Wear of High Speed, High Current Density Slip Ring Materials at Elevated Temperatures

by

David Alan Stephenson

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ABSTRACT

Wear tests were performed on two high speed, high
current density brush materials inside a chamber whose
internal ambient temperature could be varied. The tests were
conducted to study the effect of frictional and electrical
heating on brush system life. A three-pin-on-disk test geometry
was used with graphite and silver-graphite (75 w/o Ag) pins
sliding on copper and platinum flats. Specimens sliding
in air at .41 m/s under a one kilogram load showed a gradual
increase in wear with increasing temperature until some
critical temperature was reached, after which the wear became
severe. For graphite on copper, graphite on platinum,
silver-graphite on copper, and silver-graphite on platinum
this critical temperature was 300°C, 225°C, 250°C, and 225°C
respectively. In general platinum flats and graphite pins
gave lower wear than did copper flats and silver-graphite pins.
Tests with graphite sliding on copper at .16 m/s in air and
.41 m/s in wet CO₂ showed, as expected, no dependence of the
wear rate on sliding speed and, surprisingly, a higher wear
rate at higher humidities. Friction data from all tests
showed more statistical scatter than expected, but indicated
a general increase in friction with increasing temperature.

Thesis Supervisor:  Dr. Ernest Rabinowicz
Title:  Professor of Mechanical Engineering
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I. INTRODUCTION

There has been considerable research interest recently in the area of high speed, high current density brush systems! 2,3,4 The development of such systems is important to the development of lighter, more compact electric motors and generators, and to applications such as Homopolar generators which require cyclic or pulsed power. The trend in current research has been toward obtaining data at as high a surface speed and current density as possible. Such a trend is natural from a practical and economic point of view; however, the combination of high speed and high current density alter a number of wear parameters at once, often making it difficult to assign the observed effects to the influence of one or more of the parameters. It would therefore be desirable to study the effect of varying some of these parameters while holding the other factors constant.

These tests were undertaken to study the influence of the temperature of the contact interface on brush wear. At high sliding speeds and current densities this temperature can rise due to frictional heating and electrical losses. To avoid theoretically estimating the magnitude of the temperature rise due to these factors the tests were run at low sliding speeds with no current passing through the brushes. Under these conditions the interfacial temperature was assumed to be roughly equal to the ambient temperature in the test.
chamber, which was variable. The tests were performed using graphite and silver-graphite (75w/o Ag) pins sliding on a copper flat, since these are common material combinations in present slip-ring systems. Tests were also conducted with the same pin materials sliding on a platinum flat, since recent research has established that silver-graphite brushes sliding on a noble metal ring is a good material combination for high speed, high current density applications.¹

II. THEORY

II.1 Adhesive Wear Theory

No surface is infinitely smooth; on a microscopic level, it must consist of a series of coplanar ridges and depressions. Fig 2.1(a) shows a microscopic cross-sectional view of two surfaces in sliding contact. Note that, because of surface roughness, contact occurs at distinct sites, rather than over the entire apparent interfacial area. The sum of the areas of these contact sites is called the real area of contact; it can be estimated from the contact load and the penetration hardresses of the materials in contact by assuming that the extreme pressures at the sites cause complete plastic deformation there; such an analysis yields⁶

\[ A_r = \frac{L}{p} \]  

(2.1)
Fig. 2.1. Two surfaces in sliding contact.

(a) Microscopic view of sliding interface. Arrows indicate sliding direction.

(b) Enlargement of dashed box in (a), showing original interface (I) and two other possible surfaces of separation (II and III).
where $A_r$ is the real area of contact, $L$ is the normal load, and $p$ is the penetration hardness of the softer material.

It can be seen from Fig. 2.1(a) that, as sliding continues, contact will be broken and re-established at different sites continuously. Fig. 2.1(b) shows a contact site and its original interface. Since there are strong adhesive forces between the atoms of both materials at the interface, there is a finite probability that the materials will separate along some other surface (or surfaces) when contact is broken. (The actual surface of separation is generally, but not always, largely inside the material with lower bulk strength.) On a macroscopic level this process results in transfer of material from one surface to the other and in the formation of loose wear particles. The net magnitude of these effects across a surface is usually characterized by Archard's Wear Equation:

$$V = \frac{KILx}{p}$$

where $V$ is the volume of material worn away, $K$ is the adhesive wear coefficient, $L$ is the normal load, $x$ is the total sliding distance, and $p$ is the penetration hardness of the material.

II.2 Wear of Graphite

Graphite brushes consist largely of carbon black particles (about 200 Å in diameter in many cases) arranged in planes
parallel to the surface. The distance between atoms within
the planes is much smaller than the distance separating
adjacent planes, making the bonds between planes much weaker
than those within the planes. Thus any fracture within a
graphite body is likely to occur between planes. Thus graphite
brushes generally wear by transferring small, flat platelets
to the metal ring. In the ideal case these platelets build up
into a lubricating film which coats the ring and greatly
reduces sliding friction and wear.

Film formation and lubricating value are strongly influenced
by the atmosphere in which sliding occurs. In extremely
dry atmospheres graphite brushes seize upon slip ring materials
and wear away rapidly in a fine dust. Water vapor molecules
tend to cover the exposed graphite film, producing a transient
monolayer which lowers the surface free energy, the attractive
forces between sliding layers, and thus the adhesive wear. A
certain critical level of water vapor is necessary to prevent
brush dusting; for slip rings sliding in air under normal
conditions, this level is about two grams of water per cubic
foot of air. At higher temperatures, the relative humidity
of the atmosphere drops, decreasing the tendency of the water
molecules to form the lubricating layer. Thus as temperature
increases, wear should gradually rise until some critical
temperature is reached, after which no lubricating layer forms
and wear becomes severe.

Adding metal powder such as silver to graphite brushes
increases friction and wear, but improves electrical properties
considerably\(^1\). For silver-graphite brushes the optimum composition is roughly 75% silver, 25% graphite by weight. In the wear mechanisms of metal-graphite brushes the influence of the graphite predominates\(^1\). Silver-graphite brushes are known to wear by the dusting mechanism described above at temperatures above 200\(^\circ\) C.\(^{12}\)

II.3 Wear of Slip Ring Metals

Slip ring ring material selection is usually governed by the electrical properties of the surface oxide layer that forms on the exposed faces of many metals\(^{12}\). The oxide layer of copper is a relatively good conductor, so copper is commonly used as the ring material. Aluminum is not used since its oxide is an insulator; the contact resistance of an aluminum ring would be so high that heating due to electrical losses would cause a substantial temperature rise at the interface and severe brush wear.

The Noble Metals (silver, gold, palladium, platinum, ruthenium, rhodium, rhenium, iridium, and osmium) form very limited or no oxide layers under normal conditions and are thus good ring materials\(^1\). When used with metal-graphite brushes, brush and ring metal combinations that are metallurgically incompatible (i.e. that show a low degree of solid solubility and form two liquid phases when molten) give the best friction and wear behavior\(^{13}\). Based on these considerations silver and platinum are metallurgically compatible\(^5\) and therefore not
the best possible material combination available.

II.4 The Temperature Rise at the Sliding Interface

The temperature rise at the interface is estimated by modeling a contact site as a circular junction of radius \( r \). The radius \( r \) of the equivalent junction can be estimated by

\[
r = \frac{12,000 G}{p} \quad (2.3)
\]

where \( r \) is the junction radius, \( G \) is the surface energy, and \( p \) is the penetration hardness of the softer material. Using this model, the temperature rise due to frictional heating is linearly proportional to sliding velocity at low sliding speeds:

\[
\Theta_f = \frac{fLv}{4J(k_1 + k_2)r} \quad (2.4)
\]

where \( \Theta_f \) is the frictional temperature rise, \( f \) is the friction coefficient, \( L \) is the normal load, \( v \) is the sliding velocity, \( J \) is the mechanical equivalent of heat, and \( k_1 \) and \( k_2 \) are the thermal conductivities of the surfaces in contact. At higher sliding speeds the frictional temperature rise is proportional to the square root of the sliding speed:

\[
\Theta_f = \frac{fLv^{\frac{3}{2}}}{3.6J(\rho or^2k)^{\frac{1}{2}}} \quad (2.5)
\]
where \( \rho_c \) is the volume specific heat of the extended surface (the ring in a slip ring system) and \( k \) is the thermal conductivity of the extended surface.

When current is passing through the junction, an electrical heat generation term proportional to the square of the current is added to the frictional heat generation term in the above equations\(^{14}\). For low and high sliding speeds, respectively, this gives

\[
\theta = \frac{fLw + i^2R}{4Jr(k_1 + k_2)} \quad \text{(low speeds)} \quad (2.6)
\]

\[
\theta = \frac{fLw^{1/3} + (i^2R/v^{1/3})}{3.6J(\rho cr^3k)^{1/3}} \quad \text{(high speeds)} \quad (2.7)
\]

where \( i \) is the current and \( R \) is the electric contact resistance.

If the further assumption is made that contact occurs at a single circular junction whose area is given by (2.1) the relation for high sliding speeds becomes\(^{15}\)

\[
\theta = \frac{(vw)^{1/3}rp\Pi}{(\rho ck)^{1/3}3.6J} + \frac{i^2R}{3.6J(\rho cr^3k)^{1/3}} \quad (2.8)
\]

or, alternately,

\[
\theta = \frac{p^{3/4}}{1.5J(\rho ck)^{1/3}} \left( fV^{1/4}L^{1/4} + \frac{i^2R}{L^{3/4}v^{1/4}} \right) \quad (2.9)
\]
Substituting typical values for experiments performed in this investigation \((v = 0.41 \text{ m/s}, r = 0.15 \text{mm}, k_1 + k_2 = 2.5 \text{ cal/cm/}^\circ \text{C/s}, f = 0.2, L = 1 \text{kg})\) into (2.6) gives \(\theta = 13.3^\circ \text{C}\).

Therefore for the tests in this investigation the temperature at the sliding interface was roughly equal to the ambient temperature in the test chamber.

III. EXPERIMENTAL APPARATUS AND PROCEDURE

III.1 Apparatus

These tests used the geometry of three pins of the brush material sliding on a flat of the ring material. Fig. 3.1 shows the apparatus employed. The flat and pins were located inside a test chamber equipped with thermal insulation and heating coils along its interior walls. This chamber is shown schematically in Fig 3.2. The voltage in the heating coils, and thus the ambient temperature in the chamber, was controlled by a Variac V-20 voltage regulator. This temperature was measured by a thermocouple inserted through an access hole in the chamber door and connected to a Hewlett-Packard model 3440A digital voltmeter. The ring material flat was fixed through a holder to a shaft which passed through the floor of the chamber and was driven through a speed reducer by a two horsepower variable speed electric motor. The brush material pins were fixed through a holder to a
Fig. 3.1. Experimental apparatus.
Fig. 3.2. Schematic illustration of test chamber.
shaft which passed through a ball bushing at the top of
the chamber. This shaft terminated in a dead load and the
frictional force measurement system shown in Fig. 3.3.
This system consisted of a strain gauge ring transducer
contacted by a flange on the shaft. The point of contact
was roughly the same radial distance from the shaft as the
brush material pins; the force applied to the ring was therefore
roughly equal to the frictional force at the sliding interface.
The strain gauge ring output a voltage linearly proportional
to the load applied at the contact point; this voltage
was recorded by a Sandborn model 150 chart recorder, which
was connected to the transducer through a Sandborn model
150-400 power supply and model 150-1100AS preamplifier.
The procedure used to calibrate this system is described
in Section III.2 below. Due to technical difficulties
with the strain ring, a spring that obeyed Hooke's law in
the region of forces encountered was used in its place during
some of the later tests. In these cases the frictional
forces were calculated by measuring the compression of the
spring with a ruler.

The apparatus described has been used in previous
investigations; a more complete description of it can be
found in reference 16. Portions of the drive and electrical
systems were replaced during testing to insure accurate
sliding speed and temperature control. The ball bushing
was not replaced, but was examined and lubricated periodically
to insure relatively friction-free shaft rotation and more
Fig. 3.3. Friction measurement system. (a) Top view. (b) Front view. Arrows indicate direction of frictional torque.
accurate sliding friction measurements.

III.2 Procedure

Before each test both the pins and flat were abraded down to number 400 emery paper and wiped with a paper towel to remove residual grit. They were then weighed on a balance with resolution .01 mg and placed in the test chamber. After each test the flat and pins were removed from the chamber and placed on a large steel mass to accelerate cooling. Test specimens at 200°C typically reached room temperature within fifteen minutes. The flat and pins were then weighed again; the difference in weights and the material densities (given in Table A.2 in the Appendix) were then used to determine the volumes of each material worn away, which were then substituted into (2.2) to compute an adhesive wear coefficient for both the flat and pins. The wear during each test was characterized by a single wear coefficient equal to the geometric average of the pin and flat coefficients:

\[ K = \frac{1}{2}(K_{\text{flat}} + K_{\text{pins}}) \quad (3.1) \]

The specimens usually showed a weight loss during the tests; in instances when the flat gained weight, a negative wear volume based on the density of the flat material was substituted into (2.2), yielding a corresponding negative term in (3.1) above.
The frictional force measurement system was calibrated by connecting a known dead weight by a string to the strain gauge ring and suspending it over a pulley to produce a known gravitational force. Friction measurements were generally taken at the start and finish of each test, and at times one-third and two-thirds of the way through.

For tests in wet CO₂, the gas was bubbled through three flasks of slowly simmering water and introduced into the chamber through a small hole in the door. The gas flow was started fifteen minutes before sliding was initiated to insure that the original air atmosphere was displaced.

III.3 Experimental Program

As mentioned previously, tests were performed on both graphite and silver-graphite (75 w/o Ag) pins sliding on both copper and platinum flats. In order to simplify comparison of different material combinations most of the tests were conducted under the same sliding conditions. These standard tests were one-half hour long with a sliding speed of 0.41 m/s, a normal load of 1 kg, and an air atmosphere.

Additional tests were performed with graphite pins sliding on copper to verify certain theoretical expectations. Tests were run for 75 minutes at 0.16 m/s to show that the frictional temperature rise for the tests was small and the wear therefore independent of sliding speed. Tests were also performed in a wet CO₂ atmosphere under otherwise
standard conditions to determine the effect of humidity on wear.

IV. PRESENTATION OF DATA

IV.1 Test Conditions

Fig. 4.1 shows the wear data from a series of room temperature tests conducted under a 1 kg load with graphite pins sliding in air at .41 m/s on a copper flat. As can be seen, under these conditions this material combination reaches a steady state in which the wear rate is essentially zero after roughly one-half hour. Fig. 4.2 shows data for .5 and 1.5 hour tests performed under the above sliding conditions at room temperature, 100°C, and 150°C. This data shows that as temperature increases the time required to reach this steady state also increases, possibly becoming infinite at some critical temperature. A knowledge of conditions under which the steady state is reached within a reasonable amount of time could be of some economic value; however, since the apparatus used could not operate at commercial sliding speeds, it was felt that studying the wear rate as a function of temperature under non-steady-state conditions would yield more useful results. Therefore, unless otherwise indicated the tests described in Sections IV.2 and IV.3 were conducted in air for .5 hour with a sliding speed of .41 m/s.
Fig. 4.1. Weight loss vs time for graphite sliding on copper at .41 m/s.
Fig. 4.2. Variation of ratio of .5 hr. tests to 1.5 hr. tests (R) with temperature for graphite sliding on copper at .41 m/s.

\[ R = \frac{\Delta W (0.5 \text{ hr. test})}{\Delta W (1.5 \text{ hr. test})} \]
All tests were conducted with a normal load of 1 kg and a wear track diameter of 3.8 cm.

The friction data for the room temperature tests of Fig. 4.1 is plotted with that of later tests in Fig 4.5. Friction readings tended to be erratic at the beginning of all tests but to approach a constant value as sliding continued. This constant value was deemed more characteristic of the tests conditions than the initial readings, which most likely depended on finitely controllable initial factors such as surface roughness and impurities. For this reason friction values reported for all tests are the average values of readings taken during the last half of the respective tests.

IV.2 Tests on Graphite Pins

Figs. 4.3 and 4.4 show the wear data for graphite pins sliding on copper and platinum flats. Brush dusting (as described in Section II.2, page 10) occurred at 225 °C for the graphite/platinum combination. Dusting did not occur in the graphite/copper tests; the large wear coefficient at 300 °C was due to graphite burning and surface reactions in the copper which left a thin, brittle film on the flat. Friction data for the above tests is given in Fig. 4.5.

Wear data for additional tests on the graphite/copper combination is given in Fig. 4.6. One series of tests was run under the standard sliding conditions in a wet CO₂
Fig. 4.3. Wear data for graphite pins

- sliding on copper
- sliding on platinum

sliding speed = .41 m/s

K is defined by equations 2.2 and 3.1
Fig. 4.4. Enlargement of low-wear portion of
Fig. 4.3.

Log $K = -5.12 + 0.0024T$
(least-squares fit for copper data)
Fig. 4.5. Friction data for graphite pins sliding at .41 m/s

\[ f = \frac{F_{\text{friction}}}{F_{\text{normal}}} \]

- on copper
- on platinum
atmosphere; in this environment graphite burning occurred at 250 °C. A second series of tests was run in air at a sliding speed of .16 m/s. These tests were run for 75 minutes to give a total sliding distance comparable to that of the .41 m/s tests. The dashed line in Fig. 4.6 represents a least-squares fit to the graphite/copper data in Fig. 4.4. Friction data for the wet CO₂ and .16 m/s tests is given in Fig. 4.7.

IV.3 Tests on Silver-graphite Pins

Wear data for silver-graphite pins sliding on both copper and platinum flats is given in Figs. 4.8 and 4.9; friction data is given in Fig. 4.10. Brush dusting occurred at 225 °C with the silver-graphite/platinum combination. With the silver-graphite/copper combination, small abrasive particles formed at 250 °C, causing deep scratches in the flat. There was some evidence of graphite burning near the sliding interface in these tests, suggesting that these particles were derived from the silver.

IV.4 General Trends in the Data

The data presented in the previous three sections was generally consistent and repeatable. Some statistical scatter is evident, but no more than is often encountered in tribological
Fig. 4.6. Wear data for graphite pins sliding on copper.

- 0.16 m/s in air
- 0.41 m/s in wet CO$_2$

--- Least-squares fit for 0.41 m/s in air
Fig. 4.7. Friction data for graphite pins sliding on copper.

- .16 m/s in air
- .41 m/s in wet CO₂
Fig. 4.8. Wear data for silver-graphite pins sliding at .41 m/s.

- on copper
- on platinum
Fig. 4.9. Low-wear portion of Fig. 4.8.
Fig. 4.10. Friction data for silver-graphite pins sliding at .41 m/s.

- on copper
- on platinum
research. Overall, the data indicates a general increase in both friction and wear with temperature, although the silver-graphite/platinum combination shows an apparent decrease in the stable region. Graphite pins and platinum flats gave slightly lower wear than did silver-graphite pins and copper flats in most cases. All material combinations tested gave severe wear at temperatures above a definite critical value. Varying the sliding speed by a factor of 2.5 did not significantly alter the wear rate under the low speed, zero current sliding conditions. The tests in the wet CO₂ atmosphere, however, showed significantly higher wear than corresponding tests in the less humid air atmosphere.

Except for the increased wear observed in the wet CO₂ atmosphere and, to a lesser extent, the apparent decrease in wear with increasing temperature for the silver-graphite/platinum combination, the results agree fairly well with theoretical expectations. For this reason, the discussion in Chapter V (except for Section V.1) will focus largely on assessing the accuracy and applicability of the data obtained; in most cases, sufficient theoretical discussion can be found in Chapter II.
V. DISCUSSION OF RESULTS

V.1 Deviations from Theoretical Predictions

The most surprising results obtained in this investigation were those from the tests conducted in the wet CO₂ atmosphere. These tests gave significantly higher wear rates than corresponding tests run at a lower humidity; this contradicts theoretical predictions and the published results of some previous investigations⁹. Fig. 4.7 shows generally higher friction for these tests as well, suggesting that the higher wear rate may be due to increased interfacial temperatures under these conditions. Graphite burning occurred at 250 °C in the wet CO₂ atmosphere, compared with 300 °C in air, indicating that the chemical climate and/or heat transfer characteristics of the system were altered to some degree. It is also known that water vapor molecules can enter cracks in the graphite at the sliding interface which form just prior to separation of a contact site (cf Section II.1), disrupting interplanar bonds and encouraging the transfer of graphite platelets to the flat material⁶. While this is generally considered a beneficial effect that enhances film buildup and thus reduces wear, under conditions of extremely high humidity it could conceivably cause excessive brush wear. The wet CO₂ was produced by bubbling dry CO₂ through three flasks of slowly simmering water, and was therefore fairly humid; the
tests did show a slightly higher ratio of brush wear to flat wear than tests in air (cf Table A.2 in the Appendix). In the final analysis the wet CO$_2$ results suggest that the relationship between humidity and wear for graphite brushes is somewhat more complex than is currently believed; it is quite possible that an optimum humidity exists at which the wear rate is minimum for given sliding conditions. The nature of this relationship might therefore be worth further investigation.

The apparent decrease in wear with increasing temperature for the silver-graphite/platinum combination is statistically more suspect than the wet CO$_2$ atmosphere results; the friction and wear data from the tests on silver-graphite pins showed more scatter in general than the data from the graphite pin tests. While this by no means indicates that this apparent trend is due to random test errors, coupled with the lack of a theoretical reason for the trend it does indicate that more conclusive data is necessary to show that it isn't. In either case, the fact that in three of the four material combinations tested wear increased with temperature and that all four combinations gave severe wear above a certain critical temperature indicates that the theoretical reasoning in Chapter II is essentially accurate, though perhaps somewhat oversimplified in the case of more complicated composite brush systems.
V.2 Accuracy of the Results

As can be seen from Table A.1 in the Appendix, the low wear rates observed in this investigation often resulted in measured flat and pin weight losses in the neighborhood of 1 mg. This is near the threshold below which, due to the specimen handling involved in testing and random drift in the sensitive balance used, accurate weight loss measurement becomes difficult. Although the data appears generally consistent and repeatable, it should be emphasized that the numerical values of the wear rates reported are highly approximate.

Determination of the temperature at which sliding occurred was also subject to some error, due to thermal gradients within the test chamber and the finite accuracy of the thermocouple-voltmeter instrumentation. The reported values are probably accurate to within 25° C, however, and to within 10° C for tests performed below 125° C. The material densities and hardnesses used were also measured quantities; however, the errors involved in these measurements are probably insignificant compared to the weight loss and temperature errors.

The standard sliding conditions and test durations were based on data for the graphite/copper combination, and might not be as well suited to the other combinations tested. However, since the influence of graphite predominates in the wear mechanism of metal-graphite brushes and the wear rates of
the combinations studied are most strongly influenced by graphite film formation, it is reasonable to assume that any bias introduced by the test conditions was small.

V.3 Applicability of the Results

The results presented in this report were obtained from tests on sliding systems at a uniform bulk temperature and in thermal equilibrium with the ambient atmosphere. While this greatly simplified determining the temperature at the sliding interface, commercial slip ring systems operate under considerably different conditions. In a commercial system the brush temperature at the sliding interface is higher than the temperature of either the ambient atmosphere or the portions of the sliding components not near the interface. Due to these thermal gradients, the rate of heat transfer away from the sliding interface is much greater in a commercial system than in the systems studied in these tests; commercial systems, therefore, would probably show lower wear at comparable temperatures and a higher severe wear transition temperature. It is also worth noting that in commercial systems sliding occurs continuously for long periods of time, presumably leading to eventual film buildup and lower wear; the sliding conditions for these tests were chosen to prevent this from occurring. In addition, the brushes tested in this investigation were made of nearly pure materials; brushes in commercial
systems often contain impurities added to decrease chemical reactivity and thus increase the critical temperature for severe wear. Finally, silver-graphite brushes conduct electricity far better than graphite brushes, reducing electrical losses and thus the interfacial temperature rise under given sliding conditions. Thus the generally lower wear for graphite brushes observed under the given zero-current test conditions might not be observed under nonzero-current conditions.

Based on these considerations, it is clear that the results of these tests are more useful for testing theoretical hypotheses about the wear mechanisms of the materials involved than for commercial applications; tests under different thermal and sliding conditions would be necessary to produce data suitable for commercial design.
VI. CONCLUSIONS

Based on the results of the tests conducted in this investigation the following conclusions can be drawn:

(1) The high speed, high current density slip ring system material combinations tested show a gradual general increase in wear with increasing temperature until some definite critical temperature is reached, after which wear becomes severe. For the graphite/copper, graphite/platinum, silver-graphite/copper, and silver-graphite/platinum combinations this temperature is 300° C, 225° C, 225° C, and 250° C respectively.

(2) Friction also shows a general increase with temperature for the material combinations tested.

(3) The wear of the brush system materials tested is strongly dependent on the humidity of the atmosphere in which sliding occurs. Tests conducted in a humid CO₂ atmosphere produced higher wear than tests in less humid atmospheres.

(4) At a given interfacial temperature, graphite brushes and platinum rings give lower wear than do silver-graphite brushes and copper rings.
VII. RECOMMENDATIONS

It is recommended that further experiments in this area be conducted under conditions closer to those in actual slip ring systems. In particular, tests at higher sliding speeds in which the temperature at the sliding interface is higher than either the atmospheric temperature or the bulk temperatures of the sliding components would yield useful results. Other possible areas of research include further investigation into the influence of atmospheric humidity on graphite brush wear and determination of the conditions under which a steady, zero wear rate state is reached.
REFERENCES


15. Rabinowicz, E., private communication
APPENDIX

Table A.1. Table of Raw Data

This table gives the numerical values of measured quantities for all tests. These quantities and the units they are tabulated in are:

Temperature (T) \( ^\circ \text{C} \)
Weight Loss (\( \Delta W \)) \( \text{mg} \)
Friction Coefficient (f) --

The following codes are used for the indicated parameters:

**Test Duration (t)**

| 1 | 30 minutes |
| 2 | 75 minutes |
| 3 | 90 minutes |
| 4 | 3 hours    |
| 5 | 6 hours    |
| 6 | 15 hours   |

**Sliding Conditions (SC)**

| 1 | \(.41 \text{ m/s in air}\) |
| 2 | \(.41 \text{ m/s in wet CO}_2\) |
| 3 | \(.16 \text{ m/s in air}\) |

All tests were conducted under a 1 kg load.
## Tests on graphite/copper

<table>
<thead>
<tr>
<th>Test SC</th>
<th>t</th>
<th>T</th>
<th>$\Delta W_{\text{flat}}$</th>
<th>$\Delta W_{\text{pins}}$</th>
<th>f</th>
<th>Log K</th>
</tr>
</thead>
<tbody>
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Tests on graphite/platinum

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