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Results of the Mission Profile Life Test—First Test Segment: Thruster J1

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A series of long-term test segments of 30-cm-diam mercury bombardment thrusters is being conducted via the mission profile life test. The first 4000-h segment has been completed with the J series thruster, J1. Thruster and power processing units were computer controlled with software algorithms governing normal functions of startup, throttle, and shutdown as well as automatically handling a variety of off-normal conditions. A discussion of thruster operation includes test chronology and notable events and their significance. Post-test examination provides insight into thruster lifetime. Results are consistent with mission requirements of 15,000 h at 2 A.

Nomenclature

arcs	= high voltage spark
interrupt	= flag from power processor initiating computer controlled correction algorithm
EP/PPU	= engineering prototype power processor unit
EP/TLM	= EP/PPU telemetry data
FM/PPU	= functional model power processor unit
FM/Panel	= FM/PPU panel meter data
HV recycle	= arc quenching high voltage supply algorithm
J_A	= accelerator electrode current
J_B	= ion beam current
J_{CK}	= cathode keeper current
J_E	= cathode emission current
J_{MB}	= magnetic baffle current
J_{NK}	= neutralizer keeper current
$\dot{M}_C$	= cathode mass flow
$\dot{M}_M$	= main discharge mass flow
$\dot{M}_N$	= neutralizer mass flow
MPLT	= mission profile life test
P_{NK}	= neutralizer keeper power
P_{tot}	= total thruster power
T_{EV}	= main cathode vaporizer temperature
T_{NV}	= neutralizer vaporizer temperature
TLM	= telemetry
V_A	= accelerator electrode potential
V_{CK}	= cathode keeper potential
V_G	= neutralizer floating potential
V_I	= net ion beam accelerating potential
V_{NK}	= neutralizer keeper potential
$\Delta\dot{M}_C$	= change in cathode mass flow
$\Delta\dot{M}_M$	= change in main mass flow
$\Delta\eta_M$	= change in discharge mass efficiency
$\Delta\eta_T$	= change in total mass efficiency
ΔV_I	= discharge potential
η_M	= discharge mass efficiency (cathode + main)
η_T	= total mass efficiency (cathode + main + neutralizer)

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Introduction

PRIMARY electric propulsion missions require thruster lifetimes on the order of 15,000 h. To demonstrate this lifetime, a series of long-term test segments of 30-cm-diam mercury bombardment thrusters is being conducted via the mission profile life test.[1,2] Each test segment provides thruster lifetime information for a specific operating point. The full set of test segments will provide data relating to performance and lifetime over the operable range of thrust and specific impulse.

The first 4000-h test has been completed with the first J series thruster, J1. Thruster J1 and associated power processing units were computer controlled with software algorithms governing normal functions of startup, throttle, and shutdown as well as automatically handling a variety of off-normal conditions including high voltage overload and propellant overfeed.

Thruster operation provided sufficient time to achieve measurable wear and direct comparison with results of a 4165-h test of thruster S/N 901.[3] This paper includes a discussion of the test chronology and describes before-, during-, and after-test operational performance.

Post-test examination provided the data for an estimate of thruster lifetime. The general thruster condition after 4000 h was good; wear rates were measured and are reported for discharge chamber components. Results are consistent with the requirement of 15,000 h at full thrust.

Test Operations

Operation of thruster J1 began with acceptance testing at one facility and proceeded to performance mapping at a second. This was followed by the extended testing segment at a third facility and a repeat of performance mapping at the second. Coincident with the first performance mapping, an optics support redesign was in progress. To avoid delaying the test, the ion optics were switched to use an existing set of 900 series grids previously run for 1500 h. This modification was checked prior to the extended test. The test history of thruster J1 is given in Table 1. The evolution of ion thrusters from laboratory devices to operational hardware is demonstrated by thruster J1, which was operated at three different test sites, requiring three transcontinental shipments.

Interchangeability was demonstrated during the test segment in the mission profile life test facility, where three different power processing units and two versions of software

Table 1 Test history of thruster S/N J1

Test time, h	Ion beam, A	Facility	Pressure, Torr	Comments
82	0.75-2	Hughes	1×10^{-6}	Acceptance test J series grids
162	0.75-2	LeRC	2.6×10^{-6}	Performance map J series grids
33	2	LeRC	3×10^{-6}	Checkout 900 series grids
3940	2	XEOS	3.5×10^{-6}	Extended test segment
46	0.75-2	LeRC	4×10^{-6}	Post-test performance map
4263	1.96 average			

were used. There were 18 scheduled and 55 unscheduled shutdowns, allowing ample opportunity to evaluate restart and off-normal correction algorithms.

Run Hours 0-1013

Throughout the first 1013 h, problems with the engineering prototype power processing unit (EP/PPU) and the software algorithms resulted in repeated thruster shutdowns. Several times the neutralizer went out owing to either the neutralizer keeper supply going off without command, a high voltage recycle, or both. Because of deficiencies in the algorithm for correcting a neutralizer-out interrupt, thruster beam-on operation resulted in an overfed condition. There were also three instances when a noise-induced interrupt caused a premature shutdown. To compound the problem the EP/PPU design provided double-valued telemetry. The software program misinterpreted this information and was unable to correct the overfed condition. This sequence occurred nine times during the first 1013 h.

During this period there were 18 successful startups of test segments. The main cathode was ignited 29 times and the neutralizer cathode ignited 73 times without failure, indicating the cyclic capability of the cathode heaters. As shown in Table 2, nine starts were terminated by the overfeed algorithm following a neutralizer out, and three were terminated by an erroneous signal from the PPU indicating loss of dc input power (solar array interrupt) shutdown. Three segments were shut down owing to an internal PPU short which caused continual arcing when high voltage was turned on. This problem terminated the use of the EP/PPU for repair. One startup was aborted when the neutralizer went out during the startup sequence at high voltage-on. There were three scheduled shutdowns.

Run Hours 1013-3940

At run hour 1013, several changes were made which make evaluation of the events of the last 2927 h much more meaningful than for the first 1013 h. First, the failed EP/PPU was replaced with the first functional model power processor (FM1/PPU).[4] This PPU did not have the double-valued telemetry problem nor the neutralizer keeper turn-off problem of the EP/PPU. Second, a revised software program with an improved neutralizer-out interrupt algorithm was used. Rather than immediately retreating to the lowest beam current set point when reignition of the neutralizer occurred, the program would allow up to 60 s for reignition. If reignition occurred, the program would establish the same beam current rather than the lowest beam current, thus avoiding the overfeed problem associated by too high a main vaporizer flow rate. If reignition did not occur within 60 s, the program would reenter the startup phase. This provided better control of vaporizer temperatures at the time of neutralizer reignition and high voltage turnon.

Table 3 shows a summary of events from run hour 1013 to 3940. Those startups where extenuating circumstances were present (such as PPU or facility problems) were not evaluated. A discussion of the anomalous events follows.

Table 2 Summary of events, run hours 0-1013

Startups	
Successful	18
Aborted startups	
Neutralizer out during startup (V_{NK} turnoff problem)	1
Shutdowns	
Neutralizer out resulting in overfeed shutdown	9
Neutralizer out resulting in arcs and input power interrupt shutdown	3
Internal PPU short	3
Scheduled	3
Total	18
Main cathode ignitions	29
Neutralizer cathode ignitions	73
No failures of either cathode to ignite	

Evaluation of Thruster Control Algorithms

The effectiveness of the thruster control algorithms is shown by the summary in Table 3. Of the 40 startups which could be evaluated, only two were aborted, both owing to neutralizer problems. In each instance subsequent restarts were successful.

Of the 97 interrupts which occurred, 82 were neutralizer interrupts which should be preventable by set point change. Of these 82, seven were not corrected by the existing algorithms, nine were inconclusive owing to PPU hardware problems or programming errors, and 66 were successfully corrected and the operation continued.

The nine shutdowns (two aborted startups and seven interrupt shutdowns) discussed are the only shutdowns of the 57 total which can be attributed to failure of the thruster algorithms. An improvement in the neutralizer recycle sequence to eliminate outages will virtually eliminate thruster control anomalies.

Software Error Shutdowns

A programming error was responsible for the failure of the beam out of limits algorithm (J_B interrupt) to successfully effect the correction of a thruster anomaly. The error allowed less than 10 s for the thruster to recover from a beam out of limits condition rather than the intended 60 s. In six cases this error caused a J_B interrupt shutdown while the computer was in the process of correcting an interrupt; the premature shutdowns prevented evaluation of the success or failure of those algorithms to correct the original interrupt.

Neutralizer Interrupts

The neutralizer interrupt was by far the most frequent anomaly to occur during the test. Of the 82 total neutralizer outs, 60 relit within the allotted 1 min. Of these, 54 sequences resulted in reestablishment of normal run, two sequences were

Table 3 Summary of events, run hours 1013-3940

Startups		
Successful	38	
Not evaluated	17	
Total	55	
Aborted startups	2	
Shutdowns		
PPU failures	22	
Operator error	3	
Power outage/facility	2	
Software program error	6	
Interrupt/anomalies	7	
Scheduled	15	
Total	55	
Interrupts/anomalies	Total	Shutdown
Neutralizer—relit	60	1
Neutralizer—restart	22	6
Overfeed	5	0
Overfeed-arcs	7	0
Beam current	2	0
Arcs	1	0
Total	97	7
Main cathode ignitions	106	
Neutralizer cathode ignitions	135	
No failures of either cathode to ignite		

terminated by PPU shutdowns, three sequences were terminated by the J_B interrupt software programming error, and one sequence resulted in a J_B interrupt shutdown. The cause of the last failure is not known. In 22 instances, the neutralizer required longer than 1 min to relight but relit after the sequence retreated to the restart at preheat low condition. In 12 of these, the sequence continued and successfully reestablished the beam current. In four instances, the sequence was terminated by a PPU shutdown or the software programming error discussed above before the beam was reestablished. In five instances, the sequence proceeded normally until arcing began to occur, causing the neutralizer to extinguish a second time, at which time the computer commanded a shutdown. In a single instance the thruster began arcing when high voltage was reapplied and the computer eventually initiated an arcs interrupt shutdown.

Analysis of the arc count data strongly suggests that the neutralizer outages were caused by a high voltage arc. For example, during a 500-h period there were only three shutdowns but 29 neutralizer outages and 62 arcs. Roughly half the arcs caused outages. It is probable that only one incident would have occurred if the neutralizer-HV recycle sequence had been modified as is discussed below. Elapsed times between events ranged randomly from 1 to 300 h and did not appear to have any pattern which would suggest a degradation.

Overfeed

The overfeed subroutine was used 12 times during the test. The overfeed correction algorithm successfully corrected the condition in each instance. The exact cause was indeterminable although several events were associated with arcing.

Other Interrupts

Two beam current out-of-limits interrupts and one excessive arcs interrupt were experienced during normal running (not associated with startup or another interrupt). These interrupts were all successfully corrected by the computer algorithms.

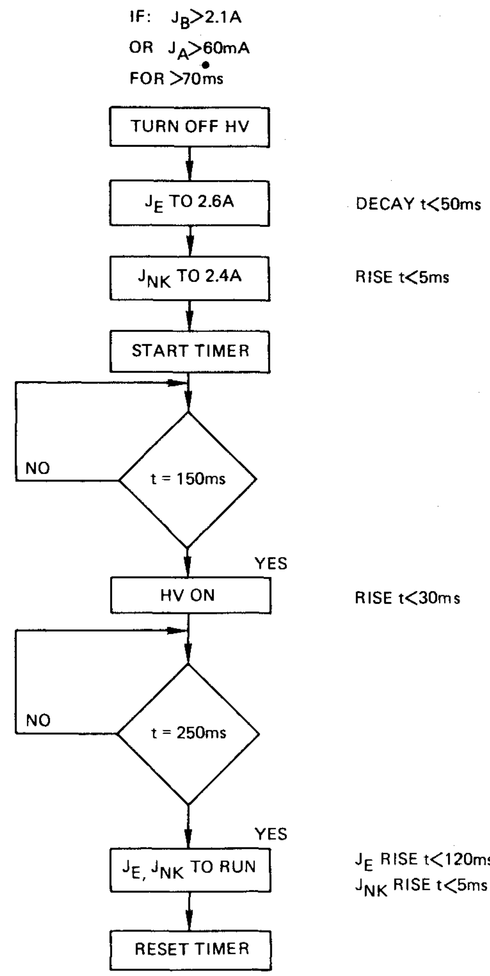

Fig. 1 High voltage recycle algorithm.

Aborted Startups

At RH 2310, two unsuccessful startup attempts were made using the standard startup/restart algorithms before a successful completion of the startup sequence was realized. Both aborted startups were due to the neutralizer going out when arcing began to occur twice within a given sequence. Two neutralizer outages within 10 min are sufficient condition to cause a computer initiated shutdown. The same problem occurred at RH 2573 when a standard restart after several PPU shutdowns was attempted. Although these problems occurred during the startup sequence, they are caused by poor selection of neutralizer keeper current set point, which makes the high voltage recycle algorithm randomly ineffective. Correction can be achieved by proper selection of the keeper set point.

Throughout the 3940 h of test the thruster operated well. Shutdowns were caused by external malfunctions in PPU or software. With one exception, the control philosophies were shown to be satisfactory. The correction for that exception, neutralizer behavior during high voltage recycle, is discussed in the next section.

Neutralizer/High Voltage Recycle Interaction

Because the apparent failure of the neutralizer to survive a high voltage recycle sequence was the only thruster control problem encountered, a test program using thruster 804 was conducted to determine if an operating set point change could be made to improve the recycle sequence. The sequence used throughout the J1 test is shown in Fig. 1. At first it was believed that the neutralizer keeper discharge would extinguish when the high voltage turned off. The neutralizer outage actually occurred when the current was switched from 2.4 back to 1.8 A.

Since the high voltage recycle sequence occurs in 300 ms, the changes in neutralizer operation occur at constant flow rate. Figure 2 shows the V_{NK} vs T_{NV} characteristic for selected conditions. At 1.8-A keeper current the maximum V_{NK} for successful recycle every time is very close to the minimum V_{NK} that maintains control stability. This requires operation of neutralizer at or very near the maximum V_{NK}. Small perturbations can thus cause outages during recycle. By increasing the neutralizer keeper current from 1.8 to 2.1 A during beam-on operation; the maximum V_{NK} for successful recycle can be increased from 12.5 to 15.5 V. The neutralizer can then be operated sufficiently far from the limit to preclude outages.

An assessment of performance penalties was made over the range of operating beam current. Flow rates were measured at values of V_{NK} near the midpoint of the ranges for 1.8- and 2.1-A keeper currents. For small variations about the steady-state operating point, the tradeoff between power and flow rate was approximately 0.8 mA = 1 W at high beam and 1.4 mA = 1 W at low beam. The summary for operating points is given in Table 4. Note that the flow rate reduction per watt of power increase is greater than required to maintain constant total efficiency. Based on these test results, the steady-state value of J_{NK} has been increased from 1.8 to 2.1 A. This value is currently being used in ongoing life test segments.

Table 4 Summary of neutralizer performance

J_B, A	V_{NK}, V	J_{NK}, A	P_{NK}, W	$\dot{M}_N$, mA	$\Delta m/\Delta P$
2.0	13.8	2.1	29.0	29	−1.9
2.0	12.3	1.8	22.1	42	
0.75	14.4	2.1	30.2	38	−2.3
0.75	13.2	1.8	23.8	53	

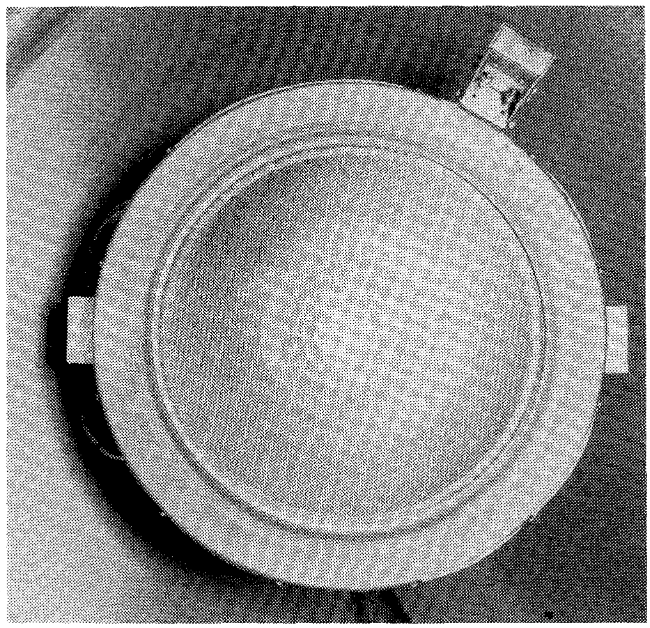

Fig. 3 General view of thruster S/N J1 after 3940 test hours.

Post-Test Evaluation

General Condition

The condition of thruster S/N J1 on removal from the mission profile life test facility after 3940 h of testing was generally very clean (Fig. 3). A chip of material on the grids observed telescopically during the test was seen to be inside the grids rather than between the grids. The general shape and size was consistent with those suggested by the telescope. However, the chip was lost on trying to remove the grids, indicating that there was no firm attachment of the chip to the screen grid. The thruster then underwent post-test evaluation prior to complete disassembly. The problem of wrinkling of the wire-mesh anode covering noted on S/N 901 did not occur on S/N J1 where the mesh was diffusion bonded to the anode.[3] The three upstream anode screw heads and the area immediately around them, had a bluish discoloration. However, no operational difficulties were noted during or after the test and the cause of the discoloration is not known.

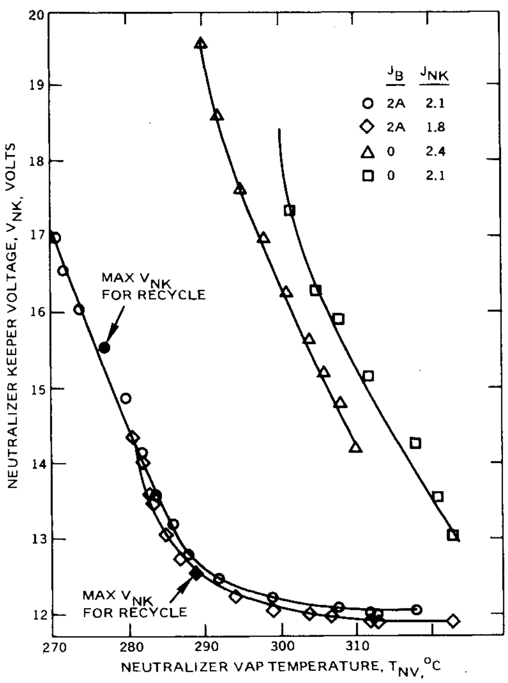

Fig. 2 Typical neutralizer control characteristics.

The change in coloration of the neutralizer housing graphite cover reflects the primary ion beam boundary. However, there was no detectable change in thickness at this point. There was also a large margin to accommodate any increase in the beam spread which might occur for any reason. Lack of this margin on the test of S/N 901 prompted an increase in length of the graphite cover.

Discharge Chamber Erosion

Erosion of discharge chamber components occurs both in the main discharge chamber and within the cathode pole piece region. Each of these erosions is governed by different plasma properties such as ion energy (plasma potential).[5] The noticeably eroded components in the main discharge chamber were the screen grid and the downstream surface of the baffle, while the upstream surface of the baffle and the pole piece surfaces are mostly eroded by ions from within the cathode pole piece.

For the screen grid a general criterion for end of life is to wear to half the original thickness, since this is the worst condition demonstrated.[6] To evaluate lifetime capability, it is necessary to determine a change in thickness over the test, and a correction factor due to the effect of pressure on sputter yield.[7] The maximum wear for this test was 18 μm (0.7 mil) in 4019 h (Table 1). The partial pressure of N_2 was determined by mass spectroscopy to be 3.5×10^{-7} Torr, requiring a correction factor of 0.7. The extrapolated screen grid lifetime at $J_B = 2.0$ A is thus approximately 30,000 h. The corresponding wear rate, corrected, is 6.4 μm/kh. For comparison, the wear of the thruster S/N 901 (corrected) was 47 μm/kh, approximately seven times greater. The primary difference between these tests was that S/N 901 was operated with a 36-V discharge, while S/N J1 was operated with a 32-V discharge.

Short-term and spectroscopic data have indicated that screen grid wear rate might be near linear with beam current. This would suggest a total screen grid capability of approximately 60,000 A-h. Additional test segments will determine the effect of beam current level on screen grid wear rate.

For the downstream baffle cover the worst case wear rate was calculated by assuming the original thickness to be the maximum design allowance of 0.89 mm at the center. Thus the maximum wear was 0.3 mm and the maximum wear rate, corrected, for 4263 h (Table 1) was 21 μm/kh. Since this component serves as a tantalum cover for sputter protection only, end of life would occur after the full thickness is eroded. Thus worst-case extrapolated lifetime would be 42,000 h.

For the upstream baffle cover the worst-case wear rate was determined using a beginning of life thickness of 0.38 mm, the thickness at the point masked by the mounting flange and a pressure correction factor of 0.7. The wear was 0.02 mm and the rate was thus 9 μm/kh. Again, end of life can be assumed to occur when the full thickness is sputtered, 42,000 h.

In general, all components within the discharge chamber which have evidenced some erosion appear to have adequate wear rate margins. The screen grid, downstream baffle cover, and upstream baffle cover all show extrapolated lifetimes of more than 30,000 h at $J_B = 2.0$ A (approximately 60,000 A-h). The existing J series thruster design does not appear to have a discharge chamber sputter erosion limitation which would preclude successful completion of a 15,000-h mission.

Sputter Material Containment

The most difficult problem to evaluate is that of containing the sputter material deposited within the discharge chamber in a manner which will not allow spalling, peeling, or flaking in flake sizes large enough to cause electrical shorts or arcs. This was one of the more severe problems encountered in the endurance test of thruster S/N 701. In that case, deposition coatings on smooth surfaces built up to thicknesses of a few hundred microns. When these coatings began to spall, they did so with length and width dimensions measured in millimeters. These flakes were large enough to cause electrical shorts and arcing. The thickness at which spalling of a continuous deposition coating begins to occur has been seen to be in excess of 100 μm (4 mil).[3] This thickness depends on, among other things, surface condition and environment.

To delay the formation of continuous deposition coatings in J series thrusters, wire-mesh covers are used in areas of potential material buildup. Thus a continuous coating could not begin until enough material had deposited to bridge the wire-to-wire gaps in the mesh. Until this point is reached, any flakes formed will have dimensions less than the wire-to-wire dimensions. Operation can continue after this point until the additional coatings become thick enough to promote spalling. The design wire mesh for thruster S/N J1 is 89-μm wire with 180-μm spacing between wires in a 94-square-mesh configuration. Thus the largest continuous strand of wire between cross wires is 450 μm compared to the smallest critical thruster dimension of approximately 500 μm between the grids. The lifetime capability of this mesh is then at least the time required to bridge the 180-μm gap plus the time required to build up an additional 100-μm thickness. Based on the results of the test of S/N 901, spalling should not occur until after this time.

The cathode pole piece assembly is the area where the deposition problem has been the most severe. The highest deposition rates were seen on the keeper surface. High power photographs show that the 180-μm gap has been reduced to 106 μm in 4263 h. Thus the worst case would see a formation of a continuous deposition coating in 7700 h corrected for pressure effects. The time required to build an additional 100-μm continuous coating is determined by the rate of deposition buildup normal to the plane of the mesh. This is not the same as the rate of mesh gap reduction, since the buildup is actually somewhat faster normal to the plane of the mesh. The maximum coating thickness was measured at about 40 μm in 4263 h. Thus the time to reach 100 μm, correcting for the pressure effect, would be about 7500 h. This leads to a conclusion that no problems of spalling should be evident until after 15,000 h of test (at $J_B = 2$ A).

Obviously, the evaluation of sputter deposition containment is approximate. The approach taken here is conservative. Both the minimum allowable buildup and the maximum deposition rate used were worst case. Probably larger buildups are tolerable and the high deposition rate used for estimating is confined to an extremely small area. The second largest buildup identified was less than half as big. Still, the manner in which spalling would eventually occur is the determining factor in the adequacy of the design and this factor is unknown. The design should be adequate, although there appears to be little safety margin.

Several possibilities for improving the spalling situation do exist. Most of the material deposited in this area is sputtered within the pole piece by ions which have energies determined by the pole piece plasma potential. This plasma potential is determined in part by the cathode keeper voltage, V_{CK}. The value of V_{CK} can be reduced by approximately 40% by a change in the keeper current set point which might be expected to result in some reduction in the amount of material which must be contained. Increasing the size of the mesh opening would increase the time needed to bridge the gap; however, this would also allow for the formation of larger flakes. The present design limits the size of flake formation to 450 μm, although photographs suggest flakes to be generally less than 300 μm.

The areas outside the cathode pole piece were also examined. The anode was examined in place and showed no signs of any buildup of material. A portion of the rear plenum cover was removed and examined. The deposition rate in the main discharge chamber appears to be so small that containment of the materials is not a problem.

Cathodes

The main cathode and insert were examined after the test. A profile of the orifice made from elastic impression material showed no evidence of any measurable change in dimensions, nor did visual inspection show any evidence of ion machining of the cathode surface. The cathode heater resistance was unchanged. The cathode insert was intact when removed, and there was no evidence of mechanical problems with the electrical attachment. Evaluation of the amount and condition of remaining emissive mix is difficult to make. The best indicator of the adequacy of the insert design, at least through the 4263 test hours, is the constancy of operating parameters as discussed below.

The neutralizer cathode orifice showed a slight chamfer of the downstream end. This chamfering is common for 30-cm thruster neutralizers and has been noted on previous tests. The chamfering occurs within the first several hundred hours and then ceases when an equilibrium shape has been obtained. The minimum diameter as determined by a fit of a precision rod into the orifice indicates minimal or no variation from the design diameter of 0.38 mm. The heat resistance measured slightly higher after the test than before, but the difference is within measurement accuracies for the technique used.

The only anomaly noted was with the neutralizer insert. When removed, the insert was cracked at the notch machined to allow for brazing of the two electrical leads. The cracking occurred at the thinnest wall, probably owing to thermal stresses. The two electrical leads were still firmly attached by spot welds to the neutralizer cathode body. The design of the insert had already been changed to eliminate the notch even before discovery of this problem. With a uniform insert wall dimension, localized thermal stresses should not be a problem.

Electrical Measurements

The thruster assembly consists of several electrical insulators of a variety of designs which must stand off from 50 to 1400 V. These insulators fall into six categories according to the voltage standoff requirements. The cathode common to anode, ground, and accel insulators all had resistances in the tens of megohms range. These represent leakages of 50 μA or less at the design voltages through all possible paths (insulators, wire harness, isolators, etc.).

The cathode keeper-to-cathode common insulators and all the neutralizer insulators, however, showed a significant reduction in resistance over the length of the test, 340 and 60 kΩ, respectively. These resistances do not make the thrusters inoperative. Cathode keeper leakage currents would be less than 300 μA. However, these leakage resistances significantly load down the 350-V ignition boost section of each keeper supply such that full ignition voltage is not available, although no problem was noted with neutralizer or cathode ignition. A spectrographic analysis of neutralizer and cathode keeper insulators shows the presence of measurable amounts of iron and nickel, suggesting the source of the leakage is deposition of facility backsputtered material. This, in turn, suggests that the shadow shielding of these insulators is inadequate. The primary concern would be the premature termination of a ground test due to this type of leakage, since backsputtering would not be a problem encountered in space.

The eight electrical resistances (seven heaters and the magnetic baffle coil) were measured at various times before, during, and after the test. Most items showed a slight increase (0.06 Ω) but some showed a decrease of the same order, indicating a measurement error associated with contact resistances. No design deficiencies were noted in this area.

The basic problem which caused the premature shutdown of the life test of thruster S/N 901 was corrected by the design modifications on thruster S/N J1. These modifications were to route the wiring through the high temperature areas near the cathode pole piece through ceramic beads securely attached to the rear frame. However, several lesser problems were noted. The spiral Teflon wrap on the Kapton insulated wires was noted to separate in several of the hotter areas. These areas included the cathode tip heater lead and the cathode vaporizer platinum resistance temperature sensor leads.

The clamp which secures two of the propellant feed lines and serves as the electrical connection for the vaporizer return was loose. Electrical continuity was as poor as 200 Ω (in series with nominal 6-Ω heater resistances) when slight pressure was applied in some directions. Under normal conditions, the clamp resistance was approximately 0.1 Ω. The wire harness guide near the neutralizer had a slight brownish discoloration although no adverse effects were noted. In general, the center area around the cathode pole piece and the area around the cathode isolator vaporizer had a bluish discoloration. The area of the main isolator vaporizer showed no discoloration.

Changes in the wire specification and the clamp design have been incorporated to eliminate the above problems. The cause and effects of the discolorations noted are not known at this time.

Ion Optics

The optics (grids) used for the extended portion of the test were not the J series design, but rather a research set of optics which had approximately 1500 h of prior testing. These grids were mounted on molybdenum rings. This substitute set of optics was used to expedite the start of the test.

Since both the electrical and propellant flow rate operating values were the same as for J series optics tested first, the information regarding screen grid erosion determined by before and after measurement is applicable to any set of optics. However, owing to the previous run history information regarding accelerator grid wear and/or screen/accel aperture wear is probably not generally applicable. Thus an assessment of the notching of two accelerator grid apertures noted at the end of the test is difficult to make. Similarly, the repeatability of the grip spacing before and after the test can not be applied to the J series design due to the difference in mounting.

Isolator/Vaporizers

The vaporizers used for main, cathode, and neutralizer on the testing of thruster J-1 differed from the present J series design in specification of the porous tungsten, housing design, and welding and fabrication procedures. Thus, although vaporizer performance was constant throughout, the results are not directly applicable to the J series vaporizer design. However, the isolator portion of these subassemblies is of the current design and were evaluated.

The neutralizer isolator is required to stand off 60 V plus margin. At the 60-V level, a series of zener diodes clamp neutralizer common to feed system (PPU) ground. Because of this low voltage requirement, the primary failure mode would be expected to be surface leakage across the isolator due to backsputtered material deposition rather than leakage breakdown through the mercury vapor inside the isolator. Normal operating voltages are several hundred volts less than the Paschen minimum for Hg. The resistance of the isolator measured cold with no Hg flow was 20,000 MΩ at 1000 V before and after the test.

The main isolator is required to withstand voltages of 1100 V with Hg flow. Owing to the design of the propellant feed manifold and thruster mounting, it is not possible to directly measure the leakage current while operating. Evaluation of the isolator under operating conditions would require a separate checkout test at the subassembly level. However, the isolator leakage was measured cold with no mercury flow. The resistance was in excess of 20,000 MΩ at 1000 V before and after the test.

The same conditions exist for the cathode isolator as for the main isolator. However, a check of the isolator resistance after the test revealed a resistance of 150 MΩ at 1000 V, cold with no mercury flow. Although this represents a very small leakage current of less than 10 μA and presents no operational difficulty, it does indicate significantly greater deterioration than for the main isolator. A detailed examination of this isolator is being conducted.

Thruster Performance

Thruster S/N J1 was characterized several times before, during, and after the life test. Prior to the test, the thruster

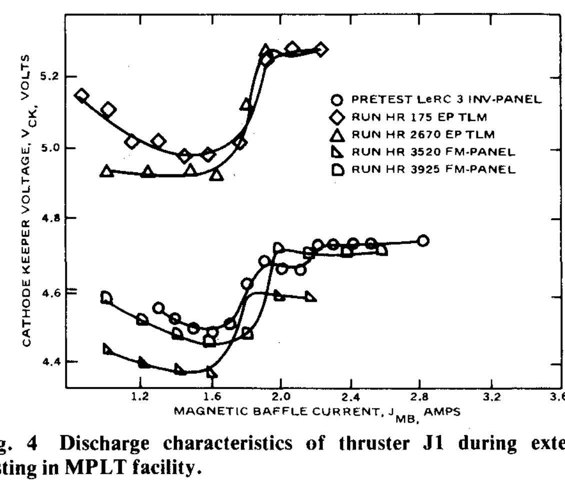

Fig. 4 Discharge characteristics of thruster J1 during extended testing in MPLT facility.

Table 5 Thruster S/N J1 before-after test performance data

Parameter	Before	After	Before	After	Before	After	Before	After	Before	After
V_I, V	1100	1100	940	940	820	820	700	700	600	600
J_B, A	1.99	2.0	1.6	1.6	1.3	1.3	1.0	1.0	0.76	0.76
ΔV_I, V	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0
J_E, A	12.0	12.0	10.0	10.0	8.5	8.5	7.0	7.0	5.75	5.75
J_{MB}, A	1.7	1.8	1.8	1.8	1.9	1.8	2.0	2.0	2.2	2.0
V_{CK}, V	4.37	5.05	4.87	5.63	5.51	6.18	6.14	7.03	6.87	7.79
J_{CK}, A	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
V_A, V	300	300	300	300	300	300	300	295	289	286
J_A, mA	7.2	3.67	3.65	2.95	2.55	2.33	1.87	1.54	1.33	1.15
V_{NK}, V	13.5	12.76	15.0	13.49	13.46	13.46	15.0	14.43	15.8	15.5
J_{NK}	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
V_G, V	19.3	10.0	10.76	10.0	10.2	10.1	10.5	10.2	10.6	9.9
M_M eq. A	1.77	2.052	1.634	1.713	1.313	1.390	1.026	1.054	0.784	0.825
M_C eq. A	0.092	0.116	0.095	0.110	0.104	0.108	0.113	0.126	0.128	0.125
M_N eq. A	0.035	0.040	0.037	0.041	0.046	0.047	0.044	0.046	0.042	0.042
η_M	0.962	0.923	0.925	0.878	0.917	0.868	0.878	0.847	0.833	0.800
η_T	0.946	0.906	0.906	0.858	0.889	0.841	0.845	0.816	0.797	0.766
$\Delta \dot{M}_M$ eq.A		+0.075		+0.079		+0.077		+0.028		+0.041
$\Delta \dot{M}_C$ eq. mA		+0.024		+0.015		+0.004		+0.013		−0.003
$\Delta\eta_M$		−0.039		−0.047		−0.049		−0.031		−0.033
$\sim P_{tot}$, W	2650	2650	1890	1890	1400	1400	990	990	705	705
$\Delta\eta_T$		−0.030		−0.035		−0.034		−0.019		−0.019

was characterized in one facility including documentation of the electrical discharge and neutralizer characteristics as well as measurement of the propellant flow rates. At run hours 1175, 2670, 3520, and 3925, the electrical characterization was repeated in the MPLT facility. Propellant flow rates were not measured at these times. The complete characterization was repeated after the test including propellant flow rates at Lewis Research Center (LeRC). Although the electrical instrumentation for the before and after tests at Lewis Research Center was the same hardware, the propellant flow measurement system had been upgraded during the interim.

The results of the before and after test comparisons are shown in Table 5. Based on the before-after data, two variations in discharge performance resulted from the test: first, shift in J_{MB} characteristics and, second, an increase in main propellant flow rate at the higher beam currents.

Periodic J_{MB} characterization throughout the test did not shown any indication of a shift. Figure 4 shows the J_{MB} vs V_{CK} curves taken at various run hours. The values of J_{MB} at which the various identifiable critical points occur are much more constant in these comparisons than in the before-after comparison only (Fig. 5). In addition, the absolute level of V_{CK} is reasonably constant for curves generated by the same type of measurement technique (PPU telemetry or digital meter panel). The constancy of the dependent operating parameters suggests no discharge variation. From run hour 1013, when the change to the FM/PPU and the improved software program resulted in longer, less anomalous test segments, through the end of the test at run hour 3940, the cathode keeper voltage was quite constant.

In general, 5-10 h of operation after a startup or major operation interruption were required to achieve equilibrium cathode keeper operation. This is because of the dependence of V_{CK} on both the thermal emission characteristics of the cathode and on facility background pressure. Once equilibrium was attained, V_{CK} was a constant 4.3-4.4 V while operating on the FM/PPU and 4.4-4.5 V while operating on the EP/PPU. The cathode vaporizer and main vaporizer temperatures, indicative of the corresponding propellant flow rates were also reasonably constant throughout this time period. The main vaporizer temperature was 300 °C ± 1 °C at the standard 2 A value of J_B. The cathode vaporizer temperature varied more, ranging from 304 to 312 °C throughout most of the time period. The fact that the main vaporizer temperature and V_{CK} did not vary as T_{CV} was changing implies that the T_{CV} variation did not indicate a change in flow rate but rather a change in calibration. The constancy of these parameters all indicated no change in the behavior, operation, or characteristics of critical discharge chamber components such as cathode and insert, magnetic circuits and field strength, optics configuration, etc., or in the propellant flow rates required.

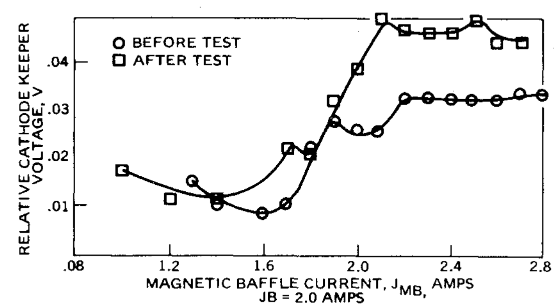

Fig. 5 Discharge characteristics of thruster J1 measured during performance mapping before and after extended test.

There are several possible reasons for the before-after differences of Table 5 and Fig. 5. Although care was taken to duplicate and calibrate the electrical and flow measurement systems, it is possible that systematic measurement errors may be responsible for these differences. The flow measurement system had been modified between tests to reduce the possibility of trapped air. If air is trapped in the measurement system, it can expand giving an optimistic flow reading. The higher main propellant flow rate after the test could be due to a small vapor leak in the new feed systems, an optimistic "before" reading, or a combination of the two. It is also possible that the measurements are accurate but that the cause of the differences in performance is associated with the exposure to atmosphere after continued operation rather than the long-term operation itself. This possibility is supported by the simultaneous change in magnetic baffle characteristics. Also, an undetected shorting of turns in the magnetic baffle coil could cause an increase in the required value of J_{MB} for specific operation. Finally, the possibility that thruster performance was degrading continually through the test (although believed unlikely) cannot be absolutely ruled out.

Conclusion

A 30-cm ion thruster S/N J1 was tested for 3940 h in a frozen mercury target facility as part of the mission profile life test effort. The thruster performance was documented before and after the test and characterized at several points during the test. The only indication of variation of performance was associated with the post-test documentation. These data suggested a decrease in total efficiency due to reduced mass efficiency might have occurred, although periodic characterizations during the test did not indicate any ongoing degradation or variations. Systematic and/or measurement errors are more likely to be the cause of this apparent variation than is a continual ongoing wearout or degradation. Further testing with better-suited life test instrumentation is required to fully evaluate this hypothesis.

The thruster was also disassembled and examined. Screen grid and other discharge chamber erosion components exhibited wear rates consistent with approximately 30,000 h of 2-A beam current operation (60,000 A-h). The surfaces specially fabricated to contain the sputtered products were examined under a high power microscope. It appears that these surfaces will adequately contain these sputter deposition coatings without spalling or peeling for 15,000 h at the 2-A beam current level. However, because the factors which control spalling are not fully identified and understood, additional testing for direct verification of this conclusion as well as increased understanding of the mechanics of spalling are considered essential.

Both the neutralizer and main cathode orifices suffered no unexpected or unacceptable erosion, and both cathodes performed acceptably throughout the test.

Some deposition material on external insulators causing a reduction in resistance was encountered. This may be related to sputtering material from the edges of the mercury target. Some separation of the Teflon over Kapton wire insulation wrappings was also noted. All electrical heater resistances and the magnetic baffle coil resistance were within measurement tolerances after the test.

The ability of the programmed algorithms to adequately control the test events was acceptable with one exception. The neutralizer extinguished 82 times during the test. This was a result of failure to remain lit throughout the high voltage recycle sequence. Subsequent testing defined a modification to the sequence which solves this problem.

No unknown failure modes were identified in this test, and the test results indicate that the known failure modes are very consistent with a projected 15,000-h useful lifetime at a 2-A beam current.

Acknowledgments

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