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Technical Memorandum 33-392

Power Matching of an Ion Thruster to Solar Cell Power Output

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Contents

Figures

Abstract

A 20-cm-diam thruster was operated over a 2:1 range of output power, allowing for continuous matching of thruster power to a varying solar cell output level. The technique of matching power by varying either the ion beam current or the net accelerating voltage is described. Ion beam current control, implemented in thruster control loops, utilized existing laboratory hardware. Stable thruster operation was achieved over a range of 1000 to 2000 W. Bistable values of mercury propellant flow at the same discharge chamber and ion beam conditions were also observed.

Power Matching of an Ion Thruster to Solar Cell Power Output

I. Introduction

Ion thrusters have customarily been operated at fixed design points, consistent with optimum ion chamber performance and long accelerator and cathode lifetimes. Useful applications (Refs. 1 and 2) dictate that these thrusters should be able to operate over a range of power output levels in order to utilize the available power from the solar cells. The solar cell output can vary over a wide range of power depending upon the mission considered. The ion thruster should be able to accommodate this power level variation with small penalty in overall efficiency.

The use of multiple thrusters, such as reported in the JPL study of Ref. 3, permits power matching in an incremental manner; that is, the turning on and off of thrusters within the array according to the power requirements. Additional matching within a power increment can be accomplished by adjusting the thruster output power level. The feasibility of accomplishing this power matching with a 20-cm-diam mercury ion thruster is described herein. Primary emphasis in this study was concentrated on a thruster utilizing an oxide-coated cathode because of the high degree of development associated with this cathode type.

II. General Power Matching Considerations

Output power from an ion thruster can be represented by the expression

$$P_b = I_b (V_b - V_p)$$

where

P_b = beam power

I_b = ion beam current

V_b = net accelerating voltage

V_p = beam plasma voltage

With respect to spacecraft reference potential, exhaust beam plasma voltage for a neutralized ion beam should be below 30 V in order to assure adequate neutralizer lifetimes (Ref. 4). Since the net accelerating voltage is normally at least two orders of magnitude higher than the nominal plasma voltage, the output power may, for practical purposes, be represented as the simple product of two terms, I_b and V_b. Accurate measurements of beam power require determination of the exhaust plasma potential.

The output power might be adjusted by changing either the beam current or the net accelerating voltage. The value of the net accelerating voltage, which is related to the specific impulse, is a function of the mission under consideration. The relationship between specific impulse and the net accelerating voltage can be represented as

$$I_{sp} = \eta_m K (V_b)^{1/2}$$

where

I_{sp} = actual specific impulse

η_m = propellant utilization fraction

K = proportionality constant

The manner in which power matching is accomplished can affect mission analysis and also the hardware considerations, as far as both the power conditioning unit and the ion thruster are concerned. If the net accelerating voltage is varied in a power matching system, then the specific impulse variations would have to be taken into account in the mission analysis. This type of output control could be accomplished at a constant beam current, and therefore, possibly allow a more extensive range in the cathode selection. At least three types of cathodes suitable for use with a mercury thruster exist, each with a demonstrated lifetime in excess of 1000 hours (Refs. 5–8). Two of these are more sensitive to variations in mercury flow and do not exhibit as simple and direct control of the emission current as the oxide-coated cathode.

The ability of power supplies to deliver a range of output voltages at high efficiency also remains to be demonstrated. These supplies have successfully demonstrated high efficiencies when operated at a fixed voltage (Refs. 9 and 10). Whenever a constant specific impulse is required, the ion beam current must be used to vary the thruster output power. Since most missions are determined at an optimum specific impulse, primary emphasis in this study will be on ion beam current variations to obtain the desired beam power. An oxide-coated cathode can be incorporated into this effort most conveniently.

In varying the output power, it is desirable to maintain overall thruster efficiency as high as possible. This overall efficiency can be represented as

$$\eta_T = \eta_m \frac{P_b}{P_b + P_l}$$

where

η_T = overall thruster efficiency

P_l = total thruster power losses

The most desirable thruster is obviously one with losses that are small when compared to the beam power. For power matching, these losses should also be proportional to beam power. Therefore, the relationship between the beam power and the losses necessary to maintain constant propellant utilization is of interest, inasmuch as this determines the operating range over which power matching is desirable. These thruster power losses are the sum of various losses and can be represented by the expression

$$P_l = P_i + P_c + P_a + P_n + P_m + P_v$$

where

P_i = ion chamber power loss

P_c = cathode power loss

P_a = accelerator power loss

P_n = neutralizer power losses

P_m = magnet power losses

P_v = vaporizer power losses

The thruster losses are listed in decreasing order of importance. For a thruster utilizing an oxide-coated

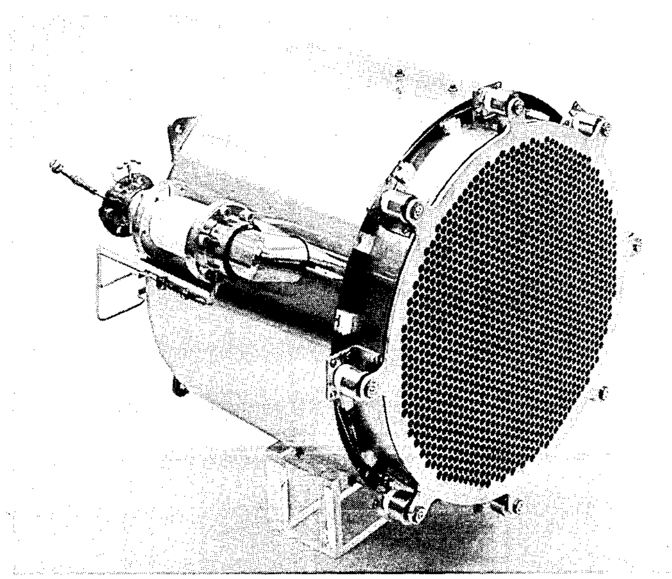

Fig. 1. A 20-cm-diam ion thruster

cathode, the majority of the losses are included in the ion chamber and cathode losses, P_i and P_c. The magnet power losses (P_m) can be eliminated if a permanent magnet thruster is used, although the residual magnetic field outside of the thruster may interfere with some science experiments aboard a spacecraft and preclude its use. The magnet power losses can be minimized by proper design, so that they represent on the order of 1% of the maximum thruster power for the size thruster (2.5 kW) and system specific weight (66 lbs/kW) considered in this study.

The maximum variation in beam power that would be encountered by an individual thruster within an array is on the order of 50%. This would occur when two remaining thrusters in an array were being throttled down to one-half power each. From a mission viewpoint, it is usually not desirable to operate within an array a single thruster at a reduction below 50% in output power.

Power matching data for the thruster is presented in the next two sections, which examine the applicability of this thruster to power matching by adjustment of first, the ion beam current; and second, the net accelerating voltage.

A. Ion Beam Current Power Matching

Experimental data were obtained on an ion thruster of the type described in Ref. 11 to determine thruster losses while the ion beam current was varied. A photograph of the thruster is presented in Fig. 1. The block diagram (see Fig. 2) of the thruster and power supplies V_1–V_8 includes their relationships to propellant feed and neutralizer.

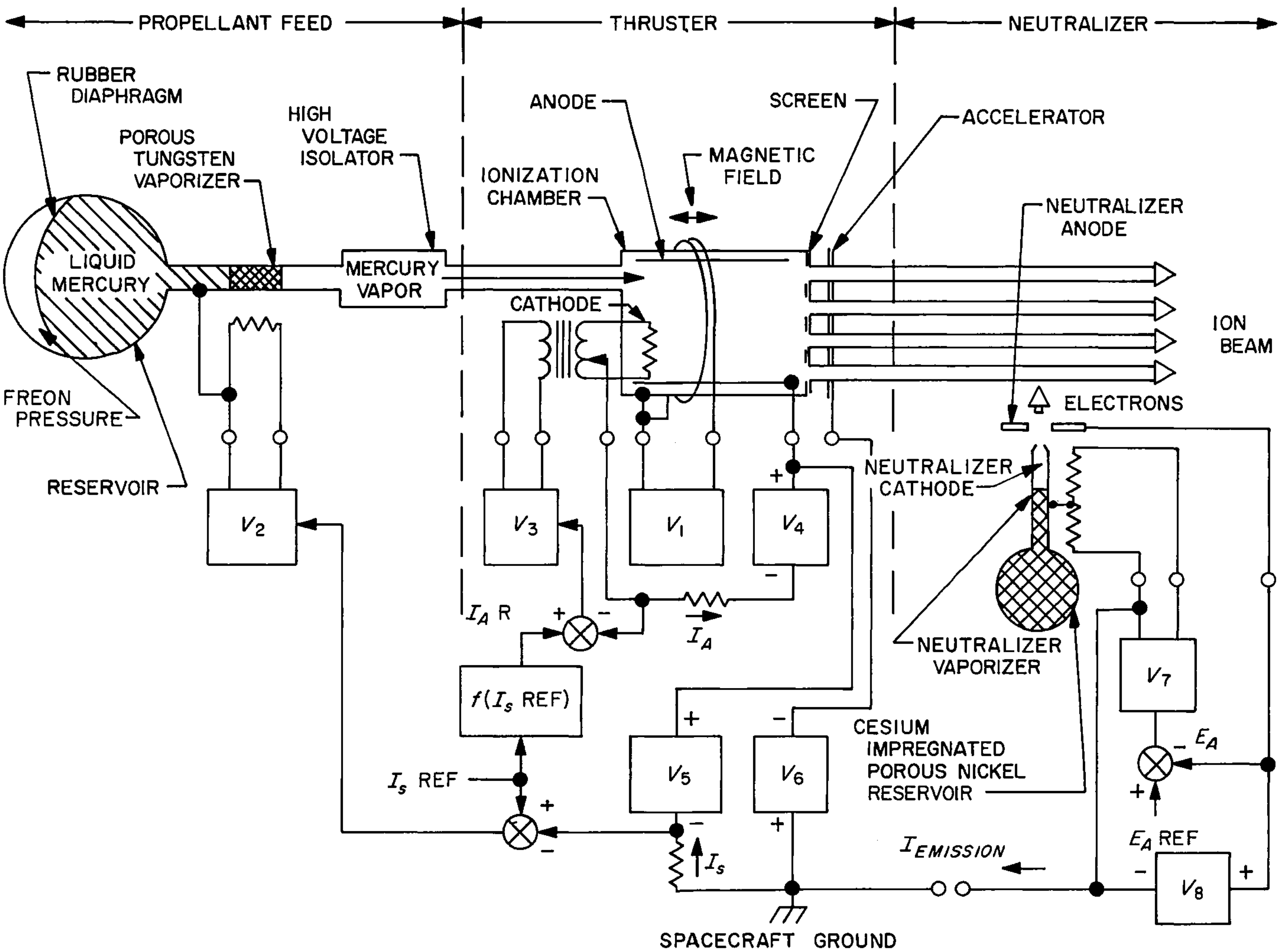

Fig. 2. Thruster and power supplies, block diagram

The cathode employed in this study was an oxide-coated spiral-wound nickel-mesh type that is described in Ref. 5. The cathode heating power dissipation for various flowrates are plotted (see Fig. 3) as a function of propellant utilization. Most power levels were observed to correlate closely with propellant utilization. The lowest propellant flow resulted in about a 10-W reduction in the cathode heating power. The thruster data indicates that small variations in cathode heating power would be necessary to maintain a constant propellant utilization over approximately a 2:1 variation in output power.

In general, cathode power increases with propellant utilization, placing an upper limit on maximum propellant usage. An additional limit might also exist from the standpoint of cathode lifetime, inasmuch as this has been observed to be a function of both ion chamber voltage and cathode emission current (Ref. 12). The emission current is included indirectly in the data of Fig. 3, since the propellant utilization may be represented as a function of the emission current divided by the mercury flowrate. The effect of lower ion chamber voltage was observed to shift the level of the cathode heating power upward, but not to introduce any flow dependence. Cathode degradation would be expected to increase the cathode heating power requirements over the cathode lifetime.

The ion chamber losses as a function of mass flow are presented (see Fig. 4) for several values of propellant utilization. These losses were observed to decrease with decreasing propellant flow. This was primarily a result of operation of the thruster in a region of current density that was above the value at which minimum ion chamber losses are usually observed. Minimum ion chamber losses for the 20-cm-diam thruster were observed near a flowrate of approximately 4 g/h, which corresponds to an ion beam density of 1.36 mA/cm^2 at 0.80% propellant utilization. Ion chamber losses below this flowrate remained essentially constant.

The remaining losses within the thruster are essentially fixed or present insignificant power variations with propellant flow. These losses totaled approximately 100 W and were essentially constant during variations in the propellant flowrate. A neutralizer was not used during these tests, but total neutralizer power losses, estimated at 50 W, were included in the thruster calculation. The overall ion thruster efficiency, η_T, was plotted as a function of propellant flowrate (see Fig. 5) for several values of propellant utilization. Although this plot was obtained for one thruster, a maximum of four operating thrusters

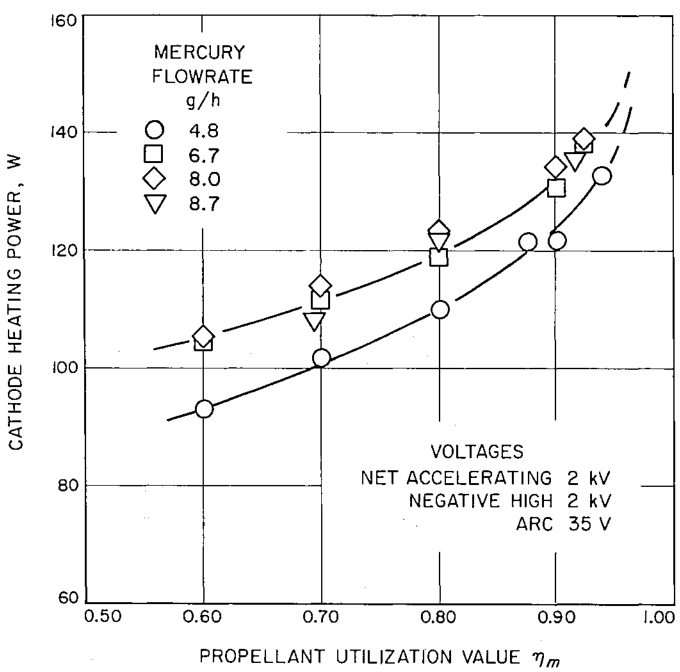

Fig. 3. Effect of mercury flowrate on cathode heating power

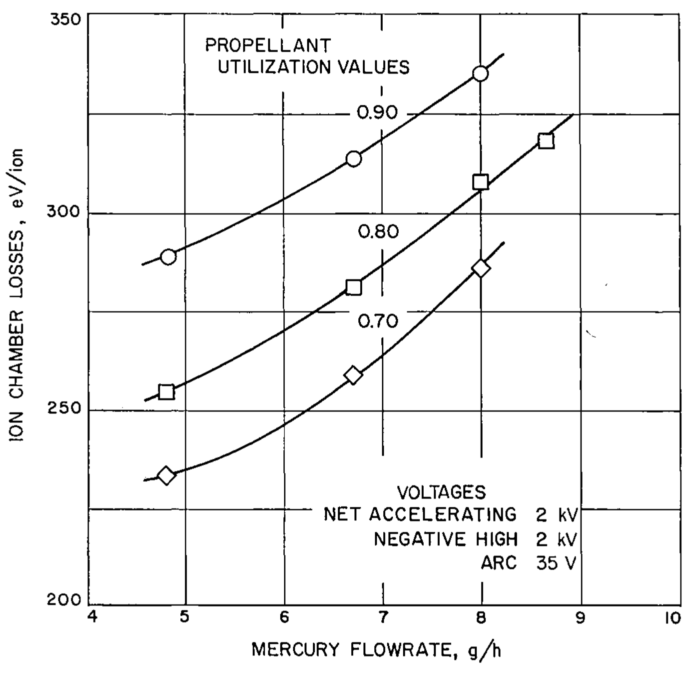

Fig. 4. Effect of mercury flowrate on ion chamber losses

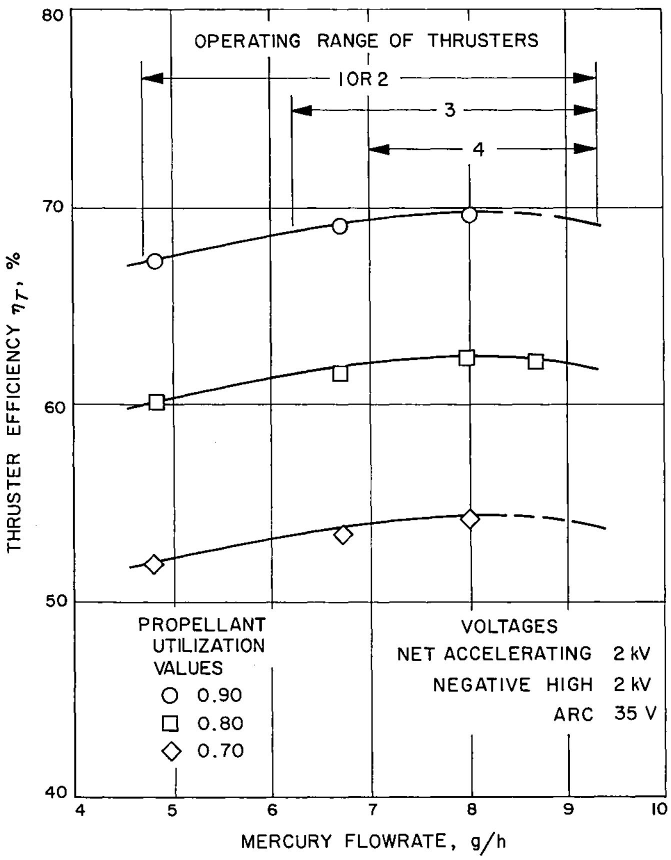

Fig. 5. Effect of mass flowrate on overall thruster efficiency

exists in the JPL array. The typical range of operation for each group of operating thrusters is also shown on Fig. 5. A loss in total thruster efficiency (about 2 to 3%), because of power matching, can be noted to exist for single thruster operation. However, the actual time that each thruster group must operate is a function of a given mission. Using thruster operating times and power levels for a Jupiter mission study, the average overall thruster efficiency was calculated to be 61.3% (where I_{sp} = 3570 s and η_m = 0.80) which is about 1.2% below the maximum efficiency obtained.

The relationship between overall thruster efficiency and propellant flowrate (which is proportional to ion beam power) is relatively flat for the particular ion thruster examined. This is because of thruster operation above the optimum point, as far as ion chamber losses are concerned. The other thruster losses were observed to remain essentially constant while the flowrate was varied. A major consideration in operating in the high current density region is that the accelerator wear is more rapid; however, it should be possible to add sufficient mass to the accelerator grid to provide adequately long lifetimes.

The relationship between the cathode emission current and the ion beam current, for the output power range of interest, is presented (see Fig. 6) for several values of propellant mass utilization. This relationship can be utilized within the thruster control system to maintain a constant mass utilization by implementing an accurate functional dependence of the desired arc or cathode emission current to the desired ion beam current. The accuracy required is a function of how narrow a range of propellant utilization control is required. A narrow range would appear to require a very accurate current specification due to the high sensitivity of mass utilization on the arc-to-ion-beam-current relationship. It is believed that the data presented in Fig. 6 is time invariant. It would be changed only by changing the thruster geometry or by varying the normally fixed thruster parameters. The variations permitted in the fixed parameters must be such as to affect the arc-to-ion-beam-current relationship only slightly.

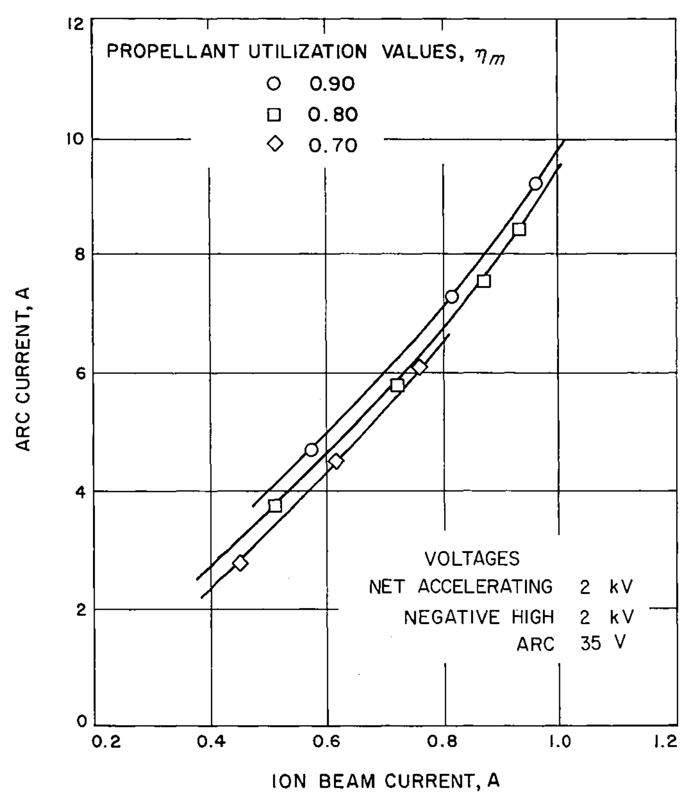

Fig. 6. Ion-beam-to-arc-current relationship for several values of constant mass utilization

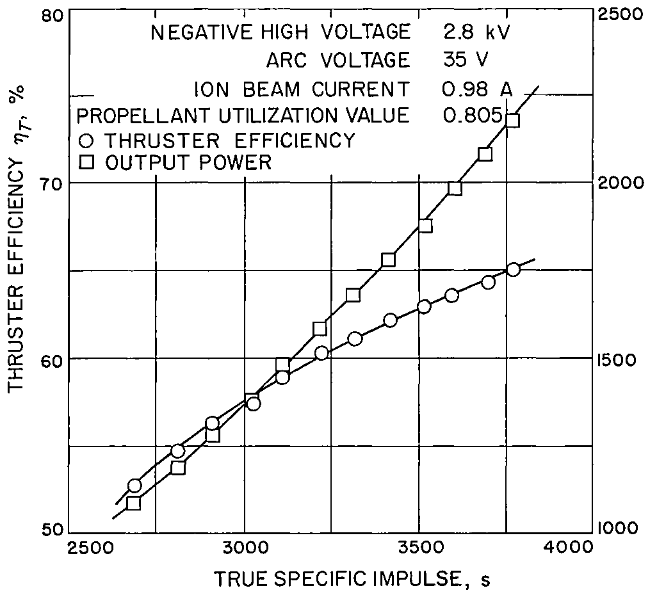

Fig. 7. Effect of positive high voltage on thruster efficiency and output power

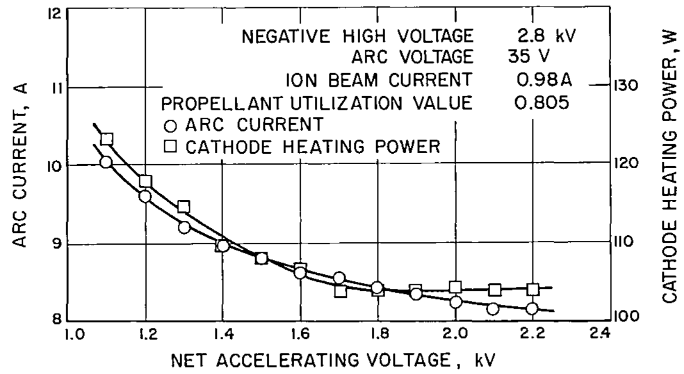

Fig. 8. Effect of positive high voltage on arc current and cathode power

B. Voltage Power Matching

Experimental data was obtained (see Fig. 7) on the power matching characteristics of the 20-cm-diam thruster by varying the net accelerating voltage, while the ion beam current was maintained at a constant value. During the excursions in net accelerating voltage, it was necessary to maintain the accelerator voltage at a large negative value to avoid excessive accelerator impingement currents. At an accelerator voltage of −2800 V, the impingement current was noted to remain essentially constant at 10 mA, while the anode voltage (net accelerating voltage) was changed. The large accelerator voltage would be expected to result in excessive exhaust beam spreading. A higher perveance screen-accelerator grid system would allow the accelerator voltage to be reduced.

In the relationship between both the cathode heating power and the cathode emission current as a function of the anode voltage (see Fig. 8), the cathode emission current was observed to follow the cathode heating power closely. As the anode voltage was decreased, larger emission currents were required to maintain the beam current constant. This was necessary, since the lower extraction voltage across the accelerator grids resulted in larger ion chamber losses. For constant ion chamber voltage and ion beam current, the ion chamber losses are proportional to the emission current.

As the power is decreased, utilizing the net accelerating voltage to adjust the thruster output power, a more rapid dropoff in thruster efficiency results. This dropoff is accentuated because both the ion chamber losses and the cathode power losses increase during decreases in the power level. Propellant utilization control for this type of power matching scheme would be combined primarily in the emission-current-to-anode-voltage relationship. In addition, this would be expected to be relatively insensitive to propellant utilization variations, and therefore, require a high degree of accuracy.

III. Control of Thruster Output Power

The control systems to accomplish the desired control of the thruster output power are presented in Figs. 9 and 10. Control loops are necessary for both methods in order to maintain the beam and emission currents at the desired values, regardless of degradation and variations. The effect of propellant flow on cathode emission (Ref. 13) has not been incorporated in the diagrams and acts as an additional disturbance on cathode emission.

In the control system to accomplish the desired control of the ion beam current (see Fig. 9), two control loops are necessary to maintain the beam and emission currents at their desired values. Refer to the data presented in Fig. 6, which includes a function generator to maintain the relationship between the emission and beam currents and to ensure a constant propellant utilization.

In the control system for the net accelerating voltage (see Fig. 10), a control loop would be necessary to maintain a constant mercury flowrate from the vaporizer.

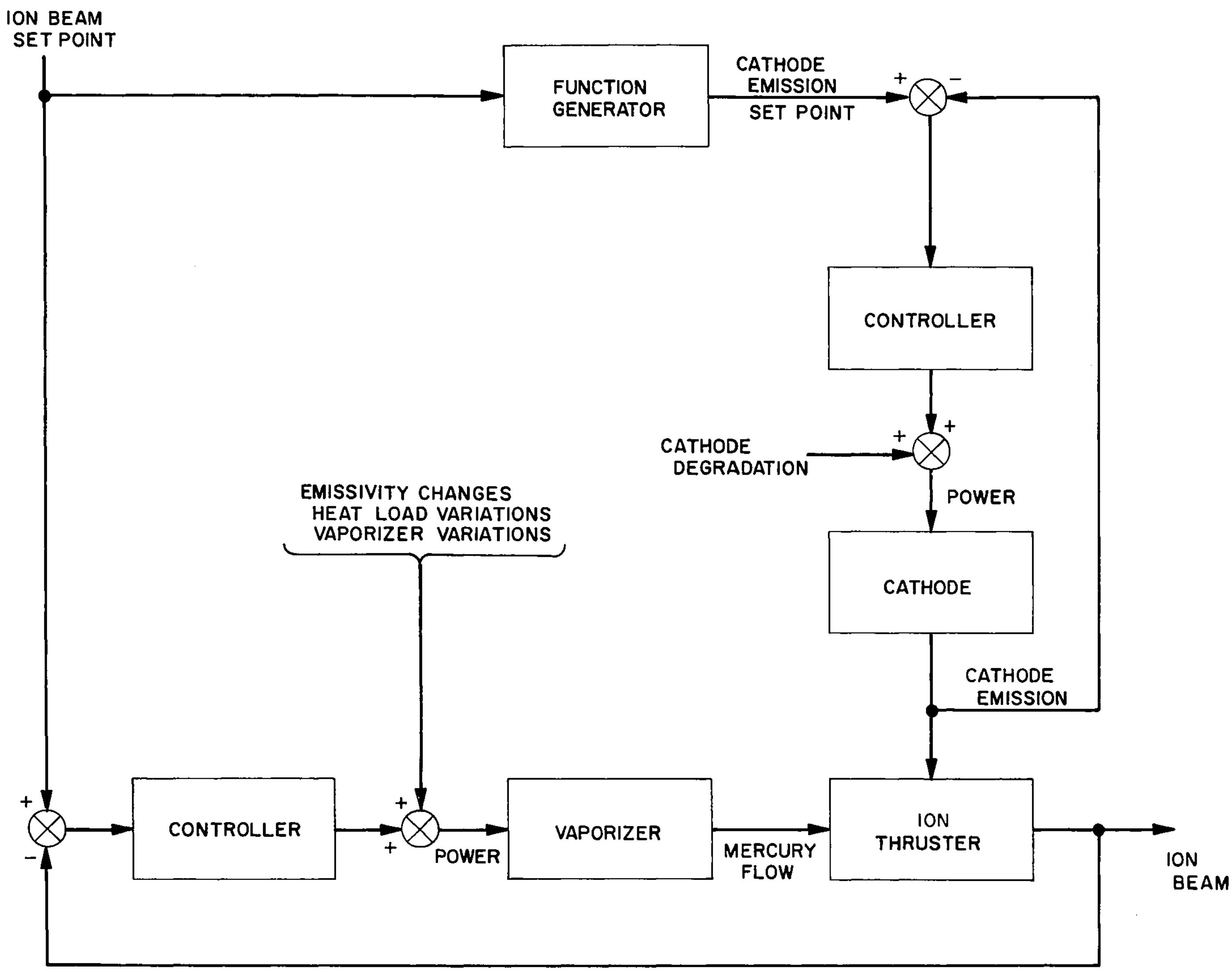

Fig. 9. Ion thruster control system for beam current power matching

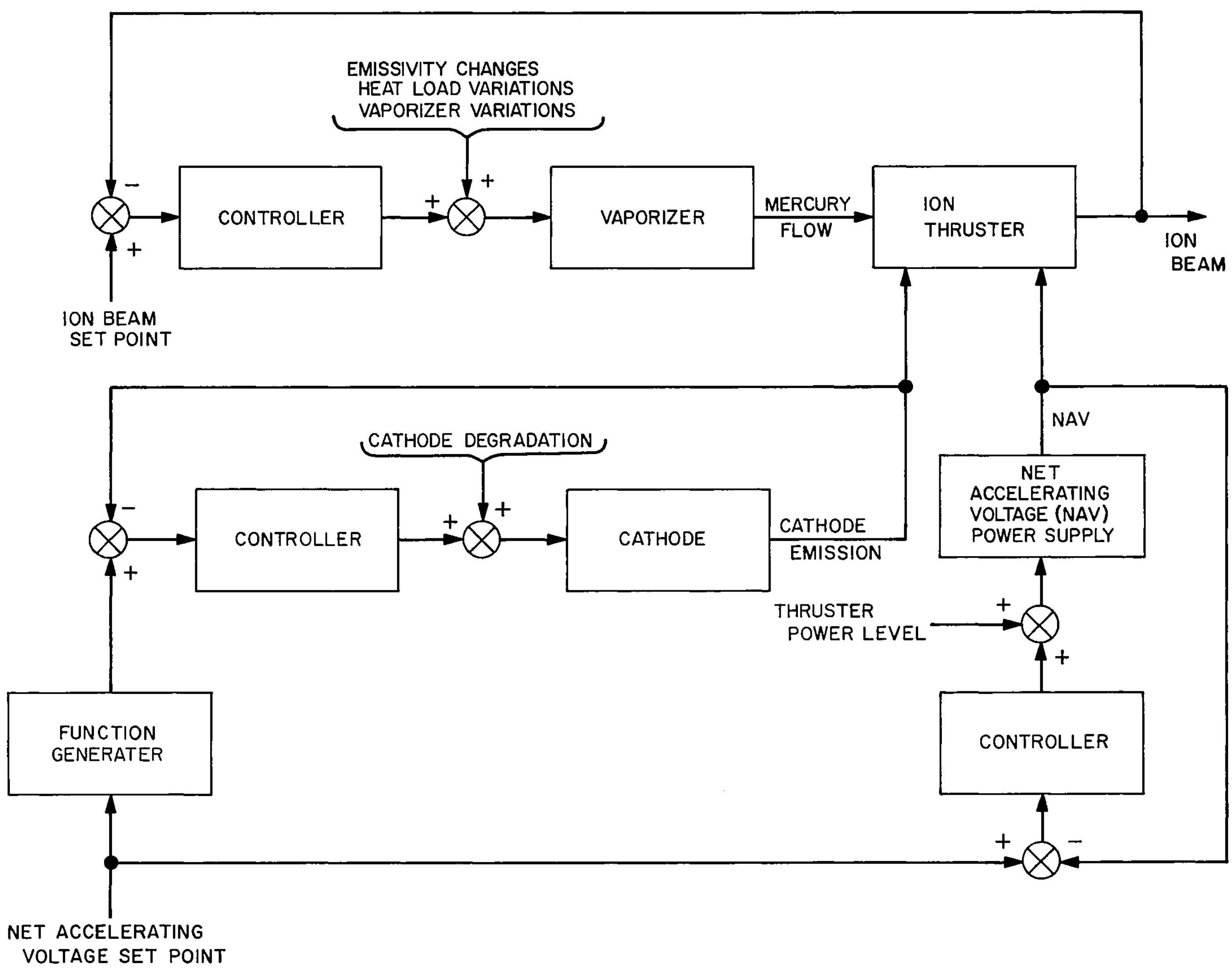

Fig. 10. Ion thruster control system for net accelerating voltage power matching

Two additional control loops would be necessary to control the cathode emission and the net accelerating voltage at the desired values. In this case, a function generator would also be necessary to maintain the proper cathode emission current while the net accelerating voltage was varied.

The control of the ion beam current, as presented in Fig. 9, was incorporated into the operation of the ion thruster, since this control method is most compatible with the power conditioner technology. Leeds & Northrup controllers, combining proportional, rate, and reset functions, were utilized for the control of the cathode emission and beam currents. The set point of the cathode emission current, specified by the ion beam current set point, was maintained by remotely adjusting the cathode emission set point using the beam current setting. The system was observed to operate stably over a range in output power of 1000 to 2000 W. The relationship between ion beam and cathode emission currents made it possible to maintain the propellant utilization within about 3% of the desired 0.80 value. During controller operation, however, it was observed that the beam-emission-current relationship did not uniquely specify propellant utilization for the thruster used. The bistable relationship noted was primarily the result of the manner in which ion chamber losses varied with propellant flow. The relationship permitted stable thruster operation to be defined at two values of propellant flow. Since operation is required at a specified high value of propellant utilization, the bistable operation must be eliminated. Modification of the ion chamber characteristics or the incorporation of additional thruster information, such as a maximum level of accelerator impingement current or plasma probe current, appears to be possible areas for further system investigation.

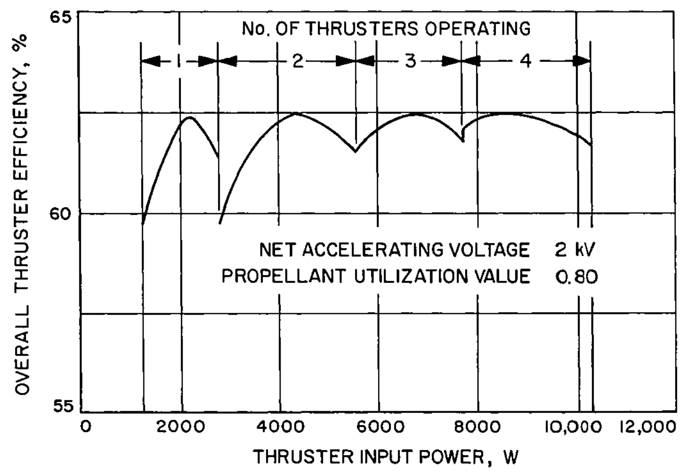

Fig. 11. Thruster efficiency as a function of input power for a four-thruster array

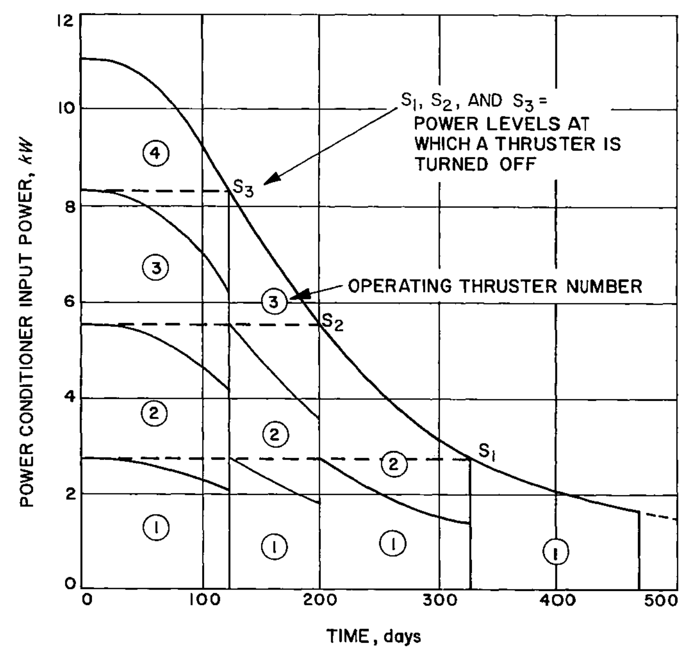

Fig. 12. Thruster system input power as a function of time for a Jupiter mission

IV. Power Matching System

The overall thruster efficiency of a four-thruster array, as a function of input power (see Fig. 11), includes the number of operating thrusters for each range. The thrusters are throttled so as to share the total output load evenly. Input power is plotted (see Fig. 12) as a function of time for a typical mission.

For a given mission, the total desired thruster output can be represented as a preprogrammed signal. This representation is desirable because contingencies exist in the solar cell output. Operation at full solar cell output presents a mission problem, inasmuch as the thrust can continue within a large contingency range (~18%). The desired output signal would be used to adjust individual thruster output.

In the diagram of a system to accomplish power matching (see Fig. 13) the five thrusters used include a spare unit for reliability purposes. The preprogrammed desired power output level would serve as an input to a logic system, which would be able to turn power conditioning and control units on and off and adjust their output by a control signal, V_N. The individual control

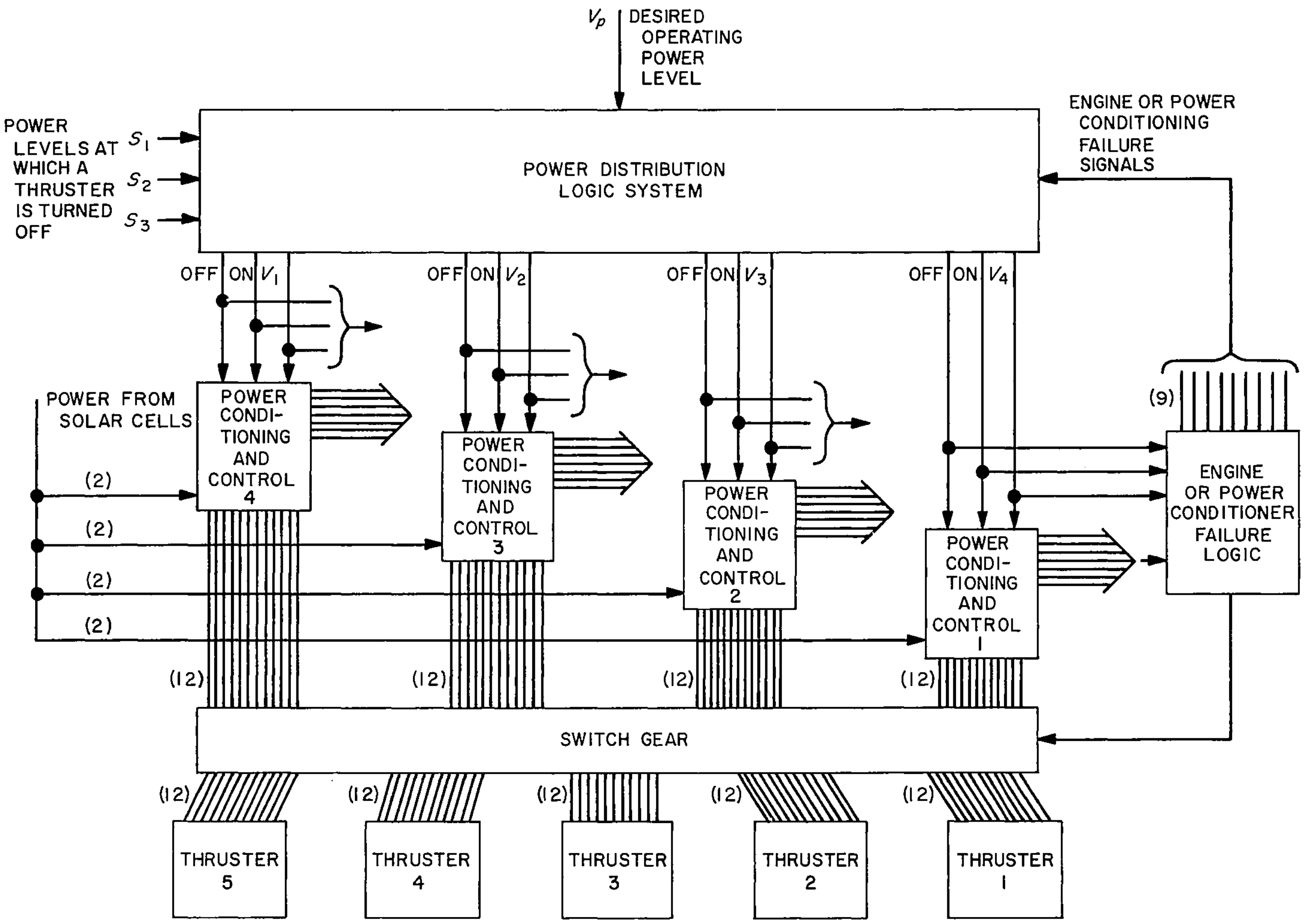

Fig. 13. Thruster and solar cell power matching system

signals would be related to the desired power level by the expression

$$V_D = N V_N$$

where

V_D = desired total power level

N = number of operating thrusters

V_N = desired single thruster power level

Set points would be used by a logic system to determine the power levels at which a change in the number of operating thrusters is desired. Signals indicating a failure in a power conditioning unit or thruster would also serve as an input to this logic system. A failure detection system would be included in the power matching system. The signals from the power conditioning unit could also be incorporated into automatic sensing circuits to shut down a malfunctioning thruster or power supply.

Switchgear would probably be necessary to connect operable power conditioning units and thrusters. The extent or necessity for this switchgear would be determined primarily from reliability considerations. Switching operations could be handled by either ground command or by self-contained logic within the failure detection system. If the round trip signal time becomes excessive, or the telecommunications load too heavy, a complete failure logic system would be necessary. In this case, the failure logic system would control the switchgear. An overriding ground command would probably be incorporated within the system.

V. Summary

Power matching data has been obtained for a 20-cm-diam electron-bombardment mercury ion thruster employing an oxide-coated cathode. Experimental data has been obtained, using both the ion beam current and the net accelerating voltage to adjust the thruster output power. Ion beam current adjustment was found to result in higher thruster efficiencies over a 2:1 range in thruster power output. A drop in thruster efficiency from 61.8 to 59.9% (where I_{sp} = 3570 s and η_m = 0.80) was obtained for this method, while the thruster output was varied from full to half power. An average efficiency for an array of four operating thrusters, as used in a Jupiter mission, was estimated to be 61.3%, representing a loss of about 1% in overall thruster efficiency because of power matching.

Control loops, which would accomplish power matching for the two methods, have been presented on the basis of the thruster data obtained. The ion beam current control was implemented in thruster control loops, utilizing existing laboratory hardware. The thruster was found to respond stably to changes in the thruster output power over a range from 1000 to 2000 W, while maintaining the propellant utilization within about 3% of the desired value. The primary propellant utilization control was combined with a function generator employed to adjust the cathode control loop. Bistable operation (high and low propellant utilization) of the thruster was noted. To eliminate the low propellant utilization mode of operation, the development of additional system logic is required so that an operating point can be uniquely specified.

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