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A 20,000-HOUR ENDURANCE TEST OF A STRUCTURALLY AND THERMALLY INTEGRATED 5-CM DIAMETER ION THRUSTER MAIN CATHODE

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A 20,000-HOUR ENDURANCE TEST OF A STRUCTURALLY AND THERMALLY INTEGRATED 5-CM DIAMETER ION THRUSTER MAIN CATHODE

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Abstract

A 5-cm diameter mercury ion thruster main cathode has completed over 20,000 hours of operation in an ongoing lifetime endurance test. The cathode operating parameters remained at acceptable performance levels throughout the test, the first 9175 hours of which were part of a thruster endurance test. After 20,000 hours, the cathode discharge was easily restarted, the tip orifice indicated negligible erosion and the tip heater showed no degradation. The cathode-isolator- vaporizer assembly, a major thruster sybsystem, has thus successfully demonstrated an operational lifetime capability of 20,000 hours, which is the lifetime goal of the 8-cm diameter auxiliary propulsion ion thruster.

Introduction

The 8-cm diameter electron bombardment mercury ion thruster presently under development at the Lewis Research Center is designed to perform long term stationkeeping and attitude control of geosynchronous spacecraft. The high specific impulse and low propellant consumption of the ion thruster make it particularly attractive for such missions. Two especially important requirements for auxiliary propulsion thruster systems are reliability and durability. The lifetime goal of the 8-cm ion thruster is an operating time of 20,000 hours.[1,2]

This lifetime capability has been successfully demonstrated by a cathode-isolator-vaporizer (CIV) assembly which has completed 20,225 hours of operation in a cathode endurance test. Further operation of the cathode is intended. The CIV assembly plays a major role in ion thruster startup and operation. Although the CIV used in the cathode endurance test was designed to operate in a 5-cm diameter Structurally Integrated Thruster (SIT-5), the design for the 8-cm diameter ion thruster CIV is basically the same.

The first 9715 hours of operation were as the main cathode in a SIT-5 thruster.[3-5] Subsequent operation was in a vacuum bell jar where, generally, the cathode discharge voltages and currents were similar to those in the thruster. After more than 20,000 hours of operation, the cathode showed little degradation and could be easily restarted.

This paper summarizes the startup and operational history over the first 20,000 hours of cathode operation. Although the operation of the CIV in the thruster has been reported previously,[3-5] results pertinent to cathode startup and operation are repeated here. Cathode performance characteristics in the bell jar after 20,000 hours of operation are presented, together with those obtained during thruster operation. Results of a post 20,000 hour cathode inspection are also given.

Apparatus

CIV Construction

Figure 1 shows a cross-section view of the CIV assembly, which is structurally and thermally integrated. The requirements of structural strength and thermal considerations dictated a close mechanical coupling between the cathode and the vaporizer. The CIV was designed to minimize the overall power requirements while maintaining satisfactory control of the vaporizer temperature.[6,7] A thermal analysis of the CIV assembly is extensively described in Ref. 7. Construction details and performance characteristics of the isolator and porous tungsten vaporizer are given in Ref. 3 through 7.

The cathode had an enclosed keeper and an alkaline-earth oxide-coated rolled foil insert. The cathode body consisted of a 0.32-cm diameter, 2.5-cm long hollow tantalum (Ta) tube with a wall thickness of 0.25 millimeter (mm). The cathode tip consisted of a 1-mm thick, 3.2-mm diameter W-2% Rh disk which was electron beam welded to the Ta tube. The downstream face of the tip was chamfered at a 45° half angle to a depth of 0.75 mm and an outside diameter of 1.78 mm. Specifications called for an orifice diameter and throat length of 0.254 mm.

The cathode tip heater was the coaxial swaged Ta type, consisting of nearly six turns and tightly fit over the cathode body. The center conductor was 0.2-mm diameter Ta wire and the Ta sheath was 1 mm in diameter. The insulator was 99.4% pure MgO. The heater was enclosed by a Ta spacer and radiation shield over which fit the insulator sleeve for the keeper cap.

The 0.254-mm thick Ta keeper cap was positioned such that the cathode face-keeper cap spacing was 1.5 mm. The keeper orifice was 2.5 mm in diameter. A swaged metal-to-ceramic joint connected the keeper cap to the insulating sleeve.

The dimensions of the Ta foil insert are given in Fig. 2 which shows an unrolled view. A small rectangular section 2.21 cm by 0.30 cm was cut from one corner so that when the foil was rolled and inserted in the cathode a cavity was formed immediately upstream to the tip orifice. The Ta foil was dipped in a triple alkaline-earth carbonate mixture. The percentages of carbonates by weight were 59.2% barium, 38.8% strontium, and 4.0% calcium. The coating thickness was about 750 microns. The insert was connected electrically to the cathode body by a 1-mm diameter Ta wire spot welded at both ends.

Electrical Systems

Figure 3 shows a schematic diagram of the SIT-5 electrical power system, full details of which are given in Ref. 3. The heater supplies were variable voltage a.c. filament transformers. The cathode keeper (34 v, 0.5 amp) and main discharge (100 v, 0.75 amp) supplies were regulated d.c. supplies with constant voltage-constant current control characteristics and automatic crossover. A separate ignitor supply (500 v, 100 ma) in parallel with the keeper supply was used for starting the cathode discharge. Blocking diodes prevented power feedback from the ignitor supply into the cathode keeper supply. Data was obtained either from digital readouts accurate to ±1% or from panel meters accurate to ±3%.

A diagram of the electrical power system for cathode operation in the bell jar is shown in Fig. 4. A collector diode arrangement was used to simulate the thruster arc discharge (ΔV_I and J_I in Fig. 2). The collector anode consisted of a solid 3.5-cm diameter Ta disk mounted 2.5 cm from the keeper face.

The heater supplies were variable voltage a.c. filament transformers. The keeper (36 v, 1.5 amp) and collector (60 v, 0.5 amp) supplies were voltage regulated d.c. supplies with current limiting capability. Discharge voltages and currents were read from panel meters accurate to ±2% for the keeper and to ±3% for the collector.

Figure 4 also shows the cathode starting configuration. An ignitor supply (1000 v, 0.1 amp) in parallel with the keeper supply was available for conventional starting. For high voltage pulse starting, the pulser was placed in parallel and a blocking diode in series with the keeper supply. The high voltage pulse was obtained by means of a capacitor discharge across the primary of a step-up transformer. A d.c. keeper voltage (sustaining keeper voltage) was applied simultaneously to sustain the discharge once breakdown occurred. The circuitry and technique are described in Refs. 8 and 9. The maximum pulse amplitude was approximately 7 KV with a 10 KV blocking diode, which was removed from the circuit during cathode operation.

Vacuum Facilities

The SIT-5 thruster, shown in Fig. 5, was tested in a vertical vacuum chamber 1.37 m in diameter and 1.83 m long. With liquid nitrogen cooled walls and the frozen mercury ion beam target, the tank pressure during thruster operation was nominally 1×10^{-6} torr. Additional details are given in Ref. 3.

The vacuum bell jar, 46 cm in diameter, was divided in half by a liquid nitrogen cooled baffle. The CIV was tested on one side of the baffle while another cathode was simultaneously undergoing an endurance test on the other side. Figure 6 shows the CIV mounted in the bell jar without the collector anode. With both cathodes operating, the bell jar pressure was generally in the low-to-middle 10^{-6} torr range.

Test Procedure

CIV Operation in Thruster

The CIV operation in the thruster was part of a broader SIT-5 endurance test, one of whose aims was to define potential thruster problems which might arise only after many hours of operation. Figure 7 shows a section view drawing of the SIT-5 thruster and the position of the CIV assembly relative to the discharge chamber. The entire propellant flow to the discharge chamber was through the main cathode. For the thruster endurance test, the propellant reservoir and Hg feed system shown in Fig. 6 were replaced by separate reservoirs and precision bore glass capillary tubes for each the main cathode and neutralizer. This arrangement enabled measurement of Hg flow rates during thruster operation.

The thruster operating values relevant to the CIV performance are presented in Table I. For the first 2027 hours the thruster was operated with a translating thrust vector screen grid and the final 7688 hours with an electrostatic type vector grid.[4,5] The discharge power was higher with the electrostatic grid because of the lower screen grid transparency (28.8% as compared with 45.6% for the translating grid). The isolator was not actively used in the electrostatic grid test because the net accelerating potential of 1300 v exceeded the isolator design voltage of 1000 v.

For evaluation and vaporizer calibration purposes, the cathode keeper discharge operated for 142 hours prior to the beginning of the thruster endurance test (not included in the total cathode operating time of 20,225 hours). During the initial evaluation test, the keeper voltages and currents were 19 - 20 v and 0.25 - 0.33 amp, respectively, and the vaporizer heater power was 6.5 w. Tip heat was not required to sustain the discharge. No special cathode conditioning preceded the initial startup of the main cathode. A convential cathode starting procedure[10] was used. The cathode was preheated with a tip heater power (P_{CH}) of 20 w and a keeper voltage (V_{CK}) of 500 v was applied. The mercury flow ($\dot{m}$) was then increased until adequate for ignition of the keeper discharge. The main cathode was restarted twice more during the 142 hour initial evaluation period.

A number of neutralizer outages and grid shorts during the thruster endurance test resulted in a partial shutdown of thruster operation. The main cathode keeper discharge was maintained in those instances to facilitate restarting the thruster. Except for a few facility problems (no loss of vacuum) and the changing of the vector grids, which necessitated total thruster shutdown, the CIV operation was essentially without interuption. The brief periods of partial thruster shutdown where only the keeper discharge was operating were also not counted in the total operating time.

CIV Operation in Bell Jar

Sputtering effects and anomalous grid erosion caused the termination of the thruster endurance test. The CIV assembly was transferred to the vacuum bell jar for further cathode lifetime endurance testing. The intent was to operate the cathode discharges at levels comparable to those in the SIT-5 thruster endurance test. As mentioned previously, a collector diode configuration was used in the bell jar to simulate the cathode-anode discharge in the thruster. As in the thruster, mercury flow rates were measured with a precision-bore glass capillary tube.

Results and Discussion

Cathode Starting

Table II presents a summary of the cathode starting conditions for the 41 starts recorded during the 20,225 hours of operation. Not included are the initial cathode startup and the two subsequent starts which occurred during the 142 hour cathode prehistory.

No difficulty was encountered in starting the main cathode during the 9715 hour thruster endurance test, including the time the cathode was exposed to air when the thruster was removed from the vacuum facility to change the vector grids. The cathode was started conventionally nine times in the thruster under essentially identical conditions, namely, $P_{CH} = 20$ w, $V_{CK} = 500$ v and $\dot{m} \sim 70$ ma equivalent Hg^+ flow.

The operation of the cathode in the bell jar is in general divided into two periods: (1) from 9,715 to 10,362 hours when conventional starting was used and (2) from 10,362 to 20,225 hours when a high voltage pulse ignited the discharge.

In the first period (647 hours duration), numerous facility problems occurred and resulted in sporadic operation of the cathode. Starting the cathode was more difficult than in the thruster, generally requiring more P_{CH} (up to 25 w), higher $\dot{m}$ (>70 ma) and a higher V_{CK} (1000 v). The preheat time sometimes exceeded several hours. An upper limit of 25 w tip heater power for all starting was chosen to avoid the risk of shortening cathode life by either possibly damaging the tip heater or overheating the cathode and thereby degrading the insert.[11]

There were seven conventional starts in this period, the starting conditions being those shown in Table II. A tip heater power of 24 w, an ignitor voltage of 1000 v and a Hg flow of at least 70 ma were used in the first bell jar start. At 10,200 hours, attempts to start the cathode at $P_{CH} = 25$ w, $V_{CK} = 1000$v and $\dot{m} > 70$ ma were unsuccessful. With the same P_{CH} and $\dot{m}$ and a sustaining keeper voltage of 300 v, a high voltage pulse then successfully ignited the discharge. Without changing P_{CH}, the cathode was readily restarted with a 1000 v d.c. ignitor voltages. At 20 - 25 w tip heater power, leakage current through the ceramic supporting the keeper cap reduced the actual keeper - cathode voltage drop to around 800 v. The cathode was conventionally started two more times at 10,224 and 10,338 hours.

After 10,362 hours of operation the cathode again would not start conventionally. The high voltage pulse method then became the primary means of cathode starting and was applied 23 times during the last 9,863 hours of operation. The cathode was deliberately shutdown four times during this period to test restart capability. The other shutdowns resulted from vacuum facility shutdowns (8), power interuptions (7), power supply failures (2) and one unknown cause. During the shutdowns the cathode was not exposed to pressures greater than 1×10^{-4} torr while in a heated condition.

Table II shows the pulse starting conditions. For all except three starts, the sustaining keeper voltage was 35 - 37 v and the equivalent Hg^+ flow was 50 - 55 ma. P_{CH} ranged from 13.3 to 20.7 w. The sustaining keeper voltage includes the 9 v drop across the blocking diode. One of the three exceptions was the first pulse start at 10,362 hours where $\dot{m} \sim 70$ ma. The other two exceptions were at 11,194 and 12,592 hours when the cathode was deliberately shutdown to test the effect of a higher sustaining keeper voltage, 300 v, on tip heater power requirements. At 11,194 hours, the required P_{CH} was 14.4 w. At 12,592 hours, a collector voltage of 100 v was also applied and the required P_{CH} was 13.3 w. Otherwise a sustaining keeper voltage of 35 - 37 v required a P_{CH} of 16 w or more. Generally P_{CH} was set initially at 16.0 - 17.5 w and occasionally increased slightly to 18.0 - 18.5 w as required.

Table III summarizes the five times when a P_{CH} greater than 20 w was applied, only three of which actually required higher tip heat. On these occasions the cathode had been previously exposed to air or bell jar pressures in the millitorr range. The other two times, at 11,174 and 13,096 hours, correspond to unsuccessful attempts to first start the cathode conventionally. At 13,096 hours the discharge was shut off and the cathode subsequently restarted with a d.c. ignitor voltage of 1000 v.

Breakdown voltages ranged from 1 - 1.5 to 6 - 7 KV for the first start, dropping to as low as 600 v for subsequent starts. Breakdown voltages were not measured for each start. The correlation between tip heater power and breakdown voltage was not investigated during this test.

Generally the discharge required fewer than five pulses to ignite and often ignited with the first pulse. The many hours of cathode preheat which were sometimes needed for conventional starting during the first 647 hours of bell jar operation were not required for pulse starting.

After a total of 20,221 hours of operation, the cathode restarted easily with a single pulse. The breakdown voltage was less than 2 KV, $P_{CH} = 16.8$ w, $V_{CK} = 35$ v and $\dot{m} \sim 50 - 55$ ma. At the same time, the minimum sustaining keeper voltage was measured to be 22.5 v. With the 9 v drop of the 10 KV blocking diode, the minimum applied sustaining keeper voltage was around 32 v. With a 4 KV diode and a drop of 2.5 v, the minimum applied voltage was 25 v.

Cathode Operation

Table IV presents a summary of the cathode operating parameters for the 20,225 hours of operation in the thruster and the bell jar. As shown in Table IV two different main cathode discharge conditions occurred during the thruster endurance test. The reason for this was the open area differences of the two thrust vector screen grid types. During the first 2027 hours with the translating screen grid (45.6% open area), the discharge voltage and current were 37 v and 0.26 amp. For the next 7688 hours with the electrostatic grid (28.8% open area), the discharge voltage and current were 38 - 40 v and 0.35 - 0.4 amp. The mercury flow rate remained the same at 32 - 34 ma. In the first 377 hours of thruster operation, 4 w of tip heater power was applied to the main cathode, resulting in a slightly lower keeper voltage for this period. For the remaining hours of thruster operation no tip heater power was applied.

Figures 8, 9 and 10 are performance maps of the main cathode characteristics at five different times during the 9715 hour thruster endurance test. Inspection of these plots shows the prominent differences to correspond to the two thrust vector screen grid types. These plots appear in Refs. 3-5 where they are discussed in more detail. They are presented here as a part of the operational history of the cathode.

The collector voltage, V_C, and current, J_C, in the bell jar were chosen to approximate the main discharge voltage and current for the electrostatic grid. V_C and J_C were insistently maintained in the ranges 36 - 40 v and 0.35 - 0.39 amp throughout the duration of the bell jar test. The keeper discharge conditions were less consistent. The keeper current, J_K, was set at a value which roughly minimized V_C.

Bell jar operation required a higher Hg flow rate than in the thruster to maintain V_C at or below 40 v. Some tip heater power was required for stable cathode operation in the bell jar.

During the first 647 hours of bell jar operation, $\dot{m}$ was 40 - 45 ma. Up to 9 w of tip heater power and a keeper current of 0.3 - 0.4 amp were required to produce the desired collector discharge conditions. Over the next 3408 hours $\dot{m}$ was increased to 45 - 50 ma and P_{CH} was reduced to below 3 w. The keeper current was 0.36 - 0.4 amp during this period. For the next 4577 hours, the operating conditions were relatively uniform. The flow was around 50 ma, the keeper current was 0.30 - 0.32 amp and the tip heater power was 2.6 w. During the final 5286 hours the flow was 50 - 55 ma, the keeper current was 0.23 - 0.29 amp and the tip heater power was 2.7 - 3.0 w. There was a discernible trend toward a higher keeper operating voltage in this final period, being 15.5 v at 14,939 hours and increasing to around 18 v at 20,225 hours, indicating possible degradation of the insert, as has been observed in other cathode endurance tests.[11-12] Over the entire lifetime test, as Table IV shows, the trend was almost consistently toward higher ranges of keeper voltage.

Figures 11 and 12 are performance maps at 50 and 55 ma equivalent Hg^+ flow of the cathode operating characteristics in the bell jar after 20,100 hours total operation. Figure 11(b) is a plot of V_C versus J_{CK} at a constant J_C = 0.37 amp. A relative minimum in V_C occurred at J_{CK} = 0.25 amp for $\dot{m}$ = 55 ma and at J_{CK} = 0.30 amp for lower $\dot{m}$ = 50 ma. As shown in Table IV, the V_C and J_{CK} for the periods of operation at 50 and 50 - 55 ma flow roughly agree with the relative minima in this plot.

Other than to note that they are dissimilar, a comparison between the performance maps in the thruster and those in the bell jar is not meaningful due to the differences in operating conditions, plasma environment and geometry.

Post-Endurance Test Cathode Inspection

Figures 13 and 14 are close-up photographs of the main cathode tip taken after 2000 and 9715 hours, respectively, of thruster operation. As can be observed in the photographs and revealed by visual inspection at the time, no significant erosion of the tip occurred. Figure 15 shows photomicrographs at high and low magnification of the cathode tip taken after 20,225 hours of operation. Microscopic examination showed the downstream edge of the chamfer to be only slightly eroded. Sputtering did occur near the upstream end of the chamfer. Figure 16 is a series of photomicrographs at various magnifications which show the condition of the chamfer in the vicinity of the orifice. The irregular surface suggests both sputtering erosion and possible deposition.

The orifice at the downstream end of the throat was measured at 0.275 mm. The minimum throat diameter was between 0.24 and 0.25 mm. No measurements of orifice size were made prior to cathode operation but specifications called for a throat diameter of 0.254 mm.

Photomicrographs of the inside and outside of the keeper cap are shown in Fig. 17. The inside of the keeper cap showed traces of spalled material around the orifice, probably sputtered from the cathode tip. The outside of the keeper cap showed negligible erosion.

After 20,225 hours of cathode operation the measured room temperature resistance of the swaged tip heater was 0.33 to 0.34 Ω, which was within the original specification of 0.31 Ω ±10%. The room temperature resistance of the isolator measured to be greater than 300 MΩ. Further operation of the cathode is intended, which precluded a measurement of the throat length or inspection of the insert. Gamma and X-ray photographs indicated no irregularities.

Conclusions

The cathode in a SIT-5 CIV assembly has successfully completed more than 20,000 hours of endurance testing. This is the lifetime goal of the 8-cm diameter auxiliary propulsion ion thruster which has a similarly constructed CIV. The cathode was a 3.2 mm diameter enclosed keeper type with a rolled foil insert.

After 20,000 hours, no significant erosion of the cathode tip was observed and the cathode was readily restarted with a high voltage pulse of under 2 KV. Although keeper voltage and Hg flow requirements increased during the test, the increases were not sufficient to impair the performance of the cathode.

After transfer to the bell jar, the cathode eventually could not be restarted conventionally within the constraint of 25 w maximum tip heater power. This degradation in starting capability, however, occurred after a number of facility problems and several exposures of the cathode to air. It was demonstrated that a high voltage pulse technique can be effectively applied to restarting the cathode where the conventional method becomes inadequate and thereby directly extend cathode life and cycling capability. The high voltage pulse method enabled cathode starting at lower tip temperatures and flow rates than required in conventional starting.

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Table I Thruster operating values.

	Translating grid (0-2027 hrs)	Electrostatic grid (2027-9715 hrs)
Thrust, mlb	0.36	0.41
Beam Current, ma	25	25
Net accelerating potential, v	1000	1300
Discharge power, w	9.6 - 10.4	13.3 - 16.0
Main propellant flow rate, ma	32 - 34	32 - 34
Isolator leakage current, μa	0.1	-----

Table II Summary of cathode starting conditions.

Type of start	Hours	Numbers of starts	P_{CK} (w)	V_{CK}* (v)	$\dot{m}$ (ma)	Location
Conventional	0 - 9715	9	20	500	~70	Thruster
	9715 - 10,362	7	24 - 25	1000	≥70	Bell jar
Pulse	10,200	1	25	300	>70	"
	10,362	1	18.9	36	>50	"
	11,174	1	20.3	37	50 - 55	"
	11,194	1	14.4	300	"	"
	11,515	1	20.3	36	"	"
	12,592	1	13.3	300**	"	"
	13,096 - 20,221	19	16.0 - 20.7	35 - 37	"	"

*For pulse starts, V_{CK} is the sustaining keeper voltage and includes a 9 v drop across the blocking diode.
**100 v was simultaneously applied to the collector.

Table III High voltage pulse starts where tip heater power greater than 20 w applied.

Hours	P_{CH} (w)	Remarks
11,174, 13,096	20.3, 20.7	After unsuccessful attempts to first start cathode conventionally
11,515, 14,605	20.3	After diffusion pump failure - bell jar pressure in millitorr range
13,270	20.2	After cathode exposed to air when Hg cleaned from bell jar

Table IV Summary of cathode operating conditions for 20,225 hour endurance test.

Location	Thruster			Bell Jar			
Period of operation	Translating screen grid		Electro-static				
	0-377	377-2077	2027-9715	9715-10,362	10,362-13,770	13,770-14,939	14,939-20,225
Hours in period	377	1650	7688	647	3408	4577	5286
Discharge (collector) voltage (v)	37	37	38-40	36-40	36-40	37-39	37-40
Discharge (collector) current (a)	0.26	0.26	0.35-0.4	0.35-0.38	0.35-0.39	0.37	0.37
Keeper voltage (v)	10-11	11-16	12-15	15-18	14.5-16.5	15.5-16.5	15.5-18.0
Keeper current (a)	0.24-0.26	0.28-0.32	0.25-0.30	0.30-0.40	0.36-0.40	0.30-0.32	0.23-0.29
Tip Heater power (w)	4	0	0	3-9	2.3-2.6	2.6	2.7-3.0
Vaporizer power (w)	6.0	5.6	5.5-5.8	5.4	5.4-6.4	6.6	6.6-7.7
Hg flow rate	32-34	32-34	32-34	40-45	45-50	50	50-55

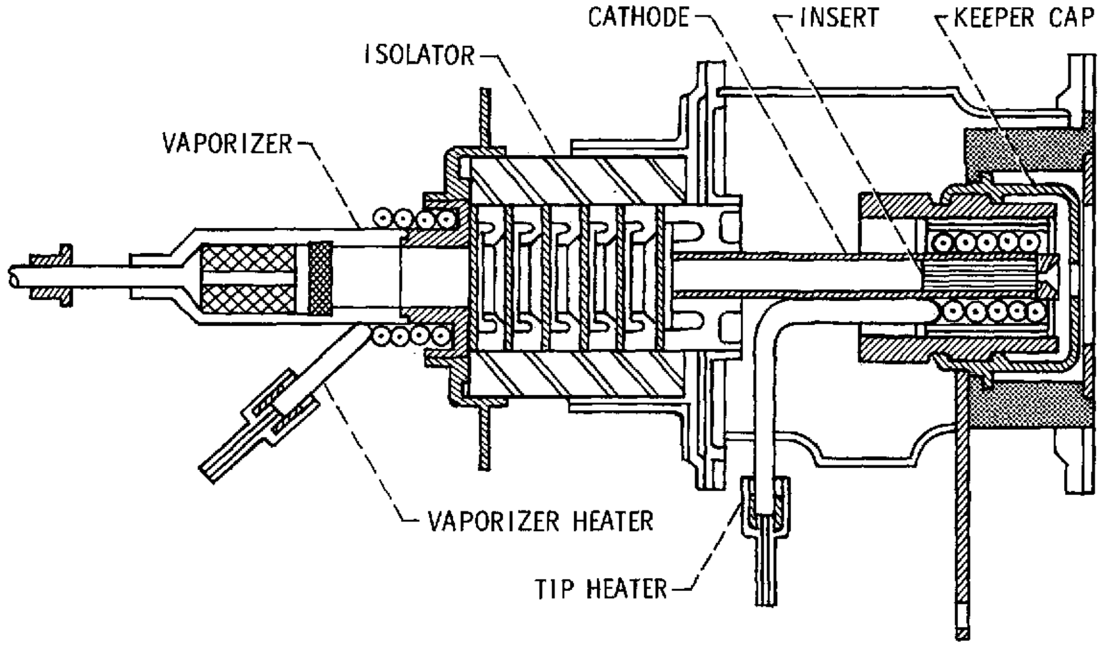


Figure 1. - Cross section view of SIT-5 CIV assembly.

E-8244

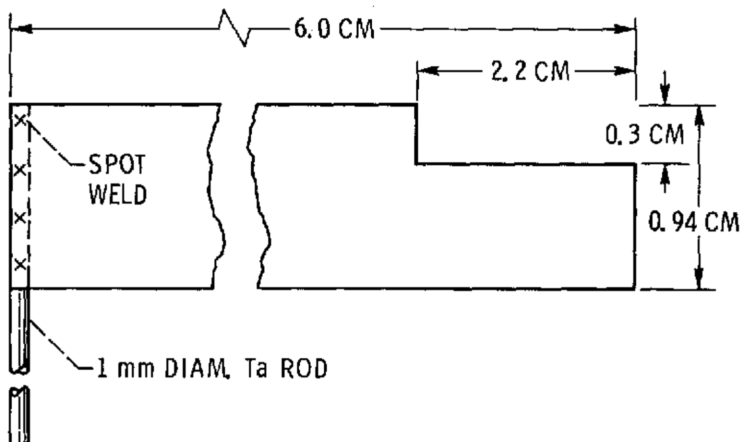


Figure 2. - Unrolled view of 0.0127 mm Ta foil insert.

MAIN CATHODE

- V_{CV} - VAPORIZER VOLTAGE
- J_{CV} - VAPORIZER CURRENT
- V_{CH} - TIP HEATER VOLTAGE
- J_{CH} - TIP HEATER CURRENT
- V_{CK} - KEEPER VOLTAGE
- J_{CK} - KEEPER CURRENT

NEUTRALIZER

- V_{NY} - VAPORIZER VOLTAGE
- J_{NY} - VAPORIZER CURRENT
- V_{NH} - TIP HEATER VOLTAGE
- J_{NH} - TIP HEATER CURRENT
- V_{NK} - KEEPER VOLTAGE
- J_{NK} - KEEPER CURRENT

ENGINE

- ΔV_I - DISCHARGE VOLTAGE
- J_I - DISCHARGE CURRENT
- V_I - NET ACCELERATING POTENTIAL
- V_A - ACCELERATOR POTENTIAL
- J_B - BEAM CURRENT
- J_A - ACCELERATOR DRAIN CURRENT
- J_L - ISOLATOR LEAKAGE CURRENT
- V_G - THRUSTER FLOATING POTENTIAL

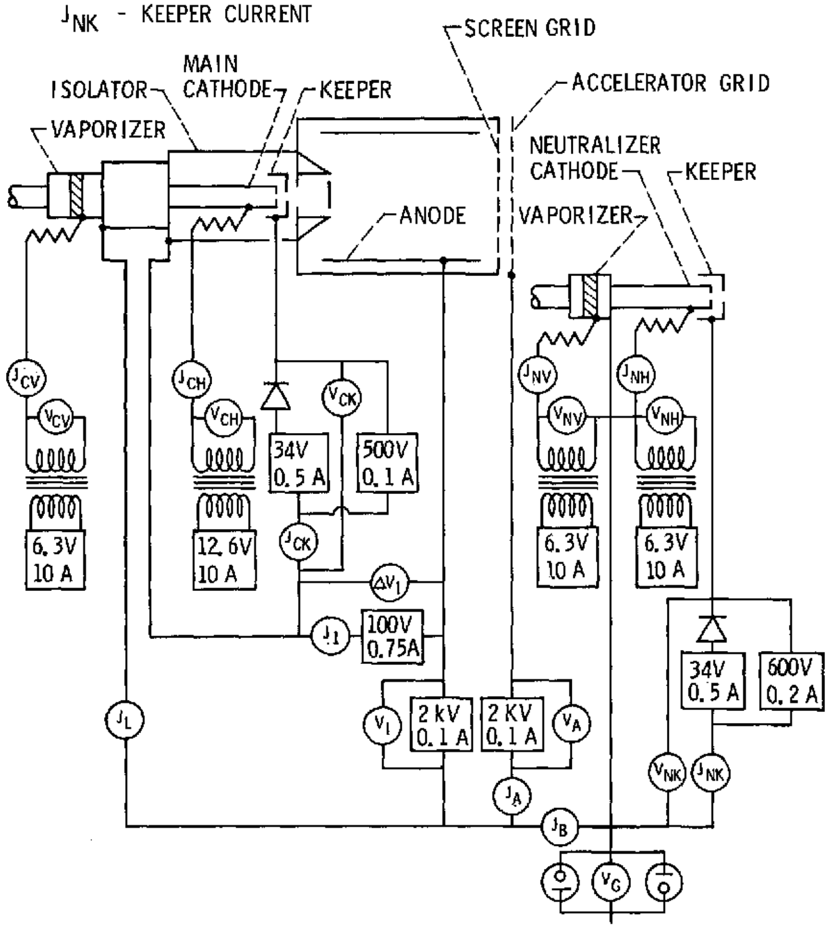


Figure 3. - Schematic diagram of SIT-5 electrical power system.

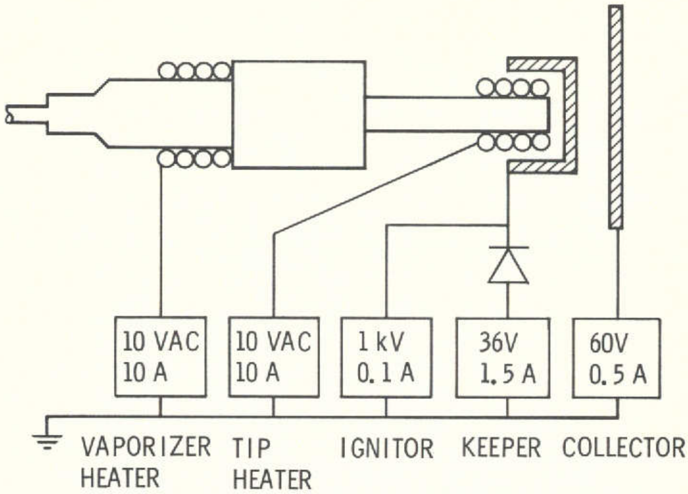


Figure 4. - Diagram of bell jar power supplies showing cathode starting configuration. (High voltage pulse supply replaces d.c. ignitor for pulse starting.)

E-8244

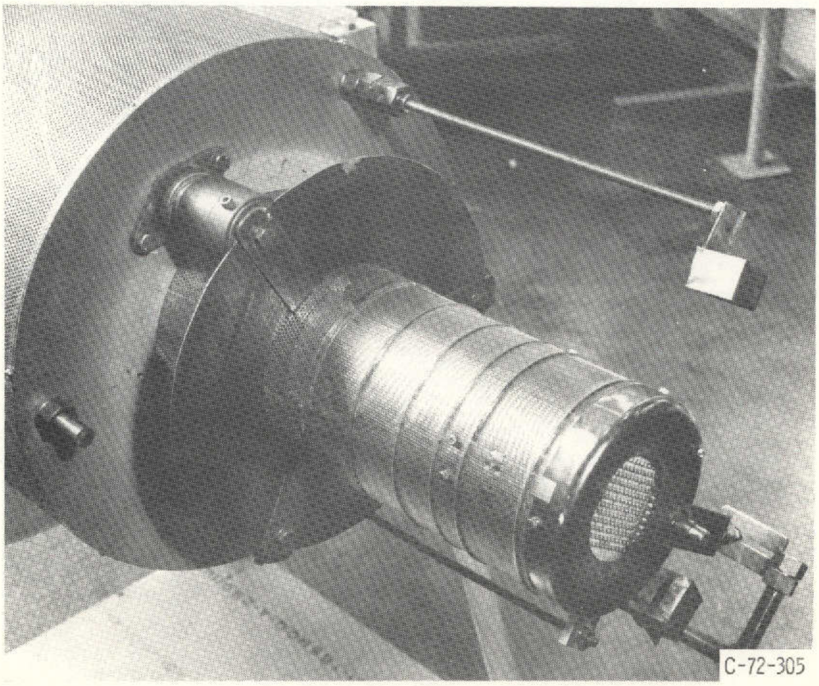


Figure 5. - Test installation of SIT-5 thruster.

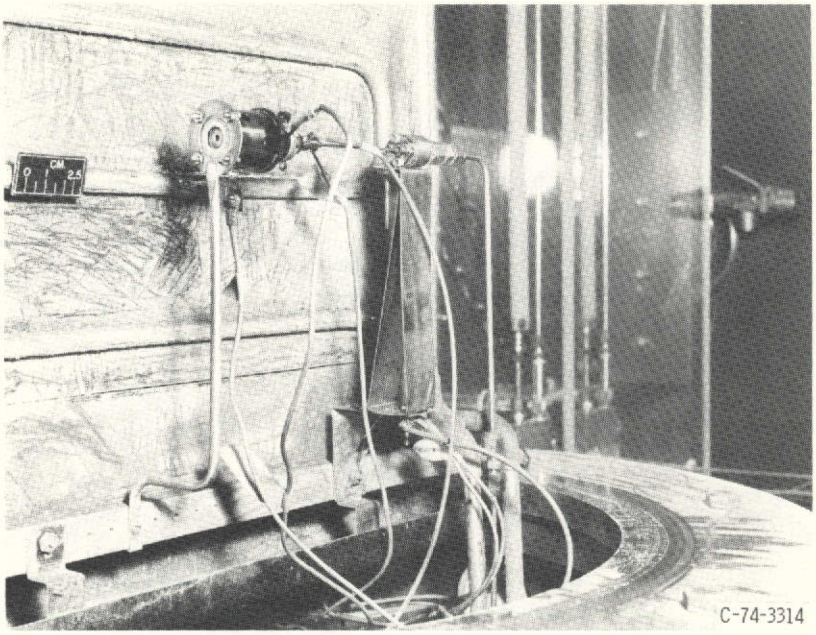


Figure 6. - CIV mounted in bell jar (collector anode not shown).

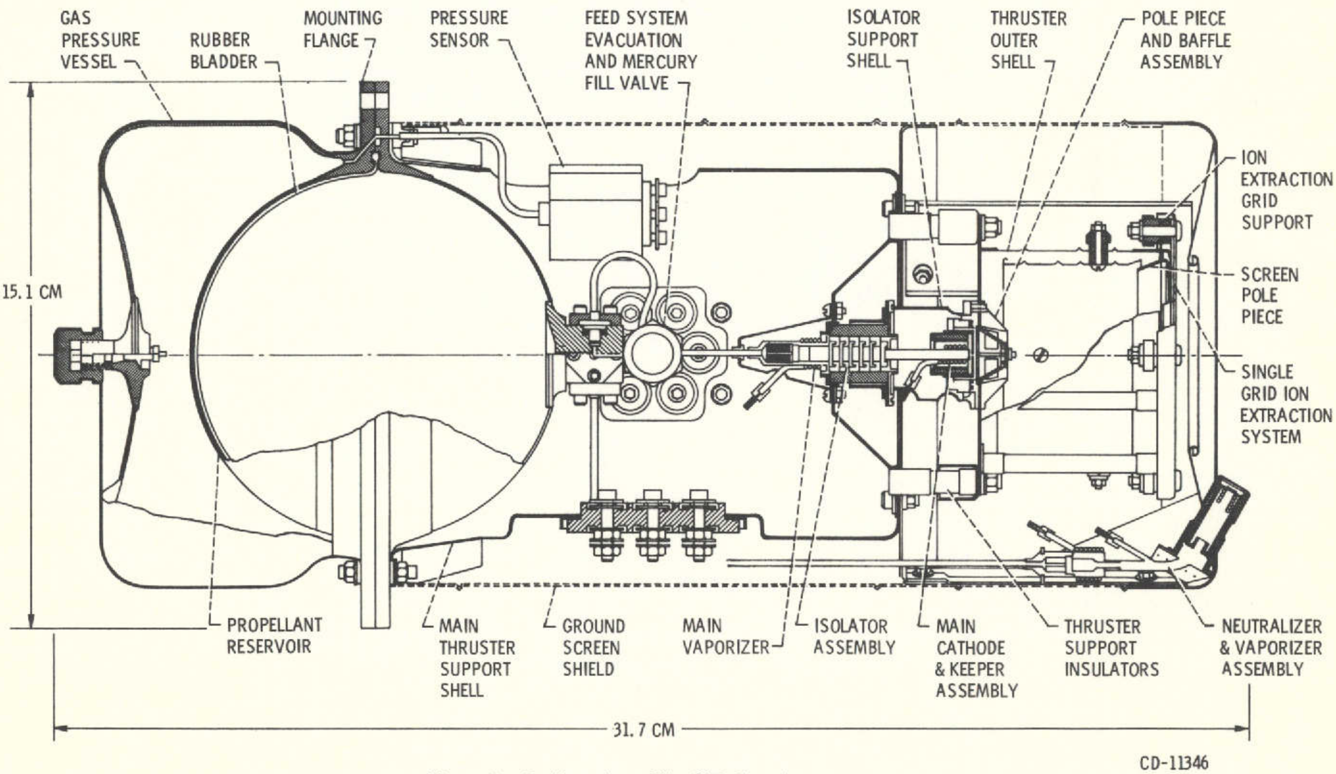


Figure 7. - Section view of the SIT–5 system.

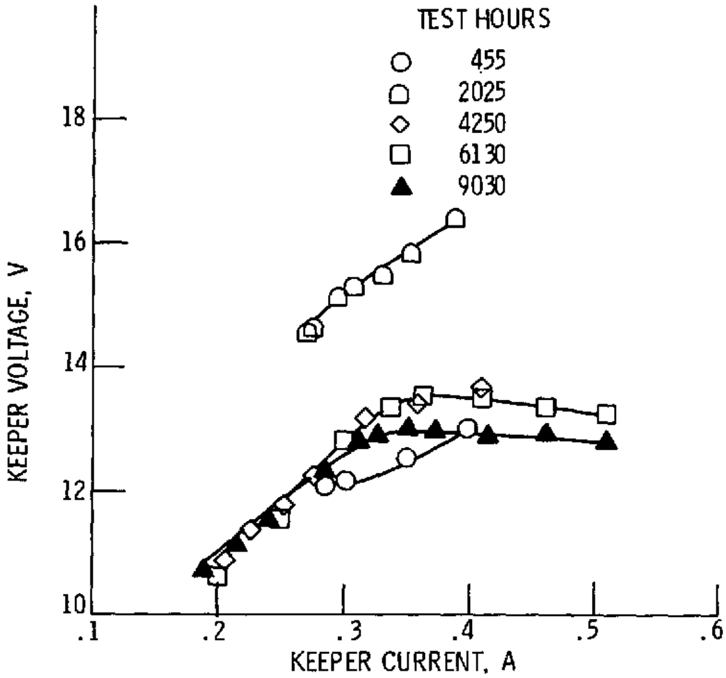


Figure 8. - Effects of varying cathode keeper current on keeper voltage at 25 mA beam current and no cathode heater power.

E-8244

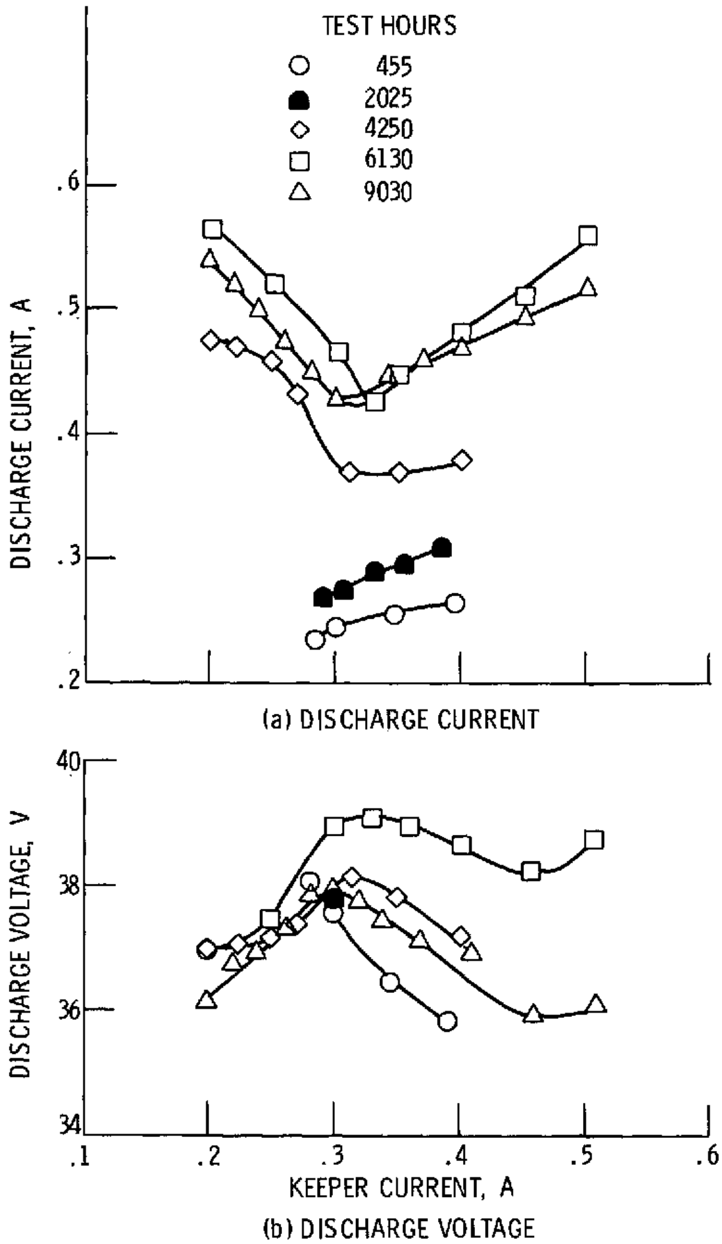


Figure 9. - Effects of varying cathode keeper current on discharge current and voltage at 25 mA beam current and no cathode heater power.

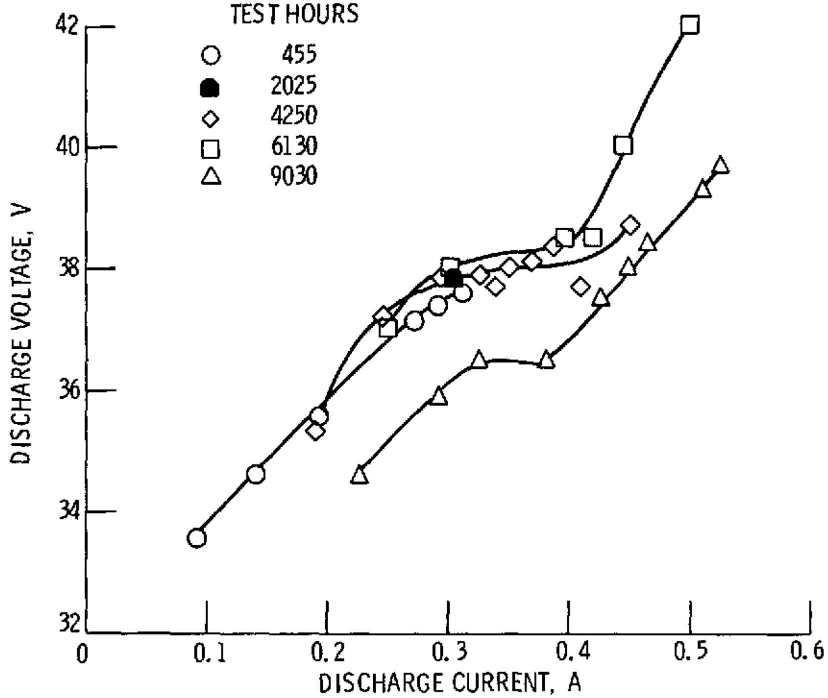


Figure 10. - Effects of varying discharge current on discharge voltage at 0.3 A cathode keeper current and no cathode heater power.

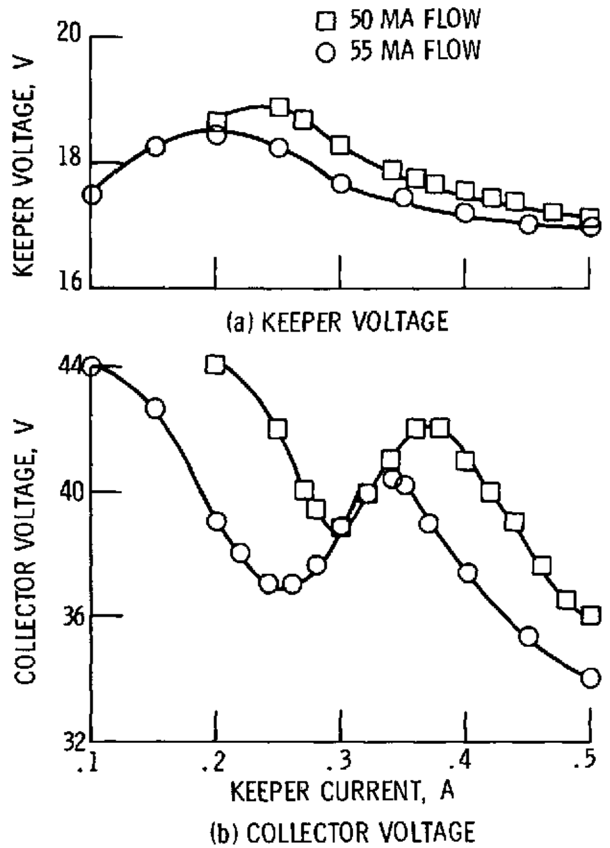


Figure 11. - Effects of varying keeper current on keeper and collector voltages at 0.37 A collector current and 3 W tip heater power after 20 100 hrs of cathode operation.

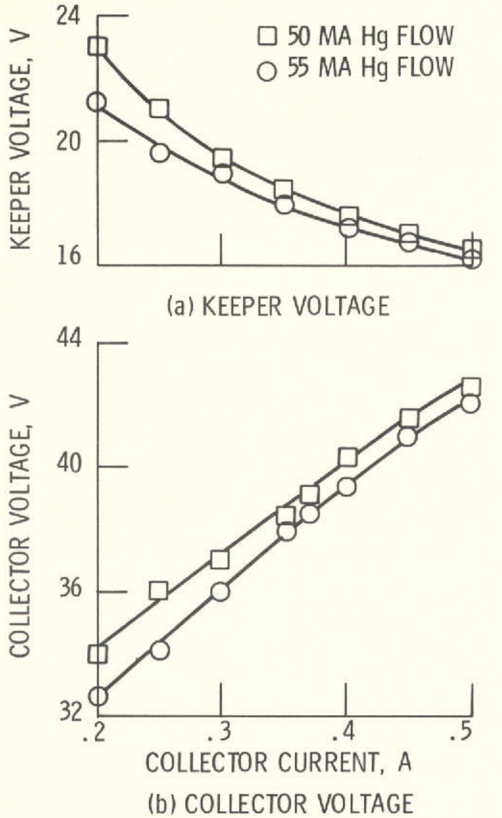


Figure 12. - Effects of varying collector current on keeper and collector voltages at 0.3 A keeper current and 3 W tip heater power after 20 100 hrs of cathode operation.

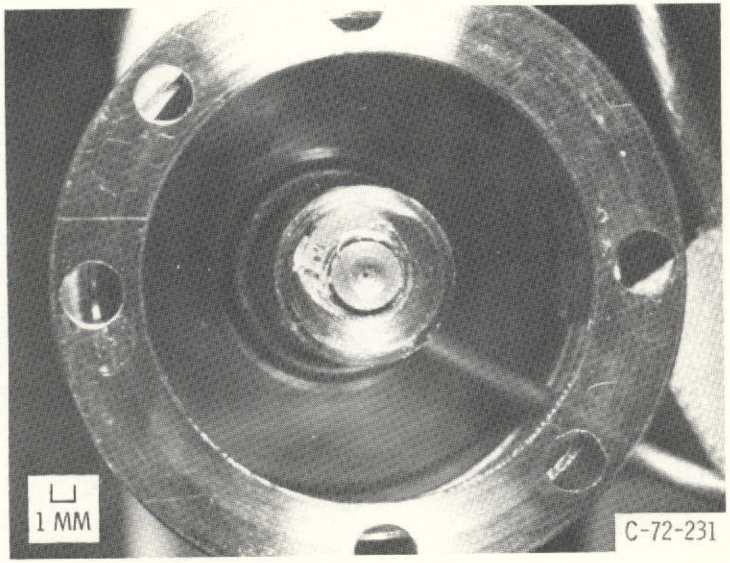


Figure 13. - Main cathode tip after 2027 hours of thruster operation.

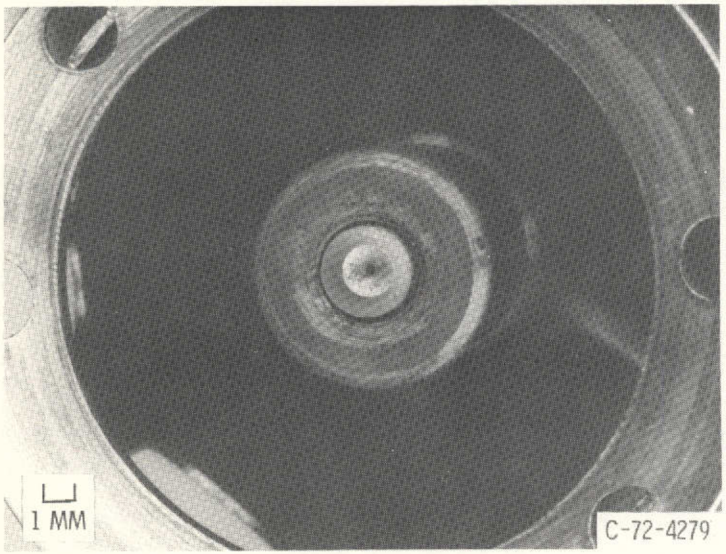
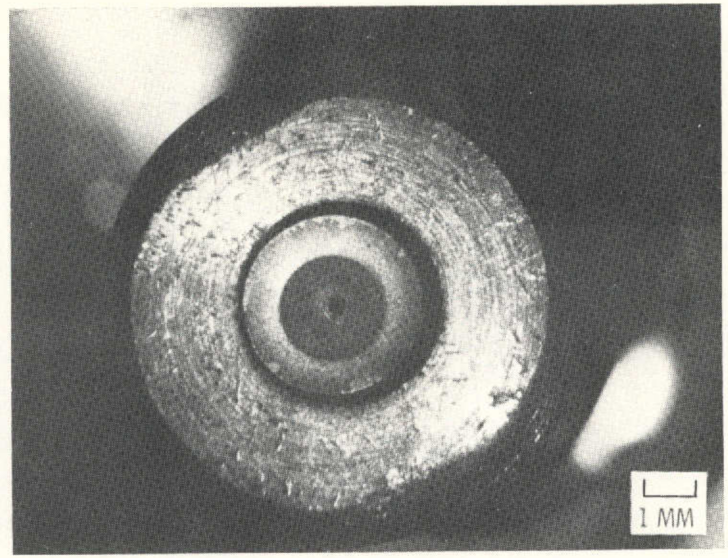


Figure 14. - Main cathode tip after 9715 hours of thruster operation.



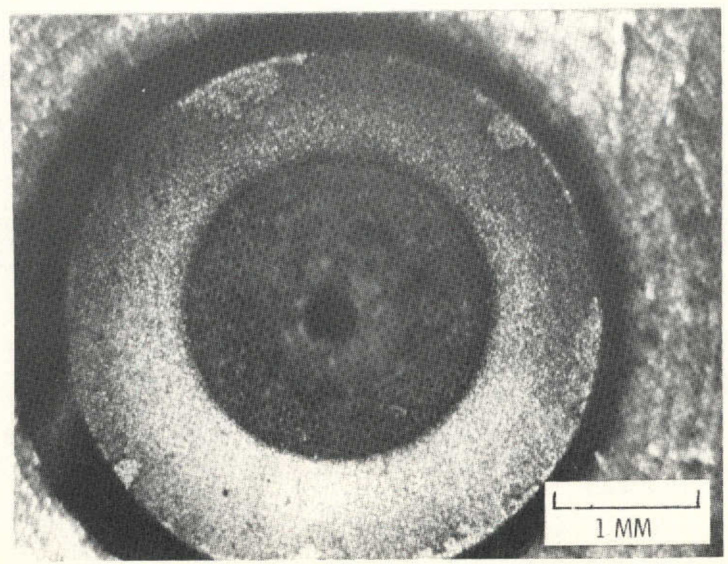


Figure 15. - Photomicrographs of cathode tip after 20 225 hours of cathode operation.

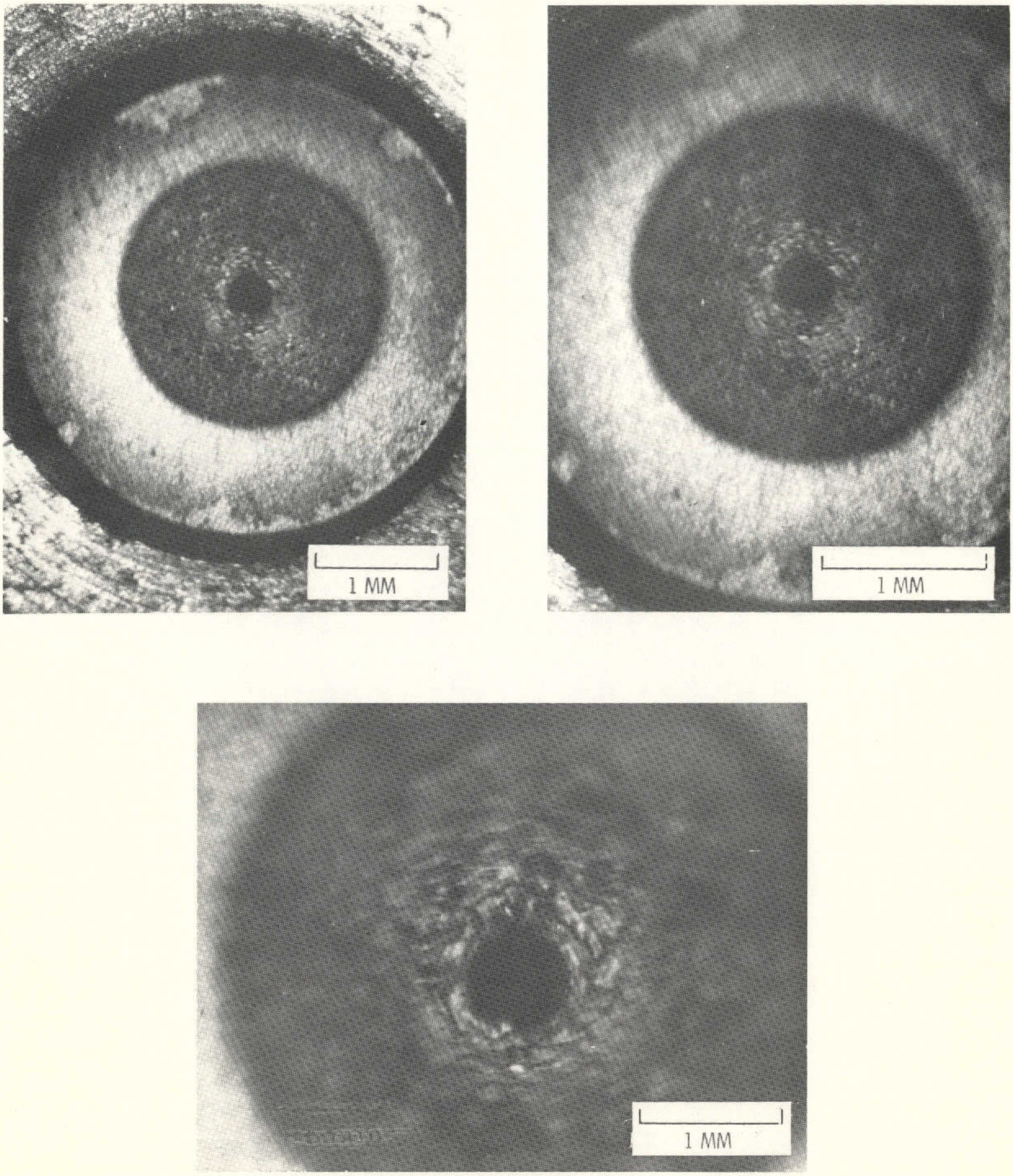
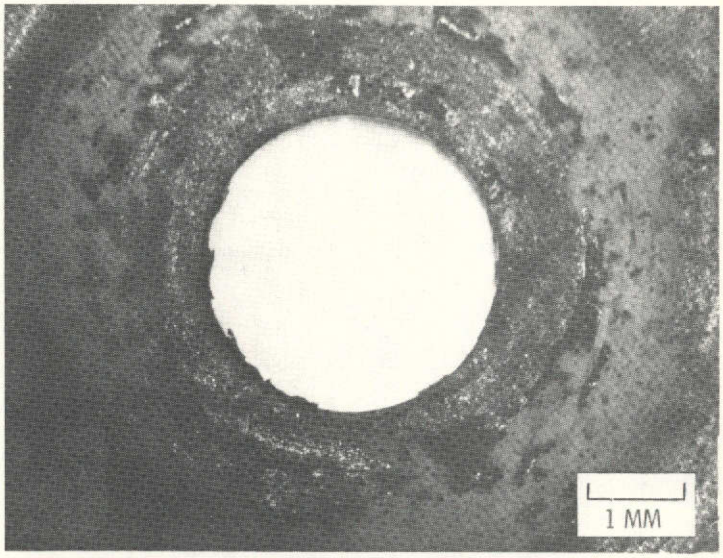
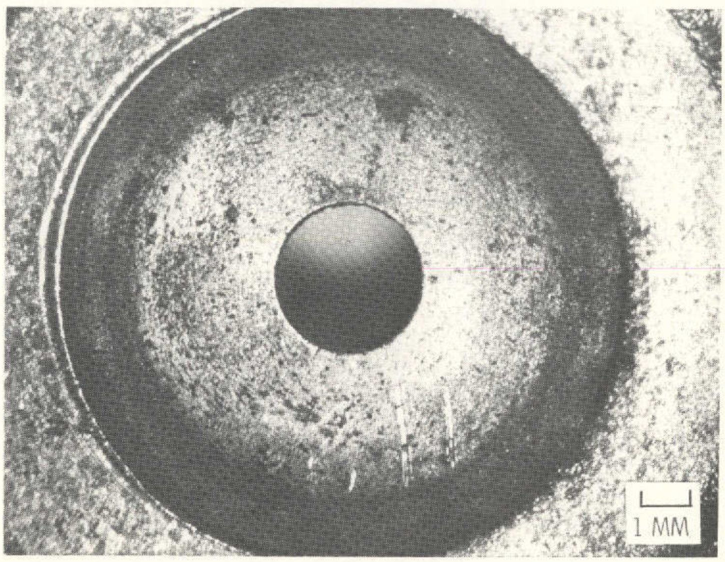


Figure 16. - Photomicrographs of tip orifice at bottom of chamfer after 20 225 hours of cathode operation.



(a) INSIDE-HIGH MAGNIFICATION.



(b) OUTSIDE-LOW MAGNIFICATION.

Figure 17. - Photomicrographs of keeper cap after 20 225 hours of cathode operation.

E-8244