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Cathode Degradation and Erosion in High Pressure Arc Discharges

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CATHODE DEGRADATION AND EROSION IN HIGH PRESSURE ARC DISCHARGES

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Abstract

Electrode lifetime has long been recognized as one of the predominant technology concerns in arcjet thrusters for space propulsion. Arcjet development of previous decades placed emphasis on performance and thruster lifetime problems were not addressed in depth.

An experimental investigation was conducted at the NASA Lewis Research Center to identify and to evaluate the various processes which control cathode erosion and degradation. A direct current arc discharge was established between electrodes in a pressure-controlled gas flow environment. The cathode holder was designed for easy testing of various cathode materials. The anode was a water-cooled copper collector electrode. The arc was powered by a dc power supply with current and voltage regulated cross-over control. The external circuit contained a ballast resistor and a low inductance choke. Nitrogen and argon were used as propellants and the materials used were 2 percent thoriated tungsten, barium oxide impregnated porous tungsten, pure tungsten and lanthanum hexaboride. The configurations used were cylindrical solid rods, wire bundles supported by hollow molybdenum tubes, cylindrical hollow tubes, and hollow cathodes of the type used in ion thrusters.

The results of the mass loss tests in nitrogen indicated that pure tungsten eroded at a rate more than 10 times faster than the rates of the impregnated tungsten materials. The BaO-W hollow tube, ThO_2-W solid rod, and ThO_2-W wire bundle all had similar mass loss rates, but the mass loss rate of the LaB_6 cathode was significantly lower than the rate of these tungsten materials. It was found that oxygen impurities of less than 0.5 percent in the nitrogen increased the mass loss rate by a factor of 4 over high purity nitrogen. At power levels less than 1 kW, cathode size and current level did not significantly affect the mass loss rate. The hollow cathode was found to be operable in argon and in nitrogen only at pressures below 400 and 200 Torr, respectively.

Introduction

Arcjet thrusters for space propulsion were an object of intensive research and development in the 1960's.[1,2] The arcjet is conceptually simple and holds promise of an electrothermal concept capable of producing a wide range of thrust at a specific impulse from 400 to 1500 sec.[3] A thrust subsystem with a nominal power level of 1 kW was developed as a possible candidate for the Space Electric Rocket Test program.[4] Specific impulse around 1000 seconds was obtained with hydrogen propellant, but overall efficiency was about 25 to 30 percent, over test times up to 30 minutes in length.

Higher power arcjets in the 30 kW range were developed and tested by several manufacturers up to around 1964.[5-9] Intended for primary propulsion of high energy missions, specific impulse up to 1500 sec and efficiencies of 40 to 54 percent were obtained with hydrogen propellant. Numerous tests were made to determine durability and lifetime. One test accumulated an interrupted total of 720 hr at which time the test was terminated voluntarily.[5] Another test ran continuously, for 500 hr.[6] Others were typically limited to 50 or 100 hr. Electrode lifetime appeared to be a predominant problem throughout the history of thruster development.

Two major reasons that prevented the application of arcjet thrusters to space missions during that period of intensive development work were (1) power technology had not yet been developed to meet the high power requirements of arcjets, and (2) missions requiring specific impulse in the 400 to 1500 sec range were not foreseeable in the near term at that time. All research and development on arcjets supported by the NASA Lewis Research Center were, therefore, relinquished by the year 1965.

New mission scenarios of the 1980's and beyond now require a reexamination of electrothermal thruster concepts, and arcjets in particular. Resistojet thrusters have been used on communication spacecrafts since about 1975. As a system, they are highly developed, efficient, and reliable.

Power systems technology has also made significant advances within the past two decades.[10,11] Power sources and processing techniques accommodating as much as 25 kW have been developed. At these power levels, arcjet thruster systems promise significant advantages in thrust, specific impulse, and efficiency. Lifetimes greater than 500 hr must be routinely achieved, however, to insure reliability for mission application.

Arc discharge phenomena which constitute the basis for arcjet thrusters have been studied for years, and analytical models have been formulated.[12,13] It is the intent of the present investigation to apply existing models to the obtained test results, to evaluate the applicability of these models, and to establish a rationale for long-lived cathode design.

The Lewis Research Center is presently engaged in a research program to address the technology gaps in the arcjet thruster concept as

presently perceived. This paper describes the electrode erosion and arc discharge characterization studies being performed, analogous to other cathode/anode studies. Refractory metal cathodes and a hollow cathode have been tested in nitrogen gas primarily at a pressure of one atmosphere and a dc arc current of 5 A. Other variables such as cathode size, arc power level, gas purity, and gas flow pattern in the cathode region have been investigated. Power levels of typically less than 1 kW were chosen to investigate because of a potential near term application.

Arcjet thruster development is far from its infancy considering the extent of effort expended decades ago. The research currently being performed seeks to develop a better understanding of electrode erosion to help overcome the barriers encountered in earlier efforts.

Apparatus

The test chamber used for the cathode experiments is shown in Fig. 1. A schematic of the apparatus is given in Fig. 2. The test chamber was constructed of pyrex. Vacuum was obtained by the use of a roughing pump, and gas could be forced into the pyrex test chamber to increase the pressure. A current-controlled voltage-regulated dc power source was used in the experiments. This power source had a 25 A, 600 V maximum capacity. Ten ballast resistors in parallel were used initially. Each resistor had a 200 W, 250 ohm capacity. In later experiments a variable resistor was used in place of the ballast resistors. A 0.5 mH, 150 A inductance coil completed the circuit.

The cathodes were supported by the structure shown in Fig. 3. The cathodes were held in place by a brass clamp. This brass screw clamp was held by a 3.81 cm long, 0.69 cm diameter hollow brass support piece. This brass support piece was silver soldered to a 19.1 cm long, 0.64 cm o.d. copper tube. The gas flowed through the copper tube to the cathode. The copper tube was insulated by a 24.13 cm long, 1.27 cm o.d. piece of aluminum oxide ceramic. The cathode itself was insulated by two aluminum oxide ceramic sleeves, 2.22 and 2.54 cm long. A boron nitride piece insulated the brass clamp from excess heat or possible arc formation. To further insure against arc formation high temperature zirconium oxide (ZrO_2) ceramic was placed between the boron nitride and the aluminum oxide sleeves.

The anode used in these experiments was constructed of copper. The anode was a 4.45 cm disk with water used to cool it during the tests. The anode and cathode were placed in the pyrex test chamber with a 5.08 cm diameter quartz tube placed over them. This quartz tube prevented sputtered or evaporated cathode material from clouding the pyrex chamber.

Six cathode configurations were tested and are described as follows:

1. Thoriated tungsten wire. Two percent thoriated tungsten wire was used as a cathode by fitting numerous 0.013 cm wires into a 0.32 cm o.d. hollow molybdenum tube. The wires protruded 0.5 cm from the end of the tube and were wrapped by an outside piece of wire to hold the other wires together.

2. Thoriated tungsten rod. As in previous arcjet work[14] a thoriated tungsten rod was used. Three sizes of 2 percent thoriated tungsten rod were used. Initially, a 0.16 cm o.d. rod was ground to a triangular cross section to fit inside of a 0.32 cm o.d. hollow molybdenum tube, and gas flowed around the rod through gaps between the molybdenum and the thoriated tungsten. Similarly, a 0.32 cm diameter rod was fitted in a 0.64 cm o.d. molybdenum tube for size comparison tests; however, the 0.32 cm cathode would not sustain an arc in this configuration, possibly due to heat transfer effects. A 0.32 cm diameter rod without the molybdenum support was then tried. The rod was ground flat on two sides to allow gas flow over the cathode. This configuration did sustain an arc. A 0.64 cm diameter rod was also used, ground to 0.32 cm on one end to allow a fit in the brass clamp. All three sizes of thoriated tungsten were ground to a 45° cone at the tip.

3. Tungsten hollow tube. A 0.32 cm o.d. hollow tungsten tube with a 0.05 cm wall thickness was used both with and without a coating of R-500. R-500 is a mixture of carbonates in an organic solvent. The R-500 was spread over the cathode prior to the experiment in an effort to enhance emission and increase cathode lifetime.

4. Barium oxide impregnated porous tungsten tube. A 0.16 cm o.d. hollow tube constructed of barium oxide impregnated porous tungsten was fitted inside a 0.32 cm o.d. molybdenum tube. The barium oxide tube extended 0.5 cm from the molybdenum.

5. Lanthanum hexaboride. A 0.533 cm o.d., 0.305 cm i.d. lanthanum hexaboride tube was fitted in one end of a 0.64 cm o.d., 2.54 cm long piece of molybdenum tube. The lanthanum hexaboride extended 0.5 cm from the molybdenum. The other end of the molybdenum was fitted with a 0.32 cm o.d. molybdenum tube to allow a fit in the brass clamps.

6. Conventional Hollow Cathode. A 0.64 cm o.d., 0.16 cm thick disk was fabricated out of thoriated tungsten. This disk, called the cap, had a 0.089 cm hole in the center. The cap was electron beam welded to a 0.64 cm o.d. molybdenum tube, 3.81 cm long. A 1.91 cm long, 0.53 cm o.d. lanthanum hexaboride hollow tube was placed inside the molybdenum tube. The end of the molybdenum tube opposite the cap was fitted, using a molybdenum bushing, with a 5.08 cm long, 0.32 cm o.d. molybdenum tube to allow a fit in the brass clamp. Due to a break in the electron beam weld during initial tests a new cathode was used in place of the original hollow cathode. This new cathode, actually a used cathode from 30 cm ion engine tests[15], had the same dimensions as the original cathode except that a 0.64 cm tantalum tube was used in place of a 0.64 cm molybdenum tube.

Procedure

Arc Starting. The method used for obtaining an arc was a transition from a glow discharge to an arc discharge. For the start of the discharge an input voltage of 400 to 500 V was required. Typically, low pressure on the order of 1 to 10 torr was also required to obtain a glow discharge. Also, a flow rate of gas, initially argon, of 300 SCCM was used throughout the experiments. The gap width - the distance between the cathode and the anode - was initially set at 0.5 cm for the arc voltage versus current measurements. Immediately after a glow discharge was initiated the arc voltage across the anode-cathode gap dropped below 100 V and an arc discharge formed.

Using argon as the propellant the cathode was allowed to run for 10 min at approximately 100 torr after the arc discharge had been initiated before any measurements were taken. For nitrogen it was found that a stable arc discharge could not be obtained with the same starting procedure as that used for argon. Thus, the arc was started as stated above using argon, and after 10 minutes the gas was switched from argon to nitrogen.

Arc Characteristics. After the initial 10 min starting period at low pressures, the pressure was increased to 350 torr and allowed to stabilize. A reading of the arc voltage was then taken at the initial current of 4 or 5 A. The current was then raised by 1 A at the same pressure and another reading was taken. These steps were repeated up to 10 A (higher currents exceeded the capacity of the ballast resistors). After a set of measurements had been recorded for a gap width of 0.5 cm, the power supply was shut off, the gap width was increased to 1.0 cm, and the starting and recording procedure were repeated. Measurements were also taken for a gap width of 1.5 cm. These tests were performed with both argon and nitrogen for all 6 cathode configurations.

Mass Loss Measurements. Using nitrogen as a propellant measurements were taken of the mass loss of the 6 cathode configurations with time. In these measurements the same starting procedure was used. For these tests, however, a pressure of 760 torr and a constant current of 5 A were used. After the 10 min argon start and the switch to nitrogen the pressure was raised to 760 torr and the cathode was allowed to run for 30 or 60 min. After this run in nitrogen the power supply was shut off and the cathode was allowed to cool in nitrogen to room temperature. The cathode was not exposed to air during this cooling period to keep oxides from forming on the cathode. After the cathode had cooled it was removed from the pyrex vacuum chamber and weighed. The process was then repeated.

Cathode Size Comparison Tests. The mass losses of three sizes of thoriated tungsten rod were compared to test the effects of surface area on the loss rate. The starting procedure for these tests was the same except that the gap width was initially set at 0.2 cm. This was due to the difficulty in starting at 0.5 cm. After the 10 min starting period the gap was increased to 0.5 cm without stopping the arc, and the test continued as the other mass loss test.

Mass Loss Versus Current Test. Tests were run to compare the effect of increasing current on the mass loss. A 0.32 cm diameter thoriated tungsten cathode was tested at 5 A and at 10 A. As mentioned previously, a rheostat was installed in place of the ballast resistors for this test. As in the cathode size test an initial gap width of 0.2 cm was used, increasing to 0.5 cm after the start of the arc discharge. The tests were then run as in the other mass loss tests.

Nitrogen Purity Test. The 0.16 cm diameter thoriated tungsten rod was used to compare the mass loss using the standard, 99.5 percent pure N_2 with the mass loss using high purity, 99.95 percent pure N_2. These mass loss tests were run as in previous tests.

Hollow Cathode Tests. Using argon, measurements of the arc voltage were taken for the range of currents 5 A to 10 A. The starting procedure and the test procedure were identical to those procedures in previous tests. The gap width was 0.5 cm, the pressure was 350 torr, and the flow rate was 300 SCCM for this current-voltage test. After these measurements were completed an attempt was made to raise the pressure. Above 350 torr in argon the arc discharge would operate, but it was not consistently stable. During some tests the arc would move from the lanthanum hexaboride to the thoriated tungsten cap, and, after a short time on the cap, the arc would extinguish.

An attempt was then made to obtain an arc discharge using 99.5 percent pure nitrogen. As in previous tests, the arc was started using argon, and, after a 10 min warmup, the gas was switched from argon to nitrogen. Under 99.5 percent nitrogen at 300 SCCM and pressures between 10 and 40 torr, however, a stable arc could not be obtained. An attempt was then made to obtain an arc discharge using 99.95 percent pure nitrogen under these same conditions. Again, a stable arc could not be obtained. Finally, a stable arc was obtained using 99.95 percent pure nitrogen at 20 to 50 SCCM and 100 to 200 torr. Apparently, low flow rates and low pressures are required to obtain an arc in nitrogen using the hollow cathode. Mass loss tests were then conducted at 100 torr and 35 SCCM.

Temperature Measurements. An optical pyrometer was used to estimate the temperature of the cathode spots as well as the temperature of the remaining cathode area. Temperature measurements were limited in accuracy. These temperatures are listed in Table 1.

Results

The results which follow include the general behavior of an arc discharge as well as the arc characteristics for a variation in operating conditions. The mass loss data considers the variation in materials, gas purity, cathode size, and current. Finally, the results of the temperature measurement tests are presented.

General Behavior

The general behavior of an arc discharge can be described in terms of the color of the plasma, the appearance of a spot of bright light on the cathode (cathode spot), and the size of the plasma. In tests with argon the color of the arc discharge seemed to be blue, with orange hues prevalent near the cathode. Because the orange color was seen primarily during the initial stages of a run it was assumed that this color was due to impurities on the cathode. In nitrogen the arc was white. The arc spot, the appearance of a point of high intensity light on the cathode at the spot where the plasma seats, has been characterized by Somerville[16] as a strong contraction of the arc column and a point of high current densities.

While other authors have postulated the theory behind this phenomenon it will suffice here to say that this cathode spot is due to a combination of heat transfer and emission effects. From the observation here it appeared that the arc spot tended to move around on the cathode at a fast rate. The spot moved much more when nitrogen was used than when argon was used. Also, the arc spot appeared to be much more intense in nitrogen than in argon for a given configuration. Another phenomenon described by Somerville[16] was the presence of a dark region, or a section of the plasma which does not emit light, due to, in part, the failure of neutral atoms to be excited to higher energy levels. In the present experiments the dark spot was observed at pressures less than 100 torr and currents less than 5 or 6 A in argon. No dark region was seen in nitrogen. Finally, it was observed that at pressures less than 100 torr the arc column was diffuse, practically filling the 5.08 cm diameter quartz tube which covered the electrodes. Above 100 torr the arc plasma would constrict to a much smaller cross-sectional area. The phenomenon can be explained by the decreased collisional path length at higher pressures, which implies a smaller cross-sectional area of the plasma.

The arc discharge presented some unusual behavior during the experiments. First, when the thoriated tungsten configurations were used it took 2 to 5 min for a stable arc to form with argon as the gas. During this period the arc would make a transition from a glow to an arc discharge, the arc would extinguish, then the glow to arc transition would repeat. This process would repeat itself until the cathode became white hot, at which time a stable arc would form. It is believed that during this conditioning period the cathode must become hot enough to allow migration of the thorium oxide to the surface of the tungsten to enhance emission. Second, in argon with the thoriated tungsten material, especially the wire configuration, the arc spot would seat on the area of the cathode near the aluminum oxide ceramic. In nitrogen, however, the arc would seat at the tip of the electrode. Finally, during the mass loss tests in nitrogen a film coating the inside of the quartz tube was observed. This film was a brown, dust-like substance which did not occur when argon was used. The film seemed more extensive when the tungsten materials were used than when lanthanum hexaboride was used. This film may have been tungsten or nitrogen compounds.

The arc voltage - current characteristics measured are presented in Figs. 4 to 6. Figure 4 is a comparison of the arc voltages versus current with nitrogen and argon for 4 different cathodes configurations. The arc voltage tends to be 20 V higher on the average for nitrogen compared to argon. Also, the general trend indicates that the arc voltage decreases as the current increases. Figure 5 is a comparison of the arc voltage vs. arc current with different gap widths as a parameter for a thoriated tungsten wire cathode. The arc voltage tends to increase as the distance between the electrodes increases; however, this difference in arc voltage does not seem to be significant for the gap widths of 0.5 cm and 1.0 cm.

Figure 6 compares the arc voltage-current characteristics of argon for lanthanum hexaboride tube with the characteristics of a conventional hollow cathode with a lanthanum hexaboride insert. The arc voltage for the hollow cathode is 10 V higher than the arc voltage for the lanthanum hexaboride for all values of current. This difference is probably due to the additional potential drop across the thoriated tungsten cap. Qualitatively, the hollow cathode presented some phenomena not seen with the lanthanum hexaboride tube. The hollow cathode had a well-defined arc column through the hole in the cap, and the arc discharge seemed to come from the inside of the hollow tube, that is, from the lanthanum hexaboride. Also, the thoriated tungsten cap was glowing during the tests. Temperature measurements indicate that the thoriated tungsten cap had a higher temperature than the thoriated tungsten rod (see Table 1). In addition to the blue plasma column an orange glow could be seen at the thoriated tungsten cap. This may be an indication of an arc discharge from the cap.

It is to be noted that the arc voltage measured in the current-arc voltage test did not necessarily correlate with the arc voltage measured later during the mass loss tests. The reason for this difference in arc voltage is not well understood at this time.

Mass Loss Tests

The mass loss of various materials is presented in Fig. 7. One can see from the graph that the mass loss rate for pure tungsten, with or without R-500, was an order of magnitude higher than the corresponding mass loss rates for the other materials. It does not appear that the addition of R-500 made a significant difference in the mass loss rate of tungsten. Lanthanum hexaboride gave the lowest mass loss rate, 1.5×10^{-4} g/min, while the loss rates for the barinum oxide and thorium oxide impregnated tungsten were approximately the same at 4.8×10^{-4} g/min for the ThO_2 - W rod, 5.0×10^{-4} g/min for the BaO - W tube and 2.2×10^{-4} g/min for the ThO_2-W wire. The mass loss for the first 40 min of the test was not included in the total

mass loss rate as the conditioning of the cathodes varied from one material to another. Also, the mass loss due to the argon start was found not to be a significant portion of the mass loss; for a 10 minute argon start the average mass loss was 0.0025 g.

Nitrogen Purity

From Fig. 8 one can see the effect of nitrogen purity on the mass loss rate. The mass loss rate for 99.5 percent pure nitrogen was 4.8×10^{-4} g/min with the 0.16 cm thoriated tungsten rod while the loss rate for 99.95 percent pure nitrogen was 1.1×10^{-4} g/min. Analysis of the gases showed that oxygen was present in the 99.5 percent nitrogen but not in the 99.95 percent nitrogen. Apparently, this oxygen in the gas enhances erosion, possibly forming compounds with the tungsten or the nitrogen. Also, it was found that the arc voltage remained approximately the same regardless of the purity of the gas.

Mass Loss Versus Cathode Size

Figure 9 gives the results of the cathode size comparison test. For a doubling in diameter size the cathode mass loss only increased on the order of 20 to 30 percent. The arc voltage remained within a 15 V range for all sized during this test. The loss rate for the 0.16 cm diameter cathode was 4.8×10^{-4} g/min and for the 0.64 diameter cathode it was 7.3×10^{-4} g/min.

Mass Loss Versus Current

Figure 10 gives the results of the comparison of a 0.32 cm diameter thoriated tungsten rod at 5 A with a similar rod at 10 A. The results indicated that doubling the current actually lowered the mass loss rate 10 percent. The mass loss rate was 6.2×10^{-4} g/min for 5 A and 5.5×10^{-4} g/min for 10 A. Since this is a small difference one can assume that the value of the current does not significantly affect the mass loss rate for this range of currents. The arc voltage for both the 5 A and the 10 A tests was in the range of 1 to 10 V.

Hollow Cathode

A comparison of the mass loss rate of the hollow cathode configuration at 100 torr and 35 SCCM with the lanthanum hexaboride tube configuration at 760 torr and 300 SCCM is shown in Fig. 11. While this comparison is not completely accurate due to the two different chamber conditions it does indicate that the mass loss rates are not radically different. The loss rate for lanthanum hexaboride was 1.5×10^{-4} g/min while the loss rate for the hollow cathode configuration was 1.1×10^{-4} g/min. Due to a mechanical failure the hollow cathode lasted much less time than did the lanthanum hexaboride without the hollow tube; however, without the tube the lanthanum hexaboride tube was found to crack, possibly due to thermal stress, and break off. Figures 12-14 show various cathodes before and after running in nitrogen.

Discussion

Arc discharges have been studied for over 50 years because of their industrial usefulness and also for purely scientific interest. To interpret the present experimental results meaningfully, it is appropriate to be mindful of a twofold objective. The underlying objective is a better understanding of the mechanisms by which dc arc cathodes suffer mass loss, degradation, and/or failure. The immediate objective is to formulate a rationale for arcjet thruster cathode design so that a specified useful life can be assured. Neither objective is exclusive of the other because of the seemingly complex nature of the cathode phenomena. Little can be gained by attributing to the cathode a seemingly mystic intelligence whereby the cathode automatically does what it needs to satisfy the imposed operating conditions.

The general observation that the discharge does not make a transition from a high voltage-low current mode to the desired low voltage-high current mode until the cathode surface is sufficiently hot and conditioned, strongly indicates that a combined thermionic-field emission mechanism is controlling. The various parameters believed to be involved can be expressed by the Richardson-Schottky equation (see Appendix A). Formulating the differential of this equation permits evaluation of the relative sensitivity of cathode emission density to the cathode temperature, surface work function, and electric field. Thus,

$$\frac{dj}{j} = (A)\frac{dT}{T} - (B)\frac{d\phi}{\phi} + (C)\frac{dE}{E}$$

(All symbols are defined in Appendix A.)

The assumption of linearity is valid only for small excursions about a steady-state operating point, perhaps of the order of 1 or 2 percent. For a typical set of assumed conditions, e.g. surface temperature, $T = 2500^{\circ}$, work function, $\phi = 2.6$ eV, and electric field $E = 10^8$ V/m, the coefficients, (A), (B), and (C), for these differentials are 10.58, -12.1 and 1.76, respectively. That is, a 1 percent decrease in surface work function affects the emission by an order of magnitude more than the electric field. It appears, therefore, that assuming a thermionic emission mechanism, the surface temperature and work function have dominant effects relative to the electric field, which may actually be about 10^4 V/m.

The majority of the tests were made at constant arc current and environmental pressure. Emission current density necessarily invokes the cathode spot area which was observable in all cases, but was not measured. However, the various observed phenomena can be compared against the model in a valid qualitative sense.

Arc Voltage-Current Characteristics

Arc Voltage. The total voltage impressed between the cathode and the anode is significant

because it affects the energy with which ions existing in the plasma impacts the cathode. The plasma column which conducts the current between the electrodes is definitely not linear unlike a pure resistance in which current and voltage are proportional. Regardless of the cathode material, the arc voltage decreased with arc current as shown in Fig. 4. Aside from plasma nonlinearities, this apparently decreasing resistivity effect is believed to be caused by the interaction of variables discussed in the Richardson-Schottky equation. The electric field effect on emission is considered minor here. The increase in discharge current was accompanied by an increase in plasma density (higher ionization) and hence an increased ion bombardment of the cathode. The resulting increase in cathode spot temperature led to higher current emission even at a lower arc voltage with no significant increase in mass loss. A question arises as to which process occurred first - the increase in current or temperature. As many models indicate, the steady-state is a dynamic balance of energies causing cathode heating, work function absorption, conductive and radiative losses. Tests should be conducted to perturb the steady-state with a sudden increase in arc current while monitoring the arc voltage and cathode temperature. It is postulated that there should be an initial rise in arc voltage until such time as the energy balance stabilized to a new equilibrium at a lower arc voltage. The cathode temperature, if measurable, should gradually increase to a new equilibrium temperature.

The effect of gas species upon arc voltage irrespective of arc current was interesting. With argon, the arc voltage fell within a band of about 10 V or less regardless of cathode material. This supports the theory that cathode temperature dominated the emission mechanism, inasmuch as, all work functions were within a 2 to 4.5 eV range and pressure was constant.

In nitrogen, the spread in arc voltage with different cathode material was much wider. The trend of decreasing arc voltage with increasing current persisted, but the reactive nature of nitrogen appeared to affect the work function effect more strongly. The generally higher level of arc voltage with nitrogen can be attributed to either or both the contaminating effect of nitrogen and the differences in plasma properties of the two gases. From the viewpoint of ion kinetic energies, assuming similarly charged species, equal energies result from the same potential fall regardless of ion mass. Dissimilarities in plasma properties between argon and nitrogen would, however, have strong effects upon their arc voltages. The differences in ionization potential, plasma density conductivity, and potential profile between the electrodes can all affect the overall arc drop.

Arc Gap Effects. The voltage-current characteristics of a given cathode material over a fourfold change in arc gap showed relatively small changes in arc voltage. The decrease in voltage with increasing current persisted at all values of electrode gap. At very small gaps, the cathode and anode fall regions were probably very close. As the gap increased, a positive column region with its characteristic voltage gradient was accommodated, thus permitting an increase in the arc voltage.

Hollow Cathode. The successful use of long-lived hollow cathodes in mercury ion thruster, suggests this type of electron emitter as a candidate in arcjets. The experimental data with a hollow cathode shown in Fig. 6 are limited because only preliminary tests have been made. An early assessment of its potential usefulness is important. The use of lanthanum hexaboride as the emissive material in a conventional and in a hollow cathode configuration gave almost identical voltage-current characteristics except that the arc voltage in the latter was approximately double that of the former. The hollow cathode configuration had a small aperture in an equipotential conducting surface through which the electron current must flow. Because no external heat was supplied, the cathode heating for thermionic emission necessarily comes from ion bombardment. It's not known what fraction of the total ion flux to the cathode emitter came from the positive column beyond the cathode aperture. A plasma existed within the cathode and was a source of ions, provided they acquired sufficient energy to heat the emissive surface. Not knowing the potential profile within the hollow cathode, it is assumed that the conducting wall of the cathode is an equipotential surface with a plasma sheath over the aperture and another plasma sheath over the lanthanum hexaboride emitter where the electron emission occurred. In effect, therefore, the hollow cathode had two sheath regions in contrast to the conventional cathode which had only one.

As described in the Results section the hollow cathode could be operated only over a limited range of pressures. Further tests are necessary to understand this observed phenomenon. It is postulated here that at low pressures, the diffuse nature of the discharge plasma permitted adequate heating of the cathode wall which in turn heated the lanthanum hexaboride sufficiently to sustain thermionic emission. As the pressure increased, the characteristic constriction of the arc confined the ion heating zone to the aperature through which all electron and ion current must pass. Unless the aperature is sufficiently large to carry this ambipolar current without a serious disruption in the plasma stability, the discharge cannot be maintained.

Cathode Mass Loss

One of the life limiting mechanisms documented from earlier arcjet thruster development was cathode failure due to erosion, melting, or catastrophic changes in cathode geometry. Although engineering solutions to this problem such as cathode material feeding and replacement are possible, the deposition of conductive material on intended dielectric surfaces or buildup of metal on dimension-critical areas such as the nozzle throat is detrimental to long sustained operations. The series of tests performed on cathode mass loss was an attempt to evaluate the rate of

material loss and the dominant factors which contribute to it.

Materials Effect. As shown in Fig. 7 and summarized in Table 1, there was a strong correlation between cathode material properties and mass loss rate. Pure tungsten with or without R-500 suffered the highest mass loss, and this material had the highest work function and cathode spot temperature. Surface applications of the triple carbonate, R-500, are short lived because of rapid loss by evaporation and sputtering. After brief exposure to a discharge, therefore, the material surface was essentially pure tungsten, in either case. The high work function and cathode spot temperature are factors which enter strongly in the Richardson-Schottky equation.

During the cathode mass loss tests in lab grade nitrogen, the average arc voltages were not significantly different for the various cathode materials. This was contrary to the trends observed during the V-I characteristics test. Aside from the large disparity in operating times of the two tests, the reasons for the difference in trends are not known. Because the imposed operating conditions of pressure and arc current were the same for all cathodes, it appears unlikely that small changes in arc voltage could make an order of magnitude increase in electric field. The temperature-work function effect is probably controlling. How this translates to mass loss is open to some speculation.

Evaporation and sputtering are considered to be significant mechanisms in cathode mass loss. Surface recession rate and mass loss of various refractory metals have been measured and analyzed.[17,18] As shown in Appendix B, increasing surface temperature increases the vapor pressure logarithmically. The evaporation rate varies directly as the vapor pressure and is therefore affected strongly by temperature. Calculated values of mass loss rate by evaporation alone at representative values of surface temperature were two orders of magnitude too low. Mass loss rate by sputtering, however, was of the right order of magnitude.

The sputtering yield for the conditions prevailing here are not known precisely. Literature data indicates that in the region of ion energies above the threshold,[18] the yield is a rapidly rising function, changing orders of magnitude over a few volts. To use the equation for sputtering loss, it is necessary to relate the ion flux rate upon the cathode to the electron emission rate. It is fortuitous that the factor $\alpha = \frac{V_c}{V_c + V_I}$ derived in Ref. 13 based upon an energy balance when applied to the sputtering equation seems to give acceptable results. The implications are clear that the complex phenomena occurring at the electron emissions site, namely the cathode spot are closely interrelated and not isolated mechanisms. It remains to be seen whether or not other observations from various tests support or refute the model upon which present understanding is build.

Gas Purity Effects. The poisoning effects of gaseous impurities on emissive surfaces are well known. The use of hot refractory metals as oxygen getters is also well documented and applied in industry. In the present tests, different sources of nitrogen gas were found to give anomalous results. For most of the tests, lab grade nitrogen of 99.5 percent purity was used. Prepurified nitrogen (99.95 percent) was used on identical cathode material and found to reduce cathode mass loss fourfold. The average arc voltage in the purer gas was about 4 V higher. It is postulated that oxygen the principal impurity, was causing chemical attack upon the hot cathode surface. The resulting oxide probably had a higher vapor pressure and surface recession rate. Also not known was the sputtering threshold of the oxide, but its sputter yield is probably higher than the pure metal.

Cathode Size. The investigation of different sizes (diameter) of the same cathode material was motivated by two reasons. A larger cathode could transfer heat from critical zones at a higher rate thus reducing thermal stresses, and possibly the mass loss rate. Even if the loss rate were constant, the availability of more material should assure longer life.

The results showed that in spite of a fourfold increase in diameter, the mass loss rate was essentially unaffected. In fact, the rate increased slightly with size. This trend is not sufficiently large to preclude gravimetric errors. The absence of size effect on mass loss is disappointing and also imperative of an explanation.

It is postulated that the principal site for mass loss is at the cathode spot, the small region of high electron emission density and ion bombardment. Estimates of emission current density have been as high as 10^4 A/cm^2. Size effects upon heat transfer are negligible because the heat input rate by ion bombardment is so high that the thermal conductivity of the cathode material is too low to permit a thermal balance by conduction. Even convection is insufficient unless the mass velocity were deliberately high and concentrated to control with forced convection. This principle has found industrial application in high current switches where arcs are extinguished by a gas blast to blow away the plasma ions.

Similarly high heat flux density has been also observed in microwave discharges.[19] Cooling air forced through an annulus surrounding a quartz discharge tube was capable of removing up to 80 percent of the input energy in a microwave discharge plasma. At low pressures where the plasma was more or less diffuse and uniformly distributed, the discharge could be maintained for unlimited periods of time. As the pressure was increased and the plasma column became more constricted, following the E-field lines into the quartz surface, the tube was intensely heated at the spot where the plasma contacted the quartz. Sustained operation even with increased cooling air flow resulted in the localized melting of the quartz tube.

In refractory metal surfaces, higher temperatures are permissible before melting. This allows for a thermal balance where the principal heat transfer mechanism is radiation. In a sense, the process is self-stabilizing. The cathode spot attains an equilibrium temperature to satisfy the requirements of the Richardson-Schottky equation for electron current density. Cathode spot heating is produced by ion bombardment. A tendency to overheat is balanced by increased radiation according to the fourth power of the temperature. Cathode spots are known to move rapidly over the cathode surface. If thermal masses were controlling, rapid movement of the spot would not be possible. A combination of a slightly lower work function spot and rapid heating of this spot can enable random movement of the emission site. Why the cathode spot does not remain at a site which is already hot and stabilized is difficult to rationalize. If it can be assumed that the effective work function of the entire cathode surface is not exactly uniform, an initial spot which gradually degrades with time causes rise in temperature to compensate for the increase in work function. To allow for loss by radiation, this temperature rise might be considerable. As the temperature of the rest of the cathode rises as a whole, another site with a slightly lower work function might reach a temperature at which emission from that site is preferential, or requires less energy input to sustain the necessary level of electron emission. It follows that external addition of heat, as from a heating element should lower the arc voltage. This effect has been observed in ion thruster cathodes operating at low pressures. External heating, however, imparts heat to the entire cathode mass, and in terms of input energy density, is probably much lower than that which is received at a cathode spot.

Based upon the above mode, the similar cathode mass loss rate for different cathode sizes is reasonable. The evaporation and sputtering site is the cathode spot. For constant pressure, plasma density and current, the spot size and emission current density should be about the same. A small effect of higher conducted heat loss from the cathode site because of size could manifest in a slightly higher ion bombardment rate to maintain equilibrium and hence a slightly higher sputtering loss. Presumably, external heating of the cathode mass to counteract the thermal loss effect should reduce the mass loss rate.

Arc Current Effects. It was initially assumed that increasing arc current would be an increasingly stressful condition leading to higher mass loss. For the two levels of arc current tested, the assumptions were not justified. Actually, the cathode mass loss was slightly lower at 10 A than at 5 A. Neglecting possible gravimetric errors, this reversal may be attributed to the lower arc voltage observed in all cathodes as arc current was increased. For a given work function surface, the increase in cathode emission current necessarily increased the cathode temperature or the cathode spot area, or both, but the resulting lowering of arc voltage also reduced the energy with which ions bombard the cathode surface. Doubling the arc current may increase the ion bombardment, but the order of magnitude reduction in sputtering yield for small changes in ion energy could result in a net reduction of cathode mass loss.

Although much higher arc currents are beyond the range of the present test apparatus some earlier arcjet thrusters have operated at current levels of 300 A or more without immediate failure. Reexamination of the V-I characteristics, heat transfer, and cathode temperature at high currents are necessary before the mass loss-arc current relationships can be assumed. Even at high currents, however, the thermionic mechanisms are believed to be applicable.

Hollow Cathode. The success of the hollow cathode has been pivotal in the lifetime capability of the electrostatic ion thruster, because all other approaches were not without undesirable fabrication, handling, and operational problems.[20] The adaptability of a hollow cathode designed for low pressure discharges to a high pressure arc discharge required investigation. It was intended that the configuration effects exclusive of the work function effect should be evaluated at this point.

From the preliminary test performed thus far, the evidences are not conclusive. As described in Results, the operable range was limited to pressures below 400 torr. The mass loss rates of the best of the conventional cathode and the hollow cathode using the same emissive material are, therefore, not directly comparable. Further, tests are planned to achieve a configuration operable over the full range of conditions and then to evaluate cathode mass loss under comparable operating conditions.

Concluding Remarks

An experimental investigation has been conducted in an attempt to gain understanding of the principal mechanisms which control dc arc characteristics and cathode mass loss. Using a thermionic emission model, most of the observed effects can be brought into qualitative agreement with the model.

The observations to date indicate that thermionic cathodes by nature cannot escape mass loss. The loss rate can be reduced by using materials with low work function and high sputter resistance. Such a material may be state of the art. A low work function reduces the need for high temperatures, hence a low requirement for ion bombardment heating which in turn reduces sputtering.

Other approaches to cathode development for arcjet thrusters are being explored. A hollow cathode designed to operate at high pressures may be a viable candidate although the basic emission mechanism may again be thermionic. Cold cathodes of various types are of interest. Photoemission and tunneling effects may be useful in obtaining electron emission without the thermionic effects.

It is well to bear in mind however, that missions for which arcjet thrusters are best suited

may not have the long life (> 10 000 hr) requirements imposed upon electrostatic ion thruster. The specific impulse and efficiency of arcjets are lower than ion thrusters, but unless these parameters are crucial to the mission, reliability and system simplicity inherent in arcjets may be more important. Propulsion technologists are inclined to search and will continue to strive for advancement of the state of art. In view of the excellent effort invested in arcjet thrusters development two decades ago, if the primary reasons for relinquishing that effort at that time no longer exists, near-term application of arcjets, as previously conceived plus modest improvements, is not an insurmountable task. The investigation reported here has been at relatively low power, namely 1 kW or less. The conclusions drawn, therefore, may not extrapolate to tens and hundreds of kilowatts of power. Suffice it to note that in the 1960's, a 30 kW arcjet was operated in hydrogen gas for 720 hr and the test was terminated at will. Such results lend optimism for the application of arcjets to a broad class of space missions.

Appendix A

Thermionic-Field Emission

The Richardson-Schottky equation relating emission current density to cathode temperature and surface work function in the presence of an electric field can be written as,

$$j = AT^2 \exp\left(-\frac{e\phi}{kT}\right)\exp\left(\frac{e\sqrt{\frac{Ee}{\pi\varepsilon_o}}}{kT}\right) \qquad \text{(ref. 12)}$$

where

j emission current density, $\frac{A}{m^2}$

A constant $= \frac{2\pi emk^2}{h^3} = 6.02\times10^5 \ \frac{A}{m^2 K^2}$

e electronic charge, 1.6×10^{-19} coulomb

m electron mass, 9.1×10^{-31} kg

k Boltzmann's Constant, $1.38\times10^{-23} \ \frac{joule}{K}$

h Planck's constant, 6.63×10^{-34} joule-sec

ϕ surface work function, joule/coul or eV/electron

T temperature, K

E electric field, V/m

ε_o permittivity of free space, 8.85×10^{-12} $\frac{couloub^2}{newton^2}$

Taking logarithm and differentials on both sides;

$$\frac{dj}{j} = \underbrace{\left(\frac{e\phi - e^{3/2}\sqrt{\frac{E}{\pi\varepsilon_o}} + 2\,kT}{kT}\right)\frac{dT}{T}}_{(A)} - \underbrace{\frac{e\phi}{kT}\left(\frac{d\phi}{\phi}\right)}_{(B)} + \underbrace{\left(\frac{e^{3/2}}{2\,kT}\sqrt{\frac{E}{\pi\varepsilon_o}}\,\frac{dE}{E}\right)}_{(C)}$$

The coefficients A, B, and C for each differential term on the right hand side can be evaluated for selected values of ϕ, T, and E

d, $\frac{joule}{coul}$	E, $\frac{V}{m}$	T K	(A)	(B)	(C)
2.6	10^6	2000	16.63	15.07	0.22
	10^6	2500	13.71	12.06	0.176
	10^8	2500	10.58	12.1	1.76
	10^{10}	2500	-21.1	12.06	17.6
4.5	10^6	2000	27.65	26.09	0.22
	10^8	2500	29.35	20.87	1.76
	10^{10}	2500	-12.3	20.87	17.6

In Ref. 12 it is noted that the Schottky equation does not hold for low fields or for composite surfaces such as oxide cathodes. Also, with electric fields of 10^7 V/m and greater, cold emission occurs. Some of the cathodes in the present investigation were oxide-impregnated, and the electric field active at the surface was unknown. From the range of parameters in the above table and the values of the coefficients, it is postulated that the equation may be applicable for qualitative evaluation of emission characteristics where the electric field may be 10^8 V/m or lower. It is interesting to note that when the electric field is of the order of 10^6 V/m, its effects indicated by coefficient C are small relative to the effects of temperature and work function, (coefficients A and B, respectively).

Appendix B

Evaporation

from Zima[18] the vapor pressure for substance is given as

$$\mathrm{Log}_{10} Pv = A - \frac{B}{T}$$

where

Pv vapor pressure, microns (μ)

A,B constants

T temperature, K

for tungsten

$A = 12.26$

$B = 40.26\times10^3$

for a temperature of 2500° C = 2773 K

$$Pv = \log^{-1}\left[12.26 - \frac{40.26\times10^3}{2773}\right] = 5.51\times10^{-3}\ \mu = 7.25\times10^{-9}\ \text{atm}$$

from Dushman[22] the evaporation rate for a given material is given as

$$W = \frac{P_v}{\sqrt{2\pi}\ \sqrt{RT/M}}$$

where

W evaporation rate, g/cm^2 sec

P vapor pressure, atm

T absolute temperature, K

M molecular weight of the evaporated material, g/mole

R universal gas constant = $8.099\times10^{-5} \ \frac{atm^2 cm^4 sec^2}{gmole\ K}$

for tungsten, M = 183.55 g/mole and for a temperature T = 2773 K

$$W = \frac{7.25\times10^{-9}}{(2\pi)^{1/2}\sqrt{\frac{(8.099\times10^{-5})\ (2773)}{183.55}}}$$

$$= 8.27\times10^{-8}\ g/cm^2 \cdot sec$$

An approximate calculation of the surface area of the 1/8" tungsten tube gives

$$Area = 0.50\ cm^2$$

therefore

$$\text{mass loss} = (0.50\ cm^2)\ (8.27\times10^{-8}\ g/cm^2 \cdot sec)$$
$$= 4.13\times10^{-8}\ g/sec$$
$$= 2.48\times10^{-6}\ g/min$$

Sputtering

the mass loss rate due to sputtering can be obtained by the following relation

$$\dot{W}s \quad Y \frac{\alpha i}{e} \frac{1}{N} Mw$$

where

$\dot{W}s$ mass loss due to sputtering, g/sec

Y sputtering yield, $\frac{atoms}{ion}$

i input current, amperes
e electron charge, 1.6×10^{-19} c/ion
N Avogadro's constant = 6.023×10^{23} atoms/mole
M molecular weight of the material

$$\alpha \quad \frac{Vc}{Vc + V_I}$$

Vc cathode fall potential
V_I ionization potential = 14.5 V for nitrogen

for thoriated tungsten M = 183.55 g/ mole

approximating the values: $Y = 10^{-3}\ \frac{atoms}{ion}^{18}$

and $Vc = 0.75\ Varc$

and Varc = 60 V at 5 A from the data for thoriated tungsten we find that

$$\alpha = \frac{(0.75)\ (60)}{(0.75)\ (60) + 14.5} = 0.756$$

and

$$\dot{W}s = \frac{10^{-3}\ \frac{atoms}{ion}\ (0.756)\ (5\ c/s)\ (183.55\ g/mol)}{(1.6\times10^{-19}\ c/ion)\ (6.023\times10^{23}\ atoms/mole)}$$

$$\dot{W}s = 7.211\times10^{-6}\ g/sec$$

$$= 4.33\times10^{-4}\ g/min$$

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TABLE 1. - SUMMARY OF CATHODES IN NITROGEN

Material	Work function	T, K Cathode	T, K Spot	Mass loss, g/min	Average arc voltage (Mass loss tests)
Thoriated tungsten rod 0.16 cm Diam.	2.6	1623	1828	4.7×10^{-4}	54
Thoriated tungsten rod 0.32 cm Diam.	2.6	1773	2020	6.2×10^{-4}	47
Thoriated tungsten rod 0.64 cm Diam.	2.6	----	----	7.3×10^{-4}	53
Thoriated tungsten rod 99.95 percent Pure N_2	2.6	1623	1923	1.1×10^{-4}	58
Thoriated tungsten rod 10 A	2.6	1873	2320	5.5×10^{-4}	43
Tungsten tube No R-500	4.5	2023	2408	2.3×10^{-3}	59
BaO-tungsten	2.0	1673	1973	5.0×10^{-4}	56
LaB_6 tube	2.6	1373	1623	1.5×10^{4}	60
Hollow cathode	2.6	1980	----	1.1×10^{-4}	53
Thoriated tungsten wire	2.6	----	----	2.2×10^{-4}	57

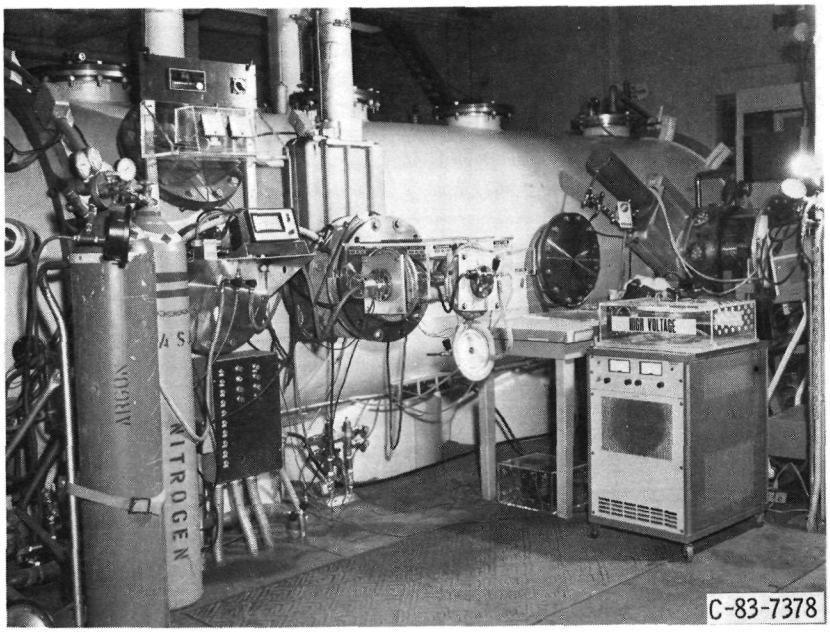

Figure 1. - Arcjet test facility.

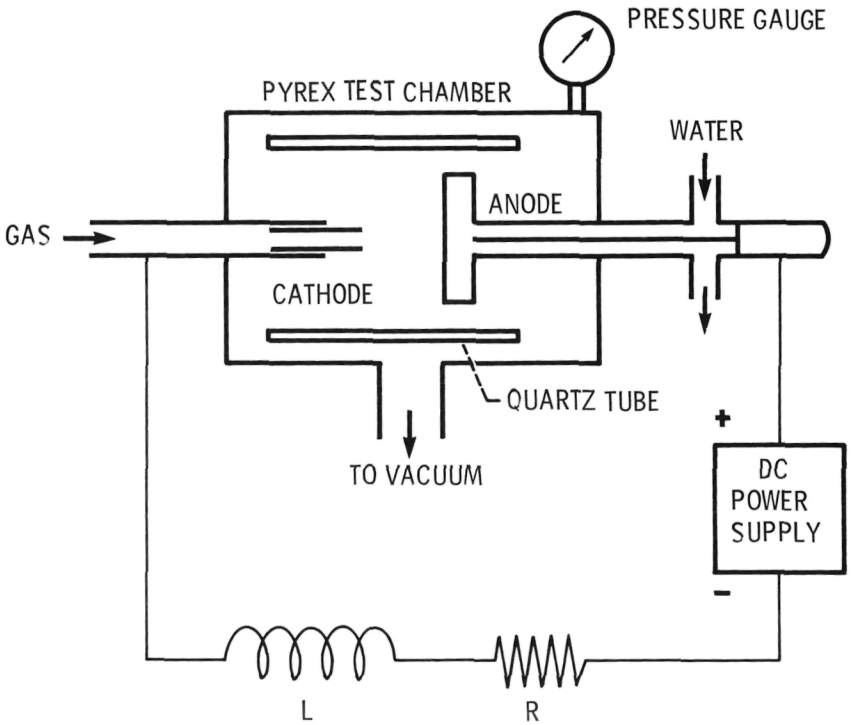

Figure 2. - Schematic, arc discharge experimental system

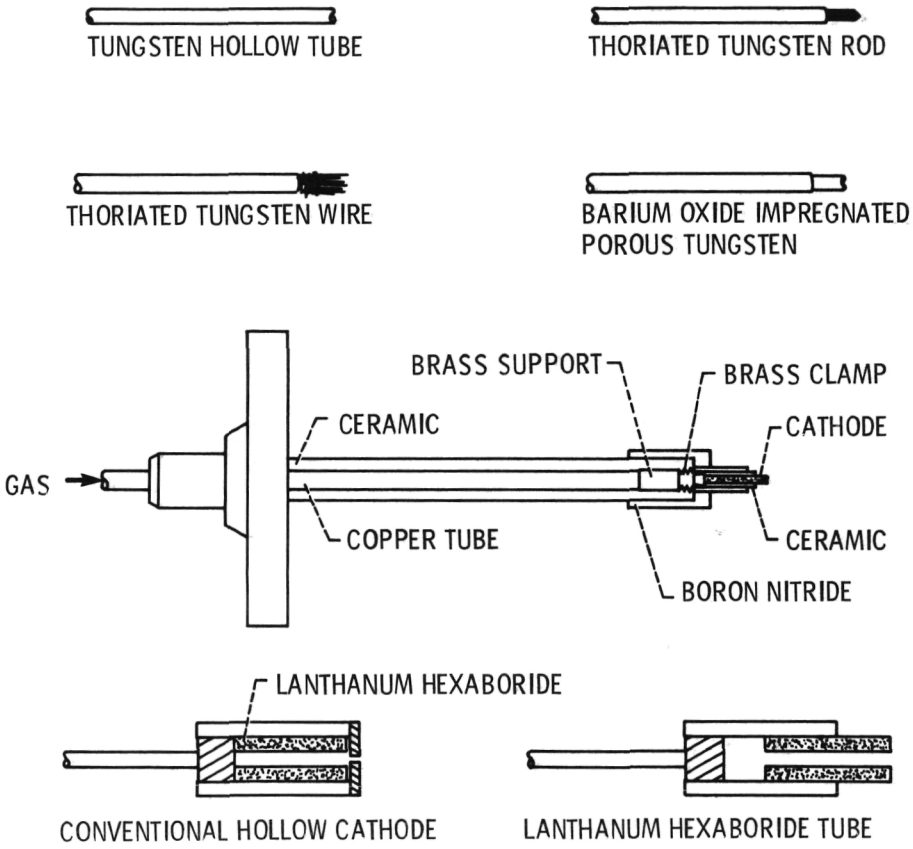

Figure 3. - Cathode support and cathode configurations.

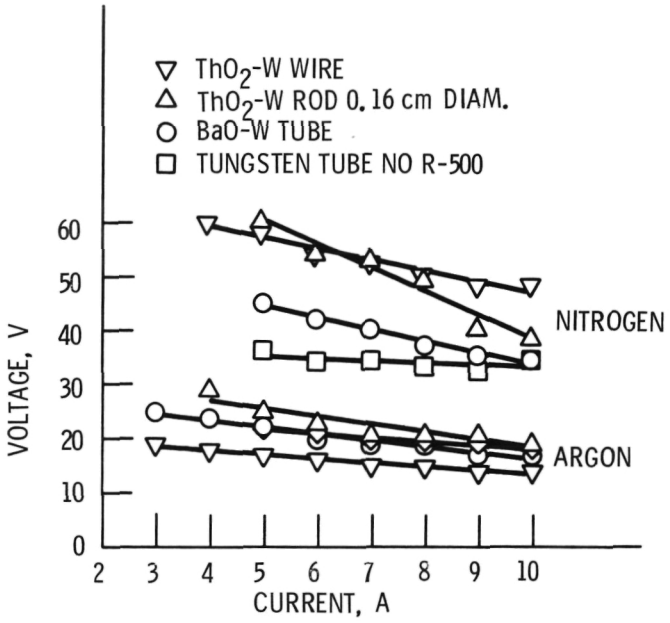

Figure 4. - Voltage-current characteristics of 4 cathodes in nitrogen and in argon. P = 350 torr, Q = 300 SCCM, Gap = 0.5 cm.

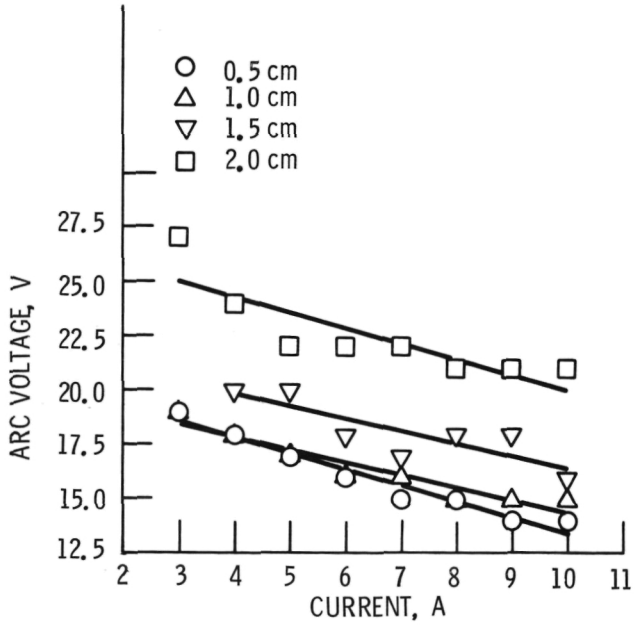

Figure 5. - Voltage - current characteristics of a thoriated tungsten wire cathode in argon at gap widths of 0.5, 1.0, 1.5, and 2.0 cm. P = 350 torr, Q = 300 SCCM.

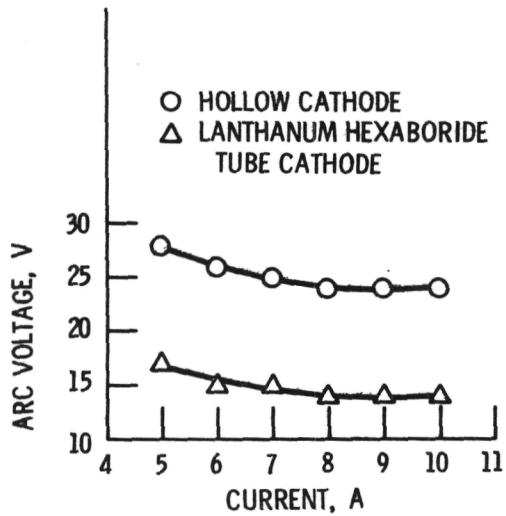

Figure 6. - Voltage - current characteristics in argon of a lanthanum hexaboride tube cathode and a conventional hollow cathode with a lanthanum hexaboride insert. P = 350 torr, Q = 300 SCCM, Gap = 0.5 cm.

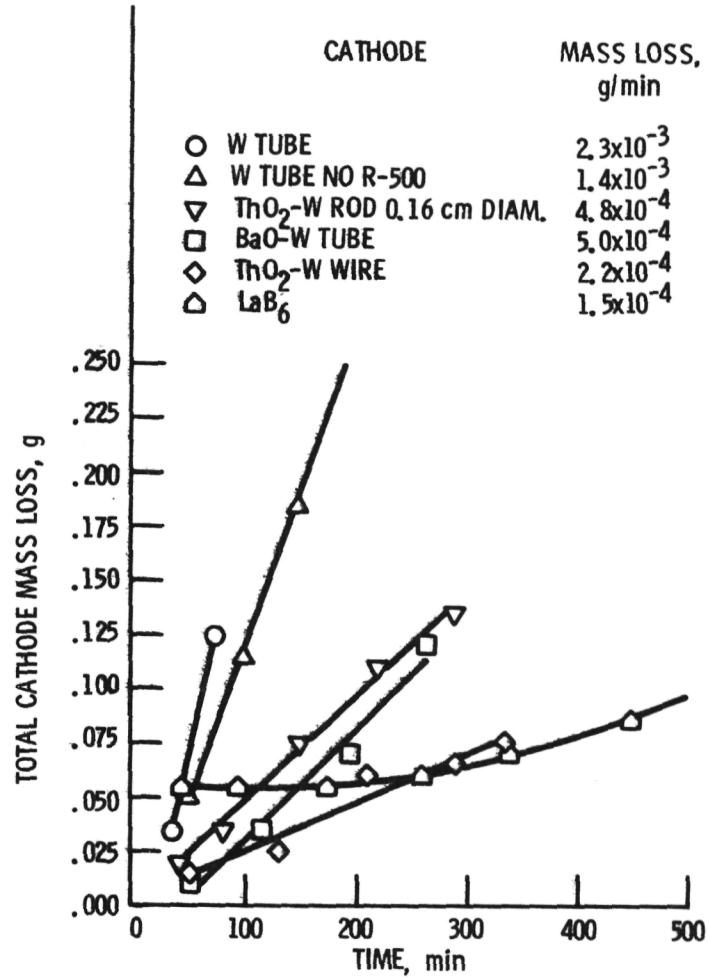

Figure 7. - Total cathode mass loss vs. time for 6 different cathodes. P=760 Torr, Q=300 SCCM, I=5 A, Gap=0.5 cm.

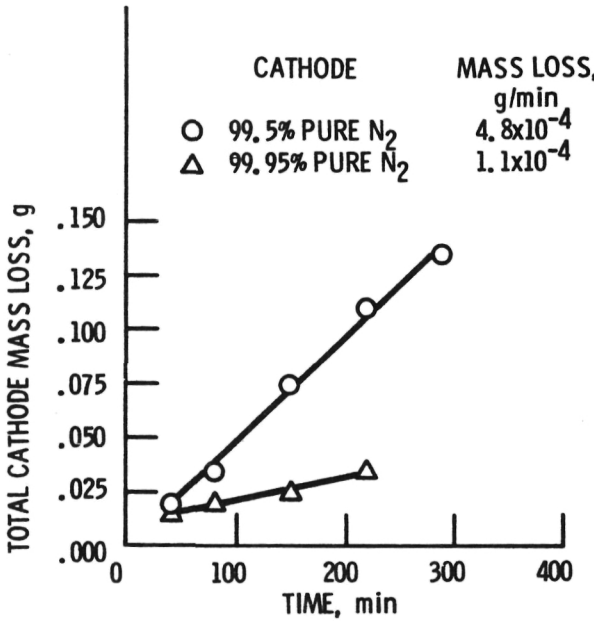

Figure 8. - Comparison of the mass loss of a thoriated tungsten rod in 99.5 pure nitrogen and in 99.95 pure nitrogen. P = 760 torr, Q = 300 SCCM, I = 5 A, Gap = 0.5 cm.

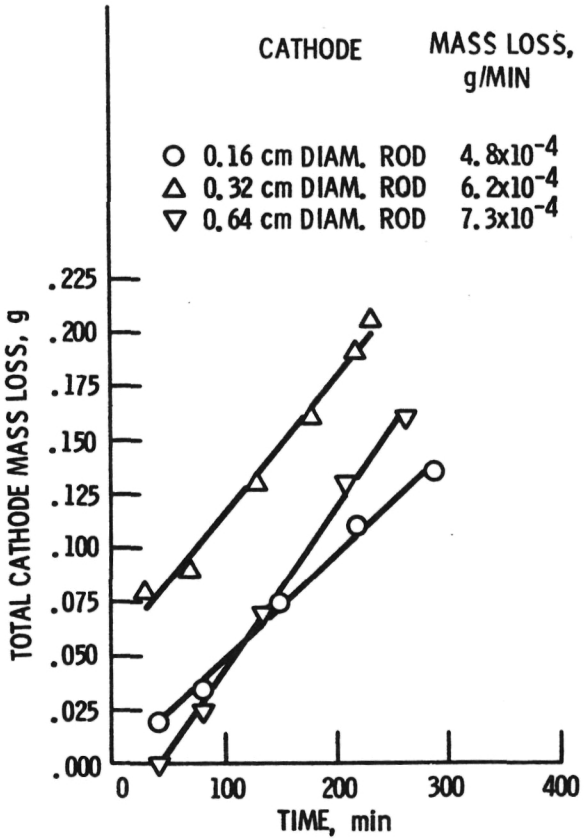

Figure 9. - Comparison of the mass loss of 3 sizes of thoriated tungsten rod. P = 760 torr, Q = 300 SCCM, I = 5 A, Gap = 0.5 cm.

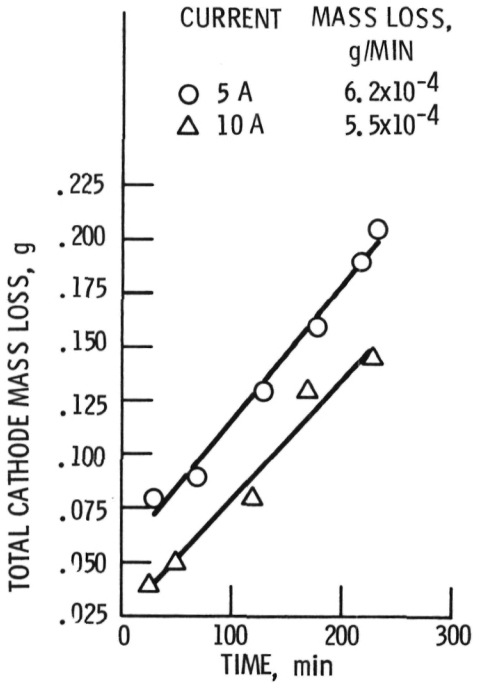

Figure 10. - Comparison of the mass loss of thoriated tungsten rod at 5 A and at 10 A. P = 760 torr, Q = 300 SCCM, Gap = 0.5 cm.

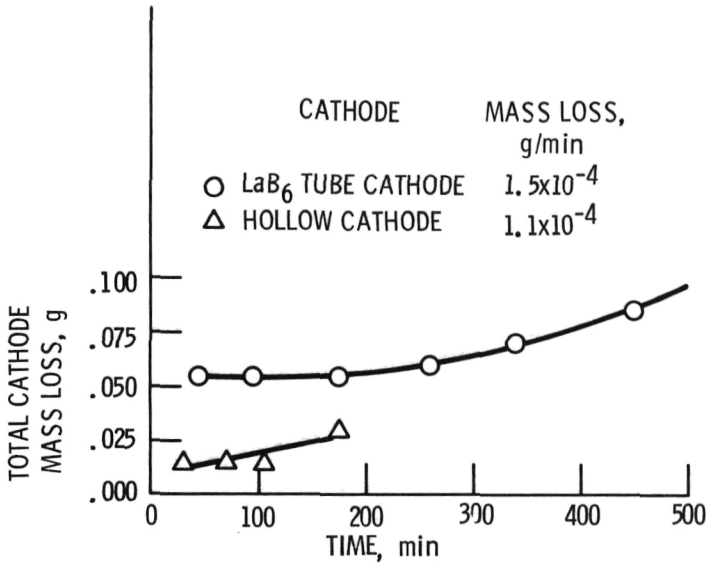

Figure 11. - Comparison of the mass loss of lanthanum hexaboride with the conventional hollow cathode. P = 760 torr, Q = 300 SCCM for lanthanum hexaboride and P = 100 torr, Q = 35 SCCM for the hollow cathode. Gap = 0.5 cm, I = 5 A.

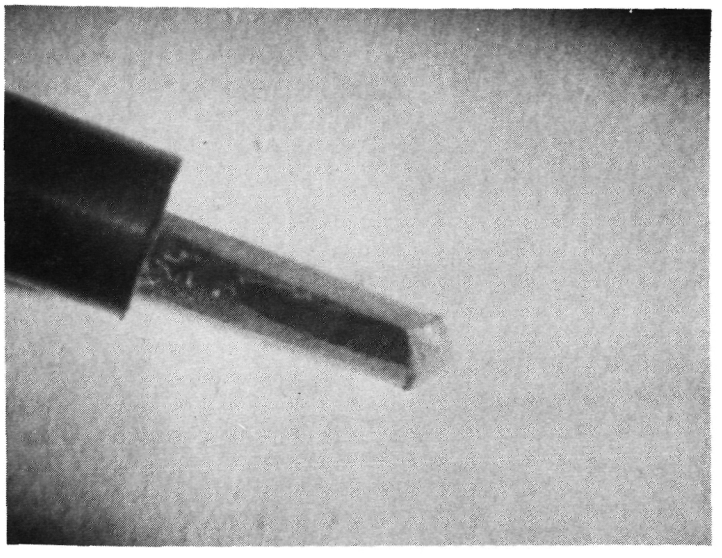

Figure 12. - 0.16 cm diameter thoriated tungsten rod before running in nitrogen.

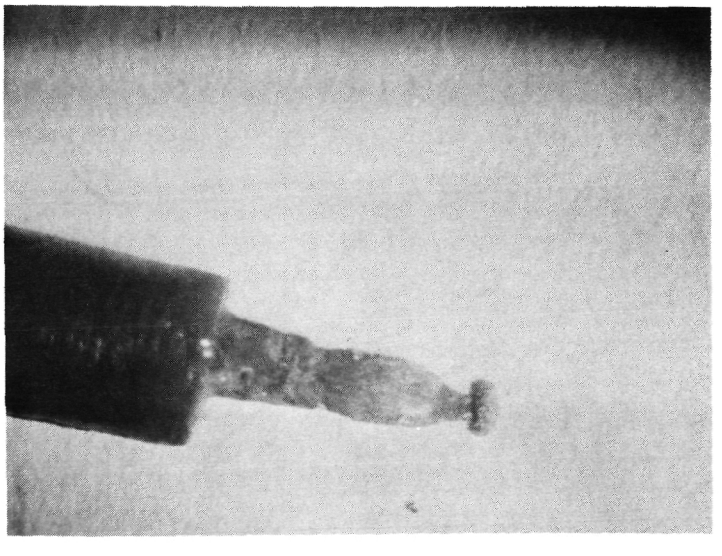

Figure 13. - 0.16 cm diameter thoriated tungsten rod after running in nitrogen.

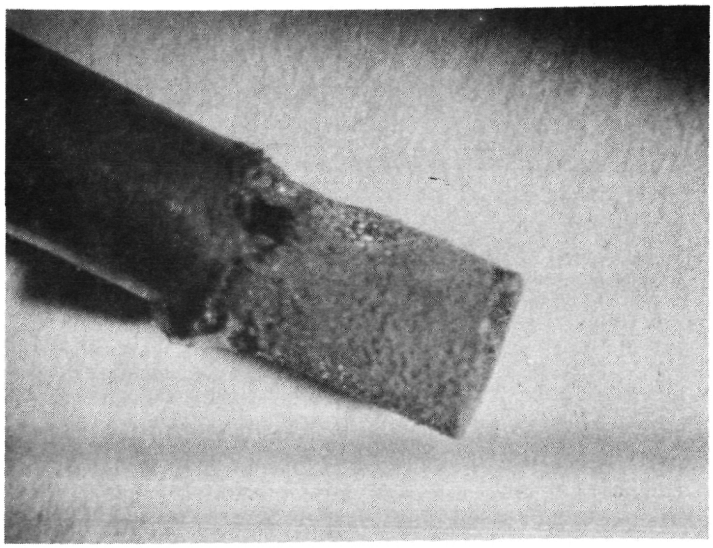

Figure 14. - Tungsten tube after running in nitrogen.

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16. Abstract

Electrode lifetime has long been recognized as one of the predominant technology concerns in arcjet thrusters for space propulsion. Arcjet development of previous decades placed emphasis on performance and thruster lifetime problems were not addressed in depth. An experimental investigation was conducted at the NASA Lewis Research Center to identify and to evaluate the various processes which control cathode erosion and degradation. A direct current arc discharge was established between electrodes in a pressure-controlled gas flow environment. The cathode holder was designed for easy testing of various cathode materials. The anode was a water-cooled copper collector electrode. The arc was powered by a dc power supply with current and voltage regulated cross-over control. The external circuit contained a ballast resistor and a low inductance choke. Nitrogen and argon were used as propellants and the materials used were 2 percent thoriated tungsten, barium oxide impregnated porous tungsten, pure tungsten and lanthanum hexaboride. The configurations used were cylindrical solid rods, wire bundles supported by hollow molybdenum tubes, cylindrical hollow tubes, and hollow cathodes of the type used in ion thrusters. The results of the mass loss tests in nitrogen indicated that pure tungsten eroded at a rate more than 10 times faster than the rates of the impregnated tungsten materials. The BaO-W hollow tube, ThO_2-W solid rod, and ThO_2-W wire bundle all had similar mass loss rates, but the mass loss rate of the LaB_6 cathode was significantly lower than the rate of these tungsten materials. It was found that oxygen impurities of less than 0.5 percent in the nitrogen increased the mass loss rate by a factor of 4 over high purity nitrogen. At power levels less than 1 kW, cathode size and current level did not significantly affect the mass loss rate. The hollow cathode was found to be operable in argon and in nitrogen only at pressures below 400 and 200 torr, respectively.

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