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# ENDURANCE TESTING OF DOWNSTREAM CATHODES ON A LOW-POWER MPD THRUSTER

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## SUMMARY

A low-power MPD thruster with downstream cathode has been tested for endurance with a series of hollow cathode designs. Failure modes and failure mechanisms have been identified. A new hollow cathode (with rod inserts) has emerged which shows promise for long life. The downstream positioning of the cathode has also been changed from an on-axis location to an off-axis location. Data are presented for a 1332-hour life test of this new hollow cathode located at the new off-axis location. Xenon propellant was used.

## INTRODUCTION

The low-power (1 kW or less) magnetoplasmadynamic (MPD) thruster is attractive for auxiliary propulsion applications such as satellite station keeping and attitude control (ref. 1). Progress on this device since 1969 has been substantial. Downstream positioning of the thruster cathode resulted in thrust efficiencies up to 24 percent at a specific impulse ( $I_{sp}$ ) of 1620 seconds (ref. 2). Additional modifications have increased the thrust efficiency to as high as 37 percent at an  $I_{sp}$  of 2200 seconds (ref. 3). Desirable systems features such as thrust vectoring with applied magnetic fields (skewed magnet coils), thruster operation from a single power supply, thruster operation from rechargeable secondary batteries, and lightweight tank storage of the xenon propellant appear feasible (ref. 4).

Data are presented on a series of cathode design and endurance experiments. The intent of these experiments is to identify problem areas that might prevent long lifetime operation of the low-power MPD thruster in space and to generate cathode designs which circumvent these problems. Thruster operating lifetimes ranging from 2000 hours (3 months) to 44 000 hours (5 yr) must be achieved to meet the goals of many of the proposed auxiliary propulsion missions.

## APPARATUS

### Thruster

Figure 1 shows what shall be called throughout this report the baseline MPD thruster. This baseline MPD thruster is identical in design and fabrication to the one tested in reference 2 with four exceptions: (1) the hollow cylinder part of the upstream pole piece is filled entirely with boron nitride, (2) a boron nitride cylindrical sleeve is used between the anode and edge wound magnets to insulate them, (3) the cylindrical anode has a single cut (about 0.5 cm wide) along its entire length parallel to the thruster axis, and (4) a tantalum shield (flame sprayed on all surfaces with alumina 0.05 cm thick) was used to protect the inside surface of the frustum-shaped part of the exhaust end pole piece from severe ion bombardment.

In this report, the greatest departure from the baseline MPD thruster is in hollow cathode design and position. Other minor thruster changes were made for some of the tests and will be discussed in the RESULTS AND DISCUSSION section treating the particular test involved.

### Hollow Cathode Designs

Four basic cathode designs were tested. These designs are interrelated with each successive design evolving from analysis of the failure modes of the previous cathode.

(1) On-axis downstream cathode (design 1). This is shown as a part of figure 1 and in greater detail in figure 2. It consists of a hollow 2-percent thoriaated tungsten cathode located on the thruster centerline. A very small amount of xenon propellant flow from the cathode was used to maintain the discharge. This flow is out of the cathode tip (orifice plate) in a direction upstream relative to the thruster body.

(2) Original off-axis downstream cathode (design 2). This cathode (fig. 3) is off the thruster axis with the tip pointing downstream. The propellant emerging from the orifice plate in the cathode tip is directed downstream at an angle of  $45^{\circ}$  relative to the thruster axis. The structure and geometry of the thoriaated tungsten hollow cathode is identical to that shown in figure 2 and is mated to the tantalum feed tube by the same tantalum-sleeve electron-beam-weld technique illustrated in figure 2.

(3) Off-axis downstream cathode with sleeve (design 3). Figure 4 shows a modified version of the off-axis downstream cathode in which a tantalum sleeve is placed about the thoriaated tungsten cathode. This sleeve was operated electrically common with the cathode and also insulated from it. A 0.035-centimeter-thick layer of alumina on the outside diameter of the cathode provided the insulation.

(4) New off-axis downstream cathode with rods (design 4). In this new hollow cathode design (fig. 5) the orifice plate is moved 2.46 centimeters upstream. This cathode uses the concept of wedging 2-percent thoriated tungsten rods into the hollow sleeve part of the cathode structure to protect the cathode orifice plate from direct ion impingement and to permit the cathode to operate at low currents. Three rods (0.101 cm o. d.) are wedged into the hollow such that an 0.025-centimeter gap exists between the ends of the rods and the orifice plate. Xenon propellant is delivered to the cathode structure by a molybdenum tube which has been electron beam welded to the cathode by means of a tantalum sleeve. The 0.038-centimeter-inside-diameter hole in the cathode orifice plate controls the flow rate. Flow exits the cathode through the many voids between rod sets and between the rods and the tube wall. A heat shield consisting of 16 layers of 0.0025-centimeter-thick tantalum foil covers the thoriated tungsten cathode. A 1.27-centimeter-outside-diameter molybdenum protecting bar (fig. 6) is mounted from the exhaust end flange of the thruster to shield the back of the cathode structure from direct impingement of exhaust beam ions. Only the cathode discharge tip is exposed to the beam. (The tip position was selected to be on a magnetic field line which has a near-to-the-centerline position when in the discharge chamber.) Physically, the cathode tip is on the centerline of the molybdenum bar, 1.27-centimeters downstream of the end of the bar. The tip points partially downstream, making an angle of  $53^{\circ}$  with the thruster axis.

#### Isolators and Polyimide Insulation

For the entire sequence of tests, the majority of propellant feed-line lengths, the solenoid valves, and the calibrated leaks were at ground potential. Isolators (shown in fig. 7) were inserted in both the anode and cathode propellant lines to isolate the anode and cathode from ground potential. All wiring connections and those segments of the propellant lines that operate at either anode or cathode potential were insulated thoroughly with an application of high voltage, high temperature polyimide tape and/or polyimide paint.

#### Vacuum Facilities

Two different vacuum facilities were used for various phases of the testing. The first vacuum facility used has a 1.5-meter diameter and is 5.0 meters long. Background pressure was maintained at  $4 \times 10^{-3}$  newton per square meter ( $3 \times 10^{-5}$  torr) or less. The thruster was mounted at one end of the tank, and the exhaust plume extended along the tank's axis. Both the thruster and tank axis were horizontal. The axes of the four oil diffusion pumps (used for primary pumping) were perpendicular to the tank axis.

The second vacuum facility used in testing was the new super-bell-jar facility of the NASA Lewis Research Center (fig. 8). This facility consists of two separate stainless steel bell jars, but only one was used for the testing described. Each bell jar has a 0.86-meter diameter and is 1.7 meters high; each is mounted on top and concentric with a single 0.9-meter diameter oil diffusion pump. Background pressure was maintained between  $8 \times 10^{-3}$  and  $1.3 \times 10^{-2}$  newton per square meter ( $6 \times 10^{-5}$  and  $10^{-4}$  torr). The thruster is mounted from the top flange plate (shown in fig. 8) with the exhaust plume pointing downward along the bell jar axis. Two viewing windows are mounted at different locations on the bell jar circumference for viewing cathode behavior and for taking cathode temperatures by means of a pyrometer.

### EXPERIMENTAL PROCEDURE

The thruster discharge is initiated by establishing Paschen law breakdown conditions using an arc starter (fig. 9). Then, the discharge power supply, the cathode current controller, and the flow rates are adjusted to the experimental conditions desired. The anode propellant flow rate is set by varying the pressure upstream of the fixed size anode calibrated leak. Cathode propellant flow is varied by the cathode current controller (fig. 9), which consists of a meter relay and a solenoid valve upstream of the cathode flow calibrated leak. (This cathode current controller is very crude compared to the state of the art in controls. It is of the on-off type and is characterized by overshoots (for a few seconds) upwards of 20 percent of desired value. A compact, simple, and much higher performance (good regulation, little overshoot) servo-control loop can be built.) As the cathode current drops below the preset (desired) value of the meter relay, the solenoid valve is activated and propellant fills the plenum (consisting of the line void between the valve and calibrated leak). The valve recloses as soon as the current goes above the desired value and remains closed (usually many minutes) until the current subsequently drops below the desired value. The flow rate can be computed from the duty cycle of the valve, the calibration curve of the calibrated leak, and the pressure upstream of the leak.

## RESULTS AND DISCUSSION

### On-Axis Downstream Cathode Tests (Design 1)

The on-axis downstream cathode (design 1) of figure 2 was operated under conditions (0.9 mg/sec xenon flow, 230 V anode to cathode, 2.2 A of discharge current and 0.023 T average magnetic field on centerline of discharge chamber) quite similar to the best data obtained in reference 2, namely, the 24-percent efficient point at an  $I_{sp}$  of 1620 seconds. Figure 10 shows the results after 47.9 hours of operation. The orifice plate is almost completely sputtered away as the sectioned part of the cathode shows. Visual inspection of the cathode tip as seen through the optics of a pyrometer indicated that the orifice plate hole had already opened to a large diameter after 40 hours of running. Cathode flow demand also increased steadily during the period of operation, indicating that the orifice plate hole was opening and that the desired current level could only be maintained by increasing flow. The severed propellant feed tube condition (readily apparent in fig. 10) began developing at the 39-hour mark.

A second test was conducted under the same conditions with cathode tip failure occurring at 50 hours. The only slight difference noted was a lack of feed-tube rupture, but dissection of the tube indicated that the tube wall was very thin (0.003 cm) and thus failure was imminent. Furthermore, the process of feed-tube deterioration appeared to be ion sputtering since subsequent tube dissections indicated that the only walls thinned were in the line of sight of ions expelled from the thruster exhaust port.

### Original Off-Axis Downstream Cathode Tests (Design 2)

The rapid rate of failure of the on-axis downstream cathodes indicated that a drastic change of cathode design and/or location was needed. The original off-axis downstream-cathode thruster (fig. 3) was selected for subsequent testing. The cathode tip position shown was selected for a number of reasons. First, the feed-tube dissections mentioned previously for design 1 showed that little ion sputtering occurred at a radius of 8.9 centimeters. Second, the ion flux density measurements made in reference 4 indicate that the ion flux density at this 8.9-centimeter radius is approximately 35 percent of that on the thruster axis; this low ion flux reduces the number of ions impinging the cathode structure. Third, even with this reduced ion flux, a magnetic field map shows that field lines having a near-to-the-centerline position in the discharge chamber do indeed cross the hollow cathode tip region. This permits sufficient plasma diffusion from the discharge chamber along these particular field lines to heat the cathode tip.

To further improve the possibility of cathode orifice plate survival, the angled downstream pointing of the cathode tip (shown in fig. 3) was employed.

In reference 4 the on-axis downstream cathode was gimballed through an arc of  $\pm 20^\circ$  with no disturbance in the shape or position of the ion flux distribution. Hence, moving the cathode off axis would appear to cause no serious detriment to thruster performance. To verify this, the thrust performance of the baseline MPD with the off-axis cathode was checked using the procedure outlined in reference 2. Thrust efficiency and thrust to power remained quite close to that recorded in reference 2. The thrust efficiency did peak at 22 percent for a specific impulse of 1870 seconds contrasted to the slightly higher peak of 24 percent at 1600 seconds as noted in reference 2. The greatest contrast was in the discharge voltage required to achieve comparable performance points. The voltage level was noted to be about 50 percent higher accompanied by a 10-percent reduction in discharge current.

Figure 11 shows the condition of this off-axis cathode tip after 80.8 hours of operation. The orifice hole is again enlarged (0.307 cm i. d. after test compared to 0.033 cm i. d. before), and a hole has been sputtered into the side wall of the cathode. This hole was located on a line-of-sight path relative to the thruster exhaust port. Also, the inside of the frustum-shaped part of the exhaust pole piece was sputtered clean of alumina; this condition necessitated the use of the tantalum pole piece shield mentioned previously. A second test which was made with this geometry and the added tantalum pole piece shield endured for 160 hours before a hole (slightly larger this time) appeared in the cathode side wall. The cathode orifice plate showed little wear. Visual data within the first few hours of operation indicated that a small crack existed in the sidewall at the location of the final failure mechanism hole. It can therefore be postulated that the cathode emitted at the cracked sidewall surface instead of at the normal orifice plate hole for most of the 160 hours of operation. Hence, the total sputtering phenomena took place at or in the vicinity of this crack.

#### Off-Axis Downstream Cathode with Sleeve (Design 3)

The short endurance times which were experienced with the original off-axis cathode (design 2) demanded additional redesign considerations. Since ion bombardment of the cathode tip (orifice plate) is the sole cathode heating mechanism, severe orifice plate sputtering is to be expected unless the average energy per ion impinging on the orifice plate is reduced. There are three possible ways to accomplish this: (1) reduce discharge voltage, (2) increase hollow cathode flow, and/or (3) increase the neutral density at the orifice plate. Reducing the discharge voltage lowers the thruster specific impulse; this is undesirable. Increasing the hollow cathode flow reduces the thrust efficiency; this also is undesirable. Hence, increasing neutral density at the orifice plate seemed



the only viable alternative, and this could be accomplished by adding the tantalum sleeve shown in figure 4. This sleeve holds neutral density high by inhibiting the radial diffusion of hollow-cathode propellant until it is many centimeters downstream of the cathode tip. To inhibit sidewall cathode deterioration, a molybdenum cathode-protecting rod (similar to that in fig. 6) was used to block out line-of-sight ions emerging from the thruster exhaust port.

Testing the baseline MPD with the design 3 cathode modifications indicated two things: (1) the tantalum shield could be electrically common with the cathode with no obvious deterioration of performance, and (2) higher cathode flow was still necessary to stabilize the operation of the discharge. It was impossible to achieve a long life test of this cathode system with a reasonable level of cathode flow because of the tendency of the discharge to be unstable. The discharge tended to extinguish itself every few minutes, necessitating a thruster restart each time. Additional redesign was necessary.

### Testing the New Off-Axis

#### Downstream Cathode with Rods (Design 4)

The new off-axis downstream cathode (fig. 5) evolved in an effort to solve the instability problems of the design 3 cathode while at the same time consolidating the desirable features of the design 3 cathode into a straightforward design. The sleeve of the design 3 cathode could be electrically common with the orifice plate, and so in the design 4 cathode the sleeve and orifice plate were machined from the same piece of thoriated tungsten. To solve the instability problem, a way had to be found to increase the density in the sleeve portion of the cathode without raising the hollow cathode flow. The three thoriated tungsten rod inserts are the means of achieving this. Tantalum heat shielding of the cathode was also added in an attempt to lower cathode loss, thus cutting the amount of ion bombardment of the cathode required to maintain the discharge current.

The thruster configuration of figure 6 was placed on endurance test in the new super-bell-jar facility. The circuitry shown in figure 9 was used. Discharge voltage (anode to cathode) was maintained at 250 volts and discharge current (passing in series through the magnets) at 2.3 amperes. Anode propellant flow was maintained at 0.8 milligram per second. Cathode propellant flow varied from less than 0.05 milligram per second to 0.3 milligram per second in response to the current controller holding the current at 2.3 amperes.

During the first 60 hours of operation, the cathode tip appeared to be uniformly hot and the plasma glow from the tip seemed to be uniformly distributed in the three holes between the thoriated tungsten rods and the wall of the cathode. The hole in the middle of the pack of three rods did not have the same type of plasma glow noted in the other holes. As the test progressed, only one, and sometimes two, of the holes were characterized

by plasma glow. The glow pattern varied in a random fashion as to number of holes and location. If the thruster was stopped and restarted, very often the glow pattern would change. The cathode tip temperature for the first 60 hours was near 1650° C and stayed within the 1540° to 1870° C range for the remainder of the test. It was necessary to stop the thruster to change propellant supply cylinders about once every 60 hours.

After 500 hours of operation, the cathode flow rate (needed to maintain the discharge current at 2.3 A) showed a sharp rise. Ignition and re-ignition of the thruster became more difficult, and frequently plasma breakdown occurred between the cathode and the outside circumference of the magnets.

After 735 hours of operation, the bell jar was opened for the first time since the start of testing. Figure 12 shows the condition of the thruster at the 735-hour mark. The two polycarbonate-plastic isolators were damaged and were leaking through the surface of the cylindrical body. The greatest leakage was on the cathode isolator, thus explaining the excessive cathode propellant demand prior to bell jar opening. Apparently the ambient temperature was high enough to melt the polycarbonate plastic, and this caused leakage with subsequent arcing. To remedy this, a new set of isolators with boron nitride bodies was used for the remainder of the test. These isolators were also placed out at a larger radius, 15 to 25 centimeters from the thruster axis. No subsequent problem was observed.

The isomica insulator which protects the exhaust pole piece was replaced after 735 hours. A hairline crack was also found in the cathode feedline many centimeters upstream of the cathode tip (in a portion of the line that remained visually cold during cathode operation) and this was welded shut before the test was resumed. The photograph in figure 13 shows another problem area, polyimide insulation failure. At the start of testing, sheets of thin (0.002 cm) polyimide material were placed around the circumference of the edge wound magnet (and secured with polyimide tape) for better electrical insulation. (The anodizing process used in magnet fabrication works well on the flat surface of the coils but on the outside diameter of the thin edges the anodization is patchy.) Failure of this polyimide sheet can be postulated as resulting from gas trapped between the polyimide and the magnets. The places where the material was either damaged or missing were the very places where arcing was detected during operation (see fig. 13). To correct this problem a polyimide paint (cured according to manufacturer's specification) was applied directly to the edges of the magnet coils and to other areas (such as the end flange of the coils) felt to be vulnerable to arcing. This proved to be a very satisfactory insulation technique for the remainder of the testing.

In all the cathode endurance testing conducted, a residue of black colored particles and dust can be found on the anode surface. It was analyzed in this case and found to contain constituents of the boron nitride and alumina insulating materials, some components of the mild steel pole pieces, tungsten from the cathode, and molybdenum from the

anode and from the cathode-protecting bar. Most of this residue fell out of the discharge chamber during the 735-hour inspection, magnet insulating modification, and isolator modification. Hence, it was decided to remove the remaining residue before testing was resumed.

A total operating lifetime of 1332 hours was achieved. The test was terminated because of severe leakage in the cathode feedline at the point shown in figure 14. At this point the tantalum sleeve (used to join the cathode to the feedline) is electron beam welded to the molybdenum line. The point of leakage was very embrittled, and the entire cathode broke loose from the feedline at this embrittled surface when the thruster was removed from the bell jar. The technique of joining the thoriated tungsten tip to the feedline using the refractory metal sleeve appears sound. However, a better choice of refractory metals should be used in the future. Using a tantalum sleeve to join tungsten to molybdenum (as done for this test) is a poor technique since the coefficient of thermal expansion of tantalum is much different from that of tungsten and molybdenum. It can be postulated that the ultimate failure of this endurance test at 1332 hours was probably due to this mismatch in the coefficient of thermal expansion causing severe stresses in the refractory metals under hot operation with subsequent embrittlement and cracking.

#### Detailed Results - 1332-Hour Life Test

Figures 13 and 14 afford a comparison of thruster damage and erosion at 735 hours and at the final 1332 hours. The molybdenum cathode-protecting bar has been sputtered on a line-of-sight from the plasma exhaust. Exact dimensions are given in the sketches of figure 15. The rate of erosion appears approximately linear with time ( $3.86 \times 10^{-4}$  cm/hr based on 735-hr data for minimum cross section and  $4.01 \times 10^{-4}$  cm/hr based on 1332-hr data). Hence, the total life of the 1.27-centimeter-diameter molybdenum bar can be projected to be approximately 3000 hours. One large disadvantage of this technique for protecting the cathode is that the sputtered bar material is a potential plating substance for spacecraft surfaces.

The pattern of cathode erosion is shown in the photographs of figures 13 and 14 and is sketched in figure 16. Tip erosion is not uniform across the cathode diameter. The photographs indicate that the tip erodes in such a fashion that the plane of the new eroded tip surface is parallel to the thruster axis. This is most apparent in figure 14 if one ignores the small piece of protruding material at the very bottom of the cathode. The rate of cathode erosion calculated from the most foreshortened side of the cathode is  $2.18 \times 10^{-4}$  centimeter per hour based on 735 hours of operation, but it is  $4.77 \times 10^{-4}$  centimeter per hour based on 1332 hours of operation. (Some of this discrepancy may be due to the period of approximately 200 hr, just before the 735-hr shutdown and inspection during which the cathode isolator was leaking and the cathode tip flow was uncertain.)

Thus, it becomes difficult without more data to project the exact life of the cathode. However, it is certain that after 1332 hours of operation, 74.8 percent of the original cathode length remains even along the most foreshortened length dimension.

The photographs of figure 17 show the cathode tip contour, in particular the hole pattern. After 735 hours, the hole at the greatest distance from the thruster body (extreme left in photograph) was the most enlarged of the three between the thoriated tungsten rod inserts and the cathode tube wall. In general, the plasma glow for the first 735 hours appeared at this hole, although there was some jumping to other holes. Yet after 1332 hours this hole is almost closed, with one of the other two holes exhibiting the largest diameter. The shift in plasma glow followed this change in hole size with the glow usually coming from the largest diameter hole. The cathode was sectioned near the orifice plate (much like what was done in fig. 10). This revealed that the hole patterns only penetrated a few tenths of a centimeter, and that beyond this the original rod geometries and the orifice plate dimensions appeared unchanged.

Figure 12 also reveals that severe sputtering of the boron nitride insulator, which fills the cylinder of the upstream pole piece, has occurred. The center part of the insulator is recessed, and a small part of the tip of the insulator which shielded the pole piece has been eroded away. The three holes,  $120^\circ$  apart, which appear black on the photograph need some explanation. At the start of testing the boron nitride insulator was held in place by three screws which were placed through the pole piece cylinder surface and radially into the boron nitride. The black spots are those places where the side walls of the screw holes have been eroded away. A careful inspection of fig. 12 reveals the screw heads at the surface of the pole piece cylinder. These screws were moved to the extreme rear part of the cylinder when testing was resumed after the 735-hour inspection.

Figure 18 shows this same insulator before testing and the condition of the insulator and upstream pole piece at the completion of testing. After 1332 hours the upstream pole piece cylinder is showing some erosion as well as the boron nitride.

Figure 19 compares the wear on the boron nitride insulator at approximately the midpoint and at the end of the 1332-hour life test. It can be seen from the dimensional changes that backplate sputtering is approximately linear with time.

An additional test was conducted in which a 2.9-centimeter-diameter cylindrical hole was machined into the surface of a boron nitride insulator at the downstream edge. A slug of molybdenum was placed into this cavity to determine if a refractory inserted into the upstream pole piece (but insulated from it) would endure better than boron nitride. The test was terminated after 72 hours because the sputtered molybdenum coated over much of the exhaust pole piece surface and created many paths that shorted anode to exhaust pole piece. In addition, the molybdenum appeared to be sputtering off much faster than the comparable boron nitride.

## Areas Needing Further Investigation

The data of the 1332-hour life-test point to areas where additional research is needed. The exact location of the cathode needs further study. A look at figures 13, 14, or 15 shows that the molybdenum cathode-protecting bar has very little wear at a position close to (1 to 2 cm) the exhaust end pole piece of the thruster. Perhaps the cathode should be off-axis but positioned a centimeter or two downstream of the exhaust pole piece. This would also eliminate the need for a protecting bar and its associated metallic sputter, a potential spacecraft contaminant.

The cathode tip wear shown in figure 14 indicates that the tip sputters in such a way as to have the plane of the tip parallel to the thruster axis. This hints that the cathode might well be placed on a radial line relative to the thruster axis with no downstream pointing at all.

Data gathered on a modified downstream-cathode MPD thruster (ref. 3) (fig. 20) is also encouraging when examining potential cathode positions. As can be seen from figure 20, this thruster has a new magnetic field pole piece arrangement but uses the cathode protecting bar and the new off-axis downstream-cathode design. This thruster evolved from a separate set of experiments in another facility which were conducted at approximately the midpoint of the 1332-hour life test. Because of the time needed to complete the life test, the performance data on this modified thruster appeared in the literature first. It is felt that this new and modified MPD thruster represents the latest in the "state-of-the-art". It should be also pointed out that the modified thruster cathode was packed more tightly, having nine 0.0125-centimeter-diameter rods inserted into the sleeve in addition to the three 0.101-centimeter-diameter rods. In contrast to the diffuse plume of the 1332-hour life-test thruster, the visible light in the exhaust of this high-performance modified thruster is very well collimated into a solid cylinder with an outside diameter the size of the hole in the exhaust pole piece. Perhaps sputtering of the cathode and/or cathode-protecting bar could be minimized by simply keeping these objects out of, or at the edge of, the collimated part of the exhaust plume.

In general, low-power MPD thruster performance improvements have always been accompanied by lowering the discharge current. For example, the high-performance thruster shown in figure 20 has a lower characteristic discharge current when compared to the thruster used for the 1332-hour life test. Lowering the discharge current potentially improves the cathode life, because less ion bombardment of the cathode tip is required. In general, and verified experimentally, the new off-axis downstream cathode with rods can operate in a stable discharge mode at lower and lower currents as the sleeve is more tightly packed with rods. Hence, additional cathode life and larger rod packing fractions appear interrelated.

The boron nitride insulator shown in figures 12, 18, and 19 sputters far too much to be of use for real missions. Again research into the processes present in the new modified downstream-cathode thruster of figure 20 may aid the endurance problem for the area of future research in that device will probably be at the downstream edge of the upstream pole piece. The data gathered during the tests of reference 3 indicated that an important process occurs within the 0.318-centimeter axial distance downstream of the upstream pole piece, although the process and/or processes were not identified.

Other more obvious changes and investigations can be made to improve thruster and cathode life. The cathode can probably be made longer giving more length to erode away. The rate of thoria depletion in the cathode should be studied. Better shaping of the magnetic field could be another way to eliminate the cathode-protecting bar. Perhaps an auxiliary magnetic field is needed to do this. As additional improvements in thrust performance are made, the endurance problem may also evolve toward a solution. Often the very energy loss mechanism that lowers performance also damages the thruster structure and reduces life.

#### CONCLUDING REMARKS

Data have been presented for a number of cathode tests including a 1332-hour life test of a new downstream-cathode thruster with an off-axis cathode location. Termination of the 1332-hour cathode life test occurred because of a failure in the cathode propellant feed tube near the sleeve used to join cathode to the feed tube. Solving this problem appears to be within the state of refractory metal technology. Other data have been presented which point to new design approaches that could make the downstream-cathode MPD thruster suitable for satellite auxiliary propulsion missions.

Perhaps the greatest potential of the new off-axis downstream-cathode arises from the possibility of clustering many cathodes about the periphery of the MPD exhaust. Many years of life could be achieved by switching in successive cathodes as old ones cease to live.

Lewis Research Center,  
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502-10.

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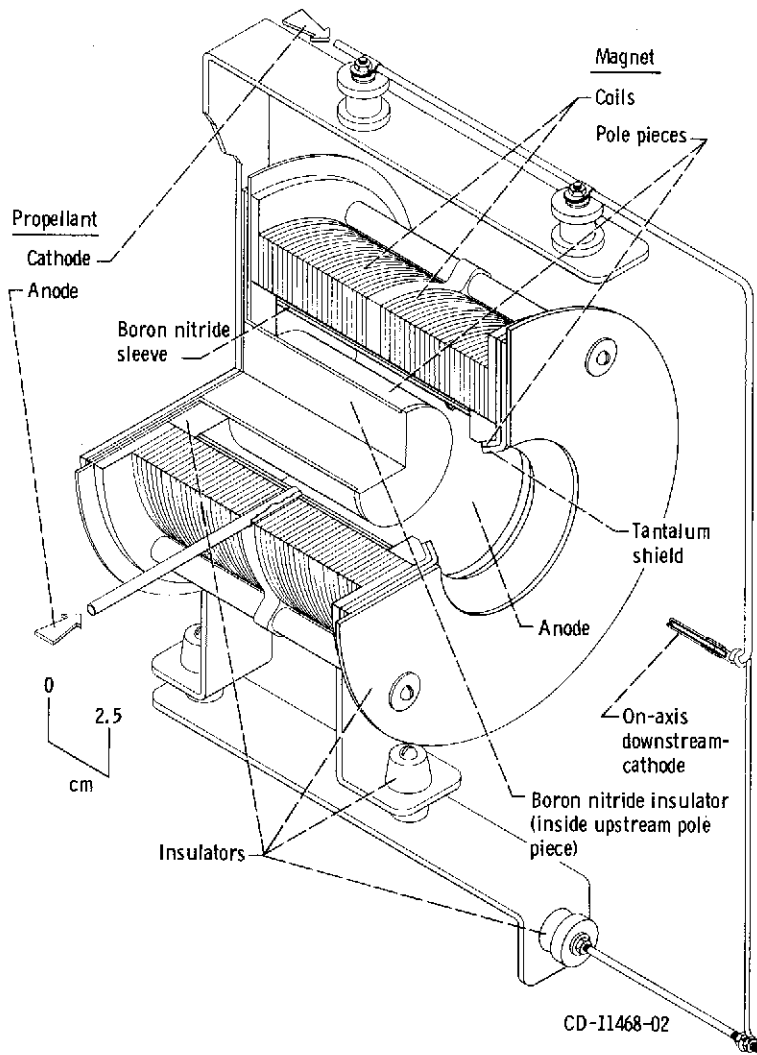


Figure 1. - Baseline MPD thruster. Cathode shown, on-axis downstream cathode (design 1).



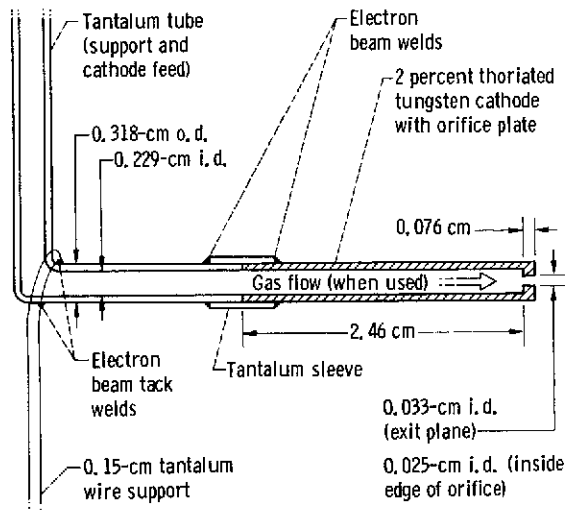


Figure 2. - Cross-sectional schematic of on-axis downstream cathode (design 1).

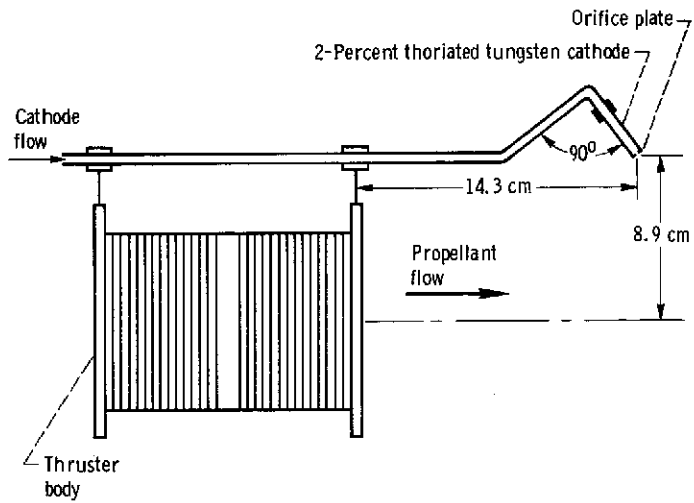


Figure 3. - Baseline MPD thruster with original off-axis downstream cathode (design 2).

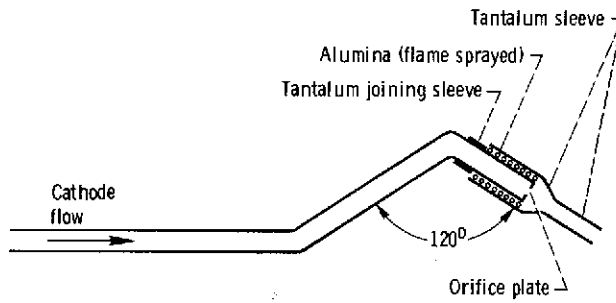


Figure 4. - Cross-sectional view of off-axis downstream cathode with sleeve (design 3).

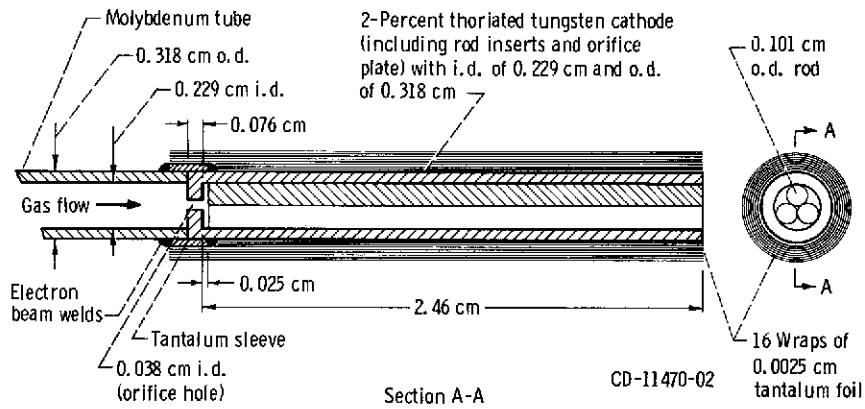


Figure 5. - Cross-sectional view of new off-axis downstream cathode with rods (design 4).

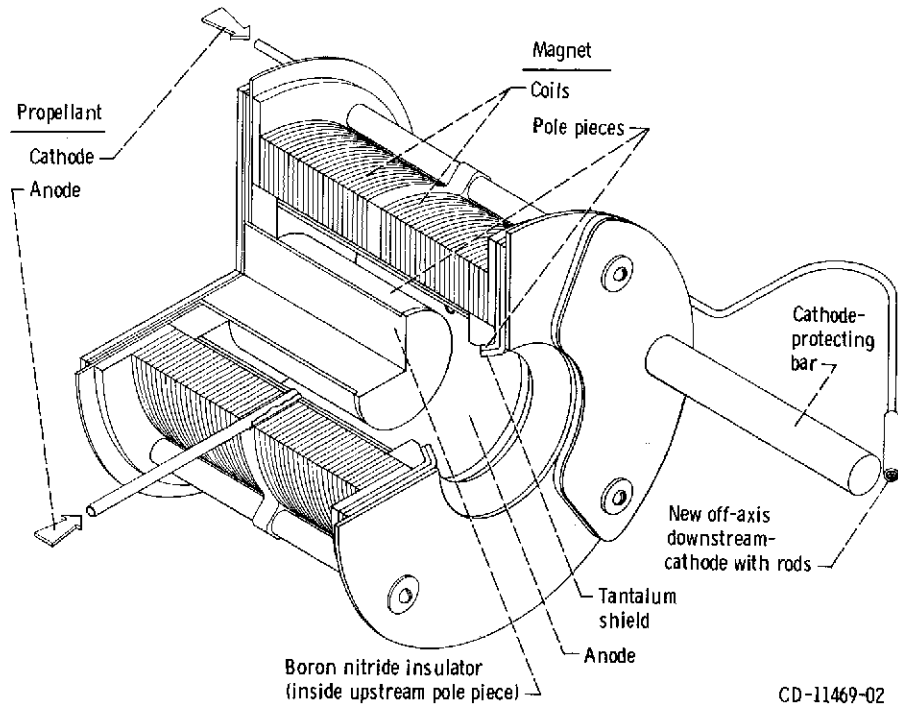


Figure 6. - Baseline MPD thruster incorporating new off-axis downstream cathode with rods (design 4). Thruster life-tested for 1332 hours.

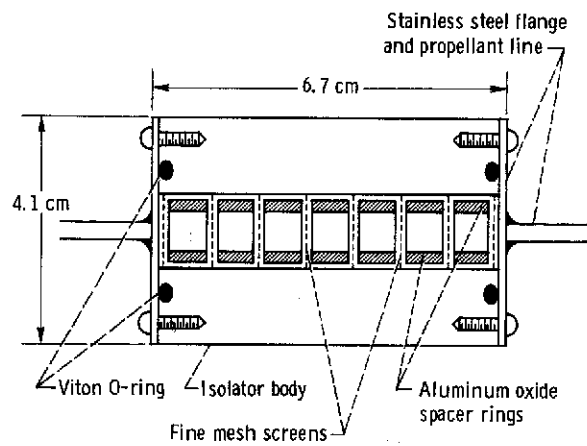


Figure 7. - Isolator cross section. Original isolators employed polycarbonate plastic bodies and final design isolators employed boron nitride bodies.

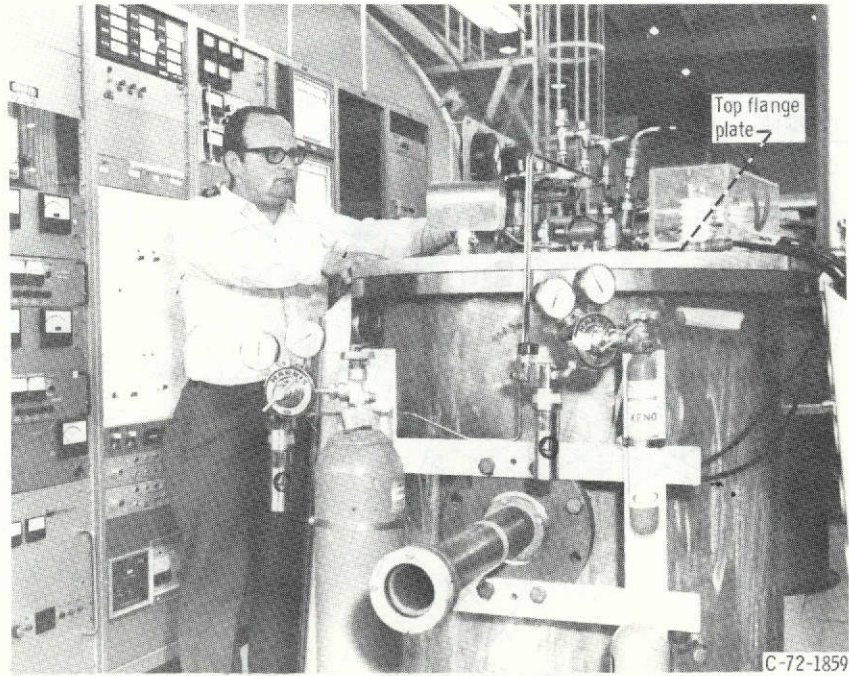


Figure 8. - Super-bell-jar facility.

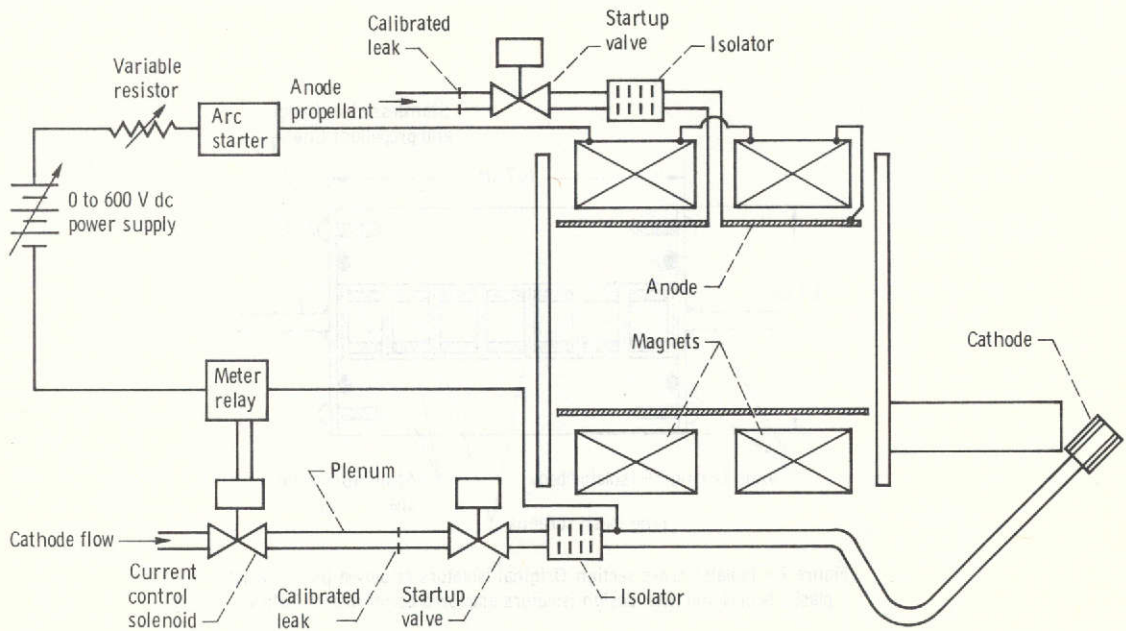


Figure 9. - Thruster circuitry including automatic on-off cathode (discharge) current control.

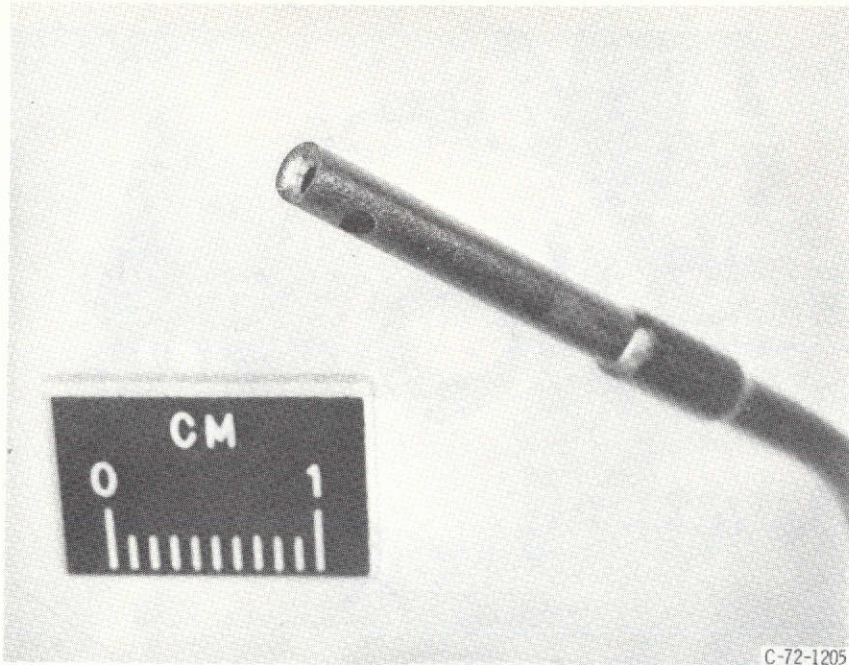


Figure 11. - Condition of original off-axis downstream cathode (design 2) after 80.8 hours of operation.

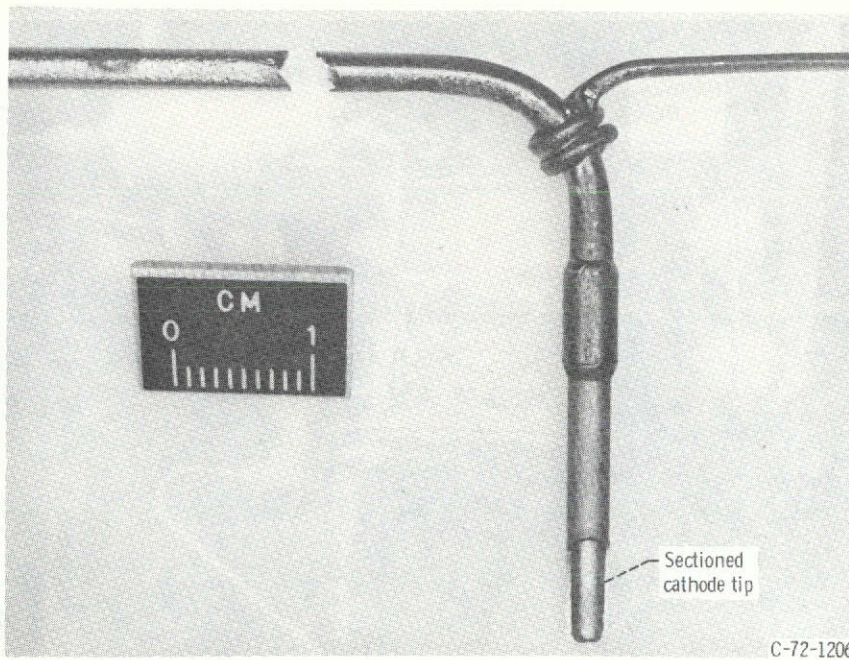


Figure 10. - Condition of on-axis downstream cathode (design 1) after 47.9 hours of operation. Cathode tip has been sectioned.

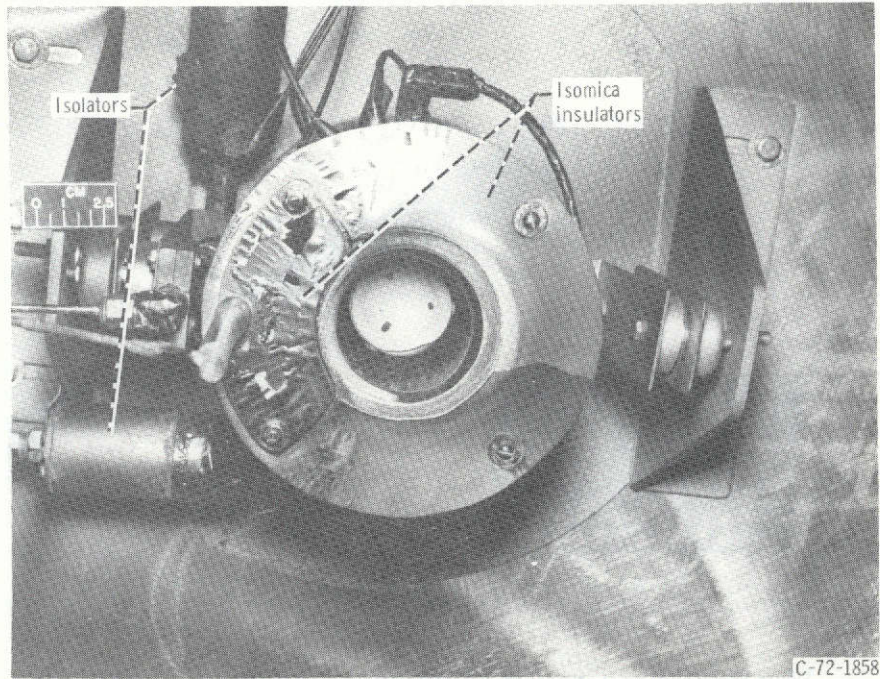


Figure 12. - Life-test thruster after 735 hours of operation.

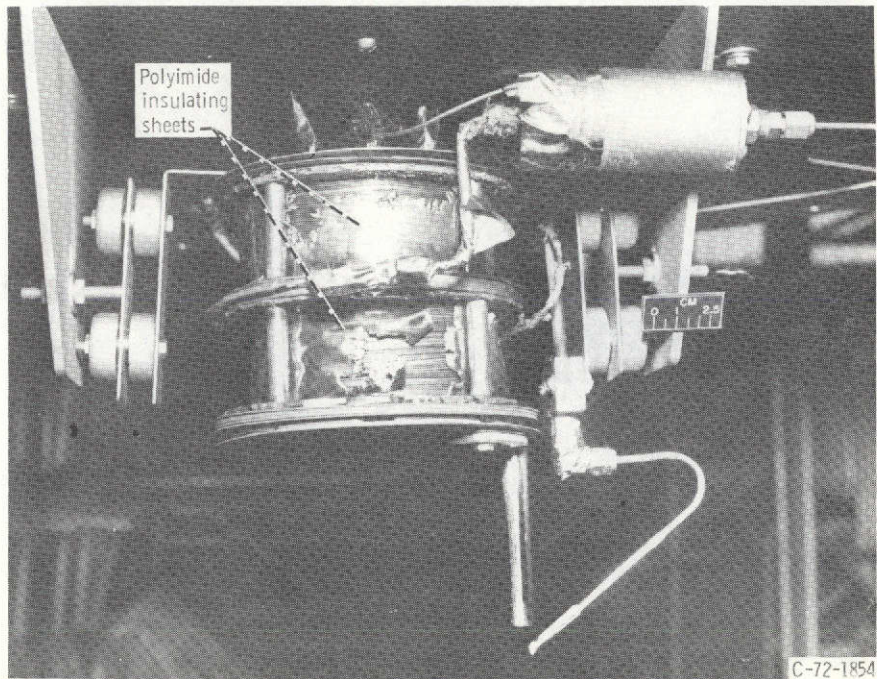
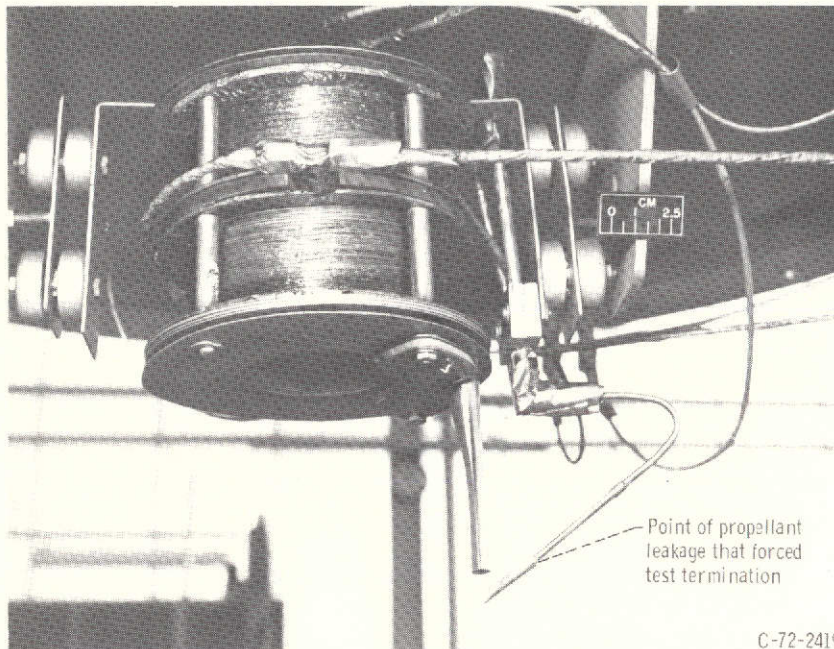


Figure 13. - Side view of life-test thruster after 735 hours of operation.



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Figure 14. - Side view of life-test thruster after 1332 hours of operation.

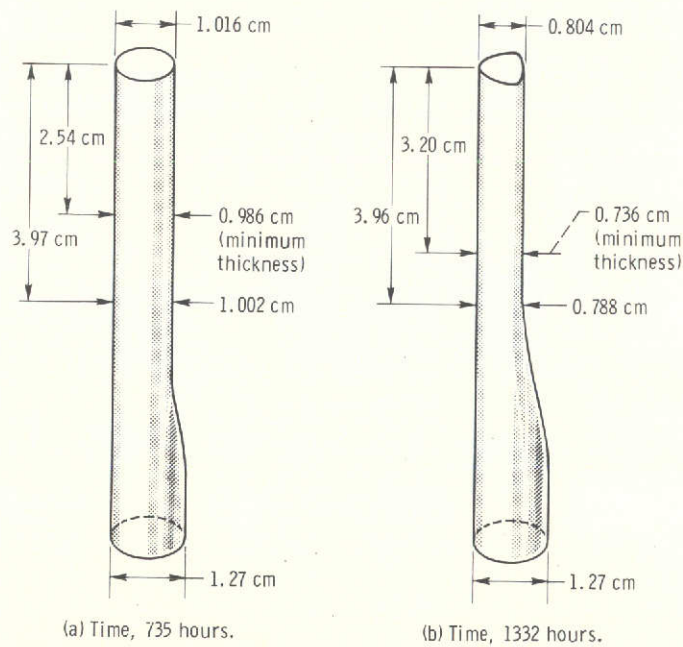
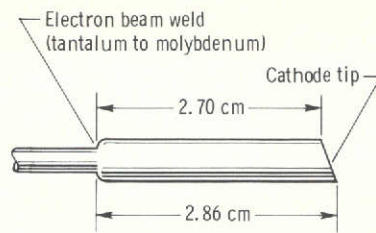
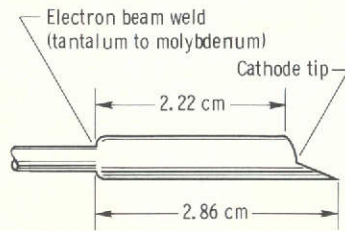


Figure 15. - Comparison of molybdenum cathode-protecting bar dimensions at two different times.



(a) Time, 735 hours.

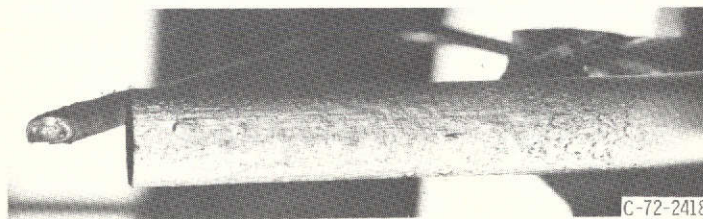


(b) Time, 1332 hours.

Figure 16. - Cathode dimensions at two different life-test times.



(a) Time, 735 hours.



(b) Time, 1332 hours.

Figure 17. - Cathode and molybdenum cathode-protecting bar at the two life-test times indicated.



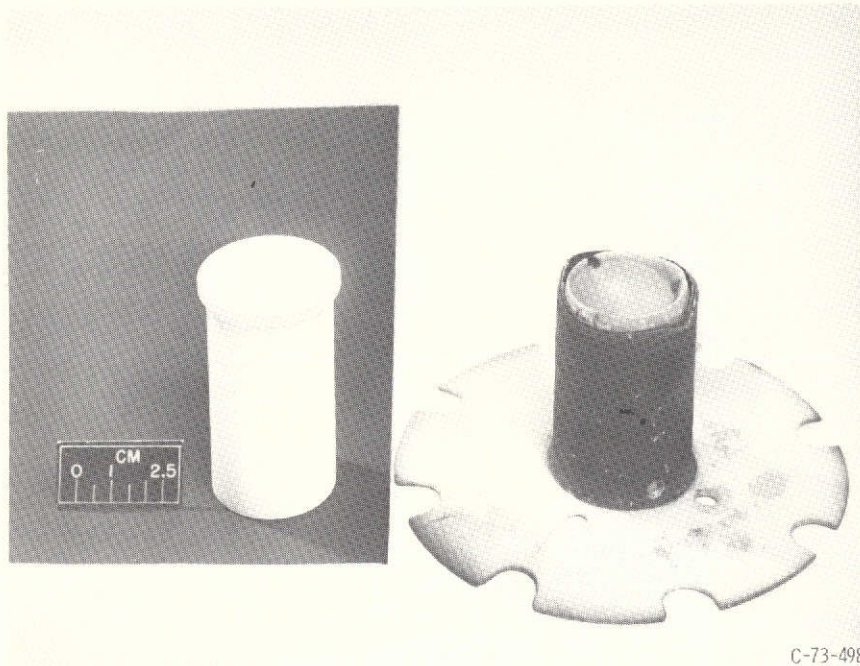


Figure 18. - Boron nitride insulator before life-testing was started, and boron nitride insulator and upstream pole piece after 1332 hours of testing.

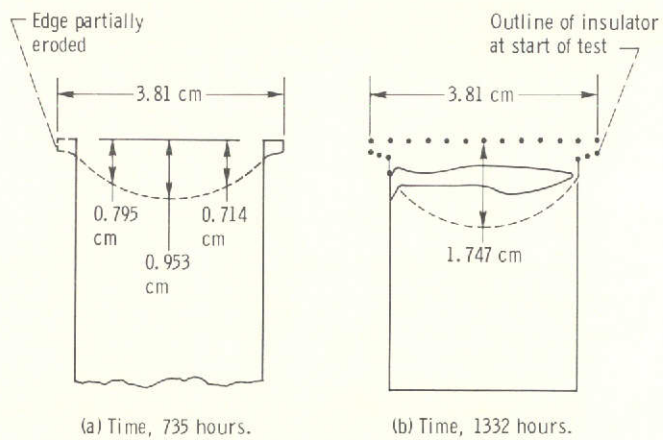


Figure 19. - Cross-sectional sketch of boron nitride insulator used inside upstream pole piece. Sputtering wear shown for two different life-test times.

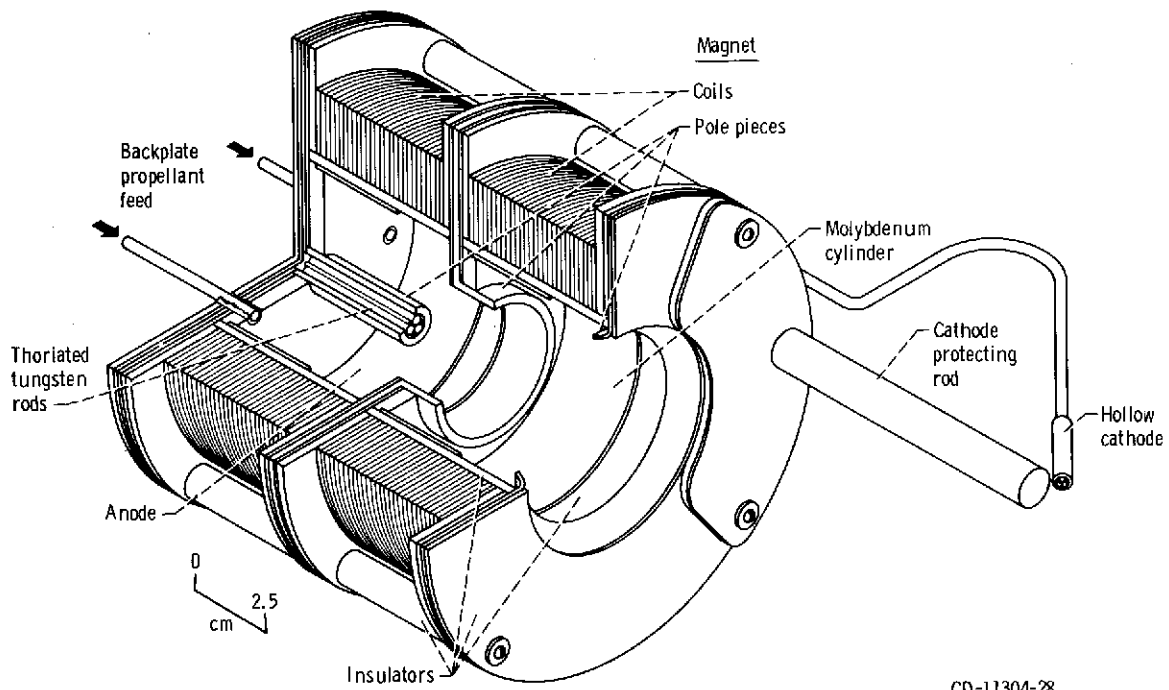


Figure 20. - Modified downstream-cathode MPD thruster using a new off-axis downstream cathode with rods.  
 (See ref. 3 for performance data.)