Operation of a Lightweight Power Conditioner with a Hollow-Cathode Ion Thruster

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Experimental system studies are under way on solar-electric primary propulsion for deep space probes, using a 20-cm-diam electron-bombardment ion thruster that has a hollow cathode as an electron source and mercury as the propellant. The thruster output power can be varied from 1000 to 2000 w with small penalties in total efficiency. A lightweight power conditioner, originally designed for operation of an ion thruster employing an oxide cathode, has been modified to accommodate the hollow cathode. The thruster and power conditioner redesign, thruster control loops, and recycle procedure to clear sustained arcs are described. Data are presented on operation with the thruster.

Introduction

THE solar electric propulsion system test (SEPST) program[1] at JPL is directed toward establishing the technology which would be required for unmanned interplanetary missions.[2,3] This paper is concerned with the thruster and power conditioning unit (PCU). Flight durability tests of an ion thruster employing a hollow cathode (i.e., cathode that uses a mercury plasma) electron source[4] with a 27-lb/kw PCU[5] are under way. The long lifetime and high efficiencies that have been obtained for this type thruster have resulted in the JPL test being modified to incorporate a 20-cm-diam hollow-cathode thruster. The PCU is a redesigned lightweight unit (originally designed and fabricated by the Hughes Aircraft Company[6]) that would be suitable for most electric propulsion missions.

The system was operated over a continuous range of output power from 1 kw to 2 kw to simulate matching power to a solar panel output in a varying solar-constant environment. Control loops for the control of beam power level and mercury propellant utilization were implemented within the PCU. Response of the system to thruster arcing, modifications to both the thruster and power conditioning unit, and results of their operation and integration are described. These modifications are to be implemented in lightweight power conditioning units with high-reliability goals, such as described in Refs. 7 and 8.

Thruster Design

The present thruster (Fig. 1) utilizes two porous tungsten vaporizers to supply mercury propellant to the hollow cathode and directly to the arc chamber, because dual vaporizers are more compatible with present thruster control and output power throttling schemes. This thruster, with the exception of the hollow cathode, cathode pole piece, and accelerator screen grid geometry, is the thruster used in the system tests described in Ref. 9, where an oxide cathode was the electron source. A conventional two-grid ion-accelerating structure was used because of the long experience and proven dependability of this grid type. The accelerating grid geometry was modified from that used in Ref. 9 to provide high-perveance ion optics. Grid dimensions are included in Fig. 1. Three support rods between the cathode pole piece and screen grid were employed to maintain the spacing between the grids.

The unique features of the design cathode pole piece (Fig. 2) are the baffle mount and the plasma retaining screen. The screen serves to reduce the surface area within the pole piece as suggested in Ref. 10. The baffle was mounted so as to provide radial propellant feed from the cathode pole piece. A similar approach was suggested in Ref. 11 and was found beneficial in reducing accelerator current levels.

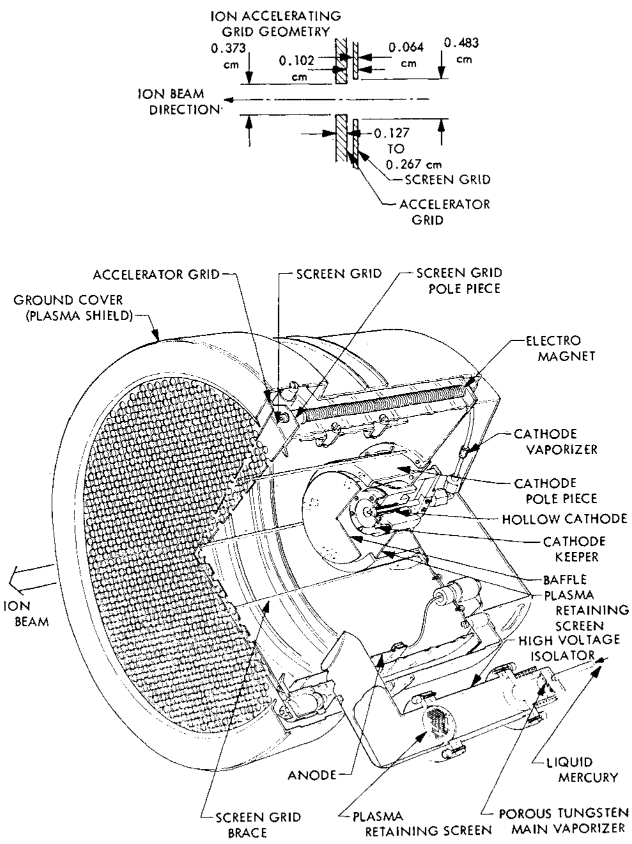

Fig. 1 The 20-cm-diam hollow-cathode ion thruster.

Presented as Paper 70-648 at the AIAA 6th Propulsion Joint Specialist Conference, San Diego, Calif., June 15–19, 1970; submitted June 24, 1970; revision received October 29, 1970. This work presents the results of one phase of research carried out at the Jet Propulsion Laboratory, California Institute of Technology, under Contract NAS 7-100, sponsored by NASA.

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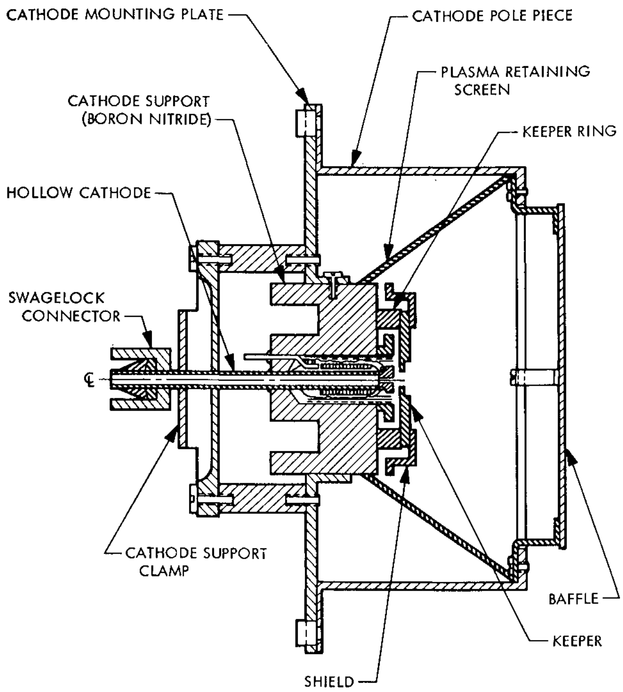

Fig. 2 Cathode pole piece design details.

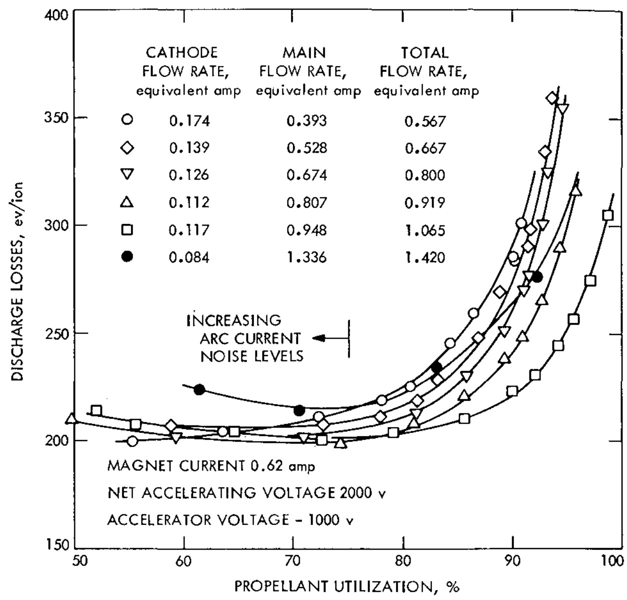

Fig. 3 Effect of propellant flowrate on discharge loss.

Thruster Performance

Thruster testing was performed in a 3 × 7-ft vacuum chamber maintained at pressures between 2 and 8 × 10^{-6} torr, with mercury flow rates from 4.25 to 10.65 g/hr (0.567 to 1.420 equivalent amp of Hg^+), using a plasma bridge neutralizer ~1 m downstream from the accelerator surface. Neutralizer operation was found necessary in order to permit low, steady-state levels of accelerator current. Large and erratic current levels were present when the neutralizer was not functioning. The thruster operation was maintained at a net accelerating voltage of 2 kv corresponding to an electrical specific impulse of 4450 sec. Because of the increased perveance of the ion extraction geometry, the accelerator voltage could be reduced to 1 kv instead of 2 kv as used in prior tests. This reduction lowered the power required of the accelerator supply and reduced the energy of ions impinging on the accelerator grid, thereby enhancing its life. An arc voltage of 35 v and a propellant utilization (ion beam/input mercury flow in amps of Hg+ equivalent) of 90% were selected for nominal operating levels.

The arc chamber losses (arc chamber power per beam ion) are presented against propellant utilization in Fig. 3 for several values of mercury flow rate. The arc voltage varied between 30 and 40 v during this mapping and was 35 v in the neighborhood of 90% propellant utilization. The arc current noise level, which was monitored by a high-speed chart recorder, usually exhibited a frequency near 300 Hz and increased in amplitude with decreasing propellant utilization. The noise-producing mechanism is not understood at this time. Thruster power losses and efficiency are presented in Table 1 for output power throttling over a 2.6:1 range for data points nearest 90% propellant utilization. Thruster efficiency, when corrected for neutralizer operation, is higher than the values predicted in Ref. 12.

Figure 4 presents the effects of propellant flow through the cathode on thruster operation. Data are presented for nominal one-half and full thruster power. The arc voltage and beam currents are shown in these figures since the cathode flow is used to control the arc voltage V_a directly and can indirectly affect the beam current, which is controlled by a second loop. For both main vaporizer flows presented, the arc could not be maintained below cathode flow rates of 0.04 equivalent amp of Hg^+ (0.3 g/hr). As the cathode flow was increased, V_4 passed through a minimum. Operation at cathode flow rates higher than the rate at which the minimum V_4 occurred resulted in increasingly noisy arc current signals. A V_4 of 35 v appears to present adequate operation over the range of thruster output power of interest, providing margin for control and avoiding both potential problem regions.

A more detalied description of the thruster and performance is presented in Ref. 13, and Refs. 14 and 15 present initial investigations of the arc current noise levels and the thruster control loops operating with laboratory power supplies.

Power Conditioner Design and Performance

A previously developed power conditioner[6] was modified[9] to operate a 20-cm-diam oxide cathode thruster. The operat-

Table 1 Hollow-cathode ion thruster performance data (net accelerating voltage, 2000 v)

Hg flow rate, equivalent amp	Arc voltage, v	Beam current, amp	Beam power, w	Power losses, w: Arc chamber	Accelerator	Cathode	Magnet-manifold	Main vaporizer	Efficiency, %: Power	Propellant utilization	Total
0.567	37.7	0.506	1012	153	11.1	4.6	8.0	9.9	84.5	90.8	76.7
0.667	36.9	0.610	1220	182	9.4	7.1	8.6	10.0	84.8	91.5	77.6
0.800	36.9	0.732	1464	203	7.5	9.9	8.5	11.4	85.9	91.6	78.6
0.919	35.2	0.836	1672	208	8.9	7.7	8.2	12.5	89.2	91.0	79.4
1.065	34.0	0.980	1960	226	12.1	5.7	8.8	11.8	88.1	92.1	81.1
1.420	36.6	1.310	2620	361	20.0	4.8	9.3	12.8	86.6	92.3	79.9

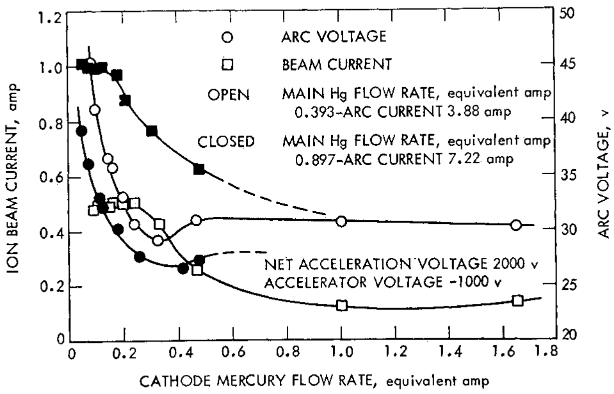

Fig. 4 Effect of cathode mercury flow on thruster performance.

ing power level of the thruster was specified by a single reference signal setting the beam current. The arc current reference for each operating point was generated by a function generator located within the PCU. The following further modifications were made to meet the requirements of a hollow-cathode thruster (the power requirements are included in Fig. 5 with the new and redesigned supplies designated): 1) new supplies to provide the power requirements for the cathode vaporizer, heater, and keeper; 2) a current regulated arc supply with higher power output capability; 3) reduction of the accelerator supply output voltage; 4) introduction of the arc voltage-cathode vaporizer current control loop; 5) introduction of the arc-current/cathode-heater-current control loop; 6) modification of the function generator; and 7) new circuits to provide telemetry outputs for the cathode supplies.

To accommodate the new and redesigned supplies, PCU was repackaged—several modules were reconstructed to remain within the boundary dimensions of 25.5 × 30 × 6 in. The weight was 37 lb including 5 lb of cabling (2 lb heavier than the original unit). The low specific weight proclaims the advantages of the modular concept of packaging. Individual modules operate at power levels where high-frequency transistors are available. High reliability can be achieved by operating components at low specific stresses. The low-power dissipation of each module eliminates the need for additional radiators and heavy heat conduction paths because the mounting chassis can be large enough to dissipate losses by direct radiation to space. The interconnections between the PCU and thruster are shown in Fig. 5. A block diagram of the PCU is shown in Fig. 6.

The accelerator consists of two modules, one operating and one on standby, containing a free-running inverter at 12 kHz followed by a transformer rectifier circuit. The output is modified to provide a nominal output of 100 ma at 1100 v and square-wave drive for the screen inverter. No modifications were introduced in the beam power supply. Seven converters in series provide the power requirements. An eighth converter on standby can replace a failed unit, identified by the digital logic, if necessary. A common filter is utilized by all converters.

The arc power supply also comprises one operating and one standby module. The required current regulation has been achieved by employing pulse-width-modulation techniques. A magnetic amplifier is used to measure the output current of the supply; its output is processed through a differential amplifier and compared to an adjustable reference. The generated signal pulse-width-modulates the inverter drive to maintain the current regulation. A 0 to 5 v adjustable reference source, derived from the function generator, modifies the output of the supply to the desired point of

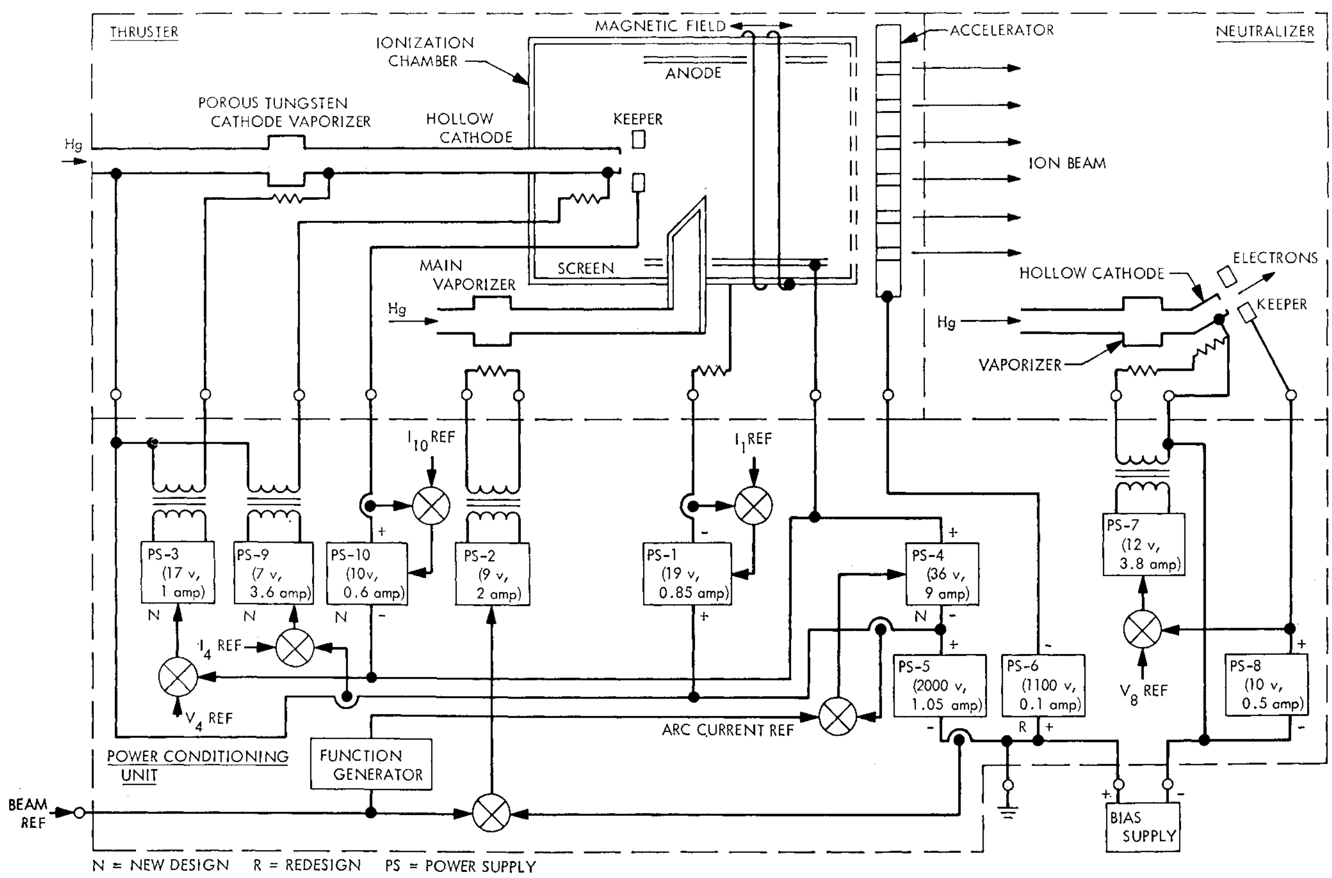

Fig. 5 Interconnections between power conditioner and thruster.

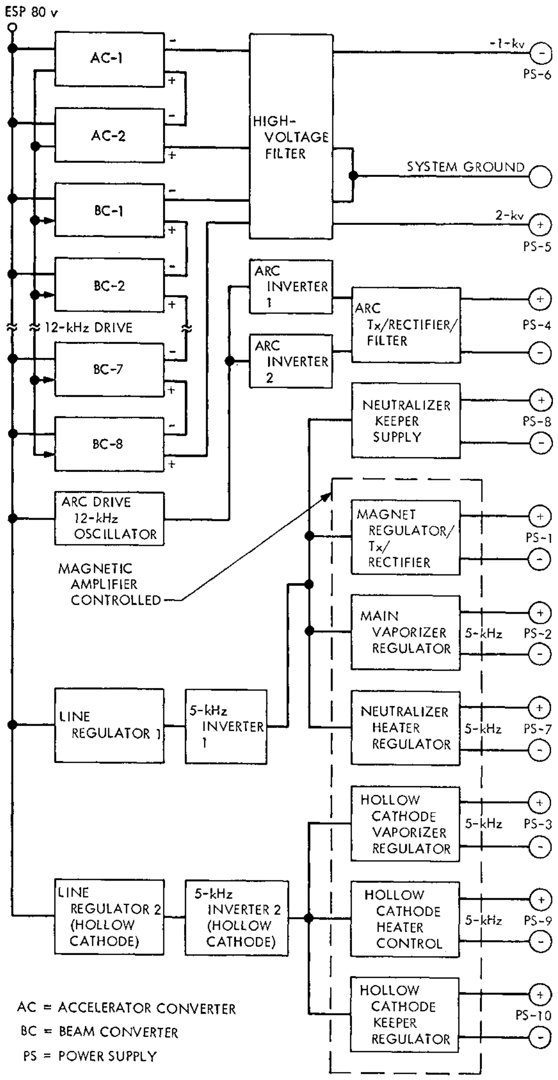

Fig. 6 Block diagram of power conditioning unit (PCU).

operation, which could extend from 2 to 9 amp (Fig. 7). The drive to the inverters is obtained from a free-running inverter operating at 12 kHz.

Two modulator subsystems within the PCU provide the power requirements of the cathode, magnet, vaporizer, and neutralizer supplies. One, unchanged from the original design, comprises a line regulator which powers a free-running inverter at 5 kHz to drive four modulator circuits. The modulators are the power supplies of the neutralizer keeper,

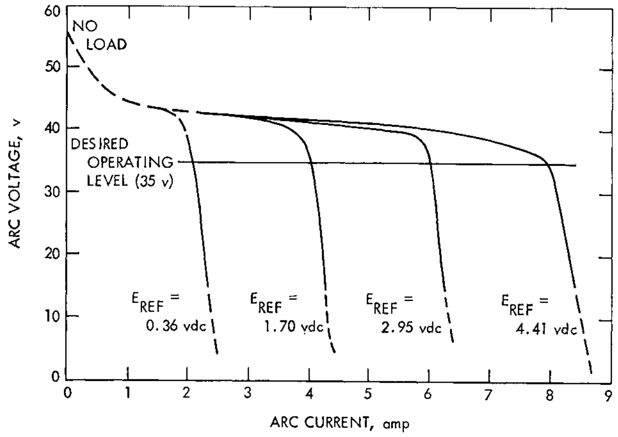

Fig. 7 Arc power supply characteristics.

neutralizer heaters, thruster vaporizer, and magnet-manifold heater. A new modulator subsystem uses another regulator and another free-running inverter at 5 kHz (formerly a redundant unit) to drive three cathode supplies (cathode heater, keeper, and vaporizer). Magnetic modulation techniques provide the regulation and control required.

The beam current reference signal is used to specify the arc current reference by means of a function generator. A linear relationship between beam and arc current can be used to determine the necessary arc current at a propellant utilization in the neighborhood of 90%.

Except for the accelerator and beam supplies, all power supplies of the PCU are short-circuit-proof; excessive current through the accelerator or beam supplies will cause these supplies to shut down. To maintain system operation and limit the beam and accel currents during turnon transient conditions, a recycle procedure was required. The recycle necessitated the shutdown and restart of the magnet and main vaporizer power supplies. The magnet supply was ramped slowly to full output to approach operating conditions without overshoot. The overcurrent trip sensors and tripping delays used are: beam current, 1.09 amp and 2 msec; accel current, 106 ma and 5 msec.

Control signals provided to the power conditioner are the same as described in Ref. 9, i.e., 1) start the system, 2) regulate the thruster output power, and 3) shut down.

The PCU has special outputs suitable as inputs to a decoder. Fifteen parameters, considered essential for determining proper functioning of the thruster, are available as telemetry outputs at a 0 to +5 v level.

The original design of the PCU had two servo loops that are necessary for the operation of the hollow-cathode thrusters: 1) the neutralizer keeper-heater loop and 2) the beam current-main vaporizer loop. Two new servo loops for the hollow-cathode thruster operation have been introduced: 1) the arc-voltage cathode-vaporizer current loop and 2) the

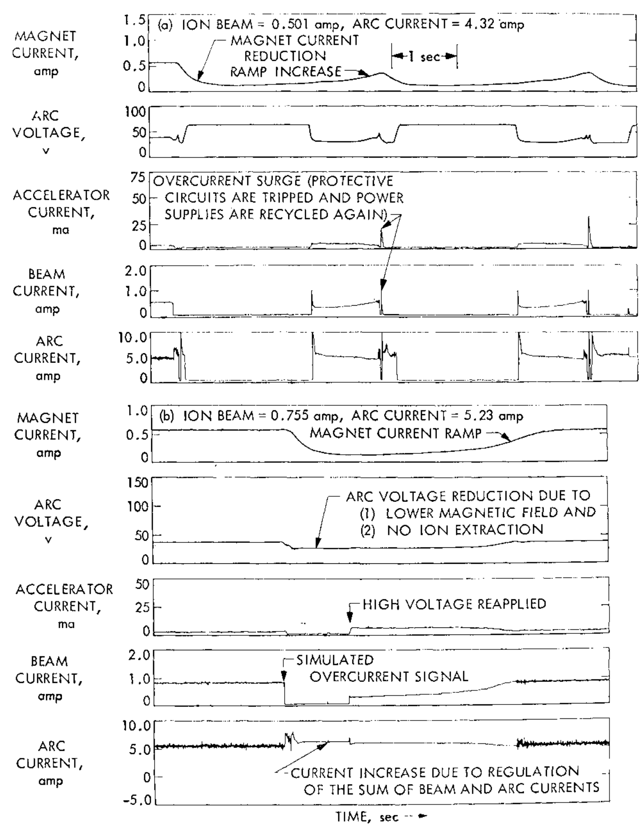

Fig. 8 Power conditioner recycle with magnet reduced (net accelerating voltage, 2000 v; accelerator voltage, −1000 v).

arc-current cathode-heater loop.[14] The latter loop was introduced to reduce the operating temperature of the hollow cathode. Gains of the beam-main vaporizer and arc voltage-cathode vaporizer control loops have been measured as 200 (I_2/I_5) and 2.6 (V_3/V_4) where I_N and V_N are the current and voltage of power supply N (see Fig. 5).

Evaluation of the PCU on a test console (before integration testing with the thruster) included measurement of the power supplies regulation characteristics, verification of logic controls, and the evaluation of the operational characteristics of the control loops. This test indicated a PCU efficiency of 90.1%, slightly higher than previously reported for this unit, when the input voltage was erroneously measured at the 80-v power supply instead of at the power conditioner.

Thruster-Power Conditioner Integration

The thruster was operated initially with a combination of PCU and laboratory power supplies. The latter were used in place of the new supplies needed to define the PCU specifications. These preliminary tests verified the cathode operation at the power levels chosen and indicated the necessity of the design of a separate 12 kHz oscillator for the arc supply when it was found undersirable to extinguish the arc plasma during a recycle when no drive was available from the accelerator supply. As the new supplies for the PCU became available they replaced the laboratory supplies in operating the thruster and were eventually integrated into the PCU. The two problems of significance during this procedure were 1) the recycle of the PCU supplies in response to thruster arcing and 2) the operation of the control loops.

Recycle Procedure

The arcs that commonly occur between the high-voltage grids can exceed the protective circuitry limits of the beam or accelerator supplies, in which case these supplies are shut off. It then is essential to reestablish thruster operation without generating surge currents,[6,9] which will exceed the protective circuitry limits. For an oxide cathode thruster, a reduction of arc-plasma density and a gradual buildup by control of the magnetic field has been very successful. This reduction and ramping of the magnetic field was therefore attempted with the modified system. Figure 8 presents the results for two levels of beam current I_b Thruster operation could usually be satisfactorily reestablished at $I_b > 0.7$ amp. Lower I_b presented a problem, however, inasmuch as the arc chamber was prone to extinguishing as shown in Fig. 8a. In the case shown, reignition occurred within 2 sec, but in other cases it took much longer.

Another problem observed during low beam power recycle was that the noise levels encountered at certain low magnetic field strengths usually resulted in excessive accelerator currents, tripping the protective circuitry. It was found further

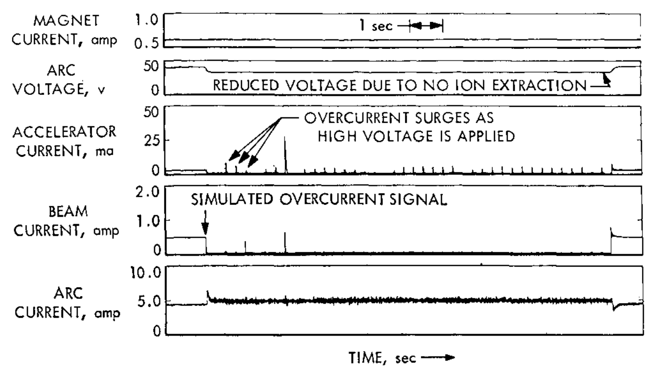

Fig. 9 Power conditioner recycle without magnet current reduced.

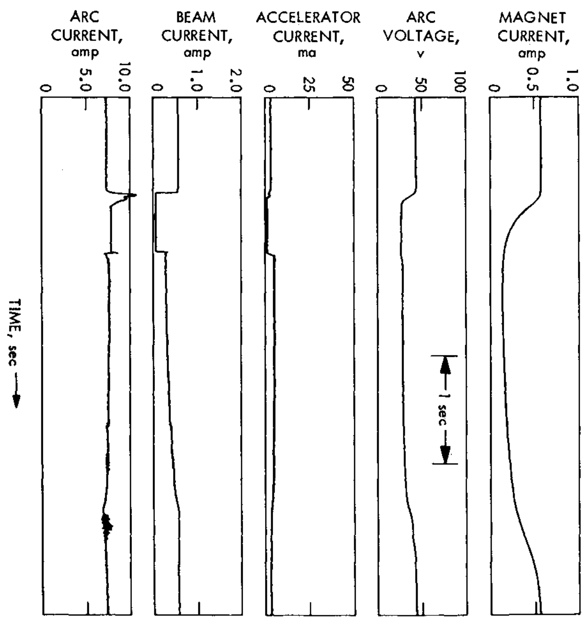

Fig. 10 Power conditioner recycle at low-beam and high-arc current.

that neutralizer operation was necessary for proper system operation. An unneutralized beam also resulted in excessively high accelerator currents during the recycle sequence.

The recycle was also implemented without reducing the magnetic field. The results are shown in Fig. 9. Current surges were noted during the application of the high voltage; however, they were not as intense as had previously been observed with the oxide cathode. These surges, for the case shown, apparently tripped the protective circuitry several times before thruster operation was re-established. Changes in PCU capacity or transient current handling ability would be necessary if the magnet current was not reduced. It was also found that electron backstreaming (electrons from the neutralizer flowing to the positively changed thruster anode) could occur during this recycle procedure. In this case the thruster operation would be reestablished at a level where

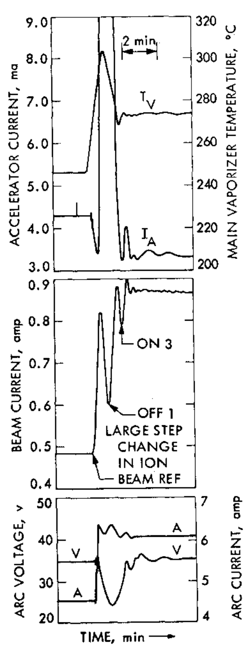

Fig. 11 Closed-loop response to a large increase in beam set point.

accelerator current was maximum, accelerator voltage was zero, and the ion beam current was high. This condition was not encountered when the magnet was reduced during recycle.

The noise problem that prevented recycle at low beam current when the magnet was reduced was investigated over a range of arc currents. Satisfactory recycle occurred when the arc current was increased a nominal amount. This recycle is presented in Fig. 10 for a 0.516 amp beam and an arc current of 7.05 amp. The recycle procedure, when using the function generator, was modified so that the arc current reference was increased during the recycle interval, thereby maintaining the plasma discharge. The arc current was restored to a level that corresponded to operation at 90% propellant utilization about 2 sec after the recycle interval.

Several methods of recycling the power supplies were found, with many avenues left unexamined. Since modification of the beam power supply or operation at propellant utilizations higher than 90% (for low-beam operation) were felt to be unacceptable solutions, increasing the arc current during the recycle interval is the present recommended procedure.

Closed-Loop Operation

Stable system operation was obtained over the entire output power range of interest with the control loops shown in Fig. 5. Several operating points were held for times up to 8 hr with no drift in the vaporizer temperatures. System operation for a step change in set-point reference resulted in stable operation after a settling time of $\sim$2 min.

A major problem was encountered with these control loops as a result of the thruster characteristics. Increasing mercury flow would eventually result in a reduction in beam current, which is the wrong direction for proper control-loop operation and results in maximum power continuously applied to the main vaporizer. This "runaway" condition was encountered during both 1) large increases in the beam reference set point and 2) loss of arc plasma for time intervals greater than about 4 sec. Figure 11 presents a 390-ma change in beam reference set point with a resulting loss of thruster control. The proper operating point was restored with a command to the PCU, which turned off the main vaporizer. When the ion beam current increased to a point where operation by the PCU could be restored, a command was given and the main vaporizer-beam loop was closed.

Limiting main vaporizer maximum power or providing better radiation cooling for the cathode vaporizer might reduce the system sensitivity to set-point changes. However, different control loops, a mercury flowmeter, or modified thruster characteristics might provide a more satisfactory solution to the problem. The "flight-type" propulsion system presently being constructed at JPL will incorporate additional logic within the PCU to recognize when the system is uncontrolled and restore proper operation by main vaporizer on and off commands.

Conclusions

Modification of an ion thruster and a light-weight power conditioning unit (PCU) to be compatible with hollow-cathode operation was accomplished successfully. Stable system operation was obtainable over a 2:1 range of output power with no major problems encountered. Improved thruster efficiency, reduced output power throttling penalties, and better propellant control remain, however, as areas where improvement are desirable. The following conclusions are drawn from this effort:

1) Thruster pole pieces and grid modifications resulted in a hollow-cathode design capable of operating over a 2.6:1 continuous range of output power with about 4% decrease in total efficiency.

2) A PCU weighing 32 lb (11.5 lb/kw, less cabling) resulted.

3) Recycle of the system in response to thruster arcing could be accomplished over a 1-kw to 2-kw range of output power. More difficulties were encountered at the low-power region because of erratic thruster behavior. Increasing the arc current during recycle provided acceptable system operation.

4) Stable system operation could be maintained with the control loops presented. Loss of control occurred with large increases in the ion beam reference. System recovery was possible with a command to the PCU turning off the main vaporizer.

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