CATHODE EROSION RESEARCH
ON MEDIUM TO HIGH POWER ARCJET THRUSTERS

W.J. Harris, E.A. O'Hair, L.L. Hatfield, M. Kristiansen
Pulsed Power and Electric Propulsion Laboratory
Texas Tech University
Lubbock, TX 79409

Abstract

Cathode erosion in medium to high power arcjets is dominated by the intrinsic electrothermal properties of the cathode material, propellant gas properties, and electrode geometry. It is also evident that several external mechanisms affect both the cathode erosion rate, and the cathode arc attachment. The most notable of these being power supply ripple. This paper summarizes experimental results of cathode lifetime tests on a wide variety of refractory materials under fixed conditions using a water-cooled experimental arcjet. The typical test duration selected for this baseline study was 100 hours at a fixed current of 250 Adc using nitrogen propellant. Among the materials tested are W-ThO2 (1%, 2%, 4%), poly and monocrystalline W, W-LaB6, W-La2O3, W-BaO2, W-Ba+Ca+Aluminate, and W-Y2O3. A companion series of erosion tests were also conducted with hydrogen propellant at a current of 100 Adc at 10 kW power levels. Related results concerning the effects of current ripple, and cold cathode start-up on arcjet cathode erosion and cathode arc attachment are also presented.

1. Introduction

The motivation for studying arcjet cathode erosion lies in the steadily increasing performance requirements placed on medium to high power arcjets. The need for specific impulses in excess of 1200 seconds, efficiencies greater than 50%, and lifetimes beyond 1500 hours have lead to large increases in the cathode current, cathode heat flux, number of cold cathode starts, and the total device charge transfer, Q = \int I(t) dt. Hence, practical limitations on the cathode’s current carrying capacity, heat transfer rate, and geometric dimensions are largely responsible for the excessive cathode erosion rates observed in most medium to high power arcjets.1,2,3 These limitations on cathode lifetime are determined by the electrothermal properties of the cathode material, the cathode heat transfer rate (or rate of cooling), and the non-equilibrium dynamics of the near-cathode plasma. Traditional 2% thoriated tungsten, used as the electrode material of choice in most arcjet and MPD thrusters, has a moderate work function of 3.5 eV, and a typical cathode current density of 5x10^7 A/m^2. In a typical 15-30 kW arcjet the resulting cathode fall voltage is 5-30 Volts with a cathode heat load of 100-300 watts.4

Since the thermionic current density is somewhat fixed by the maximum cathode surface temperature, the area of arc attachment and the ratio of plasma ion current to thermionic electron current increase significantly with increasing arc current. In high current arcjets a large fraction of the electrical current is thus provided by ions impacting the cathode surface. This space-charge limited ion current is particularly important to long-term cathode operation because it is the primary source of excess heat to the cathode surface, and is a potential source of erosion when combined with high cathode sheath potentials.

Reduction of the dominant cathode erosion mechanisms (evaporation, sputtering) is therefore best achieved by minimizing the cathode sheath potential and the cathode ion current over time. Considerable experimental evidence5,6,7 and more recent theoretical models8,9 both suggest that this can be accomplished by maintaining a low cathode work function, optimizing the cathode’s heat transfer characteristics, and stabilizing the cathode arc attachment area.

Unfortunately, due to the wide latitude of test conditions used in earlier published results on arcjet cathode erosion, direct application of individual trends to high current arcjets has been non-intuitive. Previous work on high-power 30 kW ammonia arcjets10, and low-power 1 kW hydrogen arcjets11 clearly show that the cathode erosion rate and cathode surface damage change significantly with cathode cross-sectional area. These observations verify the critical nature of cathode heat transfer characteristics and emphasizes the need for improved cathode thermal and material studies. Short duration erosion tests comparing different tungsten dispenser cathodes in low current arcjets also
Chamber two is used for arcjet cathode erosion experiments running hydrogen or nitrogen propellants at 10-30 kW power levels. This cylindrical vacuum chamber is 2 m in diameter and 3.5 m long. A Dresser 2100 cfm (59,500 l/min) Roots blower backed by two Pennwalt-Stokes 412H 300 cfm (8500 l/min) rotary piston pumps evacuate the chamber to less than 1.5 Torr with 0.05 g/s hydrogen flow, and to less than 650 mTorr with 0.4 g/s nitrogen flow. Pressure instrumentation on both systems consist of industry standard capacitance manometers (MKS Baratron Model 122A) and thermocouple gauge tubes (Hasting Model DV6M, Teledyne Televac II).

AJEX-1 Experimental Arcjet

The experimental arcjet used for basic cathode erosion experiments is a water-cooled, 10-30 kW e arcjet based on the original JPL D-1 series ammonia arcjet assembly. A diagram of the experimental arcjet appears in Fig. 1. The design features easily replaceable cathode and anode inserts mounted in non-damaging holders. Each holder is water-cooled to prevent over-heating of the various seals and insulators. The anode insert is partially water-cooled by the copper anode holder which also serves as the high current anode contact. A gas-tight seal is maintained between the anode insert and the anode holding plate by a smooth 10° tapered joint.

The water-cooled cathode holder extends through the rear Lexan insulator, and is held in place by a modified nylon Swagelok fitting. The Lexan insulator attaches directly to the rear mounting bracket and is equipped with a pressure tap for recording the arcjet's internal pressure.

Standard 0.95 cm diameter by 8.3 cm long cathode inserts are used for all high current (250 Adc, 16-25 kW) cathode erosion rate measurements. Smaller, 0.64 cm diameter by 8.1 cm long cathode

2. Experimental Apparatus

The high-power arcjet test facilities at Texas Tech University consists of two fully automated, high capacity stainless-steel vacuum systems. Chamber one is a cylindrical vacuum chamber 0.76 m in diameter by 3.4 m long. The system is used for long duration cathode erosion experiments and general arcjet diagnostics using nitrogen or argon propellants. The chamber is pumped by a Kinney KT300C 300 cfm (8500 l/min) triple-stage rotary pump assisted by a Kinney KMBD1600 1600 cfm (45,300 l/min) Roots blower. The average operating background pressure is between 0.5-1.5 Torr.

Fig. 1. AJEX-1 Experimental Arcjet

indicate much lower cathode erosion rates for certain low work function (<3.0 eV) additives, such as LaB₆, BaO, and Ba+Ca+Aluminate¹²,¹³.

To advance the study of cathode erosion in medium to high power arcjets, an experimental program was started at Texas Tech University (TTU) in 1988 with the primary objective of testing tungsten dispenser cathode materials selected for their low work function, good mechanical properties, and low erosion rate in high-current pulsed arc applications.¹⁴ By analyzing these cathode materials, significant reductions in the cathode heat load, tip temperature, and erosion rate have been realized. Over the course of this research a number of areas significant to cathode erosion have also been analyzed; namely, cathode erosion and whisker growth related to power supply ripple¹⁵, propellant injection and its effects on anode arc behavior¹⁶, and upstream static pressure profile measurements.¹⁷ This paper summarizes experimental results on cathode materials, steady-state and cold cathode erosion, and the effects of power supply ripple on cathode erosion in medium to high power arcjets.

Fig. 2. AJEX-1 anode/nozzle inserts. (a) 10-30 kW nitrogen. (b) 10 kW hydrogen.
inserts are used for medium current (100 Adc, 5-10 kW) operation on hydrogen and nitrogen propellants. Both cathode designs have simple rounded, 60° conical tips.

Fig. 2 compares the two anode/nozzle configurations run at 10 and 25 kW power levels with both nitrogen and hydrogen propellants. Examples of the electrical characteristics of the arcjet with various electrode-gas combinations appears in Fig. 3. The first anode insert, shown in Fig. 2(a), is the standard anode insert used for all 100 hour cathode material tests and ripple erosion studies performed at 15 kW in nitrogen. The internal constrictor and nozzle dimensions are consistent with the original JPL D-1 series 30 kW ammonia arcjet design using a 0.51 cm diameter, 1.07 cm long constrictor. The smaller constrictor geometry, shown in Fig. 2(b), is used for lower flowrate cathode erosion tests at 10 kWt power levels in nitrogen or hydrogen. All anode inserts were made from stock 2% thoriated tungsten.

![Fig. 3. Electrical characteristics of 10 kW and 30 kW anode/nozzle inserts.](image)

**Power Supply and Starter**

Electrical power for both TTU arcjet test chambers is provided by a custom designed and built SCR phase-controlled power supply capable of providing an open circuit voltage of 320 Vdc and a maximum sustained current of 450 Adc. A schematic of the arcjet electrical circuit including the SCR-controlled power supply is shown in Fig. 4. Input SCR phasing makes the output of this power supply continuously adjustable from zero to its full operating limit. Three user selectable regulation modes are also available: constant current, constant power, and constant voltage.

![Fig. 4. Arcjet power supply, filter, and starter.](image)

Due to SCR switching on the power supply primary, much higher secondary ripple is obtained with this power supply over conventional designs. The fixed 360 Hz ripple frequency from the power supply is filtered by an adjustable L-C network made up of 31,000 μF electrolytic capacitor banks and 2 mH saturable iron core inductors. With a single series inductor the ripple amplitude runs as high as 28%, and with two L-C stages is as low as 0.8%. Variation of the SCR firing angle with output current also causes considerable variation in the ripple factor over the power supply operating range.

Ripple amplitude and arc current are measured using a calibrated 500 Adc/100 mV resistive shunt. The ripple factor is calculated by dividing the true RMS AC shunt current by the average DC shunt current. While running, the 0.5 Ω series ballast resistor is also used to continuously monitor the ripple amplitude and arc current.

The arcjet is started using a modified Miller HF-250D-1 high frequency Tungsten Inert Gas (TIG) welding starter. The starter ignites the arc by applying high voltage pulses (1-10 kV) to the cathode at a center frequency near 850 kHz. The pulses are applied for 100-500 msec. Bursts of this duration improve the reliability of proper arc ignition when the cathode is worn, dirty, or otherwise damaged.

**Gas Handling System**

The nitrogen propellant used in these tests is bled off as vapor from a bank of two liquid nitrogen storage cylinders. The gas is delivered to the arcjet at a regulated pressure of 10 psig. Two industrial thermal-conductivity type flow controllers, a MKS Instruments Model 2259-05000(0-5 slpm) and a MKS Instruments Model 2259-50000(0-50 slpm), are used to monitor and regulate the nitrogen mass flowrate. Manufacturing grade (99.98% purity) hydrogen gas is supplied from a automatic switch-over manifold of 2x12 cylinders. A single MKS Model 1559A-200L(0-200 slpm) mass flow controller regulates the hydrogen flowrate. The flow controllers are periodically checked for calibration to within an estimated 5% uncertainty using pressure rate measurements on a constant volume cylinder.
3. Cathode Erosion - Materials

The highest rate of cathode erosion typically occurs during arcjet ignition. This period of cold-cathode operation is characterized by a highly unstable, spotty arc attachment with relatively high cathode erosion caused by sputtering, explosive evaporation, liquid droplet removal, and solid ejection of cathode material. Once the cathode becomes hot, thermionic emission increases and the cathode erosion rate drops to its steady-state value, typically one to two orders of magnitude less than the cold-cathode erosion rate. For steady-state operation the lowest erosion occurs in a diffuse mode of arc attachment where erosion is dominated by evaporation and sputtering.

<table>
<thead>
<tr>
<th>Material</th>
<th>Additive Properties</th>
<th>Density (g/cm³)</th>
<th>Average Mass Loss (g)</th>
<th>Erosion Rate (ng/C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-ThO₂ (2% - P)</td>
<td>2.6-2.9 W-Th</td>
<td>18.96</td>
<td>0.017</td>
<td>0.189</td>
</tr>
<tr>
<td>W-ThO₂ (2% - R)</td>
<td></td>
<td>19.06</td>
<td>0.020</td>
<td>0.222</td>
</tr>
<tr>
<td>W-ThO₂ (1% - R)</td>
<td></td>
<td>19.03</td>
<td>0.021</td>
<td>0.233</td>
</tr>
<tr>
<td>W-ThO₂ (4% - P)</td>
<td></td>
<td>18.41</td>
<td>0.011</td>
<td>0.121</td>
</tr>
<tr>
<td>W-La₂O₃ (2% - P)</td>
<td>2.7 W-La</td>
<td>18.52</td>
<td>0.122</td>
<td>1.36</td>
</tr>
<tr>
<td>W-LaB₆ (2% - P)</td>
<td>2.7 W-La</td>
<td>15.68</td>
<td>0.149</td>
<td>1.66</td>
</tr>
<tr>
<td>W-BaO₂ (2% - P)</td>
<td>1.6 W-Ba</td>
<td>11.89</td>
<td>0.698</td>
<td>7.76</td>
</tr>
<tr>
<td>W-Ba+Ca+Aluminate</td>
<td>2.06</td>
<td>18.80</td>
<td>1.224 (11.1 hrs)</td>
<td>122.6</td>
</tr>
<tr>
<td>W-Y₂O₃ (2% - P)</td>
<td>2.7 W-Y</td>
<td>17.98</td>
<td>0.596</td>
<td>6.62</td>
</tr>
<tr>
<td>Pure W (P) - Sintered</td>
<td>4.5 Pure W</td>
<td>19.27</td>
<td>0.092</td>
<td>1.02</td>
</tr>
<tr>
<td>Pure W (R) - Sintered</td>
<td>4.5 Pure W</td>
<td>19.25</td>
<td>0.346</td>
<td>3.84</td>
</tr>
<tr>
<td>Monocristalline W(100)</td>
<td>4.63 W(100)</td>
<td>21.63</td>
<td>0.123</td>
<td>1.37</td>
</tr>
<tr>
<td>Monocristalline W(221)</td>
<td>5.25 W(110)</td>
<td>21.60</td>
<td>0.267</td>
<td>2.97</td>
</tr>
<tr>
<td>W-ThO₂ (2% - P), N₂</td>
<td>2.6-2.9 W-Th</td>
<td>19.01</td>
<td>0.059</td>
<td>1.64</td>
</tr>
<tr>
<td>W-ThO₂ (2% - P), H₂</td>
<td>2.6-2.9 W-Th</td>
<td>19.01</td>
<td>0.0041 (80 hrs)</td>
<td>0.139</td>
</tr>
</tbody>
</table>

Sources: R - Rembar, Inc. P - Metallwerk Plansee and Schwarzkopf Dev., Inc. † Work function of W(221) was not found.

Table 2. Previously tested arcjet cathode materials. Hardy and Nakanishi[12], Neurath and Gibbs[21].

Cathode Steady-State Erosion

Considerable progress has been made on cathode material erosion studies for low power arcjets. However, until recently high power arcjets have received very little materials study. Table 2 compares materials tested in low power versus high power arcjets prior to preliminary materials work by the authors. Out of these materials, the lowest erosion rate (< 5.8 x 10⁻⁴ μm³/C) was reported by Hardy and Nakanishi[12] for W-LaB₆ at a current of 10 Adc. Neurath and Gibbs studied pure W, W-ThO₂(1%,2%), and W-Ba+Ca+Aluminate in argon and hydrogen arcs at currents up to 500 Adc. They found that W-Ba+Ca+Aluminate gave almost no erosion at 500 Adc in argon and hydrogen using water-cooled electrodes.

On the basis of availability, prior published test results, and work done at TTU by Donaldson and Kristiansen[22] on high current pulsed electrodes, several potential cathode materials were identified for high-power arcjet lifetime tests. The criteria used for selecting potential cathode materials were outlined by Donaldson[22] and Sokolowski et al.[23]:

1) high melting temperature
2) low work function
3) low evaporation rate
4) high latent heat of fusion
5) high latent heat of vaporization
6) high thermal conductivity
7) high emissivity
8) low sputtering yield
9) high electrical conductivity
10) chemical compatibility with propellant
11) thermochemical stability
12) mechanical strength
13) fabricability
14) reproducible homogeneity
15) thermal shock resistance

Based on these criteria, Table 1 summarizes the steady-state cathode erosion rates of all cathode materials obtained by and tested at TTU. The results were gathered from over twenty-five 100 hour duration runs in nitrogen (flowrate 0.4 g/s) at 250 Adc with 13% ripple. All runs used the 30 kW ammonia arcjet electrode configuration described previously. The measured erosion rates of W-\( \text{ThO}_2 \) (2%) at 100 Adc in nitrogen (flowrate 0.21 g/s) and hydrogen (flowrate 0.0375 g/s) are also reported. These results were obtained from 100 hour duration tests using the smaller 10 kW, 0.64 cm diameter cathode inserts along with the smaller anode/nozzle insert shown in Fig. 2(b).

Despite a lack of complete thermophysical data for the materials listed in Table 1, several trends are apparent. The most critical material properties appear to be the cathode work function, density (or porosity), and the melting or boiling point of the impregnant. Other critical material parameters for steady-state erosion appear to be the evaporation-recondensation rates and the cathode tip temperature which are determined by the electrothermal properties of the cathode material.

**Thoriated Cathodes**

Traditional thoriated tungsten gave the lowest erosion rate, and least damage of all the materials tested. Fig. 4 shows the steady decrease in the specific erosion rate with increasing thorium concentration. As the plot indicates, there is a 36% decrease in the specific erosion rate between the 2% and 4% thoriated tungsten manufactured by Metallwerk Plansee. The difference in erosion rates between 1% and 2% thoriated purchased from Rembar, Inc. is small (~5%) with 2% thoriated tungsten being slightly better. In general the press-sintered tungsten and thoriated tungsten materials manufactured by Metallwerk Plansee gave lowest specific erosion and least damage.

For comparison, the measured erosion rates for W-\( \text{ThO}_2 \) (2%) in Table 1 are about an order of magnitude lower than 100 hour erosion rates measured at JPL in radiation-cooled, 26 kW ammonia arcjets. The discrepancy is due in part to differences in the cathode cooling rate, propellant gas, and input power. However, the erosion rates of W-\( \text{ThO}_2 \) (2%) in Table 1 are comparable to the 0.48 ng/C measured at JPL after a 1462 hour test on the same 26 kW ammonia arcjet throttled back to 10 kW.\textsuperscript{24}

Estimates of the tungsten evaporation rate also agree with the measured erosion rates in Table 1. From Dushman\textsuperscript{25} the evaporation rate for pure tungsten is given as

\[
\dot{m}_e = A \sqrt{\frac{M}{2\pi RT}} p_v(T),
\]

where \( p_v(T) \) is the vapor pressure of tungsten at an average surface temperature, \( T \). Other variables are the spot area, \( A \), the molecular weight of tungsten, \( M \), and the universal gas constant, \( R \). Based on an estimated average spot temperature of 3000 K, a typical spot radius of 1 mm, and a tungsten vapor pressure of 0.01 N/m\(^2\), the evaporation rate of tungsten is \( 3.5 \times 10^{-8} \) g/sec. At a current of 250 Adc the calculated specific erosion rate is

\[
\varepsilon = \frac{\dot{m}_e}{I} = \frac{3.5 \times 10^{-8} \text{ g/sec}}{250 \text{ A}} = 0.14 \text{ ng/C}. \quad (2)
\]

Hence, the calculated erosion rate due to evaporation is very close to the measured values for W-\( \text{ThO}_2 \). In the case of sputtering, Hardy and Nakanishi\textsuperscript{12} calculate the erosion rate to be approximately 1 \( \mu \text{g/C} \) at 250 Adc in nitrogen. This erosion rate is 2 orders of magnitude too high for most materials listed in Table 1. The dominant erosion mechanisms therefore appear to be melting and evaporation.
Barium Activated Cathodes

Failure of the two low work function (~2.1 eV) barium impregnated cathodes, W-BaO₂ and W-Ba+Ca+Aluminate, was primarily due to their low density (high porosity) and visibly poor mechanical strength. Both materials were manufactured from press-sintered tungsten, infiltrated with BaO₂, or a mixture of 5 moles BaO, 3 moles CaO, and 2 moles Al₂O₃. During tests, the W-Ba+Ca+Aluminate was the only material to destructively fail after only 11.1 hours of operation. This result differs substantially from earlier results on W-Ba+Ca+Aluminate reported by Neurath and Gibbs[21] and Kuninaka et. al.[13], which suggests potential differences in fabrication or in the proper molar percentages of the BaO, CaO, and Al₂O₃ mixture as outlined by Jenkins.[26]

Lanthanum Activated Cathodes

With cathode work functions similar to thoriated tungsten the two lanthanum dispenser cathodes, W-La₂O₃ and W-LaB₆, gave unexpectedly high erosion rates -- an order of magnitude higher than thoriated tungsten. Because La₂O₃ and LaB₆ have melting points more than 1000 °C lower than ThO₂, the production and migration rates of lanthanum in the tungsten carrier is excessively high near the cathode tip. This condition causes a rapid depletion of lanthanum at the cathode surface, giving rise to a cathode work function near that of pure tungsten. Evidence of this is found in Table 1 where one sees that the specific erosion rates of W-La₂O₃ and W-LaB₆ are very similar to pure W. The higher melting point and density of W-La₂O₃ over W-LaB₆ also appears to slightly improve the erosion rate of W-La₂O₃.

Poly and Monocrystalline Tungsten Cathodes

Even though pure polycrystalline tungsten has an average cathode work function of 4.55 ev, it has the lowest specific erosion rate (1.02 ng/C) of all the non-thoriated cathode materials tested. This is due to the extremely high melting point and high density of pure tungsten. Comparing measured densities in Table 1, the highest density materials generally tend to have the lowest specific erosion rates. Taking the density of non-porous tungsten to be equal to the density of the monocrystalline samples (21.62 g/cm³), the porosity of the test materials varies from 0 (monocrystalline W) to 45% (W-BaO).

Since W-BaO has the highest measured erosion rate, we conclude that low porosity is another important criteria for cathode material selection. It is clear that the porosity of a material couples to cathode erosion in at least two ways: first through its effect on the cathode’s thermoelectric properties, such as the thermal conductivity, heat capacity, and electrical conductivity, and second on the tungsten grain size, mechanical strength, and diffusion rates of the impregnant material.

Similar conclusions apply to the two Russian-supplied monocrystalline W samples listed in Table 1. These samples, which have remarkably high densities, were manufactured using the Czochralski technique with each rod having a different crystal orientation parallel to the principal axis of the cathode. Before erosion measurements were made on these samples, cross-sections of each cathode were analyzed using transmission X-ray diffraction and both were verified to be monocrystalline. As shown in Fig. A1, the cathode structure is dense with no evidence of voids.

Erosion results show, surprisingly, that the erosion rates of both monocrystalline samples were on the same order as the two polycrystalline W samples. A large factor of 2 difference between the erosion rates of two samples is also observed. This difference is assumed to be due to large variations in the work function of tungsten from one crystal plane to another. As is indicated in Table 1, this variation in the work function could be as high as 0.6 eV. Cathode damage shown in Fig. A2 is also unique for tungsten cathodes, showing no crater or recrystallization at the edges.

10kW Hydrogen Arcjet Experiments

Due to repeated problems with constrictor damage at 10 kW power levels in hydrogen, Table 1 lists only one cathode erosion rate for W-ThO₂(2%) in hydrogen. The run, which lasted 80 hours before the anode failed due to a low voltage fault, gave a total cathode mass loss of only 4.1 milligrams. This compares to 59.0 milligrams for the same electrode configuration with nitrogen propellant after 100 hours. Other tests in hydrogen using different cathode-anode combinations and different electrode gaps lasted typically less than 6 hours and gave no measurable cathode mass loss.

The specific cathode erosion rate of W-ThO₂(2%) at 100 Adc in hydrogen was 0.139 ng/C. This equals the cathode erosion rates for the same material at 250 Adc in nitrogen with larger 0.95 cm diameter cathodes. The effect of cathode size is also evident from comparison of runs on W-ThO₂(2%) in nitrogen at 250 Adc and 100 Adc. Despite the 150 Adc drop in current, the cathode erosion rate increases an order of magnitude from the 0.95 cm diameter to the 0.635 cm diameter cathodes. This result stresses the
The arcjet would then run at followed by a linear ramp to 250 Adc over 30 seconds. to start on its fifth start. This result gives a loss rate of cathode was preheated at 200 Adc for 60 seconds of thorium at the surface, lost 0.645 grams after failing the HF starter for 500 milliseconds. Once running, the erosion rate. Pure W, used to simulate a complete loss in each experiment the arcjet was started by pulsing concentrations of thorium decrease the cold cathode caused

The most common method used in the welding industry, plasma spray technology, and in some arc lighting devices is high frequency starting. would be significantly enhanced by differences in the local work function, \( \phi \) as high as 2.5 eV. As the number of starts increases, the number of areas of high thorium concentration decreases as sites are destroyed or depleted during cold cathode arc ignition. Cold cathode erosion would therefore increase over time as favorable sites of electron emission are removed by repeated arcing.

For W-ThO2(2%), the data shows a mass loss after 60 starts that is more than 2 times higher than the steady-state mass loss after 100 hours of operation. This gives a loss rate of 0.63 grams/start that increases to 0.77 grams/start after 120 starts. The start-up erosion therefore exceeds the 100 hour steady-state mass loss after fewer than 30 starts.

Since the start-up damage is distributed over a large area of the cathode surface as micro-spots, the increase in the mass loss per start is potentially caused by arc ignition at local sites of high thorium concentration. Field emission current at these sites, as described by the Fowler-Nordheim equation

\[
J = \frac{E^2}{16\pi^2 \phi r^2} \exp \left( \frac{-4\sqrt{2}\phi^{3/2}v}{3E} \right),
\]

would be significantly enhanced by differences in the local work function, \( \phi \) as high as 2.5 eV. As the number of starts increases, the number of areas of high thorium concentration decreases as sites are destroyed or depleted during cold cathode arc ignition. Cold cathode erosion would therefore increase over time as favorable sites of electron emission are removed by repeated arcing.

Multiple start test results on pure W, W-ThO2(2%), and W-ThO2(4%) shown in Table 3 verify a strong dependence on thorium concentration. For W-ThO2(4%) the mass loss per start drops by a factor of 2 from that of W-ThO2(2%), showing that higher concentrations of thorium decrease the cold cathode erosion rate. Pure W, used to simulate a complete loss of thorium at the surface, lost 0.645 grams after failing to start on its fifth start. This result gives a loss rate of 0.129 g/start, and reflects the rapid increase in cold cathode erosion as thorium is completely removed from the surface.

Compared to traditional W-ThO2(2%), W-ThO2(4%) showed superior cold cathode erosion
resistance after 120 starts on fresh electrodes. This advantage over W-ThO$_2$(2%) is due to its initially higher thorium concentration which will be somewhat diminished on heavily used electrodes. Since HF starting resembles the worst case situation in "soft" start circuits where hundreds of repetitive pulses are sometimes needed to start the arcjet, the results of Table 3 are important. For applications requiring several hundred starts per mission, cold cathode erosion becomes the dominant life limiting mechanism for the arcjet cathode.

<table>
<thead>
<tr>
<th>Material</th>
<th>Ripple (%)</th>
<th>Mass Loss (g)</th>
<th>Erosion Rate (ng/C)</th>
<th>Rim Growth</th>
</tr>
</thead>
<tbody>
<tr>
<td>W-ThO$_2$(2%)</td>
<td>1.2%</td>
<td>0.040</td>
<td>0.45</td>
<td>fine</td>
</tr>
<tr>
<td></td>
<td>3.1%</td>
<td>0.026</td>
<td>0.29</td>
<td>fine</td>
</tr>
<tr>
<td></td>
<td>11.5%</td>
<td>0.020</td>
<td>0.22</td>
<td>large</td>
</tr>
<tr>
<td></td>
<td>22.8%</td>
<td>0.053</td>
<td>0.59</td>
<td>none</td>
</tr>
<tr>
<td></td>
<td>22.5%†</td>
<td>0.049</td>
<td>0.54</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 4. Cathode Erosion Rates at 1.2%, 3.1%, 11.5%, and 22.5% power supply ripple.

4. Cathode Erosion - Current Ripple

Since early tests at JPL on 30 kW ammonia arcjets, there has been speculation that power supply ripple can influence cathode erosion and cathode whisker growth. To examine this problem and its implications on cathode lifetime measurements a series of five 100 hour duration tests were conducted at various ripple amplitudes on 2% thoriated tungsten. The results of these tests are briefly tabulated in Table 4. The average run current for all tests was 250 Acd in nitrogen at a flowrate of 0.4 g/sec. Four different ripple amplitudes were tried: 1.2%, 3.1%, 11.5%, and 22.5%. Due to the low discharge voltage (~68 Vdc) of nitrogen, the average input power during tests was only 17.2 kW.

Cathode Erosion and Arc Attachment

The data in Table 4 shows that the cathode erosion rate varies strongly from 0.22 to 0.59 ng/C over the range of 1% to 22.5% ripple. The erosion rates also show a clear decrease in magnitude with increasing ripple amplitude for amplitudes less than 13%. Above 13% the erosion rate rapidly increases by a factor of two, apparently due to induced instability in the cathode arc attachment point. This trend differs from similar data published by Deininger et al.[10], which showed a possible increase in the cathode erosion rate going from 0.2% to 3% ripple.

Fig. 5 gives a plot of the cathode erosion rate versus ripple amplitude taken from Table 4. A distinct minimum appears to exist between 3% and 11% ripple. Since this amplitude range is much higher than the 0.2% to 3.0% ripple reported by Deininger et al.[10], direct comparison of these results to radiation-cooled arcjets is impossible.

Visual inspection of the cathodes also shows a large increase in the arc attachment area with increasing ripple amplitude. Cathode craters on all but the 23% ripple cathodes show a small dimple, 0.5-1.0 mm in diameter, at the center of the crater depression. As shown in Fig. 6, this center dimple is highly polished, as if melted and suddenly re-solidified. Surrounding the dimple is a ring of

Fig. 6. Cathode Damage, W-ThO$_2$(2%), 250 Acd, 13% ripple, 0.4 g/sec nitrogen.
IEPC-93-028 288

lower the erosion rate by reducing the power density at the cathode tip.

Ripple Frequency

Since the ripple erosion measurements were limited to the 360 Hz power line frequency, no indication is given as to the frequency dependence of the previous phenomena. Early work on oscillations in dc-arcs suggests that the main effect of ripple frequency on cathode arc attachment lies in its effect on the ionization rate and the plasma ion current. As shown in Fig. 8, power supply current ripple appears as a sinusoidal oscillation superimposed on the average or mean DC current.

For extremely low ripple frequencies the V-I characteristics of the arc coincide with the static characteristic shown as curve 1 in Fig. 8. At higher frequencies (curve 2) a figure similar to an ellipse evolves, having a higher voltage with increasing current than with decreasing current. The higher voltage with increasing current is caused by a lower than normal ionization rate so that a higher sheath voltage is required to supply the additional current. Conversely, on decreasing current the ionization rate is too high and the arc current flows through a lower voltage gradient.

This lag in the ion current at high gas pressures is dependent on the thermal conductivity of the cathode and of the gas. As the ripple frequency increases further, as in curve 3, it eventually reaches the thermal time constant of the cathode and the arc. At this point the impedance of the arc becomes positive, until at very high frequencies the V-I characteristic resembles a pure resistance as in curve 4. For water-cooled electrodes in hydrogen, the heat transfer rate through the cathode and the gas is high, so that the previous V-I characteristics may not become

Fig. 7. Cathode crater diameter versus ripple amplitude.

displaced material covered with dimples and pits apparently caused by filament arcing. As indicated in Table 4, at the outer edge of the ring signs of whisker growth are also observed. At ripple amplitudes above 11.5% the finer whisker structures, or roots are replaced by a heavier lip around the crater rim. At 23% ripple the center dimple is no longer present and the entire crater surface is pitted as if by heavy filament arcing.

The most intense portion of the arc therefore appears to attach to the centered dimple in the cathode crater. As the ripple amplitude increases, the arc spreads outward over the crater surface causing arc filaments to form on cooler portions of the cathode surface. As the amplitude increases to 23% the arc becomes unstable and too diffuse to stay centered on the cathode. A plot of the measured crater diameters of the five cathodes listed in Table 4 appears in Fig. 7. The plot shows the increase in crater diameter with ripple amplitude, and seems to indicate a simple linear growth in spot area. This increase in spot area seems to

Fig. 8. Dynamic V-I characteristics of an arc. (ω1 < ω2 < ω3 < ω4) Cobine[32].

Fig. 9. Arcjet AC characteristics. 150 Adc, 13% ripple, 0.40 g/sec nitrogen.
appreciable until 10 kHz or higher. A characteristic such as curve 2, however, occurs at about 10 Hz for an arc in air between carbon electrodes. Fig. 9 shows the resemblance between curve 2, Fig. 8, and an X-Y plot of the AC components of the current and voltage from the arcjet running at 150 Adc.

Fig. 9 suggests that the 360 Hz ripple frequency used in these experiments is still below the cathode-arc time constant. Based on the radius of the center dimple from the previous cathodes, \( r \approx 0.25 \text{ mm} \), the thermal time constant of the arc spot is calculated to be

\[
\tau = \frac{cm^2}{\rho c + \kappa} \quad \text{cal/cm}^3 \text{g/sec}^{-1}
\]

where \( \rho \) is the density, \( c \) is the heat capacity, and \( \kappa \) is the thermal conductivity of tungsten. This means that the effects of current ripple on arcjet cathode erosion may extend to frequencies of several kilohertz, such as those used in some arcjet power conditioning units, depending upon the heat transfer characteristics of the cathode and the propellant gas.

5. Conclusions

An experimental investigation of arcjet cathode erosion in medium to high power arcjets has been conducted at Texas Tech University. More than 12 potential cathode materials were successfully tested in a series of 25 baseline 100 hour lifetime tests using a 10-30 kW, water-cooled, nitrogen and hydrogen arcjet. Start-up erosion rates for pure W, W-ThO\(_2\)(2%), and W-ThO\(_2\)(4%) were measured in a series of 60 and 120 start tests. Changes in cathode erosion rate and cathode whisker growth were also linked to power supply ripple in a series of five 100 hour tests at ripple amplitudes between 1 and 23%. Several major conclusion are drawn from these tests:

- At arc currents consistent with high-power radiation-cooled arcjets (250 Adc), 4% thoriated tungsten gave the lowest steady-state and start-up erosion of all the materials tested. Both erosion rates were a factor of 2 lower than those of traditional 2% thoriated tungsten.

- Low work function, high density, low porosity, high melting point, and low evaporation rates were all determined to be critical material properties among the cathodes tested.

- Using HF starting, cathode start-up erosion surpassed the 100 hour steady-state erosion rate in fewer than 30 starts. For thoriated tungsten, the start-up erosion rate dropped by a factor of 2 going from 2% to 4% thoria content. This suggests a link between thorium concentration at the cathode surface and field emission during arc ignition.

- At 10 kW power levels the cathode erosion rate of W-ThO\(_2\)(2%) was an order of magnitude lower for hydrogen propellant over nitrogen propellant. Decreasing the cathode diameter from 0.95 cm to 0.64 cm also increased the erosion rate by an order of magnitude in nitrogen.

- Power supply ripple variation was found to significantly affect the cathode erosion rate, cathode-arc attachment area, and cathode whisker growth. Factor of 2 changes in the cathode erosion rate and cathode crater diameter were experienced between 1% and 13% ripple.

Based on these results, cathode erosion in medium and high power arcjets appears to be manageable given good thermal design practice, proper material selection, and good start-up techniques. Propellant gas and power supply filtering are also important determining factors for cathode lifetime.

6. Future Work

Due to problems with heavy anode erosion, the 10 kW hydrogen experiments have not been completed. Additional experiments are underway to confirm that the trends shown with nitrogen are the same for hydrogen although at lower erosion rates.

Acknowledgements

This work was supported by SDIO/IST through NASA Lewis Research Center, State of Texas ATP, and TTU CER. The authors also wish to thank Dr. Frank Curran and John M. Sankovic at NASA Lewis Research Center for their assistance with cathode materials analysis.
Fig. A1. Damaged monocrystalline W(100) cathode.

Fig. A2. Cross-section of monocrystalline W(100). 16× Cathode Tip (left). 32× Cathode Dimple (right).
References


20 Mankins, J.S., W.J. Harris, E.A. O'Hair, L.L. Hatfield, and M. Kristiansen, "Comparison of Erosion of Various Cathode Materials in a 30 kWe


