EFFECTS OF HARDNESS ON THE LIFETIME OF GRAPHITE BRUSHES USED FOR
AIRCRAFT STARTER GENERATORS

A Thesis by

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EFFECTS OF HARDNESS ON THE LIFETIME OF GRAPHITE BRUSHES USED FOR
AIRCRAFT STARTER GENERATORS

The following faculty members have examined the final copy of this thesis for form and
content, and recommend that it be accepted in partial fulfillment of the requirement for
the degree of Master of Science with a major in Mechanical Engineering.

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Ramazan Asmatulu, Committee Chair

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Krishna Krishnan, Committee Member
ABSTRACT

This study concentrates on the relationship between the hardness of three different carbon/graphite brushes and the wear rate of the brushes and heat generated within a 400 Amp starter generator. The method being proposed was to alternate the starter generator from the starting mode and the generating mode, and run each carbon/graphite brush in the starter generator for a set time and document both wear rates and heat created.

The study originated with a starter generator overheating during normal usage. The original hypothesis was that either excess carbon dust caused arcing, or the energy required to form the carbon dust was releasing too much heat, and thus the brush was too hard. The three carbon/graphite brushes chosen for this researched spanned the range of hardness for this type of material.

This thesis analyzed the surfaces of the carbon/graphite brushes to correlate grooves and pitting with the frictional coefficient. An optical microscope, AFM, and SEM were used in the analysis of the surfaces. It was found that as the hardness of the brush went up, the wear rate decreased while the overall heat on the inside of the starter generator increased.

From this research it is evident that the hardness of the brushes is the key factor in the excess heat in the starter generator. The energy that is expelled as heat as the carbon brush gradually wears is directly correlated with the increase of operating temperature. A harder brush will prolong the life of the brushes, but also increases the operating temperature to more than the unit is capable of handling.
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CHAPTER I

INTRODUCTION

1.1 Motivation

Aircraft operators have requested a longer life graphite brush in the starter generators on their aircraft. The anticipated life for the current brushes is set at 3000 hours. What aircraft operators are seeing is a brush life of approximately 300 hours. With this short lifetime, operators are replacing their brushes on an average of ten times for every time they should be replacing them. The extra time that it takes to change the brushes and the cost of the multiple brushes is increasing the cost of operating the aircraft. A brush material must be selected to increase the life of the brushes while keeping the operating temperature of the unit under the maximum limit.

1.2 Background

The brushes being used in the current configuration of the starter generator have been wearing at rates in excess of ten times the anticipated wear rate. The large wear rates have caused excessive carbon dust to gather within the unit. The surface of the commutator has a burned layer of carbon and exaggerated grooving. Thermal coatings of some of the interior components of the starter generator are being burned off, exposing those components to heat above their rated limits. Figure 1 shows a buildup of carbon dust in the armature windings. Figure 2 illustrates a burned coating on the surface of the commutator along with grooving. Figure 3 is a picture of thermal coating which has been burned through leaving exposed material.
Figure 1. Build Up of Carbon Dust

Figure 2. Burned Surface of Commutator
1.3 Objective of Study

The objective of this study was to determine the optimal brush composition to increase the life of the brush in starter generators while keeping the internal operating temperatures of the units at an acceptable level. By finding the optimal brush, the operators that have these units on their aircraft will reduce operating costs and the amount of time that their aircraft are on the ground for maintenance.
CHAPTER II
LITERATURE REVIEW

2.1 Literature Review

Most aircraft are equipped with an auxiliary power unit, or APU, which contains a starter generator. One of the main functions for the APU is to provide electrical power to the systems of the aircraft before the engines have been started. Starter generators have two functions. One is to convert electrical energy to mechanical energy to assist in starting the engines. The other is to take mechanical energy and convert it to electrical energy to help power aircraft systems. Once the engines are started, they are the main source of power for the aircraft. An APU can be either an electric motor, for applications which do not need a great amount of power or an air turbine motor.

Brushes are used in the starter generators to transfer direct current (DC) from stationary equipment to the slip rings of the generator. Every time an electric generator is used, the brushes are subjected to wear. This wear is caused by both friction, and electrical wear, which occurs because of the current passing through an electrical contact [1, 23]. In most applications, the brush life needs to be maximized. Excessive replacement of brushes leads to higher operating and maintenance costs. In the aircraft industry this is of great importance. Aircraft original equipment manufacturers (OEMs) are looking to produce products that have low maintenance costs to keep the cost for the consumer to a minimum.

There are a variety of materials that can be used for either the brushes or the commutator. The brush material is usually chosen for wear and electrical properties.
Materials suitable for the brushes are usually different grades of carbon: electrographite, carbon graphite, or metal graphite [23]. The commutator is usually made from a material such as copper, bronze, brass, or steel [18, 22, 24].

2.2 Brush Wear/Filming

The rate of wear on a graphite brush sliding against a copper commutator has been determined for a wide range of speeds, loads, apparent areas of contact, and current. The primary influence on the magnitude of the wear rate is the surface film generated on the copper. A combination of high speeds and a heavy load will provide a continuous layer of transferred graphite. Without this surface film, the wear rate per unit load is relatively high and is affected by the magnitude of the current [1, 23].

At low speeds and small loads, a surface film of large amounts of oxide will develop in the surface film which prevents the transfer of graphite, and thus the rate of wear decreases. This amount of oxidation depends on the time that is available between the repeatedly made contacts on the copper, the area of the brush, and the speed of the commutator [23, 24]. The current that passes through the oxide film, breaks it down, thus increasing the transfer of graphite, and ultimately increasing the wear rate. The higher the current, the faster the breakdown of the oxide film and transfer of graphite; and this will lead to higher wear rates [18, 24].

A good film will be chocolate brown or a burnished bronze color, not bright copper or burnt black [1, 23]. A false film can be developed from graphite if the brushes adhere to the surface of the commutator, turning it the same dark brown as a good film. Another false film can be caused by oil, which has the appearance of a good film. The
optimal thickness of the copper oxide film is only around 200 nano-inches thick [23, 24]. Changes in the current, humidity and other conditions will all affect the thickness and quality of the film.

Figure 4. Commutator with Appropriate Copper Oxide Film

The wear rate for graphite brushes has an upper limit. As the current increases, the transfer of graphite will eventually become continuous and thus cannot be increased [23]. Thus, it has been concluded that the wear of graphite brushes is a fatigue process. This is because of the repeated elastic stresses over localized regions from actual contact [23].

If a good film can be developed on the surface of the commutator, this can reduce the coefficient of friction to 10% of the original value for bare copper [24]. The friction between the brushes and copper commutator is dependent upon the temperature. As the temperature rises, the coefficient of friction decreases, but at a critical temperature, the coefficient of friction starts to rise again. Excess friction can also be caused by problems within the setup, such as excessive spring brush pressure,
a feathered edge on one of the copper bars on the commutator, or any other imperfection on the surface of the commutator [23].

![Temperature vs Friction Graph](image)

**Figure 5. Coefficient of Friction and Temperature [23]**

The key requirements for the development of a good commutator film are brush current, density, commutator surface temperature, water vapor, brush pressure, commutator surface speed, brush material, lack of contamination, mechanical integrity, and setup [18, 23].

Appropriate current density for graphite brushes is between 55-85 A/in² [9, 18, 23]. Current density may exceed these values for short periods of operation, but excessive exposure to higher current densities will cause the commutator to acquire a burnt surface that reduces brush life significantly. If the current density is under the rated amount, the surface film will reduce to less than the ideal thickness, causing excessive sparking and grooving of the commutator, and a need to resurface the commutator and replace brushes before the expected life value [9, 23].
The temperature of the commutator face for ideal operation should range between 140°F to 239°F (60°C – 115°C) [23, 24]. Within this range of temperatures, the coefficient of friction is the lowest, resulting to the longest brush life. Excessive heat will not only lead to higher brush wear rates, but also will increase the temperature of the unit, which may lead to problems if the heat generated is above the max allowable for the thermal protection of the unit.

The humidity is also a key requirement for a good commutator film. An absolute humidity of between 2-7 grains of water per cubic foot of air allows for the formation of an ideal film [23]. Humidity values greater than this will lead to excessive filming, and likewise a smaller value of humidity will result in too thin of a film. This is especially important for aircraft, which use these units during flight. At high altitudes, the relative humidity is very low. Thus, during flight, the wear of the brushes is greater than at sea level [23, 24].

Brush pressure will affect the brush wear rate. This involves more than just the pressure of the spring that holds the brushes against the commutator, but also the position of the brush relative to the commutator, coefficient of friction of the brush, commutator speed, and commutator surface finish [18, 22]. A brush pressure that is too great will cause excessive wear and limits the amount of film that can be produced. A brush pressure which is too light will allow excessive sparking, which will lead to a higher wear rate. An ideal brush pressure is between 2-8 lb/in², along with a brush angle between 20-25º [23].

The commutator surface speed influences the coefficient of friction. For commutators that run at speeds greater than approximately 6000 ft/min, a higher brush
pressure is needed, thus increasing the brush wear rate [1, 23]. Also, at higher speeds, the film develops at a lower rate than the rate at which it is being stripped off the surface. For a given rpm, a small diameter commutator will have a lower surface speed than a larger diameter commutator, thus the brush wear rate will be lower and the commutator surface will be allowed to build up to the appropriate thickness [22, 23]. Figure 2.3 illustrates how the film is distributed on the surface of the copper commutator. It helps to fill in the valleys to increase the amount of surface area through which the electric current can pass. The black represents the oxide film filling the grooves on the surface of the commutator and copper color represents the surface of the commutator.

Figure 2.3 illustrates how the film is distributed on the surface of the copper commutator. It helps to fill in the valleys to increase the amount of surface area through which the electric current can pass. The black represents the oxide film filling the grooves on the surface of the commutator and copper color represents the surface of the commutator.

2.3 Carbon

Carbon can be found in two natural crystalline allotropic forms, diamond and graphite. Diamond is composed of carbon atoms that are attached to four other carbon atoms by strong covalent bonds in a tetrahedral structure. Diamond has great resistance to plastic flow, a hardness value of approximately 70 GPa, an elastic modulus of over 1000 GPa and a specific gravity of 3.51 [26]. Graphite’s properties are on the other end of the spectrum. In the graphite form, it has properties of both a non-metal and a metal. Carbon in graphite form can be flexible, but not elastic. The thermal
and electrical conductivity is high. It also is highly refractory and chemically inert. These combinations of properties are due to its crystal structure [7].

Carbon atoms in graphite are usually arranged hexagonally in a planar condensed right system. Each layer is called a basal plane and is stacked parallel to adjoining layers. Within the rings, the atoms are bonded covalently, while the layers are bonded by Van der Waals forces [7, 26]. These two different bonding types within graphite allow it to form a solid film lubricant which is critical in a starter/ generator for the electrical properties. The weak Van der Waals bonding between layers allows the layers to slide over each other, and thus it is an ideal solid lubricant. The figure 7 illustrates the crystal structure of graphite and the atomic spacing [26].

![Figure 7. Crystal Structure of Graphite and Atomic Spacing [26]](image)

In graphite, the carbon atoms are only bonded with three other carbon atoms, not four as in diamond. Not all the valence bonds are satisfied, and thus electrons are free
to move around the crystal structure without impedance [26]. This makes graphite a
good conductor of both heat and electricity. The spacing of the atoms within the basal
planes has been measured to be 1.42 Å. The spacing between the basal planes is
relatively large when compared with other atomic spacing at 3.35 Å [26].

Graphite is not an intrinsically low friction material, but rather relies on the
presence of absorbed layers of oxygen and condensable vapors, which includes but is
not limited to water vapor and hydrocarbons, on the edges of the platelets or graphite
crystallites reducing the attractive forces between the laminates. In the absence of
these absorbed layers, the out gassed graphite will suffer rapid wear and the friction
coefficient can triple to values around 0.4 [7, 26]. When the operating temperature rises
above 100 ºC (212 ºF) the absorbed layers may deteriorate and the result is a rise in
both friction and wear of the brushes and the commutator.
CHAPTER III

EXPERIMENTAL

3.1 Test Procedure

To ensure consistency between all the tests, the armature was removed, the commutator was re-surfaced and undercut, and the brushes were re-seated. Prior to the start of each test, the following parameters were recorded:

- Overall brush length for all brushes
- Diameter and surface finish of commutator
- Pictures of brushes and commutator

After the starter generator was reassembled, all electrical cables and thermocouples were hooked up. The ambient temperature, humidity, time and date were all recorded. Next, the thermocouples started data collection. With the thermocouples recording, the speed of the unit was slowly increased to 12000 rpm and stabilized for 30 seconds, and then 200 Amps of load was applied to the starter generator.

The test was conducted in this fashion for 16 hours. After this was completed, the follow procedure was performed:

- Stop data logging of thermocouples
- Remove starter generator from drive rig
- Measure and record full length of all brushes
- Mount starter generator in starter test rig
- Start data logger to record thermocouple outputs
- Perform starting procedure
• Turn off for 1 minute
• Perform starting procedure
• Turn off for 1 minute
• Perform starting procedure
• Run data logger for 2 minutes after finishing last start cycle and then stop
• Disconnect from starter test rig
• Reconnect starter generator to drive rig

These steps were conducted until 200 hours of total testing time were completed.

After completion of the 200 hours, the starter generator was taken off the test rig and the following steps were taken:

• Measure and record overall length of all brushes
• Remove armature and measure commutator diameter and surface finish
• Take pictures of commutator and brushes
• Evaluate starter generator for any signs of wear or damage

After the first set of brushes was completed, the procedure was repeated for the other brush grades.

Figure 8. Brush Location with Springs and Starter Generator with Thermocouples
3.2 Brush Materials

<table>
<thead>
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<th></th>
<th>Brush Material A</th>
<th>Brush Material B</th>
<th>Brush Material C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Class</strong></td>
<td>Carbon-Graphite</td>
<td>Carbon-Graphite</td>
<td>Electrographitic</td>
</tr>
<tr>
<td><strong>Grade</strong></td>
<td>555</td>
<td>A2006</td>
<td>A2002</td>
</tr>
<tr>
<td><strong>Resistivity</strong></td>
<td>0.0008 ohm-in</td>
<td>0.0011 ohm-in</td>
<td>0.00065 ohm-in</td>
</tr>
<tr>
<td><strong>Hardness</strong></td>
<td>45 Shore</td>
<td>58 Shore</td>
<td>65 Shore</td>
</tr>
<tr>
<td><strong>Transverse</strong></td>
<td>3200 psi</td>
<td>3360 psi</td>
<td>7100 psi</td>
</tr>
<tr>
<td><strong>Apparent</strong></td>
<td>1.72 g/cc</td>
<td>1.76 g/cc</td>
<td>1.79 g/cc</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>80 A/in^2</td>
<td>70 A/in^2</td>
<td>80 A/in^2</td>
</tr>
</tbody>
</table>

The three brush materials that were chosen for this test were selected by their hardness's. From the original hypothesis, it was thought that the hardness of the brush was the main source for all of the heat, due to either the excessive carbon dust that was formed or the energy that it took to cause wear on the brushes. All three brushes have
approximately the same current density and resistivity, since the ability of the brushes to conduct electricity was not being tested in this experiment.

Brush A is a carbon-graphite material containing concentrated molybdenum disulfide particles. The coefficient of friction for this material is low, compared to the other two brush materials that were being tested. This brush is considered a quick filming grade brush that boasts low operating temperature and long life time expectancy.

Brush B is also a carbon-graphite material containing molybdenum disulfide particles to help compensate for low moisture environments that are encountered at high altitudes. It has stable properties throughout all temperature ranges. This brush is treated so that it is non-corrosive under high humidity and high temperatures.

Brush C is an electrographitic grade brush that was specifically designed for long life and minimal commutator maintenance. This brush is polished to prevent over filming the commutator. Over filming can lead to film stripping, and thus high wear to the commutator can be observed if the film becomes unstable. This brush has the same treatment such that it is non-corrosive under high humidity and high temperatures.
CHAPTER IV
VISUAL TESTING

4.1 Visual Testing

After the conclusion of the laboratory testing, the surface of each brush was analyzed. An optical microscope, an atomic force microscope (AFM), and a scanning electron microscope (SEM) were used. The results of these tests are shown below in sections 4.2 thru 4.4. The pitting and waviness were the characteristics which were compared between the brushes.

4.2 Optical Microscope

![Image of Brush Material A at 5x]

Deep Grooving

Large Pitting

Figure 10. Brush Material A at 5x

The surface of Brush A was heavily pitted and contained deep grooves which made obtaining images difficult, as can be seen in Figure 4.1. Brush A was the softest of the materials, and thus the surface was not uniform, unlike the other two brush materials. With this rough surface, the contact area between the brush and the
commutator, even with an appropriate film, would be minimal, leading to localized areas of current transfer. This would cause a high density of pitting, as was observed in the specimen.

Figure 11. Brush Material B at 5x

Uniform Surface

Minimal Pitting

Figure 11. Brush Material B at 5x

Figure 12. Brush Material B at 20x

Brush B showed the most uniform surface. As can be seen from figure 12, the surface has limited grooving, which can be identified from the uniform color. There are no light and dark strips which indicate grooving. This is optimal because it increases the
surface area that is in contact with the copper commutator, allowing for the electric current to be distributed over a larger area, which reduces pitting, and increases life expectancy.

![Figure 13. Brush Material C at 5x](image)

Brush C was in between Brush A and Brush B in grooving and pitting. The grooving was more extensive than Brush B, but was not nearly as pronounced as in Brush A. The amount of grooving that was present decreased the effective surface area
of the graphite brush, localizing the current flow to a smaller area, and increasing the pitting on the face of the brush as seen by comparing this to Brush B.

4.3 AFM

Brush B and C were analyzed using an AFM. Brush A was not analyzed due to the amount of heavy pitting and grooving. The AFM needs a smooth surface to work properly, and the surface of Brush A was not conducive to an AFM image.

Figure 15. Surface of Brush B with AFM
A 50 x 50 micrometer cross sectional area was looked at using the AFM. Small grooves can be seen from the 3D representation of the surface: these occur when the dragging tip of the AFM forms small grooves as it moves along the surface of the graphite.
Figure 18. Surface of Brush C with AFM

Figure 19. Surface Roughness of Brush C
The results of Brush C are similar to those of Brush B. Once again, the grooving of the AFM needle can be seen. The cross section that was chosen was in one of the grooves in order to analyze the interior surface of a groove.
4.4 SEM

Brush B and C were analyzed using a scanning electron microscope (SEM). Based on the results, Brush A was not analyzed because of the similarity it showed with Brush B.

Figure 21. Brush B Contact Surface 25X
Figure 22. Brush B Noncontact Surface 25X

Figure 23. Brush B Contact Surface 250X
Figure 24. Brush B Noncontact Surface 250X
The contact surface of Brush B shows a mild amount of pitting with discolorations at the molybdenum disulfide regions. The grooves can be seen in the 25X and 250X pictures, while the 1400X image of the contact surface shows a typical void. The noncontact surface images show a non-smooth surface. In the image of the contact surface at 250X, lighter and darker regions in the graphite can be clearly seen. This is a result from the manufacturing process and nonsymmetrical distribution of the same crystal structure throughout the brush.
The images from Brush C show considerably more pitting across the contact surface. These pits are from the arcing between the brush and the commutator because of the significant amount of grooving limits the surface area that the electric current may pass through. More grooves can be seen from the images of the contact surface of Brush C than in Brush B. The images of the non-contact surface have similar roughness to those of Brush B.
CHAPTER V
RESULTS AND DISCUSSION

5.1 Results

The results show that there were noticeable differences in both the wear and the temperature profiles between the three different brush materials. From the tests themselves, it was noted that a good commutator profile will have a thin uniform brush track without any signs of pitting or arcing. Also, uneven brush wear between the inner and outer brushes is considered normal and was not excessive. The differences in brush wear between the inner and outer brushes may be due to factors, including but not limited to:

- Temperature differences between the brush locations
- Differences in brush spring force
- Surface finish differences
- Cooling air circulation differences

5.2 Wear

After the results were analyzed, Brush C showed the highest projected brush life of approximately 3106 hours. The projected commutator life for Brush C was the lowest, but still in an acceptable range. The brush temperatures for Brush C yielded the highest for all three brushes with max temperature reaching approximately 235°C, with a noticeable difference between the positive and negative brushes. This larger variance between the positive and negative brush may have been caused by the thermocouples being positioned differently from the other tests.
Brush B tests resulted in the next highest predicted brush life of 509 hours, with a commutator wear life of approximately 9251 hours. The temperatures for these tests were stable, and accounted for the smallest delta in brush temperature between the positive and negative brush. Brush A projected the shortest brush life expectancy of only 488 hours, with a commutator projected life of approximately 44800 hours. The testing of Brush A yielded the most uneven profile for the temperature delta between the positive and negative brush.

**TABLE 2**

**BRUSH MEASUREMENT DATA, STARTING AND ENDING MEASUREMENTS (INCHES)**

<table>
<thead>
<tr>
<th>Phase of Test</th>
<th>#1 Outer</th>
<th>#1 Inner</th>
<th>#2 Outer</th>
<th>#2 Inner</th>
<th>#3 Outer</th>
<th>#3 Inner</th>
<th>#4 Outer</th>
<th>#4 Inner</th>
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<tbody>
<tr>
<td>Brush A Start</td>
<td>1.436</td>
<td>1.421</td>
<td>1.439</td>
<td>1.422</td>
<td>1.443</td>
<td>1.425</td>
<td>1.437</td>
<td>1.425</td>
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<tr>
<td>Brush A End</td>
<td>1.238</td>
<td>1.279</td>
<td>1.230</td>
<td>1.135</td>
<td>1.240</td>
<td>1.144</td>
<td>1.211</td>
<td>1.254</td>
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<tr>
<td>Brush B Start</td>
<td>1.476</td>
<td>1.480</td>
<td>1.482</td>
<td>1.484</td>
<td>1.484</td>
<td>1.489</td>
<td>1.480</td>
<td>1.493</td>
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<tr>
<td>Brush B End</td>
<td>1.267</td>
<td>1.196</td>
<td>1.279</td>
<td>1.201</td>
<td>1.266</td>
<td>1.372</td>
<td>1.268</td>
<td>1.401</td>
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<tr>
<td>Brush C Start</td>
<td>1.483</td>
<td>1.487</td>
<td>1.493</td>
<td>1.496</td>
<td>1.494</td>
<td>1.492</td>
<td>1.488</td>
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<tr>
<td>Brush C End</td>
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<td>1.440</td>
<td>1.439</td>
<td>1.452</td>
<td>1.444</td>
<td>1.437</td>
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**TABLE 3**

**BRUSH WEAR DATA, TOTAL WEAR (INCHES)**

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<th>#2 Inner</th>
<th>#3 Outer</th>
<th>#3 Inner</th>
<th>#4 Outer</th>
<th>#4 Inner</th>
<th>Total Run Hr</th>
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</thead>
<tbody>
<tr>
<td>Brush A</td>
<td>0.198</td>
<td>0.142</td>
<td>0.209</td>
<td>0.287</td>
<td>0.203</td>
<td>0.281</td>
<td>0.226</td>
<td>0.171</td>
<td>200.00</td>
</tr>
<tr>
<td>Brush B</td>
<td>0.209</td>
<td>0.284</td>
<td>0.203</td>
<td>0.283</td>
<td>0.218</td>
<td>0.117</td>
<td>0.212</td>
<td>0.092</td>
<td>206.50</td>
</tr>
<tr>
<td>Brush C</td>
<td>0.045</td>
<td>0.049</td>
<td>0.053</td>
<td>0.057</td>
<td>0.042</td>
<td>0.048</td>
<td>0.051</td>
<td>0.050</td>
<td>226.25</td>
</tr>
</tbody>
</table>
TABLE 4

BRUSH WEAR RATE (INCHES PER HOUR)

<table>
<thead>
<tr>
<th></th>
<th>#1 Outer</th>
<th>#1 Inner</th>
<th>#2 Outer</th>
<th>#2 Inner</th>
<th>#3 Outer</th>
<th>#3 Inner</th>
<th>#4 Outer</th>
<th>#4 Inner</th>
<th>Total Brush Life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush A</td>
<td>0.00099</td>
<td>0.00710</td>
<td>0.00105</td>
<td>0.00144</td>
<td>0.00102</td>
<td>0.00141</td>
<td>0.00113</td>
<td>0.00086</td>
<td>487.8</td>
</tr>
<tr>
<td>Brush B</td>
<td>0.00101</td>
<td>0.00138</td>
<td>0.00098</td>
<td>0.00137</td>
<td>0.00106</td>
<td>0.00057</td>
<td>0.00103</td>
<td>0.00045</td>
<td>509.0</td>
</tr>
<tr>
<td>Brush C</td>
<td>0.00020</td>
<td>0.00022</td>
<td>0.00023</td>
<td>0.00025</td>
<td>0.00019</td>
<td>0.00021</td>
<td>0.00023</td>
<td>0.00022</td>
<td>3105.4</td>
</tr>
</tbody>
</table>

Figure 33. Expected Hours of Brush and Commutator Life

TABLE 5

200 HOUR BRUSH WEAR RESULTS WITH PREDICTIONS

<table>
<thead>
<tr>
<th>Brush Position w/ Greatest Wear</th>
<th>Total Inches Wear During Test</th>
<th>Run Time Hrs</th>
<th>Wear Rate Inches per Hour</th>
<th>Max Allowed Wear</th>
<th>Projected Brush Wear Life in Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush A #2 Inner</td>
<td>0.287</td>
<td>200.00</td>
<td>0.0014350</td>
<td>0.700&quot;</td>
<td>487.8</td>
</tr>
<tr>
<td>Brush B #1 Inner</td>
<td>0.284</td>
<td>206.50</td>
<td>0.0013753</td>
<td>0.700&quot;</td>
<td>509.0</td>
</tr>
<tr>
<td>Brush C #2 Inner</td>
<td>0.051</td>
<td>226.25</td>
<td>0.0002254</td>
<td>0.700&quot;</td>
<td>3105.4</td>
</tr>
</tbody>
</table>
TABLE 6

200 HOUR COMMUTATOR WEAR RESULTS WITH PREDICTIONS

<table>
<thead>
<tr>
<th>Tested Commutator Wear Results</th>
<th>Commutator Physical Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start Dia.</td>
<td>End Dia.</td>
</tr>
<tr>
<td>Brush A</td>
<td>2.678</td>
</tr>
<tr>
<td>Brush B</td>
<td>2.625</td>
</tr>
<tr>
<td>Brush C</td>
<td>2.662</td>
</tr>
</tbody>
</table>

Figure 34. Length of Brushes

The above graph shows the average length of the brushes for each material throughout the testing. All three brushes started with an average length of approximately 1.48 inches, and showed a linear trend in wear rate. The hardest brush, Brush C, exhibited the least wear. Brush A and Brush B showed approximately the
same wear rate with the difference in the length of the brushes remaining relatively constant from the start of the testing to the end of the testing.

![Brush Wear Delta Between Measurements](image)

**Figure 35. Brush Wear Delta Between Measurements**

This graph shows the similarities between Brush A and Brush B through the 200 hours of generating testing time and 12 individual starts. From this graph it can be concluded that there are no advantages between Brush A and Brush B with respect to wear characteristics. Brush Material C is superior with regards to wear characteristics. As can be seen from the graph, the deltas between the measurements are the least with values ranging around 0.013 inches. If temperature was not an issue, Brush C would be the brush of choice because of the superior predicted life limit of the brush as compared to the other brush materials.
5.3 Heat – Starting Mode

Figure 36. Brush Material A Average Temperature Starting Mode

Figure 37. Brush Material B Average Temperature Starting Mode
The average temperatures during the start portion of the testing were similar for the three different brush materials, with the maximum temperature reaching approximately 206°F at the locations of the positive brushes and negative brushes. The reason for the similarities in the temperatures is due to the limited time duration of the actual test. The starting portion of the tests lasted under 5 minutes, not allowing for the temperatures to rise as in the generating portion of the testing.

The positive and negative brush positions attained the hottest values because the friction between the brushes and the commutator is the main source of the heat. Brush A and C recorded their highest temperatures at the positive brush location, and the next highest temperature at the negative brush. Brush B recorded the highest temperature at the negative brush and next highest at the positive brush. This difference may be due to a few different situations, one including a difference in brush pressure. For Brush A and C, the highest brush pressure may have been applied to the positive
brush, while on Brush B the highest brush pressure may have been applied to the negative brush. Another possibility is the length of the positive brushes for A and C may have been slightly longer than the negative brushes, and vice versa for Brush B.

5.4 Heat - Generating Mode

![Brush Material A Average Temperatures](image)

**Figure 39. Brush Material A Average Temperature Generator Mode**
The generating testing temperature graphs show that Brush A and Brush B are comparable in temperatures as they were in wear characteristics. Brush C, which is the
hardest of the three brushes, ran at an overall higher temperature with values reaching and average of 280°F at the location of the positive brush. These temperatures exceed the maximum allowable of the protective coating, and thus could not be utilized unless better airflow was obtained to help keep temperatures within an acceptable range.
CHAPTER VI
CONCLUSION

6.1 Wear

This thesis showed the results of laboratory and optical testing for three different graphite brushes tested in both generating and starting modes. The average temperatures for the generating and starting tests were analyzed. The results show the wear characteristics of Brush A and B are very similar, but both fall under the desired limit of 3000 hours. Brush A is expected to have an expected brush life of approximately 488 hours, while Brush B is expected to have a longer expected brush life of approximately 509 hours. Brush C had the best wear characteristics with an expected brush life of approximately 3105 hours.

The surface of Brush B was the most desirable. The surface had the least amount of pitting of the three brushes tested, and the grooving was at a minimum. This provides the largest surface area for the current to pass through. This reduces the pitting and lowers the operating temperature.

6.2 Heat

The temperatures for all three brushes during the starting mode of the testing showed similar numbers. This was due to the short duration in which they were run during the starting mode operation. The actual run time was not sufficient to allow the internal temperatures to exceed the maximum allowable. If the starter generators were
to be only used as a starter, then all brushes would be acceptable, with Brush C being the optimal with the expected brush life of 3105 hours.

During the generating mode of the testing, the temperature of Brush C exceeded the maximum allowable operating temperature in excess of 80°F, and thus cannot be considered as a viable option. The temperature results for Brush A and Brush B were below the maximum operating temperature with the maximum temperatures reaching 179°F and 194°F respectively. Brush A is the more conservative material, with maximum temperatures of 174°F, which gave the largest buffer between the operating temperature and the maximum limit. Brush B operating temperatures stayed below the maximum limit, but with a smaller delta between the two values. From this testing, Brush B was the optimal material of the three choices, but with the wear results not meeting the requirements, more testing with more materials and conditions must be performed.
CHAPTER VII

FUTURE WORK

The future work for this project should include the testing of more samples with a hardness that is comparable to Brush B, but with a larger scope of additives, such as molybdenum disulfide. Another avenue which should be tested is to perform the same testing in an environmental chamber. This would allow for different humidity to be tested determining what effect the amount of water in the air has on the formation of the surface film and overall wear of the brush.

Different materials for the commutator should be tested to determine the optimal material to increase the current transfer between the brushes and the commutator. Since temperature is a limiting factor, it would be useful to perform flight testing with different cooling airflow rates to determine the relationship between airflow rate and the overall operating temperature of the starter generator.
REFERENCES
REFERENCES


