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Arcjet Cathode Phenomena

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ABSTRACT

Cathode tips made from a number of different materials were tested in a modular arcjet thruster in order to examine cathode phenomena. Periodic disassembly and examination, along with the data collected during testing, indicated that all of the tungsten-based materials behaved similarly despite the fact that in one of these samples the percentage of thorium oxide was doubled and another was 25% rhenium. The mass loss rate from a 2% thoriated rhenium cathode was found to be an order of magnitude greater than that observed using 2% thoriated tungsten. Detailed analysis of one of these cathode tips showed that the molten crater contained pure tungsten to a depth of about 150 microns. Problems with thermal stress cracking were encountered in the testing of a hafnium carbide tip. Post test analysis showed that the active area of the tip had chemically reacted with the propellant.

A 100 hour continuous test was run at about 1 kW. Post test analysis revealed no dendrite formation, such as observed in a 30 kW arcjet lifetest, near the cathode crater. The cathodes from both this test and a previously run 1000 hour cycled test displayed nearly identical arc craters. Data and calculations indicate that the mass losses observed in testing can be explained by evaporation. An increase in the redeposition rate with cathode recession was postulated to explain the observed decrease in mass loss rate with time.

From measurements of the cathode crater size, estimates of the emitting area were made. These were used with realistic bounds on the crater temperature, material work function, and the electric field at the cathode to study the cathode emission process. From this, simple calculations suggest that both field and thermionic emission are involved.

INTRODUCTION

Research and development of arcjet thrusters for space propulsion began over three decades ago. In this era, numerous missions requiring primary propulsion were under consideration and so a majority of this early effort focused on 30 kW class hydrogen arcjets. It was assumed, at least at the outset, that this power level would be provided by the nuclear power plant being developed under the SNAP-8 program and that the problems associated with long term hydrogen storage would be solved. The program also included analysis and testing of smaller 1 to 2 kW devices, on hydrogen, for auxiliary propulsion. By the early 1960's it became apparent the anticipated advances in space based power availability were lagging and that missions compatible with arcjet technology had not developed. For these reasons, the NASA-sponsored arcjet program was discontinued. A comprehensive review of the effort was presented by Wallner and Czika in 1965.¹

Recently, interest in the arcjet has been rekindled. NASA began a program to develop the low power arcjet in 1983 for application to missions, such as north-south stationkeeping (NSSK) on geosynchronous communications satellites. At about the same time, the Air Force started research on 30 kW class devices for high thrust applications. It was recognized early in both of these programs that hydrazine and ammonia were the most viable propellants as the long term storage of hydrogen was as yet prohibitive from the standpoint of system mass. For compatibility with modern satellites the low power work has been centered around the 1.2 kW level with the decomposition products of hydrazine as the propellant. The high power devices have been used primarily with ammonia since any mission will require a new system design and an ammonia system would eliminate the need for a gas generator and offer a higher specific impulse than does hydrazine due to its lower molecular weight.

To be of value in the proposed missions, both the high and low power arcjets will be required to operate reliably over long periods of time. In a typical NSSK mission scenario, the low power arcjet life requirement has been estimated at 600 hours taken in approximately 1 hour increments over a

*1988 Air Force Cadet Summer Research Program.

10 year period.^{2,3} For the SP-100 reference mission a long-term life will be required, and electrode erosion is a concern. During the earlier arcjet program, endurance tests of both 500⁴ and 720⁵ hours were successfully completed at the 30 kW level, as was a 150 hour test of a 2 kW device.⁶ All of these tests were performed using hydrogen as the propellant. Ammonia was tried briefly at high power in a slightly modified engine but no long term testing took place. Tests with propellants other than hydrogen at low power met with little success.⁷ A more recent endurance test was undertaken at the Jet Propulsion Laboratory using a 1960's design arcjet with ammonia and severe cathode degradation, in the form of dendrite formation, was observed after 573 hours.^{8,9} An investigation of cathode erosion in high power arcjets is currently in progress.¹⁰

Some parametric testing of arcjet cathode erosion characteristics has been done at low power on hydrazine. These tests indicate that increasing both chamber pressure and cathode diameter decrease erosion in short term tests.³ Results from a recently completed long-term cyclic lifetest at 1.26 kW suggest that, after an initial burn-in period, the cathode reaches a steady state configuration and that erosion may not be a severe problem in this power range.¹¹

In all of the above mentioned tests, thoriated tungsten welding rods have been used for cathodes. Little work has been performed to characterize erosion over time or to examine material effects. For this report, cathode tips were fabricated from a number of different candidate materials. These were run in low power thrusters under conditions typical of those anticipated on-orbit. The tips were removed periodically for analysis and the results of the analyses are presented. A 100 hour continuous lifetest was also run for this study. The cathodes from both this and from the 1000 hour cyclic lifetest were examined and these results are also presented.

APPARATUS

Two areas of low power arcjet cathode have been investigated. The first area deals with a direct comparison of different types of cathode material. Six different cathode tips were machined to identical geometries in an effort to compare erosion rates, operating voltage, and starting characteristics of each. The second area of cathode phenomena deals with the metallurgical changes of a chosen material after a prolonged continuous lifetest. Grain structure, cathode tip geometry, and thorium oxide depletion were the main concerns.

Cathode materials comparison tests were conducted with a laboratory arcjet whose schematic is shown in Figure 1. This radiatively cooled thruster was designed to allow convenient and repeatable assembly. A 2% thoriated tungsten nozzle was used. The constrictor was 0.64 mm diameter by 0.41 mm long. The converging and diverging ends of the nozzle were conical with half angles of 30° and 20°, respectively. The anode cathode gap spacing was set by inserting the cathode into the thruster until contact was made with the anode and then withdrawing the desired amount. For the tests described herein, a gap of 0.58 mm was used. Gaseous propellant was injected tangentially into a cylindrical arc chamber just upstream of the nozzle. Gas entered through two 0.34 mm dia holes to form a vortex flow field.

Each arcjet cathode tip consisted of a cylindrical rod 3.18 mm in diameter with a 30° half angle conical tip at one end (Figure 2(a)). These tips were approximately 10 mm in length, with the conical tip at one end and an attachment pin at the other. Due to the short length of each sample, an extension rod was used to hold the cathode tip material within the arcjet thruster (Figure 2(b)). The extension rod was 3.18 mm in diameter, and 20 cm long, and made from 2% thoriated tungsten. A four prong receptacle at one end was used to grip the attachment pin of each sample. Tolerances were held such that this receptacle provided a spring loaded friction fit allowing for easy interchanges of cathode tip samples. Figure 2(c) shows the assembled cathode as it was put into the thruster. The cathode used in the 100 continuous hour test differed from that of the material comparison study in that a single piece, 3.2 mm dia by 190 mm long, thoriated tungsten rod was used. It also had a 30° conical tip at one end, and was directly interchangeable with the cathode assembly used for material comparisons.

In each arcjet test assembly the cathode was centered coaxially within the arc chamber by a boron nitride front insulator. Longitudinal grooves along the outer surface of the insulator allowed passage of propellant to the chamber injection holes and permitted regenerative preheating of the gas.

The thoriated tungsten nozzle, gas injector, and front insulator were all contained within an anode housing. Each component was positioned within the barrel of the housing and separated by graphite gaskets. The walls of the housing not only directed and preheated incoming propellant, but also served as a thermal radiator for the tungsten nozzle.

The rear half of the arcjet consisted of a boron nitride insulator which anchored the cathode extension rod and electrically isolated the propellant feed tube. A modified compression type gas fitting was used to clamp and seal the cathode in position. The propellant feed tube was threaded into a stainless steel anchor located deep within the insulator. The anchor was bored through to allow the cathode and its insulating sheath to pass axially down the arcjets center.

A coiled spring made from Inconel X-750 and a boron nitride compression plunger were located in the rear insulator. Force from the spring was used to axially compress internal graphite gaskets around the gas injector and nozzle located in the front of the arcjet. Machining tolerances were set to accommodate radial thermal expansion over the entire heating and cooling cycle. The anode housing was joined to the rear insulator assembly using two stainless steel flanges and four bolts. The flanges were designed to flex axially to maintain uniform pressure over this joint.

Testing was performed in one of two separate vacuum facilities, depending on availability. Long duration runs were normally carried out in a 0.64 m diameter by 0.64 m long bell jar. A single mechanical roughing pump with a capacity of 21000 L/min was used, which maintained an ambient pressure in the bell jar of approximately 100 Pa (0.75 torr) during arcjet operation. Other testing was performed in a tank that was 1.5 meters in diameter, 5 meters long, and serviced by four 30,000 L/sec oil diffusion pumps. Pumping speeds were such that ambient pressure inside the tank was approximately 5×10^{-2} Pa during arcjet operation. The thruster to be tested was placed within a 0.9 m diameter by 0.9 m long port extension at one end of the tank.

Propellant for all tests consisted of a hydrogen/nitrogen gas mixture at a volume ratio of 2:1 to simulate fully decomposed hydrazine. A two channel mass flow control system was used to meter and regulate both gases separately. The gases were then mixed in the propellant feed line on the way to the thruster. Each channel could be operated from a central console, or remotely through an external set point. The maximum flow rate available was 10 L/min for each gas, at a feed line pressure of up to 9.6×10^5 Pa.

A pulse width modulated power supply with fast current regulation was used to power the arcjet thruster. An open circuit voltage of 175 V dc was available with this unit and a maximum current of 12 amps could be drawn at 120 V dc. A high voltage starting pulse generator was incorporated into the power supply to initiate arc breakdown. A 4 kV pulse could be applied to the arcjet once every second until ignition occurred.

Experimental data obtained during firing included arc voltage, current, propellant mass flowrate, and inlet pressure. Arc current was measured using a Hall-effect current probe attached at a vacuum feed through on the test chamber. The probe provided excellent noise isolation and its calibration was checked prior to each test run. Arc voltage was also monitored at the vacuum feed through and reduced with a 10:1 voltage divider to avoid transient spikes to the recording equipment during startup. A digital multimeter was also used to monitor the arc voltage. An optical isolation amplifier was used to eliminate noise interference. All experimental data was recorded using an 8 channel strip chart recorder. The digital displays of various instruments were recorded periodically to obtain precise data points.

EXPERIMENTAL PROCEDURES

A major goal of this investigation was to compare the suitability of a number of different cathode material samples for use in an arcjet. Each sample was machined to the same shape, and run at as close to identical conditions as was practical. The criterion for comparison were mass loss, steady state voltage, and arc stability.

Each sample was tested in stages so that some indication of long-term trends could be inferred. The sequence began with 2 hours of operation followed by another 2 hour run and a final 5 hour run. After each of these cycles the thruster was disassembled for examination of the cathode tip.

Cathode mass loss was determined during disassemblies between each stage of testing, for a total of 3 mass loss data points. As a means to reduce effects from possible cumulative changes in test hardware over the duration of testing, an effort was made to proceed with all samples through the completion of a given stage of testing before going on to the next. Exceptions to this rule were established when the first 2 hour burn-in revealed some material samples which were at higher risk of not completing the intended test sequence. This will be discussed in greater detail in a following section.

Prior to testing, each tip sample was weighed using an electronic analytical balance. The scale was calibrated before each weighing and each cathode sample was thoroughly cleaned. Three weighings were taken and averaged for each sample. In order to determine the reproducibility of this method, one sample was weighed on two separate dates. The total weight of each tip was about 1g and the difference in weight from the two measurements was only 0.01 mg. Scanning Electron Microscope (SEM) photographs were also taken of each cathode tip prior to testing.

Each cathode sample was assembled in the common arcjet described previously using the same procedure on every occasion. The arc gap was set to 0.58 mm for each cathode and a pressure leak check was made prior to each run. The thruster was installed in a vacuum facility and all instrumentation was allowed at least 1 hour to warm up. The propellant gas flow rates were set to

give a 2:1 hydrogen to nitrogen mixture ratio at a mass flow rate of approximately 0.05 grams/second. This was given 5 minutes to equilibrate prior to ignition. After each operating period the thruster was allowed to cool briefly before being removed from the vacuum facility and disassembled. A post-test pressure check and arc gap measurement were made to verify the integrity of the arcjet.

A common test profile was intended for each cathode tip. In the initial 2 hour run, the arcjet was started at 12 A, and then turned down to 11 A (approximately 1.1 kW) after about 1 minute. The current was then left at 11 A for the remainder of the 2 hours. Current, voltage, and pressure measurements were recorded at 15 minute intervals throughout the run. After disassembly, each tip was weighed and photographed using the procedures described earlier.

The arcjet was reassembled for the second stage of testing. This began with two brief operating periods in which transient behavior was observed prior to steady state arc attachment (approximately 2 minutes). About 15 minutes of cooling time was allowed between restarts. A 2 hour 11 amp test run followed in which voltage, gas flow, and pressure were recorded at 15 minute intervals. After this second 2 hour run, the cathode tip was once again weighed and photographed.

The third stage of testing consisted of a 5 hour run at 11 A. Thruster operating parameters were recorded at half-hour intervals. This run concluded the test and the cathode tip was weighed and photographed a final time.

Following final surface analysis, each cathode sample was encapsulated and ground to reveal a lengthwise cross-section along its center axis. The surface was then chemically etched to bring out the grain boundaries. Both energy dispersive x-ray analysis (EDS) and Auger spectroscopy were used for elemental analysis on selected samples.

RESULTS AND DISCUSSION

Cathode Tip Evaluations

General Observations. As indicated in the preceding section, a controlled test sequence was attempted with each of the cathode tips in order to study the erosion characteristics of the various materials. The materials used are given in Table I. The full series of tests was possible with all of the tungsten based materials. In these tests, the arcjets ran stably and little anomalous behavior was noted. The test sequence was altered for the tip made of 2% thoriated rhenium. An abnormal amount of sparking was observed at the start of the test and this continued after the arcjet voltage had stabilized and the arcjet was running in high mode (i.e., with the anode attachment in the divergent section of the nozzle). Because of this, the test was stopped for an evaluation of the tip after 2-1/2 minutes. The results will be discussed below. Thermal stress cracking was a problem with the hafnium carbide tip and this test was also terminated after a very brief period as described below. Previously, a hafnium carbide tip was run at this laboratory in support of another program.¹² The results of this test are reported here for completeness.

Voltage-Current Characteristics. In the arcjet thruster the difference in potential between the electrodes is equal to the summation of the voltage drops across the cathode fall zone, the body of the arc, and the anode fall zone. The same anode geometry and operating conditions were used in each of the cathode tip tests and, as mentioned previously, normal, high mode behavior was observed in all the tests. Thus, any major differences in operating voltage should be attributable to differences in the cathode fall zone at the cathode tip. This assumes the gap setting was repeatable from test to test which was an initial concern in these experiments. Table II shows the operating voltages of the cathode tips at the end of the various test periods. From the Table it is obvious that there was very little variation in voltage between the tips made from the three tungsten-based materials (cathodes 1 to 4). A general trend of a gradual increase in voltage with time is displayed. This was caused by the gradual recession of the cathode tip to a steady-state condition, which has the effect of lengthening the arc. Tip recession has been documented in previous testing^{11,13} and will be discussed in more detail in following sections. The two tips of 2% thoriated tungsten gave almost identical results.

The operating voltage of the thruster with the rhenium based cathode rose more rapidly than in the tests with the tungsten based cathode tips. In these tests, the current had to be decreased as the power into the arcjet structure became excessive. This rapid rise in voltage suggests a higher rate of cathode recession, this was observed in the SEM photographs and will be discussed in the next section.

As previously discussed, only a single test of a hafnium carbide tip was performed in which steady state operation was obtained. The operating time in this test was approximately 1 and 1-1/2 hours and it was run at 10 A rather than 11 to decrease the heat load at the tip. In this test stable arcjet operation was observed but the voltage increased very rapidly, about 22 volts, over the course of the test. As in the case of the rhenium-based cathode this indicates rapid changes in the cathode tip structure. The initial voltage level, however, was similar to voltage levels observed in

other arcjet testing under similar conditions. This suggests that conditions near the cathode, such as the fall zone, were not much different for this tip than in the case of the standard metal cathodes.

Mass Loss Measurements. Many investigations of cathode phenomena in free burning arcs at pressure levels between vacuum and atmospheric have been performed.¹⁴⁻²⁰ It has been shown that under many conditions the arc current is emitted from one or more small molten spots on the cathode surface and that these spots move rapidly across the surface. Porto, et al., suggest that is likely that, for cold cathodes, these spots exhibit the same basic characteristics regardless of the ambient pressure.¹⁶ In general, these studies have indicated that erosion rates are dependent on both pressure and current but do not suggest a dependence on operating time. In fact, data presented by Hardy and Nakanishi²⁰ show that cathode mass loss rates in free burning, high pressure arc discharges are linear with time in most cases. This is not surprising in that the motion of the cathode attachment region produces constant cathode surface conditions. This is not the case in the arcjet, however. As noted earlier, the arc is forced to seat at the cathode tip by the propellant flowfield. Thus, the erosion characteristics for the arcjet may be quite different than those observed in the case of the free burning arc. Figure 3 shows the mass loss, as a function of time, for the various arcjet cathode tips tested. The mass loss rates for the tungsten-based materials are shown in Table III. From previous data a mass loss rate for the 1000 hour lifetest cathode was also estimated and included in the Table. From the Figure and the Table it can be seen that the two samples made from 2% thoriated tungsten displayed nearly identical erosion characteristics. Not enough data were collected to allow a full statistical analysis. The results of these two separate tests, however, taken with the previously noted similarity in current-voltage characteristics, indicate that the tests were run with reasonable repeatability. Figure 3 and Table III also show that the mass loss rates for the other two tungsten-based tips were higher than those observed in the two 2% thoriated tungsten based tips only over the first 2 hours of testing. After this, the mass loss rates for all the tungsten-based materials were virtually identical. A rough idea of how the erosion rate decreases over long periods of time can be extracted using the averaged mass loss data from the 2% thoriated tungsten cathode tip tests and that obtained in the 1000 hour lifetest. This analysis is based on the assumption that the dominant cathode cooling mechanism is radiative. The mass loss rate for the 1000 hour test cathode, as shown in Table III, was estimated by subtracting the averaged mass loss obtained with the two 2% thoriated tungsten tips at the 9 hour mark from that of the total mass loss measured in the 1000 hour test to obtain the mass lost after this point in the lifetest. This is certainly to be considered only an approximation as the cathode tip shape and the mass flow rate were slightly different in the lifetest than in the cathode tip tests. However, both of these would be expected to have little affect on the mass loss rate and so the data in Table III are likely reasonable. From Table III, it is evident that the mass loss rate decreases significantly with time. The mass loss rate estimated at 1000 hours is nearly an order of magnitude below the initial mass loss rate for cathodes 1 and 2. In fact, this may be an overestimation of the mass loss rate at the end of the test. Given the observed trend, the lack of data points at intermediate time intervals probably leads to an overestimate of the erosion rate at the 1000 hour point. This is consistent with the postulate that the cathode erodes quickly back from the original sharpened tip to a near steady state shape from which the mass loss rate is very small, as suggested in earlier studies.^{11,13} The decrease in the mass loss rate with time also indicates that for the case of the arcjet, in which the arc is forced to the tip by the flow field, the erosion phenomena cannot be simply described by a plot of grams/coulomb or grams/hour as in the case of the free burning arc experiments^{15,20} noted at the start of this section.

Figure 3 also shows that the mass loss of the thoriated rhenium cathode is significantly higher than that of the other tungsten-based materials. For this sample the mass loss rate after 4 hours of operation was seen to be an order of magnitude above those measured for the tungsten-based cathode tips. The melting point of the 2% thoriated rhenium tip is expected to be 200 to 300 °C below that of 2% thoriated tungsten. As will be discussed in the next two sections, the thorium oxide likely does not play a significant role in the emission process and the observed mass loss rates can be explained solely by evaporation. If this is postulated, then the fact that the rhenium-based cathode displayed a mass loss rate significantly higher than that of the tip containing 25% rhenium implies that it must have been running at a higher temperature. This could be explained by the fact that rhenium has a significantly higher work function than does pure tungsten (5.1 versus 4.5 V). Further work would be necessary, however, to confirm the postulated difference in operating temperature between rhenium and tungsten tips. Evidence will be presented in a following section to show that the arc cathode attachment occurs from a small molten crater at the cathode tip and that the dimensions of this crater are nearly constant with time. This being the case, it is unlikely that the total erosion rate would decrease with time. This suggests that as the cathode erodes back to a nearly steady state configuration, the redeposition rate increases leading to a lower net erosion rate (i.e., a lower mass loss rate).

Detailed Cathode Phenomenology

Tungsten Based Alloys. As discussed previously, all four of the tips were subjected to SEM analysis as part of the test and analysis sequence. All of these displayed similar phenomena so, for

brevity, one of the 2% thoriated tungsten tips was chosen for detailed analysis and this is presented here. Figures 4(a) to (c) show a sequence of SEM photographs of the tip taken after 2, 4, and 9 hours of operation, respectively. For comparison, Figure 4(d) shows a SEM photograph of the second 2% thoriated tungsten tip after its first 2 hour run. From these photographs, it can be seen that the shape of the tips is very similar in each case. The arc appears to have originated from a small molten crater at the tip.

At the conclusion of testing the cathode shown in Figures 4(a-c) above was sectioned, polished, and etched and then subjected to SEM analysis with both energy dispersive (EDS) and Auger spectroscopy. The entire tip in its polished condition is shown in Figure 5(a), and Figure 5(b) shows the tip after etching to bring out the grain boundaries. A number of the dark nodules observed were analyzed via EDS and found to be composed of thorium oxide. These were sintered cathodes so the presence of nodules was not unexpected. Figure 5(b) shows, however, that no nodules were present at the cathode tip. In fact, EDS showed no thorium oxide within 100 to 150 microns of the cathode tip. From the recrystallization pattern near the tip, this also appears to be the approximate depth to which the material was molten. Behind this area, the grain boundaries, though irregular, appear to be homogenous and unaffected throughout the bulk of the material as do the dark nodules. This suggests that operation does not cause gross changes in the bulk material and that there is little migration of thorium oxide toward the tip. A clearer view of this is shown in the photomicrograph of Figure 5(c) which presents a more magnified view of the region near the crater on the polished cathode tip shown in Figure 5(a). This photomicrograph shows that no thorium oxide nodules are present in the resolidified region near the crater. Thus, there is no indication that arcjet operation causes migration of thorium oxide toward the molten crater.

During the course of the SEM photography, one final observation was made. Under high magnification a number of occlusions were observed on some of the cathode tips. An example of this is shown in Figure 6. This photograph was taken early in the test cycle and shows the resolidified region of the tip. A number of pits are seen and these are approximately one to two microns in diameter. This is approximately the same size as the thorium oxide nodules seen in the earlier photograph. It is likely that these pits were sites of thorium oxide nodules which vaporized due to the extreme temperature at the tip. This temperature must be at least the melting point of tungsten at which the vapor pressure of thorium oxide is greater than 1 torr.²¹

2% Thoriated Rhenium. As described in a previous section, the 2% thoriated rhenium tip test was first terminated after only 2-1/2 minutes after excessive sparking was observed in the plume. An SEM photograph of the tip at this point is shown in Figure 7(a). From this it is obvious that a very extensive portion became molten very rapidly. The crater on the tip after 4 hours of operation shown in figure 7(b), is similar to those observed on other tips, but it does appear to be deeper as might be expected from the higher mass loss rate and operating voltage (indicating an increased arc length).

Hafnium Carbide. Hafnium carbide has recently been suggested as an alternate cathode¹² material because of its high melting point (ca 3890 °C) and low work function of about 3.5 V. Numerous attempts were made to run a tip ground from hafnium carbide. In an initial experiment with a slightly different tip geometry, the tip ran well for some time, but cracked on restart. Another tip cracked almost immediately on start up. Finally, in this study, a tip was run briefly without cracking. This was taken from the thruster for analysis. Visually the tip maintained its deep blue coloration except at the tip where its color had turned to gold. SEM photographs of this region showed that the tip had become molten. Different regions of this tip are shown in Figures 8(a) and 8(b) under high magnification. Figure 8(a) shows the border of the molten area. Large crystals seem to have formed right at the edge of this area. A region near the center of the molten area is shown in Figure 8(b). This appears to be resolidified with boundaries similar to those seen in the metal tips. Analysis of the composition in this region, however, indicated that a major chemical change had taken place as this area was found to now be composed of hafnium nitride. This suggests that a chemical reaction between the propellant and the hot cathode had taken place. While it may be possible to lessen or eliminate the stress cracking by using a hafnium carbide cermet, it is doubtful that this would change the tip chemistry and this probably means that hafnium carbide is not a viable cathode material.

Long-Term Cathode Operation

The analysis of the cathode used in a long term continuous ammonia arcjet test run at the 30 kW power level showed the formation of dendrites that grew from the rim of the cathode tip crater outward toward the anode.¹⁰ The cathode from a recent 1000 hour/500 cycle low power arcjet lifetest showed no evidence of dendrite formation¹¹. It was of interest to determine if dendrites would form at low power during long-term, continuous operation. To study this, a 100 hour continuous test of a low power (~1 kW) arcjet was run. The cathodes from both this test and the 1000 hour cycled test were sectioned and analyzed.

Different photographs of the cathode tip run in the 100 hour test are shown in Figure 9. The SEM photograph of the tip under low magnification (Figure 9(a)) shows that a small arc crater had

formed on the tip. A photomicrograph of this crater, taken looking straight at the cathode tip, is shown in Figure 7(b). The cathode crater observed is almost identical to those that have been observed in other arcjet tests.^{11,13} The tip, after sectioning, polishing, and etching is shown in Figure 9(c). As in the case of the short term tests, a resolidified area can be seen in the region of the cathode tip. The grain structure immediately behind (or underneath) this area does not appear different than that observed in the bulk. As in the shorter cathode tip tests, no thorium oxide nodules were seen in the region of the arc crater.

Similar views of the cathode tip used in the 1000 hour/cyclic are presented in Figures 10(a) to (c). This tip was originally bullet-shaped¹¹ and polished, rather than ground with a straight 30° angle. From Figures 9 and 10 it can be seen that there is a significant difference between the final shapes of these two cathode tips. From Figure 9(a), the crater on the tip from the 100 hour test is raised slightly from the surrounding surface. Figures 10(a) and 10(b) show that the cathode crater in the case of the 1000 hour test was in a depression on the tip. The explanation for this difference is not clear. It is possible that the lifetest cathode was similar in appearance to that of the tip from the 100 hour test at the 100 hour point and future testing would be required to address this issue. The arc craters observed in both tests, however, were nearly identical in size and appearance. Measurements of these craters and a similar crater from an earlier test¹³ give diameters between 0.15 and 0.20 mm. All of these cathodes were initially 2% thoriated tungsten.

Questions exist as to the actual emitting area and as to whether the emission is purely thermionic in nature. The Richardson-Dushman equation for thermionic emission is:²²

$$j_t = AT^2 \exp \left[-\frac{\phi}{kT} \right] \quad (1)$$

where j_t is the current density, k is Boltzmann's constant, e is the electron charge, ϕ is the thermionic work function of the emitting surface (in volts), and A is a constant dependent on material. The temperature in the molten pool is unknown but a temperature above the melting point of tungsten is certainly possible and early calculation, in fact, used the boiling point of tungsten to determine the emission from the tip.²³ It is also possible that Schottky-enhanced emission contributes to the current density. The equation for this can be written as:²²

$$j = j_t \exp \left[\frac{4.389 \sqrt{E}}{T} \right] \quad (2)$$

in which E is the electric field strength in volts per centimeter and j_t is the thermionic emission when $E = 0$. For the purposes of this analysis, the exponential term on the right-hand side of this equation will be called the enhancement factor and labeled γ . Using the above equations some calculations were made to bound the problem. The results are shown in Table IV. In these, a value of 60.2 was used for A .²² If it is assumed that the entire crater of a diameter of 0.0175 cm is emitting, a current density of approximately 4.6×10^4 A/cm² is required for a total current of 11A. If only the base of the crater is emitting, the current density would have to increase by about two orders of magnitude. The temperature limits used were set by the melting and boiling points of tungsten. The upper limit for the thermionic work function was set at that of solid tungsten. 3.1V was used as the lower limit as it produced nearly the correct value of the emission current density. The low limit on the field strength (10^6 V/cm) used in the calculations of field enhanced emission was chosen because values in this range have been calculated for some cases.²⁴ The upper limit of 10^7 V/cm was chosen because it was what was found to be necessary to yield the right order of magnitude for the current density in the worst case used in the thermionic emission calculation. From Table IV it can be seen that the current density obtained using the work function of solid tungsten at the melting point and with no field emission is about two orders of magnitude below that required for the case of emission from the entire crater. Using same work function and setting the temperature to tungsten's boiling point yields more than the required current density. Also from Table IV, this same result can be obtained using a work function well below that of solid tungsten. While a work function of 2.6V is typically assumed for thoriated tungsten, evidence presented earlier shows that the molten crater appears to be pure tungsten. Because the work function of molten tungsten is unknown, the assumption of a work function in the 3.1 to 3.5 V range is speculative.

Again, the values given in Table IV indicate that an electric field strength of 10^7 V/cm would be required to obtain the necessary current density in the case in which the entire crater is emitting at the melting point of tungsten and assuming a work function of 4.5 V. By assuming an elevated temperature, however, the calculations indicate that this current density can be achieved with a field strength of less than 10^6 V/cm. Little experimental data exists on field strengths near cathodes in high pressure arcs, as noted earlier, however, calculated values in the 10^6 V/cm range have been reported.²⁴ Cathode fall voltages in high pressure discharges typically range between 1 and 10 volts.²⁵ Thus, if field enhanced emission is contributing to a significant extent, the sheath thickness would have to be on the order of 10^{-5} to 10^{-6} cm.

From the above, it is probable that the observed cathode spot is molten during operation and that electrons are being emitted across the entire surface of the spot. While the evidence for the emission mechanism is not conclusive, it is likely that some combination of thermionic and field

emission is involved and that the spot temperature is somewhat above the melting point of pure tungsten.

An equation for the evaporation rate at fixed metal vapor pressure has been given by Dushman as:²⁶

$$W = P_v / \sqrt{2\pi RT/M} \quad (3)$$

W is the evaporation rate in grams/cm²-sec, P_v is the vapor pressure in atmospheres, M is the molecular weight of the material, R is the universal gas constant and T is the absolute temperature, in degrees K.

Using vapor pressure data tabulated by Margrave,²¹ this equation gives an evaporation rate of about 3.9x10⁻⁴ g/cm²-sec for tungsten at its melting point. A rate of about 6g/cm²-sec is obtained at the boiling point of tungsten. Taken across the molten area, these produce total evaporation rates of about 9.4x10⁻⁸ g/sec and 1.4x10⁻³g/sec, respectively. The latter value is very high compared to the mass loss rates observed in the testing, while the former is on the same order of magnitude as the mass loss rates observed in the cathode tip tests. Thus, since the tip is at or above the melting point of tungsten evaporation could account for the entire mass loss. The fact that the mass loss rate was observed to decrease with time, while the cathode emission phenomena remained essentially constant, suggests that redeposition of material on the cathode becomes more important as the cathode tip recedes.

This issue is important in understanding arcjet life and one final difference was noted in the appearance of the two cathodes from the long term tests. As stated, the cathode from the long term lifetest was cycled and accumulated more than 500 starts. It was evident that surface melting had occurred over the entire tip including the area on the shoulder well behind the tip crater (see Figure 10(a)). This surface melting phenomenon was not as extensive in the case of the 100 hour continuous test in which a single start was performed. From this, it is postulated that the arc ignites upstream of the cathode tip and then is rapidly forced there by the gas flow as the tip heats to a temperature that can support the emission. This phenomenon may be due to the observed depletion of thorium oxide at the tip. This would suggest the continued use of 2% thoriated tungsten as the cathode material, rather than pure tungsten for ease in starting. Further experimentation would be required to provide a better understanding of this phenomenon.

CONCLUDING REMARKS

In this study a variety of materials were tested as arcjet cathodes in a modular thruster. Periodic disassembly of this thruster allowed a comparison of mass loss rates and SEM analysis of the tips. At the conclusion of testing, the cathode tips were sectioned, polished, etched and examined in order to analyze cathode phenomena. The cathodes from both a 100 hour continuous test and a 1000 hour/500 cycle test were also analyzed for comparison.

The baseline cathode tip used in this study was made from standard 2% thoriated tungsten welding rod. This material has been used almost exclusively throughout the history of arcjet testing at both high and low powers. A second cathode made from this material was also tested and demonstrated repeatability. Tungsten-based compounds were tested in which the thorium oxide concentration was doubled and in which 25% rhenium was added. All the tungsten-based cathode materials were found to exhibit similar mass loss rates. Calculations were performed which indicated that the mass loss rates observed can be explained solely by evaporation. The operating voltages were also found to be nearly identical for the tungsten-based cathodes, indicating similar conditions existed in the tip region during operation. These findings, plus the observation of the lack of thorium oxide migration indicates that thorium oxide does not play a role in determining the steady state operating characteristics of the arcjet. Detailed analysis of one of the cathode tips showed that the arc crater was pure tungsten to a depth of about 150 microns adding strength to this conclusion. Additionally, the data indicate that rhenium can be added in some quantity, also without altering the arcjet cathode condition. The tip made from 2% thoriated rhenium was found to have a mass loss rate much higher than that of the tungsten based compounds. The tip made from hafnium carbide was found to have been molten and to have reacted with the nitrogen in the propellant to turn to hafnium nitride in the molten region. It is doubtful, therefore, that hafnium carbide is a viable candidate in any form for use in the arcjet thruster.

A 100 hour continuous lifetest was run at about 1kW to determine whether or not dendrites would form under these conditions. This phenomena was observed in a long term test of a 30 kW arcjet. SEM photographs of the cathode after testing showed no sign of dendrite growth. The cathodes from the 100 hour test and a previously run 1000 hour, cycled test had nearly identical arc craters. This indicates long term stability of the controlling emission mechanisms, however, insufficient evidence was available to establish those emission mechanisms with certainty. Simple calculations were made to bound the problem, however, and these suggested that the electron current was due to a combination of field enhanced and thermionic emission.

Comparison of the mass loss rates of the 2% thoriated tungsten cathodes from the materials tests and from the 1000 hour lifetest indicated that the mass loss rate decreases by at least an order of magnitude over this period of time. Since there was evidence indicating that the emission mechanism does not change with time, it was concluded that the redeposition rate increases as the tip recesses with time. The reason for this is not presently known.

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Table I. Cathode Tip Sample Materials

Cathode #	Material
1	2% ThO ₂ /W
2	2% ThO ₂ /W
3	4% ThO ₂ /W
4	2% ThO ₂ /25% Re/W
5	2% ThO ₂ /Re
6	HfC

Table II. Arcjet Operating Voltage at Constant Current* and Mass Flow Rate

Operating Time	Cathode 1	Cathode 2	Cathode 3	Cathode 4	Cathode 5
2 Hours	98.6	98.9	100.1	102.2	105.8
4 Hours	102.2	102.2	102.1	103.9	127.2 (10 amps)
9 Hours	102.5	106.2	104.1	107.3	

* All tests but final 2 hour run on cathode #5 run at 11 amps

Table III. Mass Loss Rates for Tungsten-Based Cathodes with Time

Hours of Operation	Mass Loss Rate (mg/hr)				Lifetest cathode
	Cathode 1	Cathode 2	Cathode 3	Cathode 4	
2	0.09	0.09	0.15	0.20	----
4	0.09	0.09	0.11	0.09	----
9	0.06	0.05	0.06	0.07	----
1030	----	----	----	----	0.01

Table IV. Cathode Spot Current Density Calculations

T (K)	ϕ (V)	E (V/cm)	j_t (A/cm ²)	γ	j (A/cm ²)
3650	4.5	0	470	1.0	470
		1×10^6		3.3	1.6×10^3
		1.5×10^6		4.4	2.1×10^3
		1×10^7		45	2.1×10^4
6270	4.5	0	5.6×10^5	1.0	5.6×10^5
		1×10^6		2.0	1.1×10^6
		1.5×10^6		2.4	1.3×10^6
		1×10^7		9.1	5.1×10^6
3650	3.1	0	2.1×10^4	1.0	4.1×10^4
		1×10^6		3.3	1.3×10^5
		1.5×10^6		4.4	1.7×10^5
		1×10^7		45	1.8×10^6
6270	3.1	0	5.2×10^6	1.0	7.5×10^6
		1×10^6		2.0	1.5×10^7
		1.5×10^6		2.4	1.8×10^7
		1×10^7		9.1	6.8×10^7

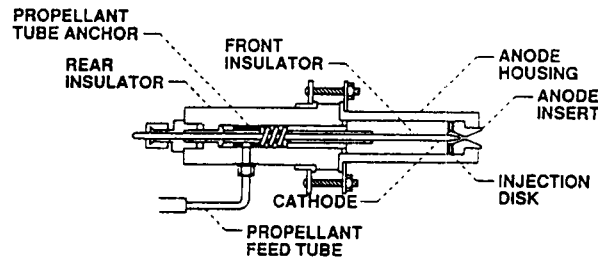


FIGURE 1. - CUTAWAY VIEW OF ARCJET THRUSTER.

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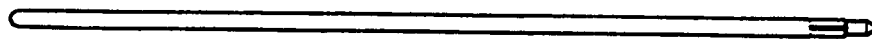
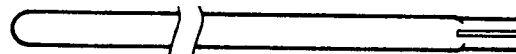


FIGURE 2. - CATHODE TIP AND SLOTTED HOLDER.

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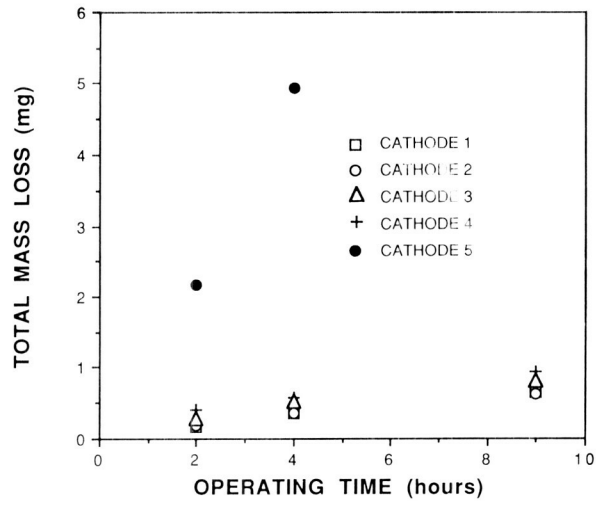
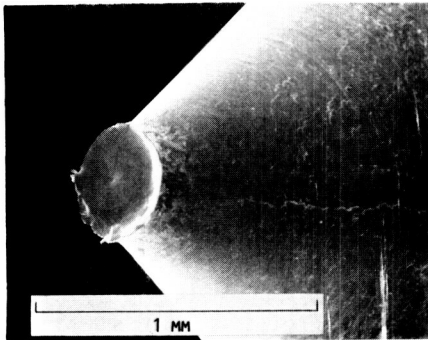
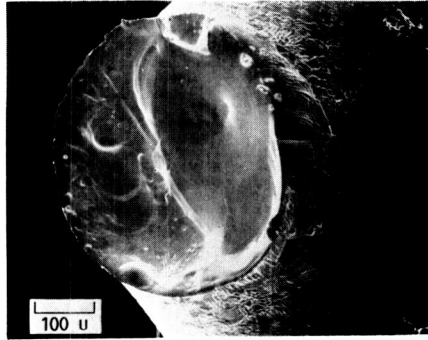


FIGURE 3. - CATHODE MASS LOSS VERSUS TIME.

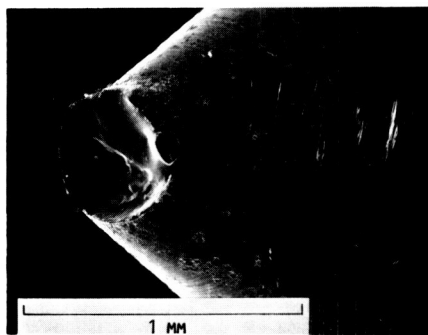
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(A) TWO PERCENT THORIATED TUNGSTEN TIP AFTER TWO HOURS OF OPERATION. (70x).



(B) TWO PERCENT THORIATED TUNGSTEN TIP AFTER FOUR HOURS OF OPERATION. (150x).



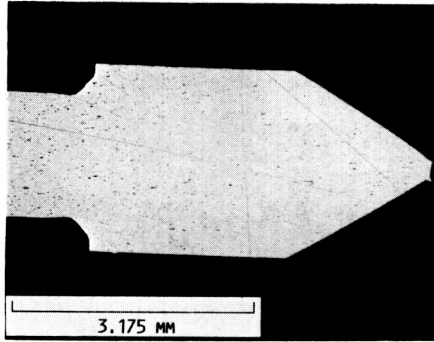
(C) TWO PERCENT THORIATED TUNGSTEN TIP AFTER NINE HOURS OF OPERATION. (70x).



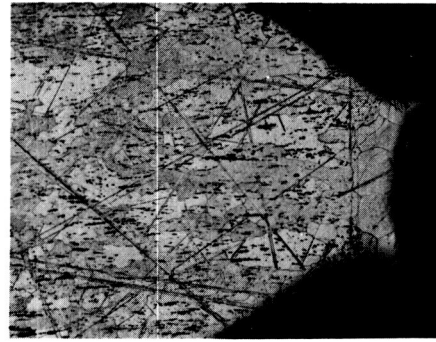
(D) SECOND TWO PERCENT THORIATED TUNGSTEN TIP AFTER TWO HOURS OF OPERATION. (150x).

FIGURE 4. - SEM PHOTOGRAPHS OF TUNGSTEN BASED CATHODE TIPS AT VARIOUS POINTS IN TESTING.

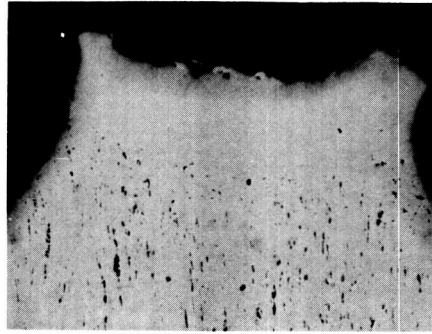
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(A) POLISHED TIP (16x).



(B) POLISHED AND ETCHED TIP (100x).



(C) POLISHED TIP (200x).

FIGURE 5. - PHOTOMICROGRAPHS OF SECTIONED CATHODE TIP IN POLISHED AND ETCHED CONDITIONS.

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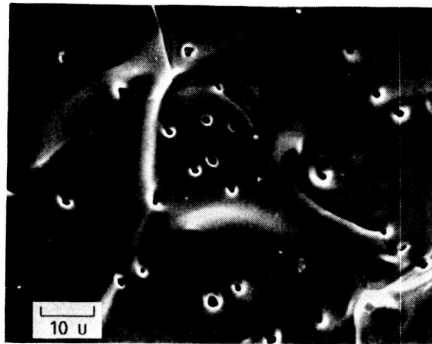
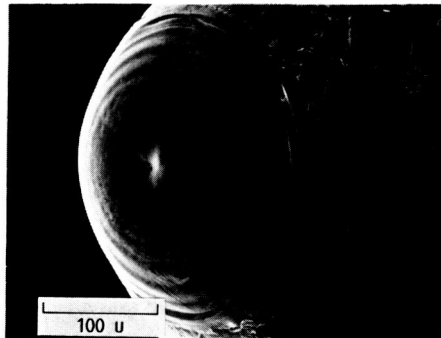
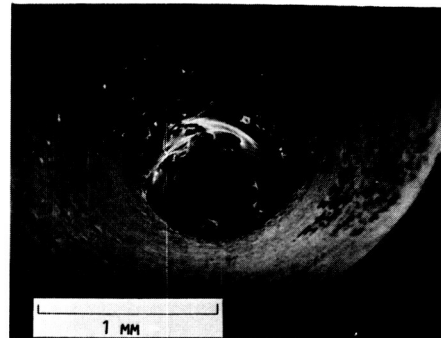


FIGURE 6. - RECRYSTALLIZED AREA OF CATHODE TIP WITH PITS (1200x).



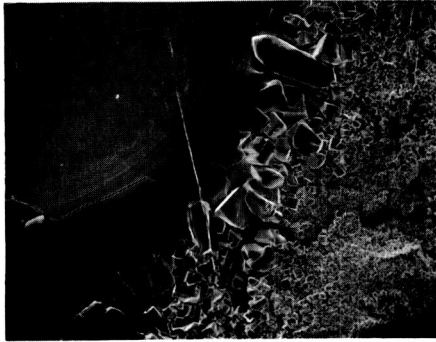
(A) AFTER TWO AND ONE-HALF MINUTES OF OPERATION.



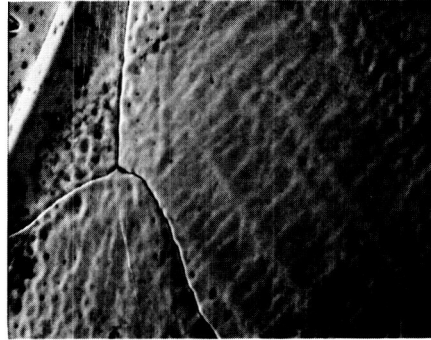
(B) AFTER FOUR HOURS OF OPERATION.

FIGURE 7. - TWO PERCENT THORIATED RHENIUM CATHODE TIP.

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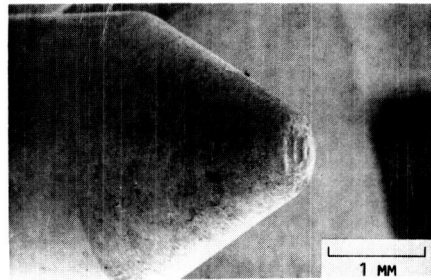
(A) NEAR BORDER OF MOLTEN AREA.



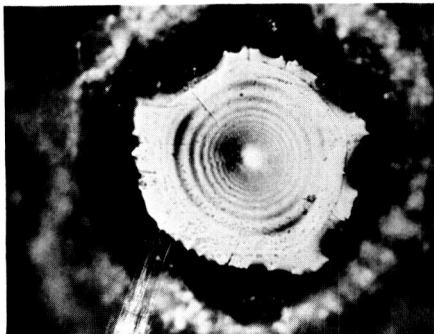
(B) MOLTEN (RECRYSTALLIZED) AREA.

FIGURE 8. - SEM PHOTOGRAPHS OF HAFNIUM CARBIDE TIP.

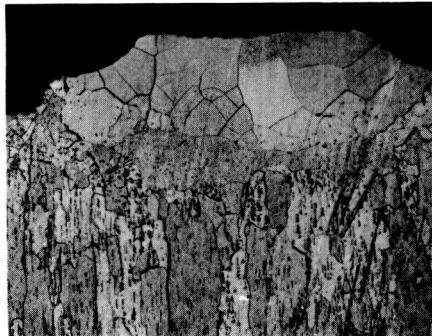
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(A) SEM PHOTOGRAPH OF TIP.



(B) PHOTOMICROGRAPH OF ARC CRATER.

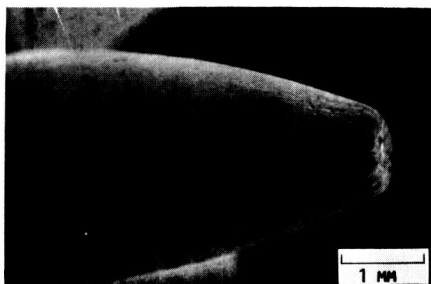


(C) PHOTOMICROGRAPH OF TIP AFTER SECTIONING AND ETCHING.

FIGURE 9. - CATHODE TIP FROM 100 HOUR CONTINUOUS TEST.

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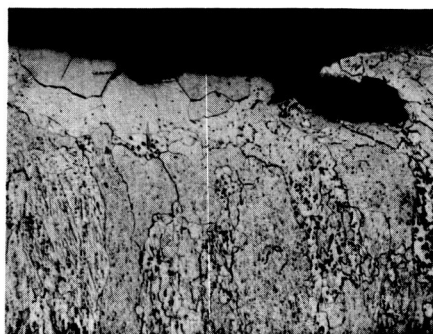
ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH



(A) SEM PHOTOGRAPH OF TIP.



(B) PHOTOGRAPH OF ARC CRATER.



(C) PHOTOGRAPH OF TIP AFTER SECTIONING
AND ETCHING.

FIGURE 10.- CATHODE TIP FROM 1000 HOUR CYCLIC LIFETEST.

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16. Abstract Cathode tips made from a number of different materials were tested in a modular arcjet thruster in order to examine cathode phenomena. Periodic disassembly and examination, along with the data collected during testing, indicated that all of the tungsten-based materials behaved similarly despite the fact that in one of these samples the percentage of thorium oxide was doubled and another was 25% rhenium. The mass loss rate from a 2% thoriated rhenium cathode was found to be an order of magnitude greater than that observed using 2% thoriated tungsten. Detailed analysis of one of these cathode tips showed that the molten crater contained pure tungsten to a depth of about 150 microns. Problems with thermal stress cracking were encountered in the testing of a hafnium carbide tip. Post test analysis showed that the active area of the tip had chemically reacted with the propellant. A 100 hour continuous test was run at about 1 kW. Post test analysis revealed no dendrite formation, such as observed in a 30 kW arcjet lifetest, near the cathode crater. The cathodes from both this test and a previously run 1000 hour cycled test displayed nearly identical arc craters. Data and calculations indicate that the mass losses observed in testing can be explained by evaporation. An increase in the redeposition rate with cathode recession was postulated to explain the observed decrease in mass loss rate with time. From measurements of the cathode crater size, estimates of the emitting area were made. These were used with realistic bounds on the crater temperature, material work function, and the electric field at the cathode to study the cathode emission process. From this, simple calculations suggest that both field and thermionic emission are involved.					
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