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FRICITION AND WEAR IN PSC CARBON AND GRAPHITE
CORE SUPPORT MATERIALS

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ABSTRACT

The commercial graphite friction couples PGX vs PGX, MHLM vs MHLM, ATJ vs ATJ and H359 vs H205 were rubbed with oscillating motion 2500- or 5000-inches in dry helium (~ 2 ppm H_2O) at R.T., 400° , and $800^\circ C$. Loads of 17.7 pounds were used to produce nominal contact pressures of 250-500 psi. The PGX and MHLM couples were also rubbed under a 4.3 pounds load (60-120 psi). A baked carbon (B205), and MoS_2 impregnated graphite (TS835) were rubbed on A-537 Grade B steel 250-inches in dry helium at R.T., 100° , and $200^\circ C$ under a 35.3 pounds load (500 psi contact pressure). Friction and wear was correlated with rubbing distance, temperature, load, pre-treatment of PGX surfaces, and surface roughness of the A-537 Grade B steel.

The dynamic friction coefficient of TS835 and B205 carbon varied over a wide range with sliding distance and temperature (0.1 to 0.7). At $200^\circ C$ TS835 had a lower friction coefficient than B205 (0.1-0.4 vs 0.5-0.7). No significant difference in wear rate could be detected between the two materials on steel surfaces of similar roughness.

The graphite on graphite couples showed similar friction and wear properties. There apparently was a wearing-in process which caused the friction of graphite outgassed at $400^\circ C$ first to increase and then decrease during initial sliding (10-100 inches). After the initial fluctuation friction was relatively constant. Friction and wear decreased with increasing temperature. The dominant friction coefficient was approximately 0.4, at R.T. and 0.3 at $800^\circ C$.

Essentially all the wear of PGX (and probably the other graphites) took place within the first 250-inches of sliding. This initial high wear rate was probably associated with a wearing-in process which established an equilibrium surface resistant to wear. Pre-treatment of PGX graphite by rubbing 250-inches at R.T. in air and $400^\circ C$ in helium did not improve the wear properties at $400^\circ C$ in helium.

FRICTION AND WEAR IN PSC CARBON AND GRAPHITE CORE SUPPORT MATERIALS

1.0 INTRODUCTION

In the reference PSC core support design there are several bearing surfaces of carbon or graphite on metal and graphite on graphite (Reference drawings numbers 90 SK 523 (Post, Base, Seat); 90 SK 1938 (Block, Insert)). There are three bearing surfaces of particular importance where components rubbing on each other will produce frictional forces and wear. These surfaces are located between (1) core support blocks, (2) posts and seats, and (3) seats and the metallic liner of the concrete core support. Oscillating sliding motion at the bearing surfaces will be produced by differential thermal expansion of components as core temperatures fluctuate. The purpose of this work was to measure friction and wear of candidate materials under simulated reactor conditions to facilitate final selection of the optimum materials.

2.0 APPARATUS

The MK II apparatus was used to simulate reactor conditions of atmosphere, temperature, loading, and sliding. The major portion of the apparatus was a vacuum chamber which was constructed to allow loading and rubbing of specimens within the hot zone. A resistance heated tube furnace surrounded the chamber. Both the furnace and that portion of the chamber within the furnace could be removed to completely expose the specimens in the testing position.

Two friction couples making up a set were rubbed simultaneously with an oscillating linear motion. A set of graphite or carbon friction couples consisted of three components, two sliders and a single plate which was rubbed on opposing sides. Metal specimens were plates which were mounted back to back and rubbed on the two exposed faces by either carbon or graphite sliders. The plates were held in a horizontal plane on a cantilevered shaft which passed through a bellows in the vacuum chamber wall. Outside the chamber the shaft passed through support bearings and was coupled to an adjustable eccentric driven by an electric motor through reduction gears. A fast response (1/4 sec full scale) strip chart recorder monitored a load cell which acted as an integral part of the shaft and gave a voltage output proportional to the force necessary to deform the bellows

and slide the two plates between opposing buttons held stationary under a vertical load. The bellows force was added or subtracted from the computed force until a mechanical device was installed which transmitted the bellows force around the load cell while allowing the load cell to measure only friction force of the specimens. The vertical load was provided by a weight suspended on the opposing end of a 7.0 to 1.0 lever arm holding the lower button. A fulcrum was provided by a pin passing through the lower arm and a yoke suspended from the stationary arm holding the upper button. Specimen temperature was monitored by a chromel-alumel thermocouple inserted into the holder of the upper button.

The arms and shaft holding the specimens were made of Haynes alloy 25 and the enclosing 3-in. O.D. tube was made of Hastelloy X. The remainder of the apparatus was constructed of 304 stainless steel wrapped with copper cooling lines. Specimens could be viewed during the experiment through a pyrex window at one end of the tube. Stainless steel reflectors within the tubes prevented excessive heat loss through the ends.

The apparatus could be evacuated by a mechanical pump and liquid nitrogen trapped oil diffusion pump system to pressures less than 10^{-5} mm Hg. The chamber could then be back-filled and purged with helium supplied through a metering system. In passing through the system all gas was first exposed to Ti and Zr chips at 800°C to remove oxidants and ensure uniform composition of the gas supply.

The gas entered the chamber within a few inches of the specimen and exited at one end. The purge gas could be exhausted to atmosphere or passed through a moisture measuring system. The moisture measuring system consisted of an electrolytic hygrometer and a dew point indicator. The dew point indicator provided an occasional direct check of accuracy for the continuously reading electrolytic hygrometer. The dew point was measured by impinging helium on a polished aluminum surface cooled on the back side by vapor from boiling liquid nitrogen. Mirror temperatures were measured by thermocouple. The dew point temperature was taken as the highest temperature at which ice formation could be visually detected after the mirror had been maintained at constant temperature for 20 to 30 minutes with a 100 cc/min helium flow.

A schematic diagram of the apparatus is shown in Figure 1. A detailed drawing of the specimen holding and loading device is shown in Figure 2.

3.0 MATERIALS

The materials making up the friction and wear couples used in this study are shown in Table 1. Helium used to simulate HTGR coolant was diaphragm-pumped atomic grade (purity 99.995%). The moisture content of exhaust helium was maintained below 10 ppm at 2 to 5 psig in order to simulate reactor conditions of 0.2 ppm at 47.6 atm. Essentially all of the experiments were conducted with a moisture content of about 2 ppm.

4.0 PROCEDURE

4.1 Calibration

During initial experiments the only significant contribution to indicated friction force not related to the specimens was due to resistance of the bellows to deformation. This force was measured and the appropriate correction factor (maximum $\pm$ 0.8 lbs) applied to the data. During the course of the work a mechanical device was fabricated which attached rigidly to the drive shaft on the motor side of the load cell and gripped the mid-span of the bellows on the specimen side of the load cell. The force required to deform the bellows during a cycle was then transmitted around the load cell but force required to slide the specimens was transmitted through the load cell. With this modification the bellows correction was no longer necessary.

4.2 Friction and Wear Experiments

Graphite and carbon specimens were machined into the form of plates and sliders with the bearing surface perpendicular to the forming direction.

The configuration and dimensions are shown in Figure 3. The rather complex shape of the graphite plate was necessary in order to properly fit the plate holding device and also provide a suitable bearing surface for the sliders. It was discovered in initial experiments with large plate bearing surfaces that the sliders wore a slot into the plate and the step which developed at the end of the

Figure 1. Schematic of Mark II friction and wear apparatus.

Figure 2. Detail of specimen holding and loading device in MK II friction and wear apparatus.

Table 1
CANDIDATE CORE SUPPORT MATERIALS USED IN THE
FRICTION AND WEAR STUDY

Core Support Design Simulation	Friction and Wear Couple Material Designation	Manufacturer	Method of Graphite or Carbon Forming
Block Material on Block Material	PGX vs PGX Graphite	Union Carbide	Molded
	MHLM vs MHLM Graphite	Great Lakes Carbon Co.	Molded
Post Material on Seat Material	ATJ vs ATJ Graphite	Union Carbide	Molded
	H359 vs H205 Graphite	Great Lakes Carbon Co.	Extruded
Base Material on Liner Material	TS835 (18 w/o MoS ₂) Graphite vs A-537 ² Grade B Steel (U.S.S. CHARPAC)	Union Carbide United States Steel	Unknown -- extrusion or molding direction determined by thermal expansion measurements
	B205 Baked Carbon vs A-537 Grade B Steel (U.S.S. CHARPAC)	Great Lakes Carbon Co. United States Steel	Extruded

Figure 3. Configuration and dimensions of graphite and carbon specimens.

slot stopped the slider before the end of a stroke and resulted in high friction force readings. The plate configuration finally adopted eliminated this effect as shown in Figure 4. During a cycle of $\pm 1/8$ -inch the changing contact area resulted in the nominal contact pressure varying by a factor of about 2.

The metal plates used to simulate the liner material were 1-1/4-in. x 3/4-in. x 1/8-in. and finished with three different surface roughnesses, (1) as rolled and pickled (25% HCl in H_2O) ~ 125 rms, (2) machine ground to 5 rms finish, and (3) as ground and scored lightly with 320 SiC paper to yield a 15 rms surface perpendicular to the sliding direction.

The following standard experimental procedure was adopted. With the specimens in place the apparatus was evacuated at R.T. to $< 5 \times 10^{-5}$ mm Hg and back filled once with He before evacuating again to $< 5 \times 10^{-5}$ mm Hg. After holding 1 hour at $< 5 \times 10^{-5}$ mm Hg the R.T. experiments were conducted in 2 psig of He flowing at 100 cc/min. For the 100° , 200° , or 400° C experiments heating was begun upon reaching 5×10^{-5} mm Hg and specimens were held at 100° , 200° , or 400° C in vacuum for 1 hour. The apparatus was then filled with He to 2 psig pressure and the experiments conducted at the respective temperatures. The experiments at 800° C were conducted essentially like that of a 400° C experiment except after filling with He at 400° C the specimens were heated to 800° C before sliding commenced.

Plates were cycled between the sliders at a rate of 35 cycles per minute with a stroke of $\pm 1/8$ -inch. Friction force readings were taken at regular intervals during an experiment. The thickness (± 0.0001 -inch) and weight (± 0.0001 gm) of each specimen was measured before and after the experiment. In order to distinguish between weight loss due to outgassing and that due to wear, weight loss was also measured for non-rubbing sliders which were placed alongside rubbing specimens of the same material so that they experienced the same thermal history. The surface roughness of the specimens was measured before and after experiments with a Brush Surfindicator Model 21-1420-00. The stylus of the Surfindicator rapidly wore a groove in the surface of the graphite so readings had to be taken before the fourth or fifth pass of the stylus over a given area to obtain a representative rms value.

With graphite on graphite experiments four sliders and two plates were subjected to each experimental condition (2 runs). With graphite-metal combinations four sliders and four plates were used (2 runs).

Figure 4. Orientation of specimens during sliding wear at the extreme end of a stroke.

5.0 RESULTS AND DISCUSSION

5.1 Base Material on Liner Material

5.1.1 TS835 (MoS₂ Impregnated) Graphite Vs A-537 Grade B Steel

The TS835 graphite was rubbed on A-537 Grade B steel (U.S.S. Charpac) at R.T., 100°, and 200°C for 250-inches. A load of 35.3 pounds was applied to give a nominal contact pressure of 500 psi. At R.T. and 100°C the surface roughness of the steel was either 5 or 15 rms and at 200°C the roughness was either 15 rms or about 135 rms (as rolled and pickled condition). The variation of the dynamic friction coefficient with sliding distance is shown in Figure 5 for individual runs. The uncertainty for friction coefficients for all work reported was estimated at ± 0.05 . The major uncertainty arose from fluctuation in friction force during a stroke. An average value was selected for each stroke.

Except for the first 10-inches of sliding at 100°C the couples with the 5 rms surface gave the lowest friction. The difference was particularly noticeable at R.T. where the maximum difference occurred at about 20-inches and the friction coefficients were about 0.72 and 0.25 for the 15 and 5 rms surfaces, respectively. At longer sliding distances the friction coefficients approached each other so that at 250-inches the coefficient was about 0.35. At 200°C the surface finish of the steel (15 or 135 rms) had little influence on friction up to about 20-inches of sliding. Beyond 20-inches the couple with the more rough steel showed a decline in friction to about 0.12 while the other couple exhibited an increase to about 0.35 at 250-inches. Friction in graphite is sensitive to surface films which develop (Reference 1). The fluctuations in friction with sliding distance is probably related in a complex manner to film development and destruction during sliding. The wear of TS835 on steel produced a surface on the graphite somewhat reflective but perpendicular to the sliding direction relatively deep grooves developed and the surface roughness increased considerably from about 90 rms to values of 200 to 400 rms. The steel surface developed a light adherent coating of graphite during the experiment. Photographs of typical specimens are shown in Figure 6. The thin film of material on the bearing surface of the TS835 was disrupted by the diamond stylus of the profilometer producing a fine powder. This was typical of the graphite bearing surfaces, in general. The carbon surface was not scratched significantly by the stylus.

Figure 5. Temperature and sliding distance dependence of friction for TS835 graphite and B205 carbon on A-537 Grade B steel of various surface roughness in dry helium.

3614-118 (a)
Slider TS835 Graphite, R.T., 15 rms Steel Surface

3614-124 (b)
Slider B205 Carbon, R.T., 15 rms Steel Surface

3614-120 (c)
Slider TS835 Graphite, 200°C, 15 rms Steel Surface

3614-132 (d)
Slider B205 Carbon, 200°C, 15 rms Steel Surface

3614-134 (e)
Slider TS835 Graphite, 200°C, 135 rms Steel Surface
(As Rolled and Pickled) Profilometer marks on slider
perpendicular to wear grooves

3614-136 (f)
Slider B205 Carbon, 200°C, 135 rms Steel Surface
(As Rolled and Pickled)

Figure 6. Typical bearing surfaces of TS835 and B205 carbon on A-537 Grade B steel (U.S.S. CHARPAC), after 250-inches sliding under 35.3 pounds load (500 psi contact pressure), at R.T. and 200°C. (Scale in inches.)

The wear of both TS835 and A-537 steel at R.T., 100°C, and 200°C for 250-inches of sliding is shown in Figure 7. Wear determined by weight loss was found to be unreliable because of the variable amount of weight loss due to outgassing of graphite and carbon specimens. Therefore, wear is presented here as a wear factor which was calculated from thickness changes. The wear factor of Figure 7 represents the volume of material removed per pound load for 250-inches of sliding. Use of the wear factor to predict wear at loads other than used experimentally is valid if wear is directly proportional to load. Because of the characteristic scatter of the wear data, boundaries have been drawn marking the extremes of wear data points in Figure 7 and elsewhere throughout the report. The uncertainty of the calculated wear factor was estimated as $\pm 0.2 \times 10^{-6} \text{ in}^3/\text{lb}$.

The wear of TS835 tended to decrease with increasing temperature above 100°C. For instance on the 15 rms steel surface the wear factor of R.T. was about $4 \times 10^{-6} \text{ in}^3/\text{lb}$ and at 200°C an average value was about $2 \times 10^{-6} \text{ in}^3/\text{lb}$. Because of the wide scatter of data and small number of data points at R.T. and 100°C the effect may be more apparent than real but Cornelius, *et al.*, (Reference 2) have reported similar observations with MoS₂ impregnated carbon graphites. They rubbed carbon-graphites both with and without MoS₂ impregnant on stainless steel in high purity argon. They reported increasing specific wear rates (cm³/cm-kg) from R.T. to 150°C for the impregnated graphite. These wear rates corresponded to wear factors on the order of 2 to $10 \times 10^{-6} \text{ in}^3/\text{lb}$ for 250-inches of sliding. At higher temperatures the wear rates decreased until at 300°C it corresponded to a wear factor of about $2 \times 10^{-7} \text{ in}^3/\text{lb}$. The specific wear rates of unimpregnated carbon graphites increased between R.T. and 400°C by about an order of magnitude (2 to $20 \times 10^{-6} \text{ in}^3/\text{lb}$ corresponding wear factors for 250-inches of sliding). The lower wear rate of the MoS₂ impregnated graphite was attributed to improved lubricity of the graphite brought about by the presence of condensable vapors (S oxidation products, O₂, N₂, CO₂) released by the MoS₂. More work would be necessary to prove or refute this speculation.

The wear of TS835 was much less on the 5 rms steel than on the 15 rms steel surface at R.T. and 100°C. At 100°C the difference was greatest. There appeared to be no difference between TS835 wear on 15 rms and 135 rms steel surfaces at 200°C.

(a) TS835 Graphite

□ vs A-537 5 rms Surface

○ vs A-537 15 rms Surface

△ vs A-537 As Rolled and Pickled (135 rms)

(b) B205 Carbon

○ vs A-537 15 rms Surface

△ vs A-537 As Rolled and Pickled (135 rms)

(c) A-537 Grade B Steel

□ 5 rms Surface

○ 15 rms Surface

△ As Rolled and Pickled (135 rms)

(d) A-537 Grade B Steel

○ 15 rms Surface

△ As Rolled and Pickled (135 rms)

Figure 7. Temperature dependence of wear for 250-inches of sliding of TS835 graphite and B205 carbon on A-537 Grade B steel (U.S.S. CHARPAC) with various surface roughness under a 35.3 pound load (500 psi contact pressure) in dry helium.

The wear of the steel with 15 or 135 rms surface finish was not sensitive to temperature and varied between 1.0 and 3.5×10^{-6} in³/lb for 250-inches at the three temperatures. The 5 rms surface had about the same wear as others at R.T. but much less wear at 100°C. Reduction of steel surface roughness from 135 to 15 rms had little influence on wear of either steel, mating carbon, or graphite at 200°C. However, steel surfaces of 5 rms showed considerably less wear than more rough surfaces for both steel and mating TS835 at R.T. and 100°C. No experiments with 5 rms surfaces were conducted at 200°C.

5.1.2 B205 Carbon Vs A-537 Grade B Steel

Experiments were conducted identical to those of TS835 vs steel except that the variation of surface roughness of the steel was limited to 15 and 135 rms. The 135 rms finish (as rolled and pickled) was used only at 200°C. The results of the friction and wear measurements are shown in Figures 5 and 6 along with results from work with TS835 graphite.

The friction of B205 on steel tended to increase with sliding distance at R.T. and 100°C. At R.T. the friction coefficient started at about 0.32 and increased rapidly at about 10-inches of sliding to about 0.65 where it remained for 240-inches of sliding. At 100°C the friction in one case increased from 0.5 to 0.65 in the first 10-inches and then remained unchanged. In a second run under apparently identical experimental conditions the friction fluctuated from 0.2 to 0.4 and back to 0.2 in the first 20-inches. Then it increased to 0.4 for the remainder of the experiment. No explanation for the difference in friction coefficient magnitude and behavior can be offered at this time.

At 200°C the sliding distance and surface roughness had little influence on friction. The friction coefficient varied between 0.5 and 0.7 up to 250-inches of sliding. The bearing surface of the B205 carbon was porous and non-reflective in appearance. The surface roughness perpendicular to sliding direction decreased during sliding from about 250 rms to values of 100 to 150 rms. The roughness of the plate remained essentially unchanged by the sliding action, however, there was an adherent carbon film developed on the steel bearing surface. Photographs of typical specimens are shown in Figure 6.

Wear in terms of the wear factor for 250-inches of sliding is shown in Figure 7 for B205 vs A-537 steel. There was considerable scatter of data but a weak trend toward increased wear of both carbon and steel with increasing temperature is evident. This observation is in fair agreement with results by Cornelius, et al., mentioned previously (Reference 2). For B205 the wear factor varied between about 0.9 and 10×10^{-6} in³/lb during these experiments while the mating steel surface had wear factors which ranged from 0.4 to 3.0×10^{-6} in³/lb. The surface roughness appeared to have little effect on wear for the two surface conditions 15 and 135 rms at 200°C.

5.2 Post Material on Seat Material

5.2.1 ATJ Vs ATJ Graphite

ATJ graphite was rubbed on itself at R.T., 400°C, and 800°C, for 2500-inches in dry helium under a constant load of 17.7 pounds. However because of the plate configuration the contact pressure varied between about 250 and 500 psi during a complete cycle. Static friction coefficients were measured at 400°C by manually moving the plate very slowly. By this technique the static friction was determined and found to be 5 to 10% higher than dynamic. Differences of this magnitude at the start of a stroke were usually not detectable during normal mechanical cycling because of electronic and mechanical limitations of the recording equipment. Because of program time limitations static friction was not measured for other couples.

The results of the dynamic friction coefficient measurements are shown in Figure 8. At R.T. the friction remained about constant at 0.18 to about 30-inches of sliding then it increased gradually to about 0.38 at 2500-inches. At 400°C the friction increased rapidly during the first 20-inches of sliding from 0.4 to about 0.8 and then decreased rapidly to about 0.35 at 40 to 100-inches. The friction coefficient remained between 0.3 and 0.4 for the remainder of the experiment except for one brief excursion of one run out of two to about 0.65 at 200-inches. This brief increase probably was brought about by a temporary breakdown of the surface film which developed at 400°C. Similar fluctuations in friction have been reported for graphite in air but normally at much longer sliding distances (Reference 1).

Figure 8. Temperature and sliding distance dependence of friction for ATJ vs ATJ graphite and H205 vs H359 graphite under 17.7 pounds load (250-500 psi contact pressure) in dry helium.

At 800°C initial increase in friction from 0.35 to 0.43 was observed at 4-inches followed by a decrease to 0.25 to 0.28 at 20-inches. At 400°C the initial increase and subsequent decrease in friction was usually accompanied by an audible high frequency noise which stopped upon decrease of the friction force. This effect was reproducible and apparently was associated with the amount of gas adsorbed on the graphite. When ATJ graphite was first outgassed at 400°C for 1 hour, 5×10^{-5} mm Hg and then cooled to R.T. before sliding a similar fluctuation in friction was observed; without 400°C vacuum outgassing the initial fluctuation in friction was absent. The results of that work are shown in Figure 9. In addition to the initial rise and decay of the friction coefficient of the outgassed graphite the friction was about twice that of non-outgassed graphite at the start and it remained higher until at about 1000-inches they became similar.

Although the friction at room temperature varied greatly depending upon whether or not the graphite had been outgassed the wear of the specimens in either case was very similar as shown in Figure 10. Both sets of specimens had wear factors of 8 to 50×10^{-6} in³/lb. This represents a case of friction characteristics failing to be a good guide to prediction of wear.

Although there was much scatter of data the wear rates of ATJ at 400° and 800°C was on the average about an order of magnitude lower than at R.T. Experiments by Cornelius, et al., (Reference 2) rubbing graphite on steel in dry argon have shown a maximum in wear at 400°C corresponding to a wear factor of about 200×10^{-6} in³/lb for 2500-inches sliding. Upon heating from 400°C to 600°C the wear decreased by two to three orders of magnitude. This observation raises the possibility that in the ATJ vs ATJ system there may be a maximum in wear rate between R.T. and 400°C. If a maximum exists intuition suggests it may be closer to 400°C than R.T.

The difference in wear rates was readily apparent by observation of specimens. The wear surface at R.T. was non-reflective and deeply grooved parallel to the sliding direction. The surface roughness perpendicular to the sliding direction increased from about 100 to 350 rms. At 400° and 800°C the bearing surface was reflective and the surface roughness perpendicular to sliding was from 30 to 60 rms. Photographs of typical specimens are shown in Figure 11.

Figure 9. Effect of 400°C vacuum bake on R.T. friction of ATJ graphite on ATJ graphite in dry helium. (17.7 pound load, 250-500 psi contact pressure.)

(a) ATJ vs ATJ

(b) H205 Slider vs H359 Plate

Figure 10. Temperature dependence of wear for 2500-inches of sliding of ATJ vs ATJ graphite and H205 vs H359 graphite under a 17.7 pound load (250-500 psi contact pressure) in dry helium.

3614-28 (a)
ATJ vs ATJ, Room Temperature

3614-32 (c)
ATJ vs ATJ, 400°C

3614-36 (e)
ATJ vs ATJ, 800°C

3614-98 (b)
H205 Slider vs H359 Plate, Room Temperature

3614-102 (d)
H205 Slider vs H359 Plate, 400°C

3614-110 (f)
H205 Slider vs H359 Plate, 800°C

Figure 11. Typical bearing surfaces of ATJ vs ATJ and H205 vs H359 graphites after sliding 2500-inches under 17.7 pound load (250-500 psi contact pressure), at R.T., 400°, and 800°C. (Scale in inches.)

5.2.2 H205 Vs H359 Graphite

H205 sliders and H359 graphite plates were rubbed under the same conditions described for ATJ vs ATJ graphite. The friction as a function of sliding distance is shown in Figure 8. At R.T. the friction coefficient was initially 0.25 and it gradually increased to about 0.40 at 2500-inches. At 400°C the friction coefficient was initially 0.22 and increased rapidly to about 0.72 at 10-inches of sliding. The friction then decreased rapidly to a constant value of about 0.32 at 100-inches. At 800°C there was an initial rise in friction coefficient slightly above 0.4 but beyond about 8-inches of sliding it decreased to about 0.28.

The wear of H205 on H359 is shown in Figure 10. The wear was highest at R.T. (6 to 20×10^{-6} in³/lb) and it decreased by an order of magnitude at 400° and 800°C (0.8 to 2×10^{-6} in³/lb). The bearing surface at R.T. was non-reflective and grooved parallel to the sliding direction. The surface roughness was about 180 rms perpendicular to the sliding direction. Both the H205 and H359 surfaces looked similar. At 400° and 800°C the bearing surfaces were reflective and the surface roughness perpendicular to the sliding direction varied between 40 and 70 rms. Photographs illustrating typical specimens are shown in Figure 11.

5.3 Block Material on Block Material

5.3.1 MHLM Vs MHLM

Specimens of MHLM vs MHLM graphite were rubbed 5000-inches at R.T., 400°, and 800°C. Loads of 4.3 and 17.7 pounds were used at each temperature to produce nominal contact pressures of 60-120 psi or 250-500 psi during a cycle. The friction coefficient as a function of sliding distance for the three temperatures is shown in Figure 12 where each curve represents the results of two runs. The general shape of the curves was reproducible and similar to that of the graphites in the preceding section. At R.T. the initial friction coefficients were about 0.20 for the 17.7 and 4.3 pound loads, respectively. The friction increased with sliding until at about 50-inches for the 17.7 pound load and 400-inches for the 4.3 pound load the friction coefficients were about 0.40.

At 400°C the initial friction coefficients were about 0.28 and they rapidly increased to about 0.70 at 10 to 20-inches of sliding. The friction coefficient then decreased to about 0.35 at 200-inches for the 17.7 pound load and

Figure 12. Temperature and sliding distance dependence of friction for PGX vs PGX and MHLM vs MHLM graphite under 4.3 pounds load (60-120 psi contact pressure) and 17.7 pounds load (250-500 psi contact pressure) in dry helium.

1000-inches for the 4.3 pound load. At 5000-inches the friction coefficient of specimens with a 17.7 pound load had increased to about 0.40 while the more lightly loaded specimens had a coefficient of 0.25.

At 800°C the friction of the specimens with two different loads behaved essentially the same. The coefficient was initially about 0.35 and it increased to about 0.38 at 4-inches and then decreased gradually to a constant 0.28 at about 80-inches of sliding.

The bearing surface of the specimens rubbed at R.T. was grooved parallel to the sliding direction and the roughness perpendicular to sliding was measured as 450 to 500 rms. At 400°C and 800°C the surface was reflective although scratches parallel to the sliding direction were apparent. The roughness perpendicular to the sliding direction was about 30 rms. Photographs of typical specimens are shown in Figure 13.

The wear data for MHLM had an exceptional amount of scatter as shown in Figure 14 (b). There was more than an order of magnitude scatter in wear factors at R.T. (9 to 150×10^{-6} in³/lb). The average wear at 400°C and 800°C was about an order of magnitude less than that at R.T. Wear factors at these temperatures ranged from 1 to 8×10^{-6} in³/lb. The wear factors appeared to be essentially independent of load.

5.3.2 PGX Vs PGX

Specimens of PGX vs PGX graphite were rubbed 5000-inches under conditions of temperature and load duplicating those described for the MHLM vs MHLM experiments. The friction coefficients as a function of distance for the three temperatures are shown in Figure 12. The general shape of the curves was reproducible and similar to that of MHLM. For both loads at R.T. the initial friction coefficient was about 0.18. The coefficient increased with sliding distance until at 1000-inches a relatively constant value of 0.52 and 0.40 was indicated for the 4.3 and 17.7 pound loads, respectively.

At 400°C the initial friction coefficient was 0.22 for the 4.3 pound load and it increased rapidly to 0.8 at about 40-inches. The coefficient decreased gradually during sliding until at 5000-inches it was 0.22 again. The specimens under a 17.7 pound load had an initial coefficient of 0.35 which increased to about 0.75 at 20-inches. The friction coefficient then decreased to about 0.32 at 300-inches and it fluctuated between 0.30 and 0.35 for the remainder of the 5000-inches.

3614-86

(a)

Room Temperature

3614-92

(b)

400°C

3614-96

(c)

800°C

Figure 13. Typical bearing surfaces of MHLM vs MHLM graphite after 5000-inches of sliding under 17.7 pounds load (250-500 psi contact pressure), at R.T., 400°C, and 800°C. (Scale in inches.)

Figure 14. Temperature dependence of wear for 5000-inches of sliding of PGX vs PGX and MHLM vs MHLM graphite in dry helium under 4.3 pounds load (60-120 psi contact pressure) and 17.7 pounds load (250-500 psi contact pressure).

At 800°C the 4.3 pound load produced an initial friction coefficient of 0.35 which increased rapidly to 0.40 at 5-inches and then decreased to 0.22 at about 15-inches. The coefficient then increased slowly to a constant value of about .28 at 500-inches. The friction coefficient of the specimens with a 17.7 pound load behaved similar to that of a 4.3 pound load except that after a maximum of 0.4 at 3-inches it declined to a constant .28 at 50-inches without passing through a minimum.

The bearing surfaces of the PGX specimens looked much like those of MHLM under similar sliding conditions. At R.T. the grooves developed parallel to the sliding direction. The surface roughness perpendicular to sliding was 600 to 700 rms. At 400° and 800°C a reflective surface developed with a surface roughness of about 50 rms perpendicular to the sliding direction. Figure 15 shows the wear surface of some typical specimens and cross sections of the wear track. The wear at R.T. and characteristic grooving was obvious under unaided visual inspection. The photomicrograph of the R.T. wear track cross section (Figure 15 c and d) shows smoothly rounded ridges and relatively sharp grooves on one surface and mating surface ridges and grooves. There was no obvious relation between the graphite microstructure and the profile of the grooves. However, the presence of local hard constituents dispersed in the material probably gave rise to the ridges and grooves. Smoothly rounded and sharp ridges appeared on both plates and sliders. The wear at 800°C was barely discernable in the cross section photo (15 f). The wear factors of PGX on PGX for 5000-inches of sliding at R.T., 400°, and 800°C are shown in Figure 14. Wear was highest at R.T. and varied between 20 and 40 x 10⁻⁶ in³/lb for 5000-inches. At 400°C the wear varied between 3 and 20 x 10⁻⁶ in³/lb and at 800°C it varied between 1 and 7 x 10⁻⁶ in³/lb. The wear factors for the lightly loaded specimens were somewhat more than those for the more heavily loaded specimens, but the difference is probably not significant in view of the overall scatter in the data. Specimens were not rubbed 5000-inches under a 4.3 pound load at R.T. However, the data from R.T. experiments with 17.7 pound loads probably gives a good approximation of wear under 4.3 pound loads since no significant load dependence of wear factor was observed at higher temperatures for PGX or MHLM graphites.

3614-56
Room Temperature

(a)

Mounting
Compound

3614-56
Room Temperature, Cross Section of Plate Wear

(b)

I
0.05-in.

3614-56
Room Temperature, Photomicrograph of Cross Section of
Plate Wear Track

(c)

M21996-2

Mounting
Compound

I
0.01-in.

3614-56
Room Temperature, Photomicrograph of Slider Mating
Surface for (c)

(d)

M22243-2

3614-54
800°C

(e)

Mounting
Compound

3614-54
800°C, Cross Section of Plate Wear Track

(f)

M21998-4

I
0.05-in.

Figure 15. Typical bearing surfaces of PGX vs PGX graphite after 5000-inches of sliding under 17.7 pounds load (250-500 psi contact pressure), at R.T. and 800°C. (Scale in inches.)

5.3.3 Load Dependence of Friction in PGX and MHL Graphites

The friction coefficients for two different loads (4.3 and 17.7 pounds) followed the same pattern but the fact that they differed significantly at times during a run is interesting and represents a deviation from the theoretical concept that the friction coefficient should be independent of load. The apparent deviation from theory may be the result of a complex wearing-in process in which development of an equilibrium surface is dependent primarily upon the amount of material removed from or rearranged on the bearing surface. If the surfaces which develop during wearing-in have different characteristic friction coefficients then the sliding distance at which these coefficients are assumed will be dependent on load. For instance, changes in slope of the friction coefficient curve which occur at a given distance for the 17.7 pound load should occur for the specimens under a 4.3 pound load after about four times ($17.7/4.3$) further sliding. The friction coefficient vs distance curves for MHL at R.T., 400°, and 800°C and PGX at 400°C support this conclusion. After the equilibrium surface is attained the classical laws of friction may apply. More work would be needed to confirm this conjecture.

5.4 Related Work

5.4.1 Sliding Distance Dependence of Wear

Wear data of materials is often presented in terms of a specific wear rate with units of (volume of wear) per (unit sliding distance) (unit load). Valid use of these data for prediction of wear at other than experimental conditions requires that wear in the system under consideration be directly proportional to load and sliding distance. In the work with MHL and PGX graphite the evidence indicated wear was approximately proportional to load (Figure 14) at least for 5000-inches of sliding. In order to determine if the rate of wear varied with sliding distance PGX couples were rubbed for 250-, 2500-, and 5000-inches at 400°C under a 4.3 pound load. The results are presented in terms of wear factors in Figure 16. The wear factors for the three sliding distances fell within the range of about 5 to 16×10^{-6} in³/lb. This was about the same range of values calculated for specimens rubbed only 2500-inches. The data indicated that most of the wear measured at 2500- and 5000-inches took place during the first 250-inches of sliding. The rapid wear probably corresponded to a wearing-in

Figure 16. Effect of sliding distance and "wearing-in" pre-treatment on wear of PGX on PGX graphite in dry helium under a 4.3 pounds load (60-120 psi contact pressure).

process which established an equilibrium surface more resistant to wear. This property is likely to be common to all the graphites studied here. The major significance of this finding is that most wear and dust production will probably take place in the first 5% of life for a part designed for a total of 5000-inches of sliding.

5.4.2 Pre-treatment of Graphite to Reduce Wear

The finding that most wear of PGX on PGX took place during initial sliding suggested that a wearing-in process was taking place. Some wearing-in pre-treatments were given PGX specimens in an attempt to determine if significant reduction in wear could be obtained by prior wearing of a bearing surface. Results of this work would help determine the feasibility of surface preparation of graphite reactor components to reduce wear and dust production. Wearing-in treatments and subsequent wearing experiments were conducted as shown in Table 2. The results are shown in Figure 16 in terms of wear factors.

Rubbing of PGX at 800°C resulted in a wear factor about a factor of 2 lower than shown by the non-treated material at R.T. The other pre-treatments and subsequent experiments at 400°C did not yield a significant change in wear compared with non-treated PGX graphite.

The surfaces developed during pre-treatment wearing-in at R.T. and 400°C were evidently disrupted during the interval between their formation and subsequent rubbing at 400°C. On the other hand, surfaces formed at 800°C apparently were effective in preventing wear at R.T. The friction coefficient vs distance curves shown in Figure 17 provide interesting supplementary evidence for these conclusions.

When rubbed at R.T. the PGX previously rubbed at 800°C showed a decreasing friction coefficient (.25 to 0.10) up to about 800-inches, whereas the non-treated specimens showed an increasing coefficient (0.15 to 0.5). At 800-inches the treated specimen exhibited a sharp increase of friction coefficient to 0.45 which then decreased to about .38 at 2500-inches. The sharp increase in friction may have corresponded to partial or complete destruction of the surface developed at 800°C.

Table 2
PRE-TREATMENT EXPERIMENTS
(PGX VS PGX, 4.3 LBS LOAD)
(60 TO 120 psi CONTACT PRESSURE)

Number	Pre-Treatment	Wearing Experiment
1	2500-inches sliding 800°C, dry He followed by 1 month exposure to laboratory air	2500-inches sliding R.T., dry He
2	250-inches sliding 400°C, dry He followed by 2 weeks exposure to laboratory air	2250-inches sliding 400°C, dry He
3	250-inches sliding R.T., laboratory air 1 hour subsequent exposure to laboratory air	2250-inches sliding 400°C, dry He
4	None	2500-inches sliding R.T., 400°, 800°C, dry He

(a) Room Temperature

— No pre-treatment

-x-x- Specimens pre-treated by sliding 2500-inches at 800°C in He, 4.3 lbs load followed by 1 month exposure to laboratory air

-+- Rubbed in air -- no pre-treatment

(b) 400°C

— No pre-treatment

-x-x- Specimens pre-treated by sliding 250-inches at 400°C in He, 4.3 lbs load followed by 2 weeks exposure to laboratory air

o-o- Specimens pre-treated by rubbing 250-inches in air at R.T. followed immediately by the experiment in He.

Figure 17. Effect of a pre-treatment "wearing-in" on friction of PGX vs PGX graphite under a 4.3 pound load (60-120 psi contact pressure) in dry helium.

At 400°C the treated and non-treated specimens had very similar friction coefficient vs distance characteristics suggesting the wearing-in process was essentially the same in each case. An interesting deviation was the rapid rise and decline of friction for a non-treated specimen at about 200-inches. This transient condition may have been the result of a temporary breakdown in the developing surface.

The bearing surface developed by rubbing in air at R.T. was reflective and smooth as opposed to the non-reflective and rough surfaces produced at R.T. in dry helium. It is interesting that although the sliding distance and friction coefficients were lower for PGX in R.T. air relative to helium at 800°C (Figures 12 and 17) the wear factors were similar (0.9 to 3.2×10^{-6} in³/lb in R.T. air vs 1 to 6×10^{-6} in³/lb in 800°C helium) as shown in Figure 16.

5.5 Summary and Conclusions

The friction couples PGX vs PGX, MHLM vs MHLM, ATJ vs ATJ and H359 vs H205 were rubbed with oscillating motion 2500- or 5000-inches in dry helium (~ 2 ppm H₂O) at R.T., 400°, and 800°C. Loads of 17.7 pounds were used to produce nominal contact pressures of 250-500 psi. The PGX and MHLM couples were also rubbed under a 4.3 pounds load (60-120 psi). A baked carbon (B205), and MoS₂ impregnated graphite (TS835) were rubbed on A-537 Grade B steel 250-inches in dry helium at R.T., 100°, and 200°C under a 35.3 pound load (500 psi contact pressure). Friction and wear was correlated with rubbing distance, temperature, load, pre-treatment of PGX surfaces, and surface roughness of the A-537 Grade B steel.

The following major conclusions with regard to relative friction and wear properties can be drawn from the experimental results.

- TS835 and B205 Vs A-537 Grade B Steel
(Base Material Vs Liner Material)

The friction coefficient of TS835 on A-537 steel at 200°C was significantly lower than that of B205 on steel (0.1-0.4 vs 0.5-0.7). At R.T. and 100°C a complex relationship of friction coefficient and distance existed which made comparison difficult. The range of coefficients observed was 0.1 to 0.7.

Wear of TS835, B205, and steel plate was about the same for steel surface roughness of 15 or 135 rms (as rolled and pickled). Significantly lower wear was obtained by use of steel plate with a 7 rms surface roughness.

No significant difference in wear rate could be detected between TS835 and B205 on similar steel surfaces. Wear of steel was about the same under both materials except at R.T. where the B205 produced less wear than TS835.

Wear was not very sensitive to temperature. Wear factors of 2 to 8×10^{-6} in³/lb were typical for TS835 and B205. Wear factors for the A-537 steel were in the range 1 to 3×10^{-6} in³/lb when rubbed on TS835 and 0.4 to 3×10^{-6} when rubbed on B205.

• ATJ Vs ATJ, H359 Vs H209
(Seat Material Vs Post Material)

The friction characteristics of the two material couples were complex but similar.

There apparently was a wearing-in process which caused significant initial fluctuation in friction coefficient, particularly at 400°C, (0.40 to 0.85). However, from approximately 200-inches to 2500-inches the friction coefficient was constant at about 0.38, 0.35, and 0.28 for R.T., 400°C, and 800°C, respectively.

Wear decreased with increasing temperature.

The wear data had considerable scatter and the materials were similar enough so that one graphite was not clearly superior to the other. Ranges of wear factors were 7 to 50×10^{-6} in³/lb, 0.7 to 4×10^{-6} in³/lb, and 0.7 to 1.5×10^{-6} in³/lb at R.T., 400°C, and 800°C, respectively.

• MHLM Vs MHLM, PGX Vs PGX
(Block Material Vs Block Material)

The influence of sliding distance on friction was complex but similar for the two material couples.

As with the graphites discussed previously there apparently was a wearing-in process which caused initial fluctuation in friction coefficients particularly at 400°C (0.2 to 0.8 for PGX). However, by 100- to 200-inches the friction coefficients were relatively stable at 0.35 - 0.5, 0.22 to 0.40, and 0.30 to 0.32 for R.T., 400°, and 800°C respectively.

Because of the wide scatter of data and apparent similarity of wear properties one couple was not obviously superior to the other. Ranges of wear factors were $20 \text{ to } 40 \times 10^{-6} \text{ in}^3/\text{lb}$, $3 \text{ to } 15 \times 10^{-6} \text{ in}^3/\text{lb}$, and $1 \text{ to } 7 \times 10^{-6} \text{ in}^3/\text{lb}$ for PGX at R.T., 400°, and 800°C, respectively. For MHLM the ranges were $9 \text{ to } 150 \times 10^{-6} \text{ in}^3/\text{lb}$, $2 \text{ to } 9 \times 10^{-6} \text{ in}^3/\text{lb}$, and $1 \text{ to } 9 \times 10^{-6} \text{ in}^3/\text{lb}$ at R.T., 400°, and 800°C, respectively.

• Sliding Distance Dependence of Wear

Essentially all the wear of PGX sliding 5000-inches at 400°C in dry helium took place within the first 250-inches of sliding. This initial high wear rate was probably associated with a wearing-in process which established an equilibrium surface resistant to wear.

• Pre-treatment of Graphite to Reduce Wear

Pre-treatment of PGX graphite by rubbing 250-inches at R.T. in air and 400°C in helium did not improve the wear properties at 400°C in helium. However, specimens rubbed 2500-inches in helium at 800°C showed about a factor of 2 less wear in helium at R.T. relative to non-treated specimens.

• Relative Wear of Graphite in Air and Helium

Wear of PGX graphite during 250-inches of sliding at R.T. in air under a 4.3 pound load was about an order of magnitude less than that for sliding 2500-inches in helium at R.T. ($0.9 \text{ to } 3.2 \times 10^{-6} \text{ in}^3/\text{lb}$ vs $18 \text{ to } 38 \times 10^{-6} \text{ in}^3/\text{lb}$). However, wear during 2500-inches sliding of PGX at 800°C in dry helium was similar to that for 250-inches in air at R.T. ($1 \text{ to } 6 \times 10^{-6} \text{ in}^3/\text{lb}$ vs $0.9 \text{ to } 3.2 \times 10^{-6} \text{ in}^3/\text{lb}$).

6.0 RECORDS AND PERSONNEL

Experimental work was performed by R. Hansen, C. Creutz, R. Earle, and R. Frazee. Data were recorded in General Atomic Notebook 3614.

7.0 REFERENCES

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