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Abstract

Missions currently under consideration for primary electric propulsion require useful system lifetimes of 15 000 hr. The Mission Profile Life Test is planned to conduct a program of long term test segments of 30 cm diameter thrusters and power processing units under computer control. Each test is designed to provide thruster lifetime information for specific operating conditions. With this information, accurate predictions of lifetime for virtually any mission profile can be made. The first test segment has completed 2700 hr of a planned 4000 hr test with a J-series 30 cm thruster. The last 1600 hr have used a Functional Model power processing unit operated in vacuum. The thruster-PPU was controlled by a HP 21MX computer with software/ algorithms developed to control start-ups, throttling and a variety of off-normal conditions. Comparison of test results have shown very good constancy of thruster operation throughout. Only a minor operational problem related to neutralizer performance during high voltage recycle has been noted. Evaluation of discharge chamber erosion and spalling phenomena must wait completion of the test, but no results or circumstances inconsistent with a 15 000 hr useful life have been noted.

Introduction

Missions currently under consideration for primary electric propulsion require useful propulsion system lifetimes of 15 000 hr.¹ The principal elements of such a system are the 30 cm Hg bombardment thruster and the power processing unit (PPU). An additional requirement is the demonstration of adequate control algorithms over a 15 000 hr period. These algorithms must control start-up, steady state operation, throttle, detection and correction of off normal conditions, and shutdown of the thrusters. Verification of the lifetime of the current electric propulsion system design, especially the 30 cm thruster, is the objective of the Mission Profile Life Test (MPLT), currently being conducted by Xerox EOS under NASA Lewis Contract. This test is planned to conduct a program of long term test segments, with each segment designed to provide lifetime information for specific thruster operating conditions. This will allow for accurate predictions of lifetime for any mission profile. The MPLT facility is capable of handling three thruster - PPU systems simultaneously, all being controlled by a common HP 21MX computer. Details of the facility are provided in Ref. 2 and

in a companion paper.³ The first test segment was begun in December, 1978 with thruster S/N J1 and has accumulated 2700 hours of a planned 4000 hr test segment. This paper compares thruster performance data and other operational characteristics taken at various times during the test segment and evaluates the results in light of the life-limiting mechanisms described. A discussion of the thruster control algorithms is also presented.

Objective of MPLT

The objectives of the Mission Profile Life Test (MPLT) are (1) to conduct a program of long term tests to document thruster characteristics, especially discharge chamber erosion, as a function of operating point in order to allow prediction of thruster performance for any mission profile; (2) to demonstrate extended duration operation capability of thruster and power processor designs; and (3) to investigate operation of interactions between thruster-PPU systems. Fulfillment of these objectives essentially involves lifetime verification of the thruster, demonstration of reliable PPU operation throughout the thruster useful life, and the adequacy of thruster control algorithms to control the system, using PPU hardware and computer software capabilities.

Thruster Life Limiting Mechanisms

There are basically five mechanisms which might limit the useful lifetime of the 30 cm thruster to something less than 15 000 hr. A brief discussion of each of these mechanisms follows.

(1) Internal erosion. Internal discharge chamber components, especially the screen grid, are eroded by ion bombardment by low energy ions from the discharge plasma.^{4,5} These ions have energies equal to the product of the plasma potential (~ 32 V) and their charge. A doubly charged ion would then bombard discharge chamber surfaces with an energy of 64 eV.

This is considered to be the prime life limiting mechanism. Verification of sufficiently low erosion rates to provide for a 15 000 hr useful thruster life is one of the prime objectives of the MPLT. The end of life criteria is taken to be the greatest wear experienced without adverse effects on thruster efficiency or performance or control.

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A conservative limit on screen grid wear was defined by the test of thruster S/N 7016 in which operation with a half eroded screen grid was demonstrated. Thus the minimum allowable screen grid thickness at end of life is considered to be 1/2 the beginning of life value of 0.38 mm (0.015 in.). The maximum screen grid erosion is 0.19 mm (0.0075 in.) which, assuming linear wear, corresponds to a wear rate of 0.013 mm/1000 hr = 127 Å/hr (0.5 mil/1000 hr).

Current predictions of wear rates indicate adequate lifetime. For other discharge chamber components which are part of the magnetic circuit, the maximum wear is that which will not effect the dimensions of the magnetic mild steel pieces and affect the magnetic circuit. This means the tantalum covers of these pieces cannot wear through. Since these covers are typically 0.76 mm (0.03 in.) thick in the region of maximum wear, wear rates must be less than 0.005 mm (2 mil)/1000 hr. Worst case wear rate measurements of these components are less than half this value.⁷ A more detailed discussion of discharge chamber erosion is given in Refs. 4, 5, 8, and 9.

(2) Deposition and spalling. Internally sputtered material is deposited and accumulates on discharge chamber surfaces which, because of their location and/or potential, are not subject to continuous ion bombardment.^{4,5} These deposits form layers of materials which can, if not properly contained, spall and peel, eventually causing electrical shorts and arcing.⁶

The assessment of end of life due to this phenomenon is difficult to make since the flakes of sputtered material are formed and spall in a random manner. However, the onset of spalling, although not necessarily dictating end of life, certainly would indicate the beginning of the final stages of thruster useful life. Based on current, short term test results, it appears that spalling should not present a problem within 15 000 hr of operation. However, because of the lack of long term test results, this area is considered to be somewhat undefined. Long term verification of spalling control techniques is a prime objective of the MPLT. A further discussion of spalling is given in Refs. 4, 5, and 10.

(3) External erosion. Components outside the discharge chamber, such as the ground screen, neutralizer components, and the accelerator grid are bombarded by ions. These ions can be either high energy primary (beam) ions or low energy secondary ions. The high energy ions have energies equal to the product of the beam voltage (600 to 1100 V) and their charge. The low voltage ions are usually formed by a charge exchange collision or within the neutralizer plasma and usually have thermal energies. Some low energy ions are attracted by the accelerator grid and do sputtering damage to this grid with an energy equal to the accelerator potential (typically ~300 V). End of life is considered to occur when a component is eroded sufficiently that it can no longer establish the necessary equipotential surface. In the case of the accelerator grid, this would result in improper focusing of ions and/or repelling of electrons. In the case of ground screen surfaces this would result in electron backstreaming to positive high voltage surfaces which would manifest itself as erroneous beam current. Neither the 4165 hr test of thruster S/N

9017 or accumulative test results obtained through short term tests have indicated that wear of any of these components is inconsistent with a 15 000 hr useful life.

(4) Cathode degradation. Either the main or neutralizer cathodes can degrade by loss of the low work function material impregnated in the cathode inserts and/or by erosion of the cathode orifices.

Depletion of the inserts would be reflected by increasing keeper voltage in the case of the main cathode and increasing flow rate in the case of the neutralizer. Another indicator would be increased difficulty in lighting the discharges. None of these indicators were observed to occur during the 4165 hr test of Ref. 7. Erosion of the cathode and neutralizer orifices are directly measured and there has been no evidence of any erosion which would limit lifetime to less than 15 000 hr.

(5) Propellant isolator leakage. If any isolator begins to conduct significant leakage current and the isolator impedance becomes significantly low, then the various potentials of the thruster and PPU are no longer free to assume values necessary for beam neutralization without reference to spacecraft potential. In fact the spacecraft could become an integral part of the neutralization procedure.

A discussion of propellant isolators is presented in Ref. 11. To date no problems of isolator leakage in a properly controlled test environment have been noted. This includes the 4165 hr test of S/N 901,⁷ which had the exact isolator design of those used on the J series thrusters.

Life Verification Test Plan

The principal questions regarding thruster erosion rates are (1) are these rates constant with time and (2) how do they vary with thruster operating point, particularly beam current and discharge voltage. If the answers to these questions are in hand, then accurate predictions of lifetime for virtually any mission profile can be made.

The test matrix for thruster lifetime verification is shown in Fig. 1. It is designed to provide full power lifetime information in intervals of 500, 1000, 4000, 10 000, and 15 000 hr. Since the accuracy and evaluation of the 500 hr test segment is least critical, test results already obtained at Lewis have fulfilled this test requirement. Since thruster S/N 903 (modified) was technically very similar to the J series thruster and was tested in the Hughes facility with a frozen mercury target, these test results have fulfilled the 1000 hr test requirement. The 10 000 hr test segment is scheduled to be conducted in the Hughes life test facility. The remaining tests are being or will be conducted in the MPLT facility.

The lifetime verification matrix addresses the question of sensitivity to the thruster operating point by providing for four test segments having different beam currents and three test segments having different discharge voltages. The length of these segments has been selected as 4000 hr since this is of sufficient duration to cause measurable erosion and/or sputter deposition if wear rates are excessive, and allows for easy comparison with previous tests. All of these tests are to be conducted at the MPLT facility.

The test matrix for the MPLT is shown in Fig. 2. This figure includes power processor/thruster assignments and shows the current status and schedule for each segment.

Facility and Test Hardware Description

Vacuum Facility

The MPLT facility is described in detail in Ref. 2 and in companion paper, Ref. 3. The facility consists of three systems, each having a thruster lock chamber which can be isolated from the main tank, data acquisition system, and PPU power system. All three systems are controlled on a time sharing basis by a thruster control computer.

Thrusters

The thrusters under test are the 33 cm J series thrusters.¹ These thrusters operate over a 4:1 power input range up to a maximum of 2700 W nominal. The maximum power corresponds to a beam current of 2 amps at a voltage of 1100 V. This corresponds to a thrust of 130 mN (typical) at a specific impulse of 3000 sec (typical).

Power Processing Units

Two PPU's are available for test. The Electrical Prototype (EP) PPU¹² contains prototype series resonant circuitry which could be later packaged for flight. It contains flight-type magnetics and commercial parts for which flight quality units are available. The mechanical-thermal packaging design is not flight-type since this is an electrical prototype only.

The Functional Model (FM) PPU¹ contains the same circuit design, magnetics and components as the EP/PPU. A complete mechanical-thermal design was done so the FM PPU is a flight weight system capable of surviving vibration and long term vacuum testing.

In addition a lab type power supply system is available for operation of the third MPLT system.

Computer/Software

The computer used for control of the tests is a HP 21MX. The algorithms for thruster control are described below and the software programming is described in Ref. 1. The software for the computer is structured in two parts. The first part provides for thruster control functions which need not be changed as test thrusters and/or PPU's are changed. This part contains basic thruster control algorithms and PPU data acquisition programming. The second part contains set points and calibration constants which may differ from thruster to thruster or from PPU to PPU. All software is input to the computer via paper tape.

To date, two versions of the software computer programs have been used. The first designated 1119, was used for the first 767 hr. Minor deficiencies in the algorithms and programming errors were corrected in the second version, designated 0212, which has been in use since run hour 767.

Thruster Control Algorithms

Demonstration of the adequacy of the thruster control algorithms to control a thruster-PPU for long periods is a major objective of the MPLT. The responsibility for executing a thruster control algorithm can reside with either the PPU control hardware, or the thruster controller software, or both. In general, any function which must be executed within seconds of a sensed state or condition must be handled by the PPU hardware. Those functions which need not be executed in such a short time frame can be handled by the thruster controller software. Table 1 shows the library of thruster control algorithms and the assignment of responsibility for each. Detailed information on the programming of these algorithms is given in Ref. 1.

Vaporizer Control and High Voltage Recycle

The vaporizer closed loop proportional control and high voltage recycle (arc) algorithms require millisecond type responses and hence are handled completely by the PPU hardware. The details of these two algorithms are discussed in the indicated references.

Vaporizer control is checked periodically during a test segment. The most direct method of assessing this algorithm is to check vaporizer control loop response to the controlled step changes which occur during the normal throttle algorithm.

Since the high voltage recycle algorithm is executed periodically throughout the test as normal recycles occur, the effectiveness of this algorithm can be assessed by a review of the entire test segment.

Start-Up

The start-up algorithm is one of the more critical algorithms for thruster control. It is shown in the logic flow chart of Fig. 3. The start-up consist of three preliminary phases; preheat high, preheat low, and ignition heat, before entering the run phase where the beam is extracted. The algorithm is designed to never exceed the minimum possible power availability. This requires the initial beam turn on to be 600 V at 0.75 amp with no overshoot. After a brief period during which software checks are made to assess the success of the start-up and correct any anomalies, the thruster is available to be throttled to whatever power level is available.

The purpose of the preheat high phase is to heat both cathode tips to nominal starting temperatures and to heat the propellant isolator and feed system to temperatures high enough to prevent condensation. These power supply settings are shown in Table 2. The preheat low phase turns on the neutralizer vaporizer and lites the neutralizer keeper discharge, and continues to heat the isolator and feed system but at a reduced power level.

This allows for some pre-determination of the final main vaporizer temperature to achieve proper propellant flow rates for a controlled turn on of the high voltage without beam current overshoot. During this phase, the cathode tip heater remains on. At the beginning of the ignition heat phase the isolator heater power is turned off and the

cathode vaporizer turned on. The main discharge is lit and allowed to idle while control of the discharge is established. At the conclusion of the ignition heat phase, the high voltage is turned on and the beam extracted.

In order to determine if thruster control characteristics relative to the start-up algorithms have changed, thruster start-up is documented at specific intervals during a test segment.

Throttling

The throttling algorithm involves sequentially changing the 5 parameters which define a thruster steady state operating point. These are (1) beam current reference J_B , (2) discharge current J_D , (3) magnetic baffle current J_{MB} , (4) screen voltage V_S , and (5) neutralizer keeper voltage reference V_{NK} . The last four parameters are all some function of the beam current, J_B .

The discharge current is defined by $J_D = 6 J_B + 2$ (amps) for all throttling profiles. The screen voltage is related by $V_S = 400 J_B + 300$ (V) for the throttling profile used in the MPLT. The magnetic baffle current and neutralizer keeper voltage are related to the beam current through the particular thruster acceptance test data.

When throttling down in beam current the parameters should be changed in the order listed above; when throttling up the order is reversed. This procedure insures that the thruster will not drift into a mode where there is excessive propellant flow rate or inadequate screen voltage to extract the referenced beam current. Either of these conditions are primary causes of loss of control and low mode. The order of the magnetic baffle set point and neutralizer keeper voltage set point changes are less important but testing has demonstrated the above order to provide the most stable overall control. As the speed of execution of these set point changes increases the order becomes less important.

In general, these 5 set point changes should be effected within a 5 sec window and each beam current reference should be held for a minimum of 30 sec to achieve stable vaporizer proportional control. Vaporizer control stability also requires beam current reference changes to be made in increments of 0.1 amp or less and screen voltage changes in increments of 50 V or less.

Executing the throttling algorithm periodically throughout a MPLT test segment will highlight changes in the thruster control characteristics as they relate to both throttle and vaporizer proportional control.

Shutdown

The shutdown algorithm involves throttling to the lowest beam current (power level) in the throttle algorithm. When this point is reached, all power supplies are simply turned off.

Pre-Conditioning

Pre-conditioning is a requirement for activating the low work function material within the main and neutralizer cathodes. It involves maintaining power levels for specified times. Each

cathode heater is operated at 2.5 amps (typically 1/3 of start-up power) for 3 hr, then allowed to cool for 30 min and finally operated at normal start up power for 1 hr. The cathodes should again be allowed to cool down prior to a normal start up. Since this algorithm does not involve dynamic control of a thruster, no evaluation during a test segment is required.

Off-Normal Algorithms

Of the five off-normal detection and correction algorithms, four require the PPU to sense the off-normal condition and alert the computer via an interrupt. However, the response speed to the interrupt is not critical within tens of seconds, and thus correction is handled by the computer. In the fifth case, loss of main vaporizer control, both detection and correction are computer functions.

The flow charts of these 5 algorithms are shown in Figs. 4(a) to (e). The general approach in each case is the same. The necessary set point changes and/or resending of applicable set point commands in case of anomalous set point changes, are performed. After a wait which can range from 1 sec to 60 sec, a recheck of the off-normal condition is made. If the condition still exists, another attempt is made. In the case of neutralizer out, J_B , and V_S interrupts, failure to correct in two tries will result in a thruster shutdown. In the case of the excessive arcs algorithm, Figure 4(b), five attempts are allowed. Further a maximum of 10 V_S and/or J_B interrupts are allowed in any 1 hr period. Any in excess of 10 will result in a thruster shutdown.

The low mode algorithm of Fig. 4(e) is the most complex. Low-mode is a term which refers to a loss of control of the main vaporizer. Under normal control, the beam current will increase with increasing main propellant flow. Thus the beam current telemetry signal is used for a negative feedback input to a proportional controller to control the main flow. However, if the main flow becomes too excessive, the beam current will begin to decrease with further main flow increases resulting in a very low beam current and the controller keeping the main vaporizer full on trying to increase the beam. This is the "lowmode" condition. Low-mode is characterized by a high accelerator current (J_A) due to the high neutral flow rates which result. The algorithm turns off the main vaporizer until the accelerator current is again normal at which time closed loop control can be re-established. "Normal" accelerator current varies as a function of beam current level and as a result software programming techniques play a part in determining how the "normal" value is determined and how the necessary checks to prevent trapping operation within a loop are effected.

No attempt to induce a "typical" off-normal condition to exercise these algorithms is made during the MPLT. Experience has indicated that an induced off-normal condition more often than not will complicate software response and make evaluation of the algorithm difficult.

Thruster Performance

Several facets of thruster S/N J1 performance and operation can be compared at different points in the thruster's life to date. Data have been obtained at or near run hours 0, 1175, and 2670 to

characterize basic discharge chamber and neutralizer performance. Throttling, start-ups, and re-cycle have been examined at these points in time to assess the repeatability of thruster operation in these areas. Isolator leakage currents were measured at run hour 2670 for comparison with test start values and at the same time, a telescopic viewing of the grids was made. Further, the uncontrolled thruster electrical parameters have been examined for constancy through the first 2700 hours.

Start-Up and Throttle

Numerous start-up and throttle sequences have been performed through the first 2700 hours. In the absence of extenuating circumstances such as PPU problems or restart attempts too soon after an off-normal shutdown, all start-ups have exhibited the same characteristics. Ignition of the neutralizer and main discharges typically require less than 2 min, the time being governed by warm-up time of the vaporizers. Response of control loops during throttle appears the same at run hour 2700 as run hour 0, requiring typically less than 10 sec to reach equilibrium conditions. No anomalies have been noted which would suggest changes in control characteristics and/or degradation of cathode inserts which adversely affect either the start-up or throttle algorithms.

Discharge Chamber Characterization

The easiest discharge chamber signature to identify and characterize is the magnetic baffle characteristic.¹⁴ Figure 5(a) shows the variation of cathode keeper voltage, V_{CK} , and cathode vaporizer temperature, T_{CV} , as a function of magnetic baffle current, J_{MB} . As J_{MB} is increased, the discharge voltage tries to increase and the control loops will respond by increasing the cathode flow rate, thus keeping the discharge voltage at the 32 V set point. At the same time V_{CK} decreases ~ 100 mV to some minimum value and then begins to increase. At some critical value of J_{MB} , a change in discharge chamber operation occurs. This is evidenced by the large increase in both V_{CK} and T_{CV} (proportional to cathode flow rate). After passing through this transition region, both parameters again become far less sensitive to J_{MB} variations. The normal operating point is generally selected to be the J_{MB} at which the minimum keeper voltage occurs.

The run hour 0 data was taken in the Lewis facility just prior to beginning the MPLT and used different instrumentation than for the characteristics obtained at run hours 1175 and 2670. The latter two characteristics were obtained using FM 1 telemetry and MPLT data support equipment. The important comparison is the value of J_{MB} at which these critical points occur. Since both J_{MB} current meters were calibrated to a third standard, Fig. 5(a) verifies that no change has occurred in discharge operation through 2670 hours. Similar data and results for beams of 1.3 and 0.76 amps at run hours 0 and 2670 are shown in Figs. 5(b) and (c). The difference in the absolute values of V_{CK} and T_{CV} at a given J_{MB} is again due to the different instrumentation used.

Neutralizer Characterization

The neutralizer characteristic is one which relates the neutralizer keeper voltage, V_{NK} , to

neutralizer flow rate or temperature, T_{NV} . These curves are shown in Fig. 6 for normal beam on and beam off conditions. Beam on data is presented for run hours 1175 and 2670. These data were taken using FM 1 telemetry and the same data support equipment at both run hours. The only significant change is a shift of the characteristic to lower vaporizer temperatures. The factors most likely to affect operation in this manner is the slightly higher pressure for run hour 2670 and/or a gradual intrusion of the vaporizer porous tungsten plug by liquid propellant. This latter effect has been noted in other tests⁷ and is believed to be associated with tungsten porosity and/or vaporizer fabrication techniques.

Figure 6 also shows run hour 0 and 2670 beam off characteristics. These data were generated in different facilities with different instrumentation. Thus direct comparison is somewhat difficult. However, all characteristics do tend to exhibit the same voltage levels for the same beam current operating points.

Figure 7 shows the minimum value of V_{NK} obtained from characteristics like those of Fig. 6 as a function of J_B . These curves are all within a 650 mV band. Considering the number of factors such as facility pressure and instrumentation differences which can affect these parameters, this is felt to be good agreement. Note for example the difference between the two run hour 0 curves at 2 amps is essentially the same as for the two characteristics taken 1500 hr apart. The only noticeable difference appears to be the low V_{NK} (min) at low beam for the Hg target MPLT facility opposed to a non-Hg target facility. None of the above mentioned anomalies are consistent with or believed to be caused by neutralizer insert degradation.

However, some difficulty of neutralizer response to a high voltage recycle has been noted. As will be discussed, there have been a significant number of instances of the neutralizer going out. It is felt that virtually all of these instances were caused by a high voltage recycle situation. During that portion of the recycle sequence when the high voltages are off, the neutralizer keeper current is switched by the PPU from 1.8 amps to 2.4 amps. This change in state occurs at essentially constant neutralizer flow rate since recycle times are on order of only several hundred milliseconds. This means the neutralizer operation must change along and vertical line from the beam on characteristic (fig. 6) to the beam off characteristic. This operation is momentarily close to or exceeds the maximum voltage of the neutralizer keeper supply and this quite probably, because of the plasma dynamics involved, is the cause of neutralizer out conditions resulting from high voltage recycles. Several possible means of changing the curves of Fig. 6 are currently under investigation. Other than this neutralizer anomaly, no problems with the high voltage recycle sequence have been noted through the first 2700 hours.

Thruster Electrical Parameters

Another indication of change in thruster performance with time is a change in the uncontrolled electrical parameters with time. For example, the cathode keeper voltage, V_{CK} , is uncontrolled and a change in the main cathode emission characteristics would be reflected by a change in V_{CK} .

Similarly, the neutralizer floating potential, V_G , would be indicative of neutralizer changes and the accelerator impingement current would change with changes in the ion production and/or extraction processes.

Since each of these parameters is a function of facility pressure and other ambient phenomena, comparisons must be made only after several hours of running such that equilibrium conditions can be established. Figure 8 shows V_{CK} as a function of run hour for times which fulfill this requirement. These values are constant to less within one telemetry count (1 count = 0.18 V). Note that the telemetry values for the EP and FM are slightly different. During operation with the EP the cathode keeper supply randomly turned off, preventing data in the periods shown. The neutralizer floating potential as read by PPU telemetry was constant at $9.242 \text{ V} + 0.87 \text{ V}$ (+1 count) with the EP and constant at $7.52 \text{ V} + 0.87 \text{ V}$ (+1 count) with the FM. The accelerator impingement current was constant at $4.7 \text{ mA} + 0.2 \text{ mA}$ (+1/2 count) with the EP and constant at $3.77 \text{ mA} + 0.2 \text{ mA}$ for the FM.

Mercury Propellant Isolators

The mercury propellant isolator leakage currents were measured at run hour 2670 with all other thrusters off. Leakage currents were typically 25 μA at 1000 V. This is considered to be slightly higher than expected, it is not indicative of leakage problems. It should be noted that the electrical configurations of this thruster requires both main and cathode isolators and numerous electrical standoffs be evaluated while connected in parallel. The combined leakage of main and cathode isolators on thruster 901 after 4165 hours was $\sim 40 \mu\text{A}$.

Visual Inspection

The accelerator grid of the thruster was scanned at run hour 2670 with a high power telescope. The only anomaly found was what appeared to be a small metallic sliver shown in the photo of Fig. 9. Evaluation of the source of this sliver from the photo is difficult. The sliver is located at approximately 1 o'clock using the neutralizer as a 12 o'clock reference, and approximately 2.5 cm in from the last row of accelerator grid holes. No other anomalies were found on the grid face. It should be noted that this particular grid set had accumulated more than 1500 hr of test prior to the MPLT.

Inspection of the baffle as viewed through the grids showed no apparent erosion or spalling problems. Final determination must wait until the test is complete, at which time thruster components can be examined in detail and total propellant usage measured.

Chronology of Test Events

The first test segment of the MPLT described in this paper can be further divided into 3 sub-segments according to PPU and software program. These sub-segments are shown in table 3. During the first sub-segment, complications arose from both the EP/PPU and software program (1119) deficiencies. The software deficiencies were corrected at run hour 767 by changing to software program 0212. At run hour 1013, the FM/PPU S/N 1 was substituted

for the EP/PPU. Each change significantly improved the operational reliability of the test. A general discussion of the subsegments 1 and 2 is presented, followed by a more detailed discussion of sub-segment 3.

Run Hours 0 to 1013

The first 652 test hours were generally uneventful. However, at run hour 652, the EP PPU began to randomly change set points and fail to respond to some commands. The neutralizer keeper, cathode keeper, cathode tip supplies, and the inverter common to these supplies would turn off while running and/or fail to respond to an on command. To assess the nature of these problems, the EP/PPU was operated at atmosphere from run hour 652 through 733 (81 hr). This helped but did not eliminate the problems. The EP/PPU was then operated in vacuo from run hour 733 to 767 (34 hr) at which time the EP/PPU was permanently committed to air operation.

Other complications arose from deficiencies in software tape 1119. During a neutralizer out condition, the software would erroneously turn on the high voltage leading to severe arcing, which would in turn generate enough noise to set the solar array interrupt signal. The software, thinking that the input DC voltage had been lost, commanded a system shutdown.

Another serious flaw in system control arose from the PPU telemetry design which permitted all telemetry channels to roll over to zero rather than saturating at full scale when the 7 bit telemetry register was exceeded. This feature misled the software during the low mode correction algorithm into believing that accelerator impingement currents were low, when actually they were in excess of the 25 mA range of the telemetry. The software was unable to correct low mode under these conditions.

The telemetry design deficiencies were corrected in all hardware and the software was reprogrammed. Use of software program #0212 was begun at run hour 767 and has been in use since.

During the first two sub-segments totalling 1013 hr there occurred 15 neutralizer out interrupts. Thirteen of these eventually resulted in system shutdown, with the immediate cause usually being the inability to cure the resulting low mode condition due to the telemetry overflow. In 5 of these events, the neutralizer keeper supply was known to have turned off. The supply status in the other events is not known. The first neutralizer event occurred 487 hr after the start of the test segments; the second event 163 hr after the first event, and all succeeding events on an average of 41 hr after the previous event.

At run hour 1009, the EP/PPU was removed from the PPU chamber where it had been operated at atmosphere with water cooling and installed next to the facility where cooling was done by fans. Initially, this cooling was inadequate, and resulted in 3 shutdowns due to high PPU temperatures. During the trial attempt to start at run hour 1013, the excessive temperatures apparently caused failure of the beam supply transformer insulation causing a short.

Run Hours 1013 to 2700

The chronology of FMI/J1 testing is shown in table 4. Testing from run hour 1013 to 1015 were for the purpose of checking out the FMI. The period from 1015 thru 1175 had 4 neutralizer out events. During the last event, a PPU latch-up occurred. This involves both input SCR's being turned on and shorting the input bus. Due to failure of the protection hardware, the PPU was allowed to operate this way for several hours. From run hours 1175 to 1180 thruster characterization data was taken manually.

During run hours 1013 through 2700, 28 neutralizer out events occurred, 8 of which caused a system shutdown when the computer software was unable to relite the neutralizer. No distinct quantitative pattern is evident on examining the chronological data. It is believed that these events are caused by the neutralizer going out on a high voltage recycle and it also appears that these events occur more frequently with time for any one period. In 11 instances, the neutralizer would quickly relite within a matter of seconds and normal operation was then resumed; in other instances the software program must re-enter the start-up algorithm at pre-heat low as shown in Fig. 4(a). The only other anomalous events were four instances of low mode which are believed to have resulted from a high voltage recycle.

At run hour 2670, thruster J1 was again characterized to provide for performance comparison with data taken at run hour 1175 and data taken prior to the start of the MPLT as previously discussed.

During run hours 1013 through 2700 (and continuing), the FM/PPU was operated in vacuum. Cooling water temperature was maintained at a temperature of 49.2° C and base plate temperatures near the beam supply transformer were 58° C.

Conclusion

The first test segment of the Mission Profile Life Test involving thruster J1 has completed 2700 hr of a planned 4000 hr test. The last 1600 hr using the functional mode PPU S/N1. Comparison of data taken at the beginning of the test, at run-hour 1175, and at run-hour 2670 has indicated no change in thruster performance and operation over this time span. Thruster control algorithms have been shown to still provide effective control of the thruster. The uncontrolled thruster operating electrical parameters; cathode keeper voltage, neutralizer floating potential, and accelerator impingement current have all remained constant throughout.

The only operational anomaly appears to be an increasing tendency for the neutralizer to go out during a high voltage recycle (arc). Evaluation of the erosion and spalling characteristics must wait for completion of the test segment when a detailed examination of discharge chamber component can be made. A single sliver was noted on the grids during the examination conducted at run hour 2670. However, its origin and other circumstances are not known. No other anomalies involving discharge chamber erosion and spalling have been noted.

In general, no results inconsistent with a 15 000 hr useful lifetime have been noted.

The FM/PPU has demonstrated almost 1700 hr of vacuum operation with typical base plate temperatures of 58° C. Although the PPU has experienced several latch-ups of the SCR's, no component damage has been experienced. Design modifications to lessen the latch-up problem will be incorporated at the tests conclusion.

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TABLE I. - THRUSTER CONTROL ALGORITHMS

Algorithm	Responsibility
Vaporizer control High voltage arc (recycle) Start-up Throttle Shutdown Precondition Off-normal Neutralizer out Excessive arcs Beam current out of limits Screen voltage out of limits Loss of main VAP control (low mode)	PPU13 PPU14 Comp/PPU Comp Comp Comp Comp/PPU Comp/PPU Comp/PPU Comp/PPU Comp

TABLE 2. - THRUSTER SUPPLY CONDITIONS DURING STARTUP PHASES

Phase	Main vap, A	Cath vap, A	Neut vap, A	Cath tip, A	Neut tip, A	Neut kpr, A	Neut kpr set, V	Cath kpr, A	Disch/sol htr, A	Discharge, A	Discharge set, V	Screen/accel (hi voltage), V	Beam set, A	Mag baffie, A
Off	Off	Off	Off	4.25/0*	Off	Off								
Preheat hi	Off	Off	2.0	4.25/0*	4.0/0*	On	17V	On	7.0	X	X	Off	X	Off
Preheat lo	Off	Off	2.0	4.25/0*	4.0/0*	On	17V	On	5.0	X	X	Off	X	X
Ignition-heat	Off	2.0	2.0	4.25/0*	4.0/0*	2.4	17V	1.0	X	6.5	36	Off	X	1.5
Run	1.5	2.0	2.0	4.25/0*	4.0/0*	1.8	15V	1.0	X	6.5	32	600/300	0.75	1.8

*Current at hi value if corresponding discharge is not lit and at zero if it is lit.

TABLE 3. - SUB-SEGMENTS OF THRUSTER J1 TEST SEGMENT

Sub-segment	Run hours	PPU	Software
1	0-767	EP	1115
2	767-1013	EP	0212
3	1013-2700	FM-1	0212

TABLE 4. - CHRONOLOGY OF TEST OF THRUSTER S/N J1 WITH FM/PPU S/N1 THROUGH RUN HOUR 2700 EVENTS INDICATED BY RUN HOUR AT WHICH THEY OCCURRED

Start-up	Neutralizer out	Low mode	Shut down due to			Start-up	Neutralizer out	Low mode	Shut down due to				
			Anomaly	Latch-up	Facility				Schedule	Anomaly	Latch-up	Facility	Schedule
1013						1496	1613*			1613			
1013						1613	1614*			1614			
1014			1015			1614		1869 1904					
1015	1024* 1147 1156* 1175						1974 2008						
1175			1175			2095				2310			2095
1177					1177	2310	2310* ²			2310			
1178					1178	2310	2310* ²			2310			
1180					1180	2310		2312					
1182			1182				2336 2361*						
1182										2361			
1251 ¹						2361	2401 2419*						
								2419					
			1479			2575	2461 2482					2573	
1479	1496*		1496				2577 2601 2608 2623						

All neut out events for which data available indicates H.V. recycle. * = Repeat FHT Ia.

¹Shutdown caused by anomalous operation of adjacent system.

²Neut out shutdown during start-up.

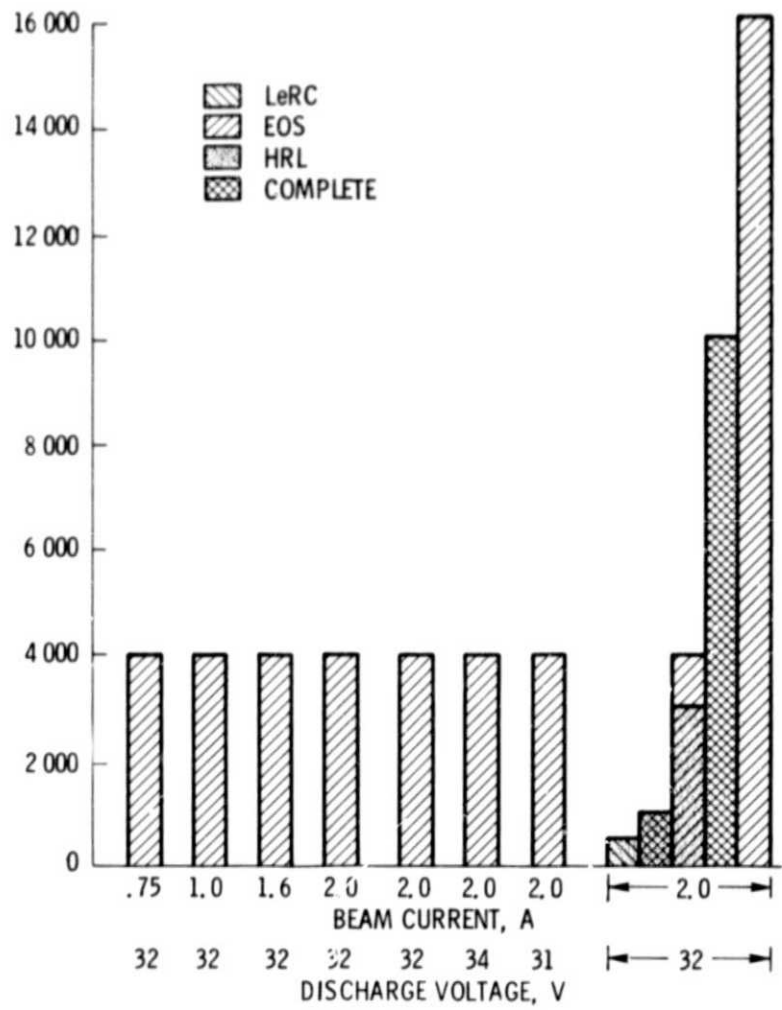


Figure 1. - Life verification test matrix.

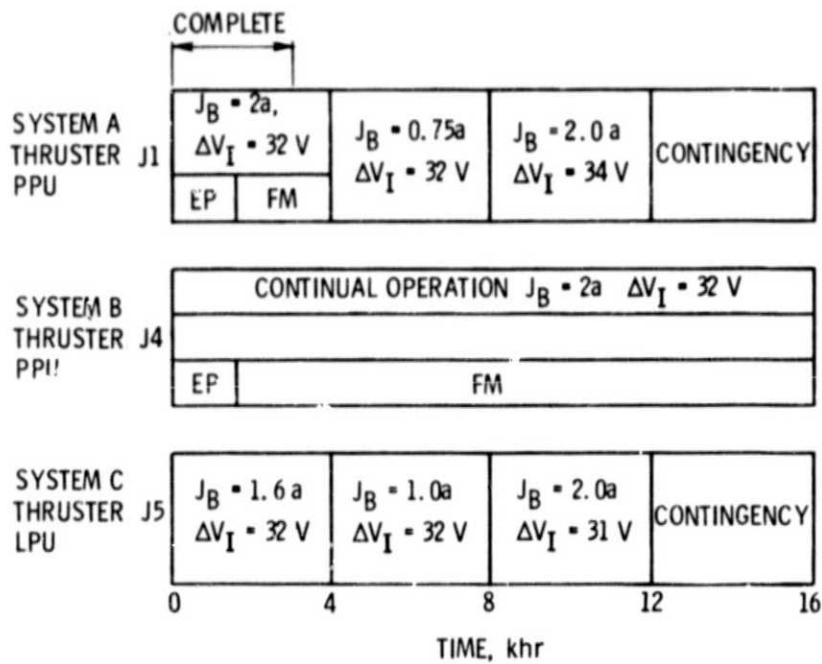


Figure 2. - Mission profile life test matrix (tests will not necessarily run concurrently). J_B = beam current; ΔV_I = discharge voltage.

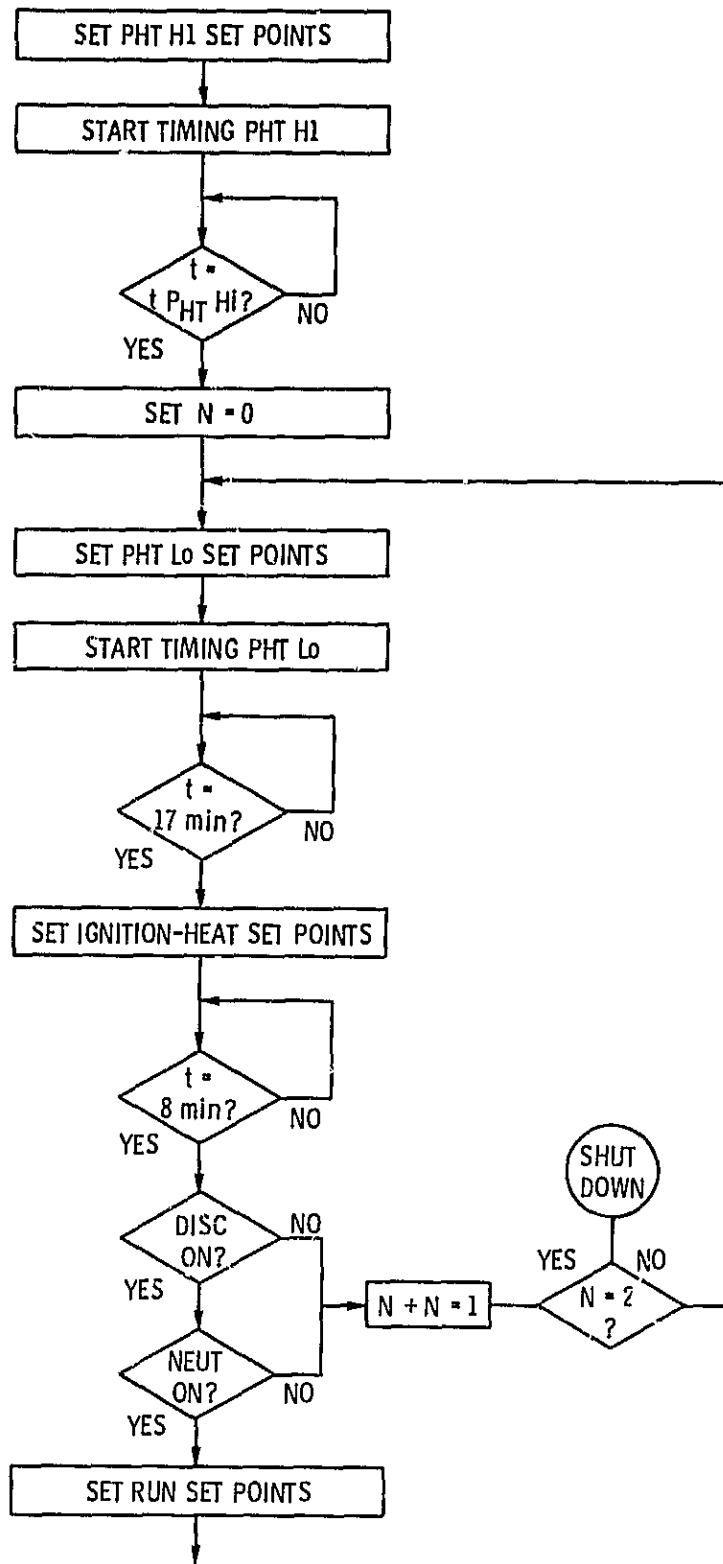
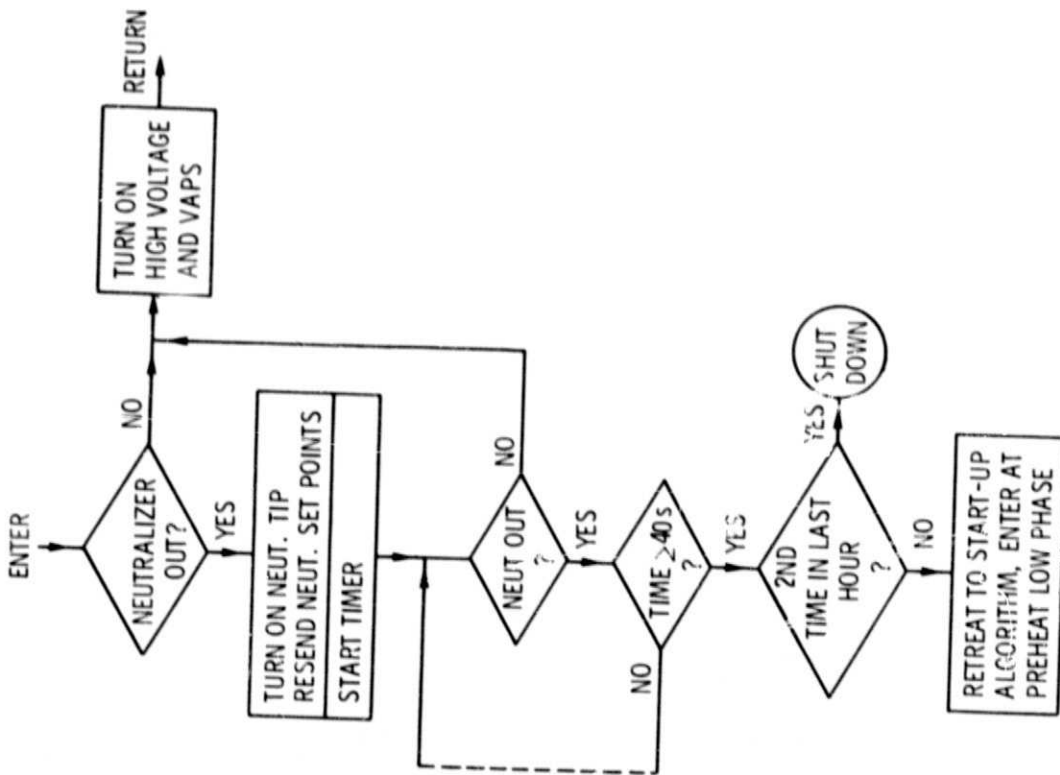
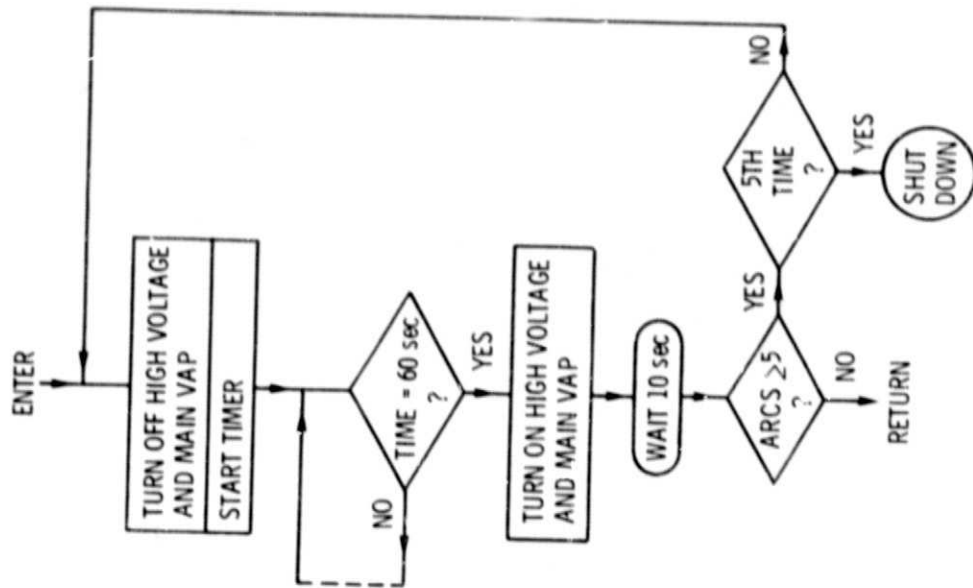


Figure 3. - Thruster start-up algorithm.



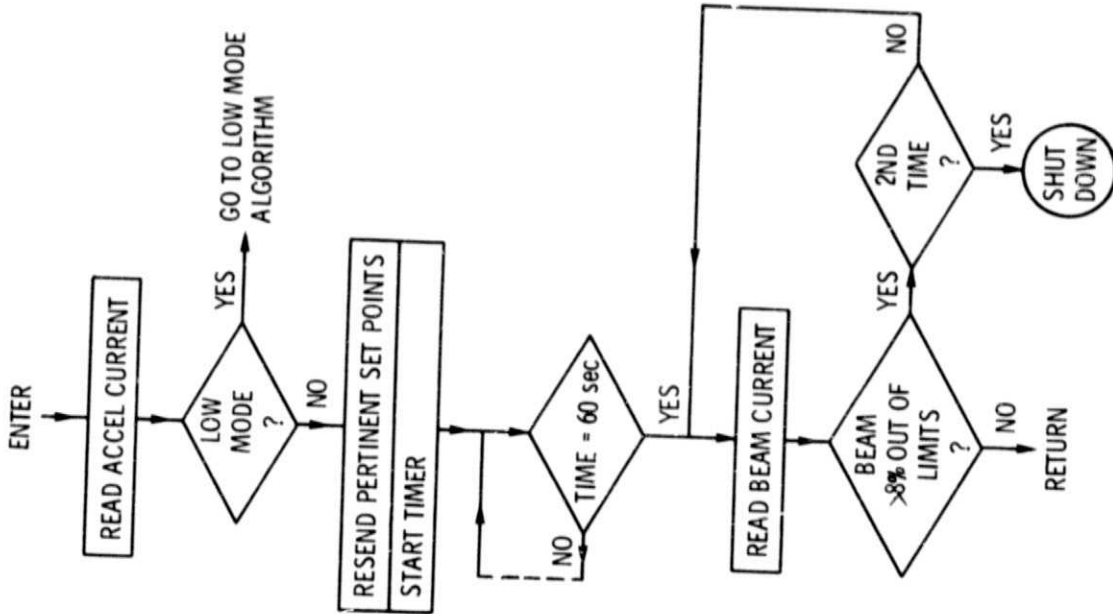
(a) NEUTRALIZER OUT.

Figure 4. - Off-normal algorithms.



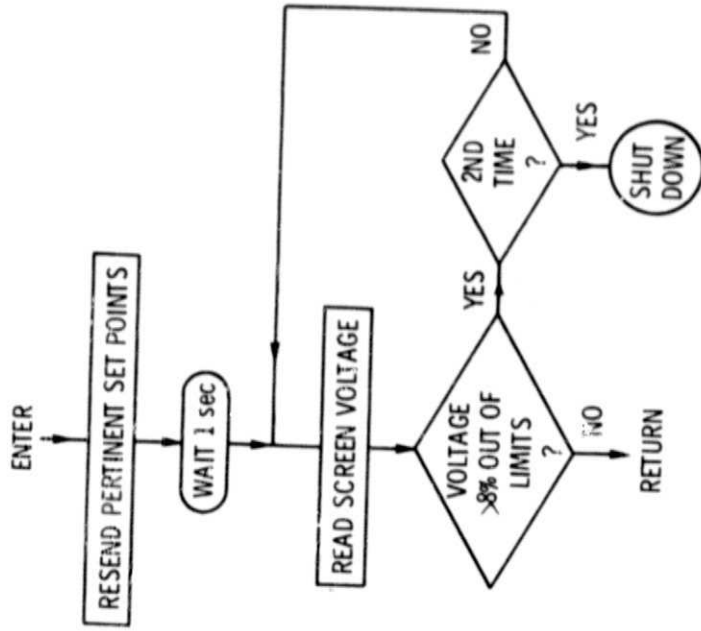
(b) EXCESSIVE ARCS.

Figure 4. - Continued.



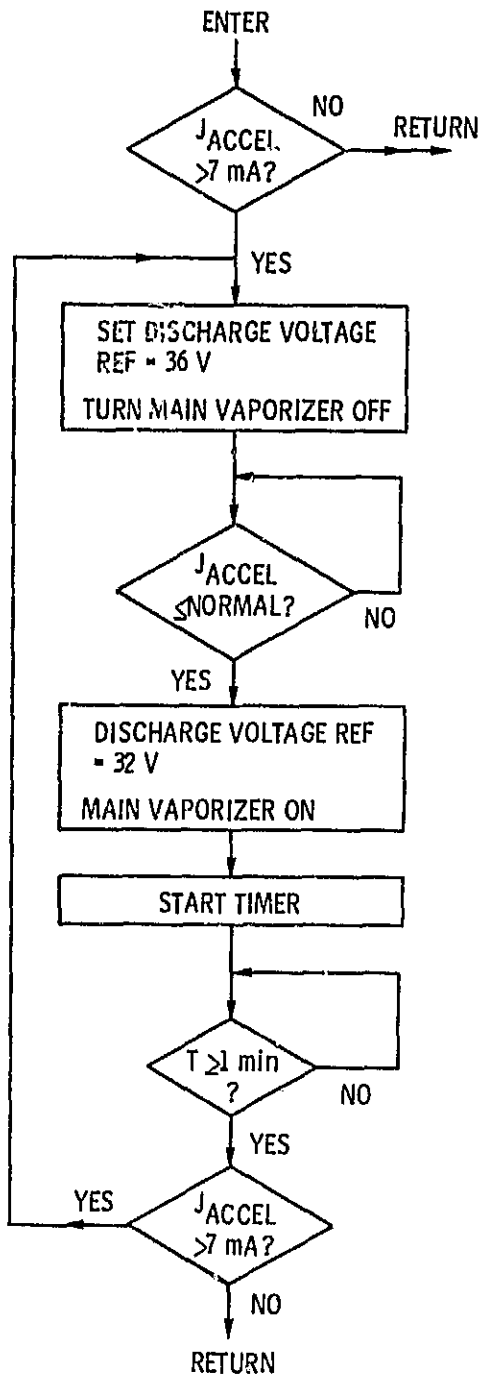
(c) BEAM CURRENT INTERRUPT.

Figure 4. - Continued.



(d) SCREEN VOLTAGE INTERRUPT.

Figure 4. - Continued.



(e) LOW MODE ALGORITHM.

Figure 4. - Concluded.

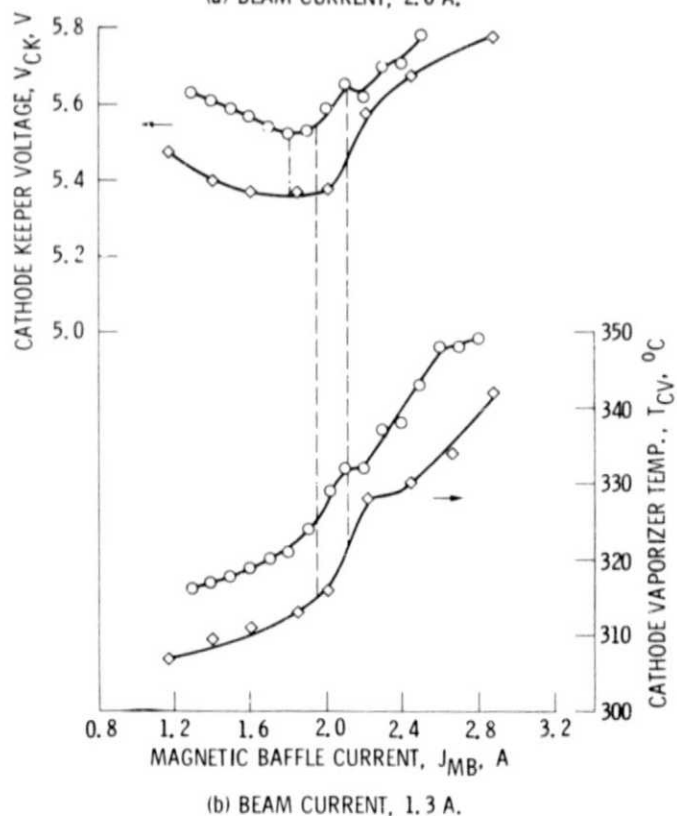
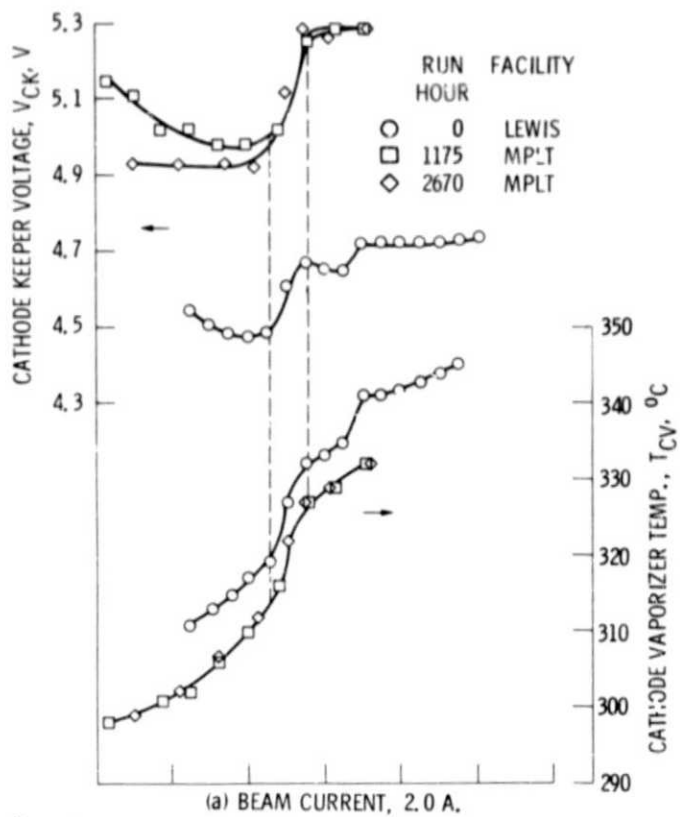
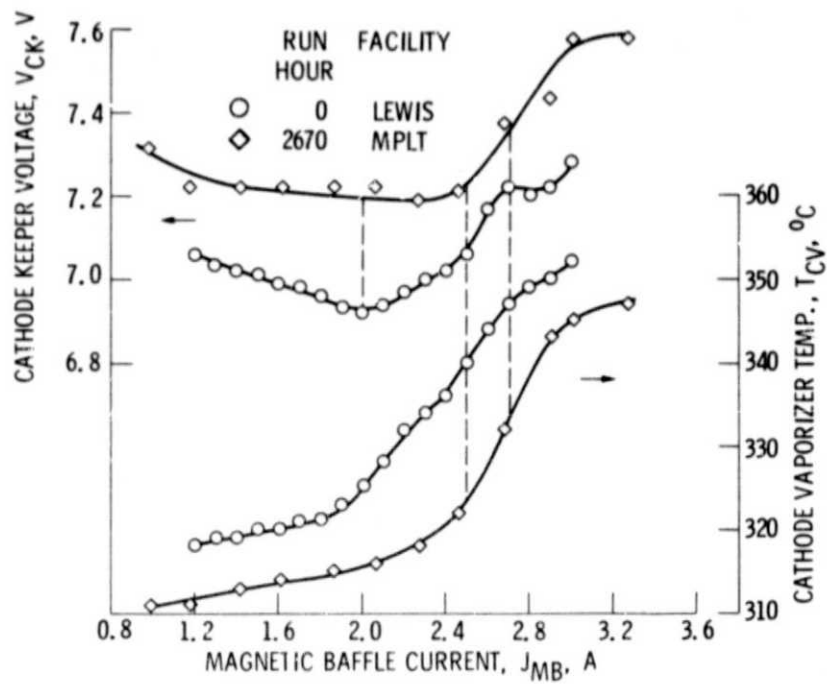


Figure 5. - Discharge chamber characteristics for thruster S/N J1.



(c) BEAM CURRENT, 0.76 A

Figure 5. - Concluded.

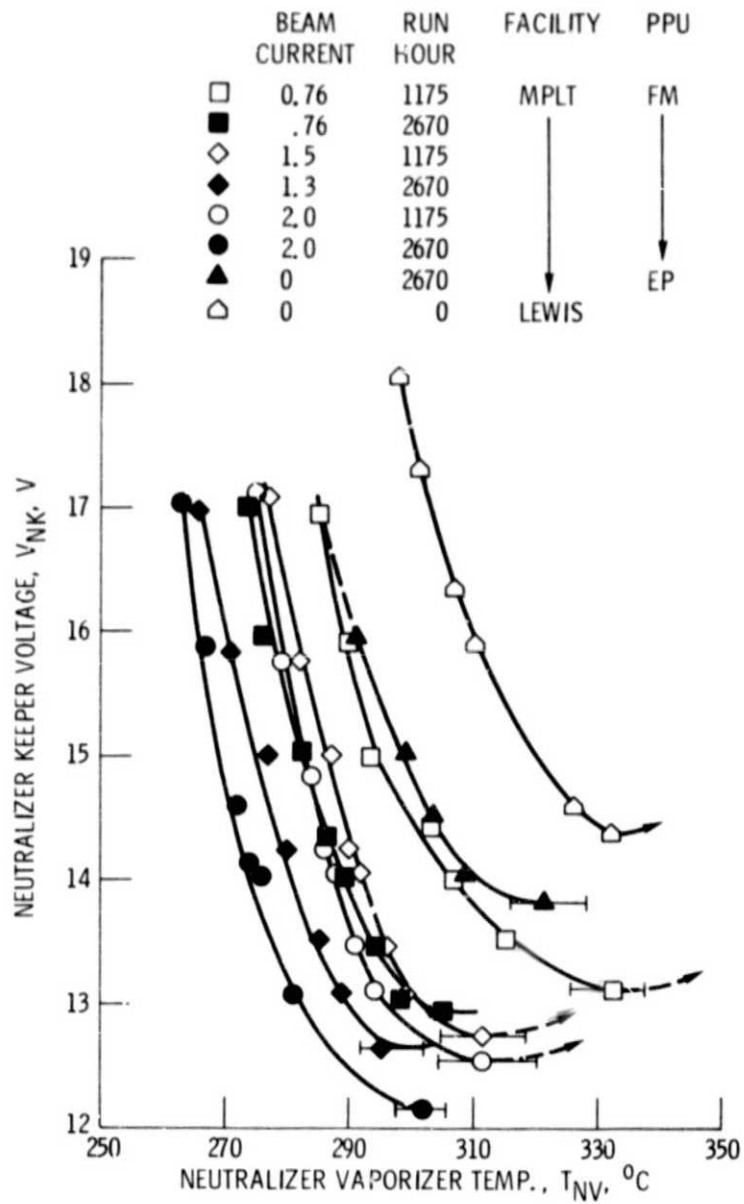


Figure 6. - Neutralizer characteristics for thruster S/N J1. Neutralizer keeper current, 1.8 A with beam; 2.4 A without beam.

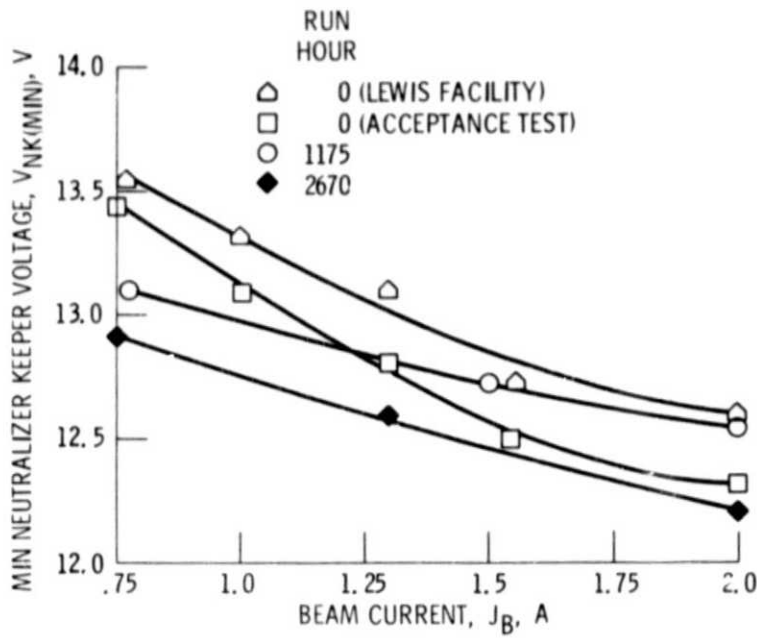


Figure 7. - Minimum neutralizer keeper voltage as a function of beam current for thruster S/N J1.

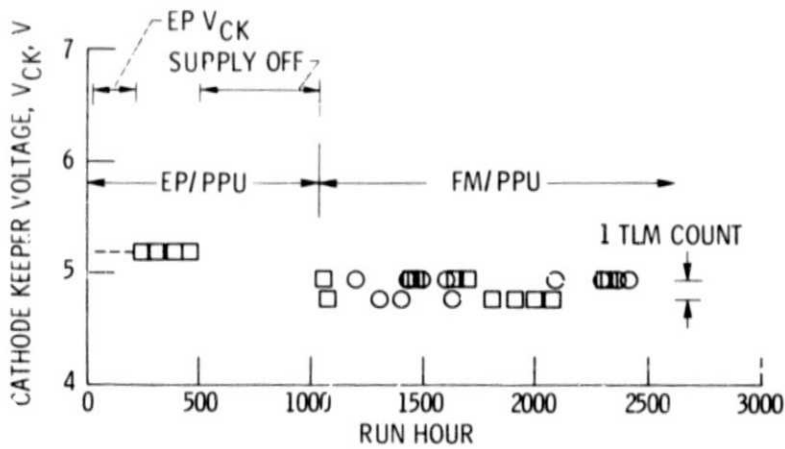


Figure 8. - Cathode keeper voltage as a function of time for thruster S/N J1.



Figure 9. - Photograph of sliver on grids of thruster S/N J1 at
run hour 2670.

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