of Synthetic Sea Water

Synthetic sea water was prepared with reagent grade chemicals and distilled water as prescribed by Reference 30. Most chemicals were premixed into two stock solutions. Sea water was mixed in small batches of about two and a half liters as required. A third stock solution was not used because all elements were required in trace amounts only. Preparation is as follows:

Stock Solution #1.

In 10 liters of distilled water, dissolve:

Magnesium chloride, hydrated	3889.0	grams
Calcium chloride, anhydrous	405.6	
Strontium chloride, hydrated	14.8	

Stock Solution #2.

In 7.0 liters of distilled water, dissolve:

Potassium chloride	486.2	grams
Sodium bicarbonate	140.7	
Potassium bromide	70.4	
Boric acid	19.0	
Sodium fluoride	2.1	

Dissolve in about 8 liters of distilled water:

Sodium chloride	245.3	grams
Sodium sulphate, anhydrous	40.9	
Stock solution #1	200	ml
Stock solution #2	100	ml

Dilute to 10 liters.

APPENDIX E

Average Characteristics of Carbon Samples

Carbon No.	Shore Hardness	Apparent Density gm/cc	Relative Porosity	Compressive Strength	Transverse Strength	Coeff. of Thermal Expansion in/in/F	Impregnant	Type*	% Ash
1	90	1.85	0.3	33,000	10,000	-	-	CG	1.98
2	90	1.67	3.1	22,000	5,900	-	-	CG	-
3	90	1.77	0.2	30,000	8,500	2.2x10^6	-	CG	0.5
4	100	1.70	0.1	37,000	13,000	2.2	-	CG	5.5
5	100	1.85	0	35,000	11,500	-	-	CG	-
6	95	1.90	0.3	37,000	13,500	2.2	-	CG	10.0
7	95	1.80	0.5	25,500	7,000	2.2	-	CG	5.5
8	75	1.78	0.5	15,000	7,000	-	Syn. Resin + Plastic	CG	10.0
9	75	1.80	0.4	30,000	10,000	-	Syn. Resin	CG	10.0
10	55	1.75	0.6	19,000	8,000	-	Syn. Resin	CG	1.0
11	92	1.78	0	33,000	11,000	1.2	No. 72	CG	-
12	Rockwell L-54	1.49	2.1	8,375	4,285	25.3	-	Plastics + Resin	-
13	95	1.80	1.1	30,000	11,000	2.5	6-8% Syn. Resin	CG	3-4
14	95	1.73	4.3	-	6,000	-	-	CG	3.0
15	45	1.55	2.1	-	3,500	-	-	CG	1.0
16	40	1.60	1.2	-	2,500	3.7	-	EG	0.15
17	65	1.70	2.1	-	3,000	-	-	EG	0.25
18	15-20	1.70	2.6	-	3,000	4.5	-	EG	0.10
19	45	2.36	3.5	-	8,000	20.0	35% Lead in Mix	CG	-
20	51	1.75	5.9	-	3,500	113.5	-	CG	0.14
21	27	2.37	0	-	-	-	SAE 11 Babbitt	CG	-

* CG: Graphitic Carbon; EG: Electro-Graphitic Carbon

TABLE XI

Average Characteristics of Carbon Samples

Order of Hardness		Hard-ness	WEAR Order of Merit				
No.	Carbon	(Shore)	Monel K	Chrome	Stellite 6	Bronze G	Silicon Monel
5	USG 47	100	-	3	3	7	3
4	USG 39	100	1	11	13	6	12
7	USG 88	95	3	8	10	4	7
6	USG 86	95	4	2	11	1	6
14	351	95	-	13	7	11	14
11	CDJ-72	92	8	9	14	2	10
13	W128-5	95	-	17	2	13	11
1	USG 14	90	-	1	1	5	2
3	USG 35	90	-	7	17	14	9
2	USG 30A	90	-	6	16	15	17
8	P-61A	75	6	4	6	8	4
9	P-692	75	5	5	8	3	5
17	E-25	65	-	18	19	18	20
10	P-62W2	55	7	10	9	12	15
20	6208	51	-	20	12	16	13
15	H	45	-	14	18	17	18
19	5473	45	-	15	4	9	1
16	EH	40	-	19	20	-	19
21	6493	27	-	16	15	-	-
18	3499	20	-	21	21	19	16
12	Arguto	Rockwell-L	2	12	5	10	8

APPENDIX F

Shaft Materials

1. Composition

Aluminum Bronze	90 Cu, 10 Al
Bronze G	90 Cu, 10 Sn
Chrome Plate	electroplated on high carbon steel
Monel K	66 Ni, 29 Cu, 0.9 Fe, 0.75 Mn, 0.5 Si, 0.15 C, 2.75 Al
Silicon Monel	63 Ni, 30 Cu, 2 Fe, 0.9 Mn, 4 Si, 0.1 C.
Stellite 6	30 Cr, 56 Co, 3 Ni, 3 W, 1.5 C, 3 Fe, 1 Si, 1 Mn, 0.5 other.

2. Hardness

	Hardness	Relative Hardness
Aluminum Bronze	Rockwell A 42.7	1.7
Bronze G	Rockwell A 25.0	1.0
Chrome Plate	Rockwell C 102.	7.7
Monel K	Rockwell A 53.3	2.1
Silicon Monel	Rockwell A 62.0	2.5
Stellite 6	Rockwell A 69.0	2.8

APPENDIX G

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