3-17-93
E-7584

NASA Technical Memorandum 106023

100-kW Class Applied-Field MPD Thruster Component Wear

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Prepared for the
Tenth Symposium on Space Nuclear Power and Propulsion
sponsored by the University of New Mexico
Albuquerque, New Mexico, January 10–14, 1993

NASA

100-kW CLASS APPLIED-FIELD MPD THRUSTER COMPONENT WEAR

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Abstract

Component erosion and material deposition sites were identified and analyzed during tests of various configurations of 100 kW class, applied-field, water-cooled magnetoplasmadynamic (MPD) thrusters. Severe erosion of the cathode and the boron nitride insulator was observed for the first series of tests, which was significantly decreased by reducing the levels of propellant contamination. Severe erosion of the copper anode resulting from sputtering by the propellant was also observed. This is the first observation of this phenomenon in MPD thrusters. The anode erosion indicates that development of long life MPD thrusters requires the use of light gas propellants such as hydrogen, deuterium, or lithium.

INTRODUCTION

Applied-field magnetoplasmadynamic (MPD) thrusters are currently under consideration for primary propulsion applications on Earth-orbit, planetary robotic, and manned missions (Gilland et al. 1990 and Hack et al. 1991). MPD thrusters have demonstrated the capability to operate at high power levels using a simple, robust design. However, the relatively low efficiencies and limited lifetime of thruster components measured to date have precluded the use of MPD thrusters in actual missions. The combined requirements of high current conduction, heat rejection, and plasma confinement lead to a variety of stresses on the cathode, anode, and insulator which can severely limit the lifetime of MPD thrusters.

While all MPD thruster components are subject to wear, most work has focussed on the cathode. Cathode erosion has long been identified as the major life-limiter of MPD thrusters. The lowest, most reliable cathode erosion rates measured prior to 1991 predicted total impulse values that were two or three orders of magnitude below the estimated requirements for a lunar or Mars cargo vehicle (Sovey and Mantenieks 1988). Total lifetimes are difficult to estimate, however, because of the paucity of MPD thruster lifetests and the wide range of cathode erosion rates reported in the literature. While reported mass loss rates range over five orders of magnitude (Sovey and Mantenieks 1988), significant progress has been recently made in the measurement of erosion rates, cathode surface diagnostics, and modeling of the erosion processes which has led to an improved understanding of the causes for the wide range of cathode erosion rates. Results to 1991 were reviewed by Myers et al. (1991). Only cathode erosion rates have been documented in steady state MPD lifetests. The only detailed erosion measurements of other thruster components were made by Rowe (1981) and Polk et al. (1987) in multi-megawatt, pulsed MPD thrusters.

This paper presents studies of erosion and deposition sites made using various configurations of steady-state, 100 kW class, water-cooled, applied-field MPD thrusters. Thrusters were operated over a wide range of operating conditions, including discharge currents from 500 to 2000 A, argon propellant flow rates from 0.025 to 0.140 g/s, and applied magnetic field strengths from 0 to 0.2 T. Thruster performance and scaling relationships have been reported elsewhere (Myers 1991 and 1992). Accumulation of several to thirty hours of run time on a number of thrusters permitted identification and measurement of lifetime limiters. Erosion measurements were made of 2% thoriated-tungsten rod cathodes, $4BaO-CaO-Al_2O_3$ impregnated tungsten rod cathodes, and impregnated hollow cathode configurations. Deposition and erosion sites were also identified on the boron nitride insulator and water-cooled copper anodes.

APPARATUS AND TEST PROCEDURE

Two vacuum chambers were utilized to test twelve applied-field MPD thruster configurations. Support equipment included a propellant metering system, water-cooling apparatus, the power system, and a data acquisition system. This section provides a brief description of the thrusters and test equipment, further details can be found in papers by Sovey et al. (1989) and Myers (1991 and 1992).

Thruster and Magnet Assemblies

A schematic of a typical MPD thruster is shown in Figure 1. Propellant was injected into the thruster through the boron nitride backplate using an annulus at the cathode base and twenty-four equally spaced 0.16 cm diameter holes at the mid-radius between the cathode and anode. Most of the thrusters had 0.64 cm radius, 7.6 cm long, 2% thoriated tungsten rod cathodes, though other radii and lengths were also tested. In addition to the 2% thoriated material, two impregnated tungsten cathodes were tested. The first was a 0.64 cm radius, 7.6 cm long rod, the second was a hollow cathode with an outside radius of 1.5 cm, an inner radius of 1.0 cm, and a length of 6 cm. The hollow cathode is shown in Figure 2. The anodes were 2.54 cm, 3.81 cm, and 5.1 cm in radius and 7.6 cm and 15 cm long. All anodes were water-cooled copper.

The thrusters were mounted inside solenoid coils which were used to generate a magnetic field in the thruster. The thruster exit plane was always even with the end of the coil. Depending on the anode size two 15.3 cm long coils were used in these tests, the first had a bore radius of 15.3 cm, the second had a bore radius of 20.3 cm. Magnetic field strengths of up to 1.66×10^{-4} T/A and 8.48×10^{-4} T/A were obtained at the centerline of the magnet exit planes for the 15.3 and 20.3 cm magnets, respectively, and the field magnitudes for the tests ranged from 0 to 0.2 T.

Facility and Test Support

The MPD thruster tests were conducted in two vacuum facilities. The first consisted of a 3 m long by 3 m diameter test port attached through a 3 m diameter gate valve to the main 7.6 diameter, 21 m long, vacuum chamber. The second consisted of a small 1 m diameter, 1 m long, test port attached to the main 4.6 m in diameter and 19.6 m long vacuum chamber through a 1 m gate valve. For tests in the latter facility the thruster was extended beyond the gate valve to prevent damage to the valve during thruster operation. Both tanks used 20 diffusion pumps to maintain facility pressures below 0.07 Pa (5×10^{-4} torr) during thruster operation, which ensured that the ambient pressure did not influence the performance measurements (Myers 1991).

Thruster power was provided by a series-parallel network of six welding power supplies which could provide up to 3000 A at 130 V. The magnetic field solenoid utilized a single welding supply providing up to 1500 A to the coil. Both supplies and thrusters were isolated from ground. A 1400 V pulse ignitor supply was used to initiate the discharge. Argon propellant mass flow rates were regularly calibrated using a constant volume calibration system. For later tests the propellant lines were evacuated and purged to test the feed system for leaks.

Thruster start-ups have been recognized to have an influence on the erosion rate of the cathode. While starting discharge current, propellant mass flow rate, and the applied-field strength were adjusted to reduce the discharge ignition erosion, no attempt was made to optimize the procedure. Electrode mass loss resulting from a cold starts, usually in the range of 3-30 μg/C was estimated to be insignificant compared to the mass loss resulting from the much lower steady state rates integrated over the entire test durations.

EXPERIMENTAL RESULTS AND DISCUSSION

Cathode Erosion

Evaporation and effects due to propellant contamination have been recognized as the main cathode erosion mechanisms (Myers et al. 1988, Polk et al. 1990 and Auweter-Kurtz et al. 1990). Both effects were observed in our tests. Much higher than expected cathode erosion was observed during the first series of tests. A typical example of the severe "groove" erosion at the base of a 2% thoriated tungsten rod cathode is shown in Figure 3. The rear of the groove is directly under the boron nitride backplate as shown in Figure 1. This highly localized erosion led to several cathode failures in which the cathode actually broke at the groove. It appeared that most of the eroded tungsten from the groove had redeposited on the cathode, resulting in a smaller total mass loss than anticipated from the large size of the groove. This result shows that simple mass loss measurements must be supplemented with an understanding of the spacial distribution of the erosion in order to accurately identify thruster life limiters.

The erosion rate decreased after "high purity" argon (99.995%) was replaced by "high purity research" grade argon (99.999%) in our tests. However, the measured cathode erosion rates still varied from 0.038 μg/C to 0.57 μg/C from test to test, and the groove type erosion still occurred occasionally. It was not until a procedure of vacuum purging the propellant lines before every test was initiated that the groove erosion was not observed. The impact of oxygen and water vapor on the erosion rate of thoriated tungsten rod cathodes has been discussed previously by Polk et al (1990) where he pointed out that at cathode temperatures above 1200-1300 °C, tungsten oxides volatilize faster than they are formed, so that the limiting rate process is the flux of oxygen and water to the surface. Auweter-Kurz et al. (1990) also reported significant cathode erosion rate reductions by replacing welding argon with high purity argon (99.998%) and the addition of drying deoxygenation device in the propellant line. The very large contaminant density, contaminant temperature, and cathode surface temperature gradients at the cathode base which result from the high current concentration in that region may yield the observed highly-localized erosion distribution.

The measured cathode mass loss rates obtained in this study are compared to representative values from the literature in Table 1. While there is considerable overlap in the data, both recent work of Auweter-Kurtz et al. (1990) , Polk et al. (1990), and early work by Ducati et al. (1964) have resulted in substantially lower values than reported here. The lower erosion rates likely resulted from the different operating conditions and chamber designs, which yielded higher cathode surface pressures and increased the redeposition rate of evaporated cathode material (Myers 1988 et al. and Polk et al. 1990). The redeposition phenomena may also explain the difference in mass loss rate for the impregnated tungsten rod cathode, 0.09 μg/C, and the impregnated hollow cathode, 0.03 μg/C, since the pressure inside the hollow cathode was estimated to be over a factor of 10 higher than that on the surface of the rod cathode. For example, in the tests of Auweter-Kurtz et al. (1990) the pressure in the vicinity of the cathode was over 100 torr, whereas the estimated pressures on the rod cathodes used in these tests is below 0.1 torr, and the measured hollow cathode pressures were between 1 and 5 torr.

In addition to erosion resulting from the presence of propellant contaminants, MPD thruster cathodes erode due to simple evaporation and sputtering of the cathode material. Myers et al. (1988) and Polk et al. (1990) showed that for typical operating conditions the dominant cause of mass loss is evaporation. To reduce this loss and satisfy the requirement for high emission current, cathode materials are chosen which have a low work function and are capable of operating at high temperatures. Two percent thoriated tungsten, which has a work function of approximately 3.3 eV (Rieck 1967), has usually been used for MPD cathodes, because it appears to satisfy both of the above requirements. However, while the thoria mass loss is not significant, depletion of the thoria from the cathode eventually leads to cathode failure because of the resulting higher surface work function, 4.5 eV, associated with pure tungsten. Thoriated tungsten cathodes usually operate near 3000 °C (Myers et al. 1988, Auweter-Kurz et al. 1990 and Polk et al. 1990). Above 2600 °C, the thoria in the cathode is totally reduced to thorium. Above 2300 °C the thorium evaporation rate exceeds the diffusion rate to the surface (Polk et al. 1990), leading to an increased work function and increased operating temperature. The high operating temperatures lead to tungsten surface evaporation (Myers et al. 1988, Auweter-Kurtz et al. 1990, and Polk et al. 1990). As mentioned above, the net evaporation rate of the tungsten and impregnant will be reduced by backscattering of the ejected atoms off the ambient plasma, indicating that thruster designs should position the emitting surface in a high pressure region. The lowest reported mass loss rates, measured by Auweter-Kurtz et al. (1990) and Polk et al. (1990), were obtained with cathodes in ambient plasmas at pressures of 20 to 150 torr, which is higher than even the hollow cathode pressure in this study.

For cases with reduced propellant contaminants, the erosion rate of the barium impregnated tungsten rod cathode was about 2.4 times higher than the lowest thoriated tungsten cathode erosion rate, even though the operating temperature of the barium impregnated cathode was almost 1000 °C lower . Because of the depletion of barium in such a cathode takes place at considerably lower temperatures, it is believed that most of the mass loss observed in this experiment was the impregnated material. Cathodes using the impregnant generally operate in the 1000 °C to 1200 °C range in order to ensure low depletion rates of the impregnant material (Sarver-Verhey 1992).

The principal advantage of the hollow cathode geometry appears to be a reduced depletion rate of the low work function impregnated mix via a reduced operating temperature and increased material redeposition rate. The barium impregnated hollow cathodes have been tested in MPD thrusters by Mantenieks and Myers (1991). The measured erosion rate of the hollow cathode in our test was about three times lower than that of the rod cathode made of the same material. Analyses of material deposited inside the thruster indicate that most of the mass lost from the hollow cathode was barium. At the deposition sites, the ratio of barium to tungsten by weight was 6.7. This again shows that simple mass loss measurements of cathodes can be misleading, because the high barium loss rate will likely lead to a runaway increase in material work function. Improved hollow cathode designs are essential to provide sufficiently low operating temperatures and high emission site pressures for adequate cathode lifetime.

Boron Nitride Insulator Degradation

Two failure mechanisms were observed with the boron nitride insulators. The first was erosion at the annulus of the cathode base. It was found that the insulator eroded away from the downstream face, gradually forming an expansion cone. An example of this kind of damage is shown in Figure 4. While erosion was rapid with new insulators, the erosion rate appeared to decrease with time as the surface receded from the hot cathode. It was found that the insulator mass loss could be reduced by starting with a flared annulus and increasing the gap between the insulator and the cathode.

There are two potential causes of the boron nitride erosion. The first is that tungsten evaporated from the cathode is deposited on the boron nitride and forms a BN-W eutectic (Jahn 1968 and Rieck 1967). Most tungsten borides and nitrides have melting temperatures below 2000 °C, which could explain the high material loss rate. The second potential cause is the presence of oxygen or water vapor in the propellant . While boron nitride can be used in an inert and reducing atmospheres up to 2800 °C, in oxidizing atmospheres the maximum operating temperature may drop as low as 985 °C (Sohio 1984). While not quantified, based on visual inspection the boron nitride erosion rate appeared to decrease following initiation of the vacuum purge procedure described above.

The second boron nitride failure mode was a radial crack in the insulator, sometimes accompanied by localized melting of the boron nitride around the crack. The localized melting around the crack appeared to be a result of an electrical breakdown through the crack. This was supported using video cameras to image the internal chamber surfaces during operation, which showed the cracks appearing and suddenly becoming intensely luminous. While the cracks never occurred with the 2.54 cm radius thrusters operating at powers below 100 kW, all 5.1 cm radius backplates cracked when the thruster power exceeded approximately 90 kW. Video records show that the cracks developed during thruster operation and not during start-up or shut-down when thermal shocks would be at their maximum. On at least two occasions the cracks suddenly developed within a five second time span following seven hours of stable operation. The cracks have sometimes resulted in substantial propellant leakage and electrical breakdown between external thruster surfaces. The incidence of cracking was reduced, but not entirely eliminated, by increasing the width of the annulus between the cathode and the boron nitride.

In addition to the erosion and cracking, considerable deposition was found on the insulator after several of the tests. While not presently considered a failure mechanism, the deposition was severe enough with the 5.1 cm radius thruster anodes to resul in peeling of the deposited layer from the insulator. The deposition layer was found to contain mainly copper and tungsten which came from anode and cathode, respectively. Deposits on the boron nitride may lead to eventual shorting between the cathode and anode.

Anode Erosion

Previous work on MPD thruster component wear has not identified the anode as a potential life limiting thruster component. The only anode failure modes identified in the literature were localized melting resulting from unstable thruster operation or improper thermal design (Goodfellow et al. 1992 and Esker et al. 1969), which permitted operation at temperatures above the melting point of the anode material. However, these were not considered fundamental limitations because thrusters would not be operated under unstable conditions, and more detailed thermal design would reduce the anode operating temperature to a level consistent with long term operation. However, this study has revealed a new anode erosion mechanism which may limit the use of high molecular weight propellants for even low temperature anodes.

Testing with anode radii of 2.54 cm, 3.76 cm, and 5.1 cm revealed that the surface texture of the larger two sizes changed with time, with the surface becoming rougher more rapidly with the largest anode. No surface texture changes were observed with the 2.54 cm anode. Not only did the larger anodes became rough, but small very localized protrusions developed on the copper surface. The spikes became quite pronounced in the 5.1 cm radius anode, reaching up to 1 mm in height for some tests. The surface texturing had a pronounced orientation, with helical patterns appearing on the anode surface. The tips of the protrusions were pointing in the opposite direction of the expected direction of plasma rotation resulting from the radial current and axial applied-field interaction. Spikes or cones are commonly produced by ion sputtering when surfaces of low sputter yield metal are sputtered in the presence of local deposits or contaminants of higher sputter yield metals (Kaminsky 1965). Tungsten particles from the cathode are most likely responsible for the cone formation on the anode surface.

This anode erosion phenomenon was studied in more detail by conducting an extended test. The thruster consisted of a hollow cathode with a 5.1 cm radius, 15.2 cm long anode. The thruster was operated at 60 kW with a 1400 A discharge current and 0.14 g/s argon propellant flow rate. After 33 hours of uninterrupted operation a pinhole water leak developed approximately 2.0 cm from the anode exit plane and ended the test. The anode surface appeared shiny, though roughened, except for approximately 4.0 cm length from the backplate, where deposition and peeling of a thin film was evident. The shiny area was covered with a number of small sharp protrusions approximately 0.5 mm in height.

The anode was sectioned to measure the erosion of the anode surface. The anode cross-section is shown in Figure 5 It is evident that the surface erosion increased toward the exit plane. A maximum erosion rate of 0.1 mm/hr was measured at the downstream lip of the anode surface. To the best of our knowledge, this is the first observation of this erosion mechanism in a MPD thruster.

Similar surface texturing has been observed in materials processing experiments for sputtered materials under energy argon bombardment (Kaminsky 1965 and Behrish 1981) indicating that atom or ion sputtering may be the cause of the erosion. Assuming a uniform radial velocity profile, for the estimated specific impulse of approximately 1500 s, the argon atom energy should reach up to 50 eV, which is high enough for argon ions to overcome the estimated anode voltage drop of approximately 20 V and impact the anode surface with an energy of approximately 30 eV. This is over the 25 eV sputtering threshold energy for copper sputtering by argon. If charge-exchange collisions take place near the anode surface, neutral atoms may hit the anode with the full 50 eV energy. The copper sputter yield for perpendicular impingement is approximately 0.05 atoms/ion at 30 eV incident energy, and this increases to 0.2 atoms/ion at 50 eV (Behrish 1981). At non-normal incidence, the sputter yield of energetic argon ions on copper may increase by a factor of two (Kaminsky 1965). While attempts were made to estimate the erosion rate due to sputtering, it was not possible given the uncertainties in angle of incidence of the incoming particles, incident energies, and incident particle fluxes.

The sputtering erosion mechanism clearly only becomes an issue when the propellant energy exceeds the sputter threshold for the anode material. Given that metal sputter yields at the same energy level do not vary by more than an order of magnitude, it will not be possible to eliminate the sputter mass loss by using alternative anode materials. Thus, the solution to this problem is to choose a light propellant which has an extremely low sputter yield at energies of tens of electron volts. Propellants such as hydrogen, deuterium, and lithium, satisfy this requirement for the exhaust particle velocities required for missions of interest (Gilland et al. 1990 and Hack et al. 1991).

CONCLUSIONS

Erosion and deposition sites were analyzed for the cathode, insulating backplate, and anode of various configurations of 100 kW class, applied-field, water-cooled MPD thrusters. Initial severe cathode erosion was significantly reduced by using the highest purity propellant available and vacuum purging the propellant lines. The resulting rod cathode erosion rate of 0.04 μg/C was in close agreement with some past measurements, though the lowest rates found using cathodes in higher pressure environments could not be duplicated. It appears that the cathode erosion rate may depend strongly on thruster geometry and operating conditions due to the backscattering of evaporated material by the ambient plasma.

Boron nitride insulator erosion was reduced by both the improvement in propellant purity and increasing the cathode - insulator gap. Cracking of the insulator was also reduced, but not entirely eliminated. Deposition of cathode and anode material found on the downstream side of the insulator tested may result in insulator failure for extended tests.

Anode erosion attributed to argon heavy particle sputtering was observed for the first time. An extended test and subsequent analysis revealed that the erosion rate reached 0.1 mm/hr at the exit plane of the 5.1 cm radius anode. This erosion mechanism places a severe limit on future high power water-cooled MPD thruster testing with heavy gas propellants, though the problem can potentially be avoided by using either hydrogen or lithium.

Acknowledgements

The authors thank John Naglowsky, Larry Schultz, David Wolford, Jerry LaPlant, Peggy Yancer, John McAlea, Rob Butler, John Miller, Gerry Schneider, Bernard Loyer, Cliff Schroeder, David Wehrle, and Shawn Reese for their invaluable assistance during this project.

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TABLE 1. Comparison of Steady- State Cathode Erosion Rates

CATHODE TYPE	EROSION RATE µg/C	PROPELLANT	REFERENCE
2% ThW rod	0.038 - 0.57	Argon	This paper
$4BaO\text{-}CaO\text{-}Al_2O_3$ /W rod	0.09*	Argon	This paper
$4BaO\text{-}CaO\text{-}Al_2O_3$/W Hollow Cathode	0.03*	Argon	This paper
2% ThW rod	0.18	Argon	Myers et al. (1988)
2% ThW rod	0.0015 - 0.03	Argon	Auweter-Kurtz et al. (1990)
2% ThW rod	0.0016	Argon	Polk et al. (1990)
2% ThW rod	$4x10^{-5}$	Hydrogen	Ducati et al. (1964)

* Mass loss mostly barium

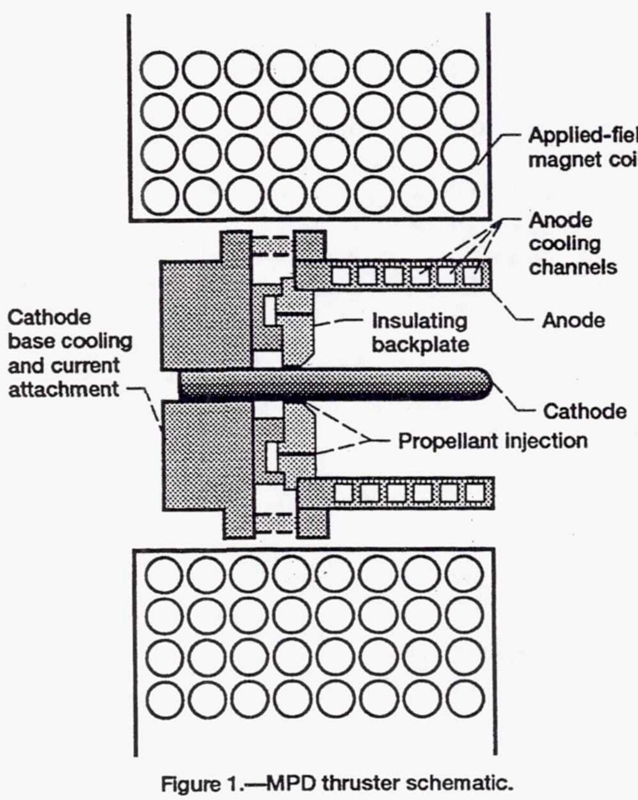

Figure 1.—MPD thruster schematic.

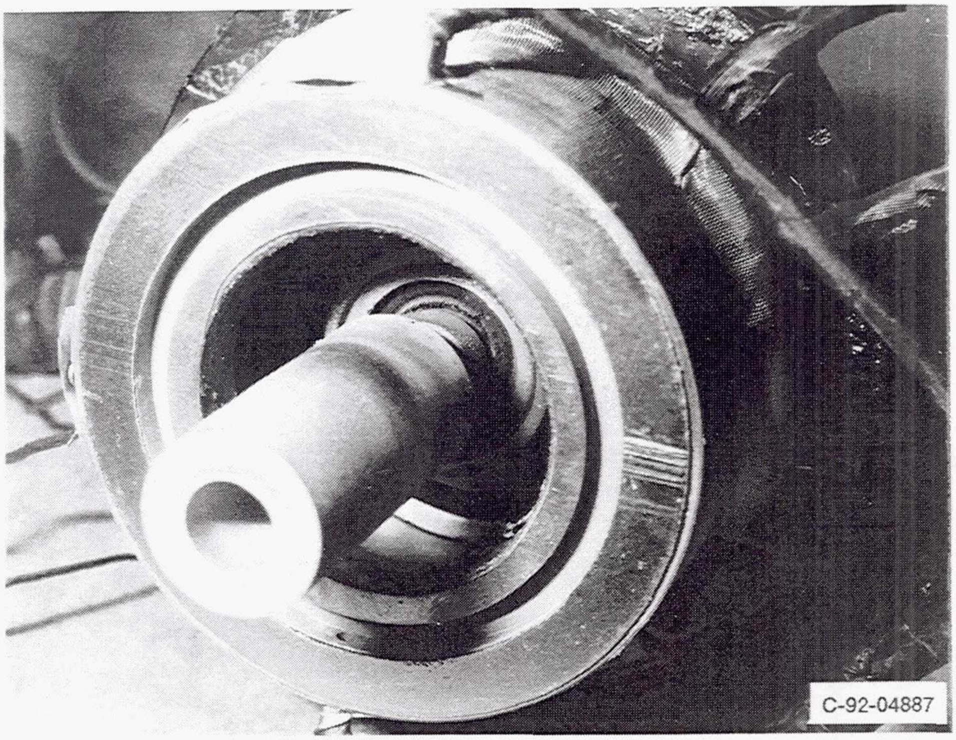

Figure 2.—Hollow cathode thruster without anode.

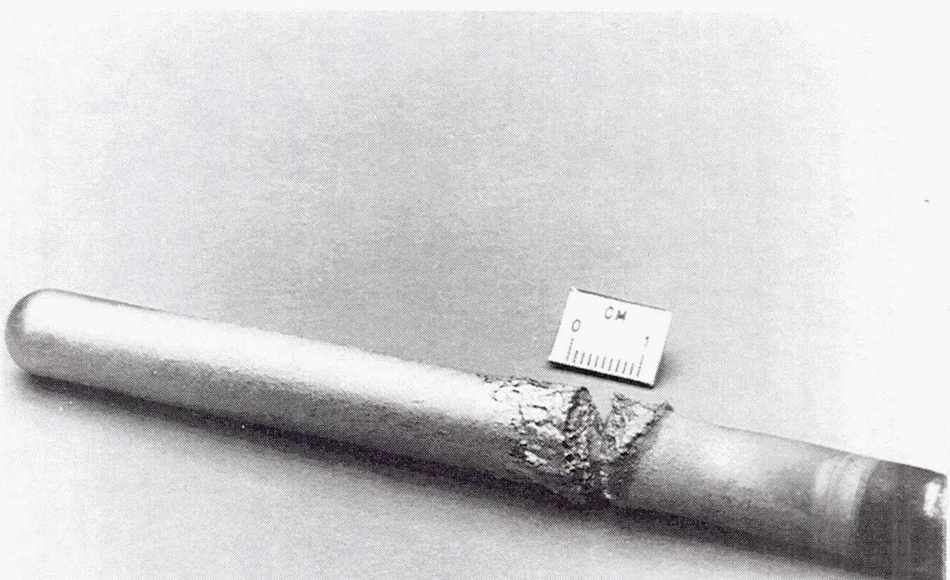

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Figure 3.—"Groove" erosion in 2% thoriated tungsten.

Figure 4.—Degradation of boron nitride insulator.

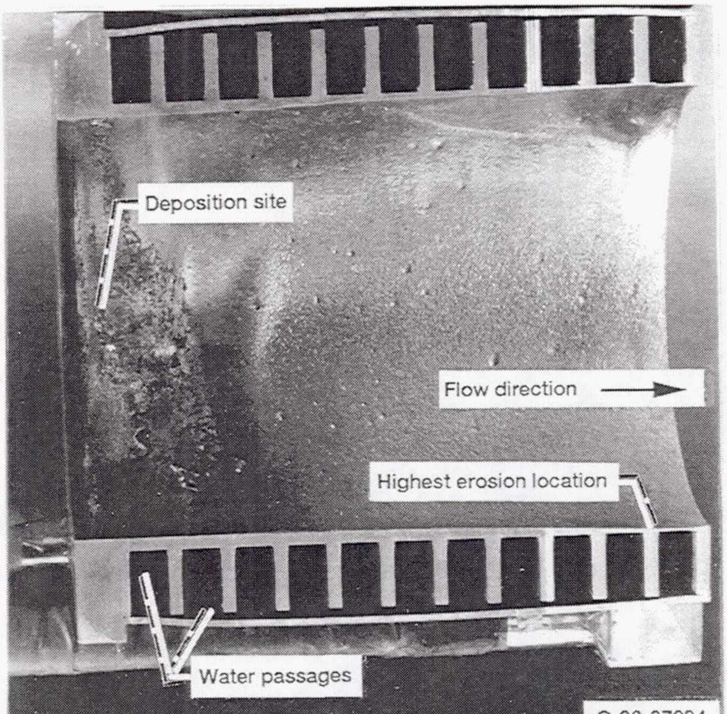

Figure 5.—Cross section view of sputter-eroded water-cooled anode.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1993	Technical Memorandum

4. TITLE AND SUBTITLE
100-kW Class Applied-Field MPD Thruster Component Wear

5. FUNDING NUMBERS
WU–506–42–31

6. AUTHOR(S)
Maris A. Mantenieks and Roger M. Myers

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
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Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–7586

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–106023

11. SUPPLEMENTARY NOTES
Prepared for the Tenth Symposium on Space Nuclear Power and Propulsion sponsored by the University of New Mexico, Albuquerque, New Mexico, January 10–14, 1993. Maris A. Mantenieks, NASA Lewis Research Center, Cleveland, Ohio. Roger M. Myers, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142. Responsible person, Maris A. Mantenieks, (216) 977–7460.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 20

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
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14. SUBJECT TERMS
Space propulsion; Electric propulsion; MPD thrusters; MPD thruster lifetime

15. NUMBER OF PAGES
12

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

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Space Administration

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