Development of a Liquid-Mercury Cathode Thruster System

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A 20-cm LM cathode thruster system has been developed for operation at beam currents $I_B = 0.5$–1.0 amp and a beam voltage $V_B \leq 2$ kv. At the maximum beam level, the total source energy per ion is $V_S = 315$ ev/ion at a mass utilization efficiency $\eta_m = 89\%$. Discharge chamber performance is essentially unchanged for operation at a reduced beam voltage $V_B = 1$ kv. The thruster employs a conventional thin-screen, high-transparency (70%) ion-extraction system and an LM cathode which is thermally integrated with the thruster body. A mercury feed subassembly provides electrical isolation from the propellant supply while regulating liquid mercury flow to the thruster. At full-rated power, the LM cathode operates at an equilibrium temperature $T_K = 200°C$. With an over-all mass of 6 kg (exclusive of propellant and reservoir), the system operates with an over-all efficiency of $\eta_T = 72\%$ at a specific impulse $I_{sp,\,eff} = 4040$ sec or alternatively with $\eta_T = 60\%$ at $I_{sp,\,eff} = 2710$ sec.

Introduction

A SOLAR-PHOTOVOLTAIC-POWERED electron-bombardment thruster system must demonstrate efficient and reliable operating capability within the constraints imposed by space missions. These constraints include the capability for electrically isolating an individual thruster from the propellant reservoir and, for interplanetary missions, the ability to throttle the ion-beam over a 2-to-1 current range while maintaining high over-all efficiency. The liquid mercury (LM) cathode thruster has demonstrated the ability to satisfy these requirements.[1]

Proceeding from existing component technology, a 20-cm-diam electron-bombardment thruster system (designated LMT-20-II) has been developed at the Hughes Research Laboratories.[2] It includes a 20-cm, thermally-integrated LM cathode thruster and all of the components necessary for measurement and control of mercury flow to the thruster. It has been operated at ion-beam currents in the range $I_B = 0.5$–1.0 amp with an effective specific impulse $I_{sp,\,eff} \leq 4040$ sec. The system (Fig. 1) requires only electrical inputs and a supply of liquid mercury for its operation. The thruster and mercury feed subassembly are characteristically enclosed within a single ground-screen shroud, although the experimental design permits the two subsystems to operate as separate units so that they could be developed separately. The feed subassembly consists of a high-voltage isolator, an electromagnetic pump, a flowmeter, and a single-capillary flow impedance. It facilitates precise measurement and control of the propellant flow rate while providing electrical isolation between the thruster and the mercury reservoir. The total weight of the thruster, the ion-extraction system, the mercury feed subassembly, and the ground-screen shroud is ~6 kg. The present work has not included development of a prototype discharge igniter or LM cathode neutralizer, although provision has been made for incorporating both of these elements; laboratory versions of a high-voltage spark igniter[3] and of an LM cathode neutralizer[4] have both been demonstrated previously.

The development of the LM cathode thruster system establishes a credible alternative to the hollow-cathode electron-bombardment thruster systems presently under consideration for various space applications. Its inherently long cathode life should result in high system reliability. System life in excess of 10^4 hr can be projected from the earlier operation of a 20-cm LM cathode thruster for 4500 hr with no erosion or degradation in the performance of the cathode.[5] In addition, direct measurement and control of the mercury flow rate in the LM cathode system avoids the necessity for precise regulation of the discharge power supply as is required when flow is controlled indirectly from the known electrical characteristics of the operating thruster.[6,7]

The LMT-20-II system has been designed such that integration can readily be accomplished into the SEPST III (Solar Electric Propulsion System Technology) system presently being developed at the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. In addition to being mechanically compatible with the SEPST III system, with only slight modification the LM cathode system is capable of being electrically integrated with the power-conditioning circuitry used with SEPST III hollow-cathode thrusters. Circuitry which is particular only to the LM cathode system will be described below.

This paper describes the design and operation of the LMT-20-II thruster system. The description is divided into sections concerned with the LM cathode thruster, the mercury feed subassembly, system operating efficiency, and the power-conditioning and control system.

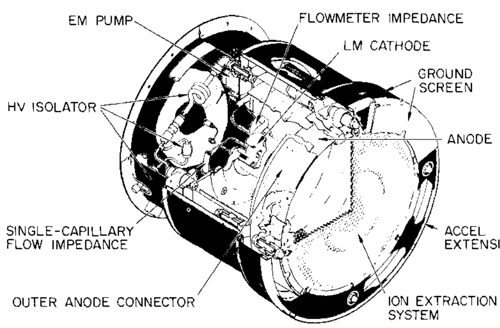

Fig. 1 Isometric drawing of the 20-cm LM cathode thruster system (LMT-20-II).

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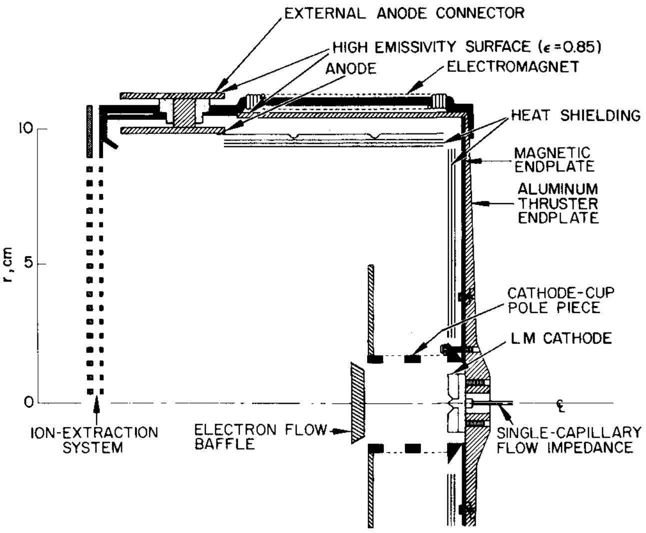

Fig. 2 Schematic cross section of the LMT-20-II thruster.

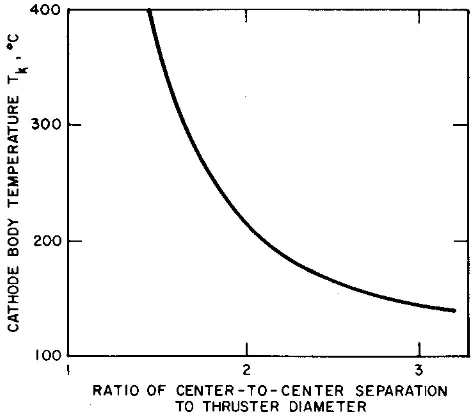

Fig. 4 Dependence of cathode temperature on spacing between thrusters in an infinite array.

LMT-20-II Thruster

Design

The basic configuration of the thruster is shown in Fig. 2. Electrons and mercury vapor are supplied to the thruster discharge by a single-capillary fed, high-temperature LM cathode (Fig. 3). The cathode is fabricated entirely of molybdenum and is mounted on the aluminum endplate of the discharge chamber. Because this cathode operates most efficiently at temperatures below 300°C, proper thermal design of the thruster is important. In the LMT-20-II system, discharge heat deposited at the cathode is conducted radially along the thruster endplate and radiated to space from the cylindrical aluminum walls of the thruster. Radiation from the walls is enhanced by covering the surfaces with a high-emissivity ($\epsilon = 0.85$) thermal control coating, which consists of a water solution of potassium silicate and titanium dioxide in a dry weight ratio of 1 to 4. All other discharge heat is thermally decoupled from the surfaces which radiate cathode heat by heat shielding placed over the downstream surface of the discharge chamber endplate and over the upstream two-thirds of the inner surface of the anode. Heat generated within the discharge chamber is dissipated by radiation to space through the ion-extraction system and from the external anode connector which is also covered with the high-emissivity coating.

Uniform propellant distribution within the discharge chamber is promoted by screened propellant-diversion ports in the cathode-cup pole piece. Electron flow into the discharge chamber is regulated by an electron flow baffle, the axial position of which is variable in order to facilitate performance optimization. The thruster magnetic field is generated by eight uniformly spaced electromagnets. The ion-extraction system, which is 70% transparent, is similar to one used in the SEPST III system at JPL.[8]

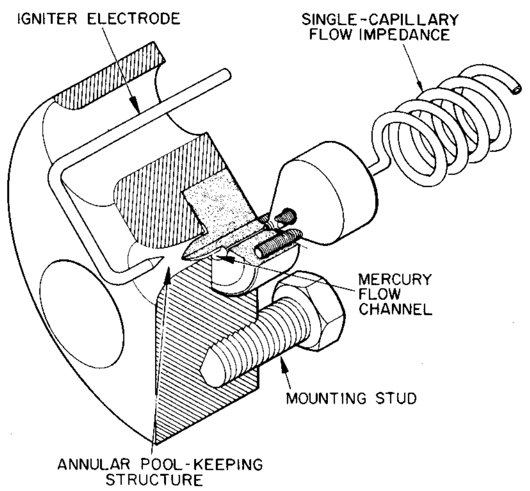

Fig. 3 LM cathode.

Thermal Analysis

The thermal characteristics and limitations of the LMT-20-II system have been analyzed. The geometrical distribution of heat inputs was determined from a physical theory which was verified earlier by comparison with the temperature profile measured with a 30-cm thermally-integrated LM cathode thruster.[2] The analysis indicates that the cathode temperature is 121°C for a single thruster operating at a beam current $I_B = 1.0$ amp when thrust chamber heat shielding is employed. In experimental operation of the thruster system thus far, a higher cathode temperature of 200°C has actually been measured. This indicates a functional inadequacy in the current technique for installing discharge chamber heat shields that must be corrected prior to further thermal testing.

Similar analysis has been carried out (assuming the use of effective heat shielding) for an infinite linear array and a two-dimensional clustered array of identical thrusters. Analysis of the linear array, for the case in which the thrusters are placed directly against one another indicates that the cathode attains a temperature of 164°C which is well within the efficient operating range for the LM cathode. The infinite two-dimensional cluster was studied for the general case in which the ratio of center-to-center separation to thruster diameter was variable. The results (Fig. 4) indicate that this ratio must be greater than about 1.7 for efficient thruster performance. For closer thruster spacings, additional means of heat dissipation is required. This can be provided by allowing heat conduction between the thruster and the spacecraft (in the analysis, no such mechanism for heat transfer was allowed) or by using an additional radiator which can be connected to the thruster cathode by a heat pipe or other means.

Mercury Feed Subassembly

To supply propellant to the LMT-20-II system, a laboratory-prototype mercury feed subassembly has been developed with emphasis on simple, reliable operation. As shown in Fig. 5, the subassembly contains all elements necessary to provide liquid mercury propellant in a measured and controlled manner. This subassembly includes a high-voltage isolator, an EM (electromagnetic) pump, a mercury flowmeter, and a single-capillary flow impedance.

For laboratory experiments a piston driven reservoir provides liquid mercury to the feed subsystem. The piston displacement as a function of time yields an accurate measure

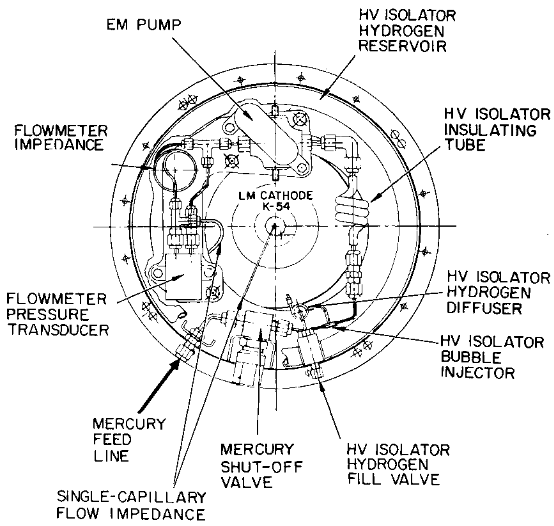

Fig. 5 Mercury feed subassembly.

of the flow rate which supplements the instantaneous value obtained from the flowmeter. A shut-off valve facilitates handling of the thruster system outside the vacuum environment without the possibility of atmospheric contamination of the stored mercury. The isolator permits operation of the thruster at a potential that is different from that of the propellant storage reservoir. Mercury pressure can be regulated as needed to control the mercury flow rate by means of an electromagnetic pump.

High-Voltage Isolator

In operation of the LMT-20-II system, high-voltage isolation from the propellant supply is achieved by introduction of small hydrogen bubbles into the mercury stream as it passes through an insulated section of tubing. After leaving the insulated section, the bubbles enter a porous section of flow line formed of sintered stainless steel through which they are vented to vacuum. Bubbles are injected at a rate such that at least one bubble is present in the insulated portion of the feed line at all times.

Satisfactory performance has been demonstrated in system operation by a lightweight model of the isolator in which the insulating section consists of a helical coil of glass tubing with an uncoiled length of 30 cm. A supply of hydrogen sufficient for 10,000 hr of operation is stored in a titanium reservoir at a pressure of 400 psig. The flow of hydrogen gas is regulated by controlling the temperature of an iron diffuser element thereby causing hydrogen to flow through the diffuser into a small plenum chamber. By periodically raising the temperature of the plenum, the gas is expanded and forced into the mercury stream. A 1-cm-long bubble is injected every 30 min by application of a 2.8 min heating pulse. A power level of 7.0 w is required during the pulse; no power is required during the other 28 min. Prior to installation in the LMT-20-II system, this isolator was operated satisfactorily as a separate component for an accumulated 550 hr.

Electromagnetic Pump

An electromagnetic pump is included in the mercury feed subassembly which is capable of producing a pressure difference of 0.6 atm when driven at 20 amp; its electrical power consumption is less than 2 w. The over-all dimensions are 5 cm × 5 cm × 3.5 cm and its mass is 301 g. The pump was operated satisfactorily as a single component for an accumulated 800 hr with a total of 2.4 × 10^6 amp-hr of mercury flow equivalent circulated through it.

An exploded view of the pump is shown in Fig. 6. The body is formed of nylon which is impregnated with 20% glass

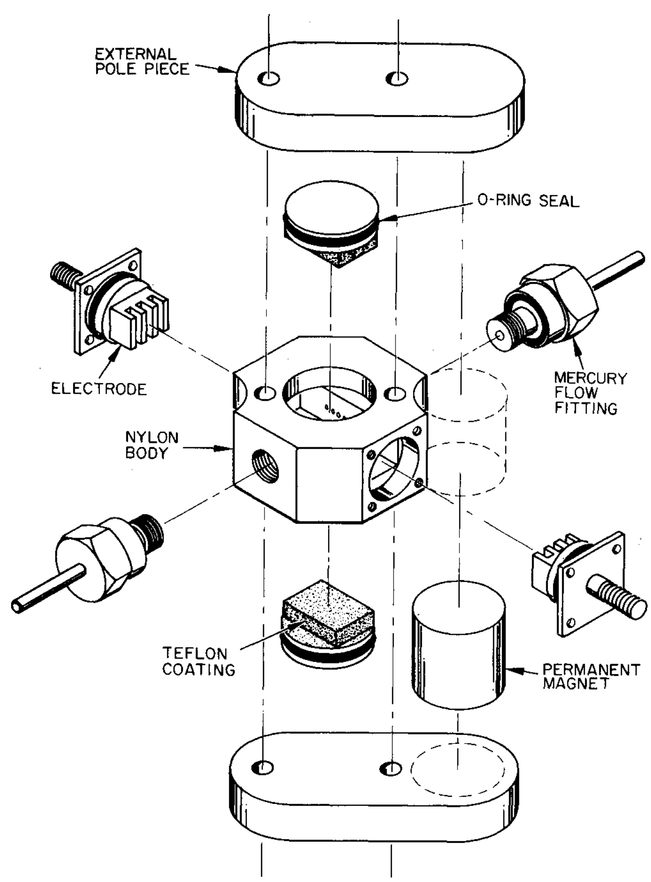

Fig. 6 Electromagnetic pump.

reinforcing. This material possesses high strength, high service temperature, and a low coefficient of thermal expansion. Narrow channels are cut into the nylon body between the pumping region and the mercury feed line in order to discourage eddy currents in the mercury flow. The pump is designed so that a magnetic field of 7 kgauss is concentrated in a narrow pumping region which is 0.025 cm wide and 1.27 cm on each side. The magnetic pole pieces are coated with a thin layer of teflon (0.003 cm thick) which is sprayed and baked onto the surface to provide electrical insulation from the mercury. The current carrying electrodes are made of molybdenum which was chosen because it exhibits negligible contact resistance with the mercury. All unions of electrodes, pole pieces and flow fittings with the nylon body are sealed with rubber O-rings.

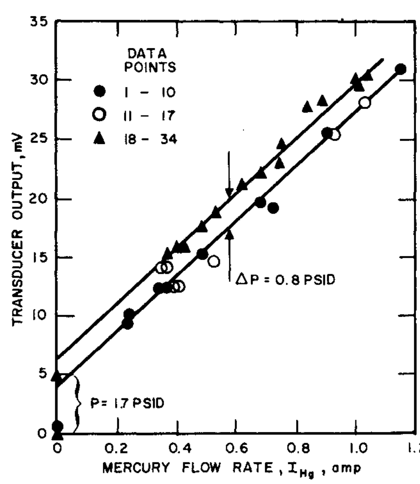

Fig. 7 Mercury flowmeter calibration characteristics.

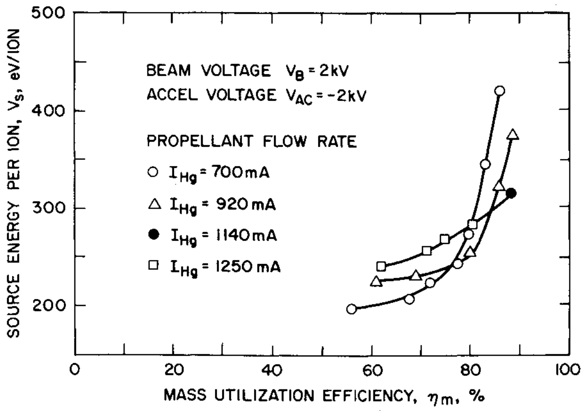

Fig. 8 Discharge chamber performance of the LMT-20-II thruster.

Mercury Flowmeter and Single-Capillary Flow Impedance

The mercury flow rate through a single-capillary flow impedance has been shown to be a linear function of the pressure drop across its length.[9] In the LMT-20-II system this characteristic is being exploited in the current development of a mercury flowmeter which utilizes a differential pressure transducer to measure the pressure drop across a calibrated section of the capillary flow impedance. A Winsco Model PB415 differential pressure transducer was used§ which yields a 25 mv signal output for an applied pressure difference of 10 psid. The transducer output is linear to within 1% of full scale. This transducer measures the pressure drop across a single-capillary flow impedance consisting of a 915 cm length of 0.0178 cm i.d., type 304 stainless steel tubing. This flowmeter impedance is attached to the upstream end of a greater flow-control impedance (1060 cm length of 0.014 cm i.d., type 304 stainless-steel tubing) which leads to the LM cathode.

The flowmeter was calibrated by correlating the electrical output signal of the pressure transducer with the mercury flow rate as determined by the rate of displacement of the piston of a gas-pressurized mercury reservoir. Data points (Fig. 7) were acquired at a rate of only one or two per day to insure that each value of the mercury flow rate would be determined to the same high accuracy anticipated from this instrument. The first ten data points confirmed the high expectations held for the flowmeter, exhibiting a linear output characteristic with a signal amplitude of 24 mv/amp of mercury flow equivalent within a standard deviation of $\pm 1\%$ over the range 0.2–1.2 amp. Data points 11–17, however, show a marked increase in scatter as the calibration characteristic undergoes a change to a new value, which is described by data points 18–34. The new linear characteristic has the same slope, with a standard deviation of slightly greater than $\pm 1\%$, but it lies 0.8 psid above the previous slope; the zero-flow rate intercept shifted from 1.7 to 2.5 psid.

The existence of a nonzero intercept is believed to indicate the presence of minute gas bubbles which are lodged within the liquid mercury feed system; if these gas bubbles were not present, the pressure drop across the capillary impedance would approach zero for zero flow rate, and no fluctuations could occur. More stringent procedures to assure complete outgassing of the feed subassembly and of the mercury itself (including vacuum distillation of propellant directly into the reservoir) are currently being developed to eliminate this source of error.

Table 1 Efficiency of the LMT-20-II thruster system at two I_{sp} levels

Effective specific impulse $I_{sp,\,eff}$, sec	4040	2710
Beam voltage V_B, kv	2	1
Beam current I_B, amp	1	1
Source energy/ion V_S, ev/ion	315	315
Beam mass utilization efficiency η_m, %	89	89
Neutralizer coupling voltage[a] V_{N-C}	30	30
Neutralizer mass flow fraction[a] $\eta_{m,N}$	3	3
Accel interception current I_{ac}, ma	6	25
Thruster power $P_B = I_B V_B$, w	2000	1000
Discharge power $P_S = I_B V_S$, w	315	315
Neutralizer power $P_N = I_B V_{N-C}$, w	30	30
Accel electrode power $P_{ac} = I_{ac}(V_B - V_{ac})$, w	24	75
Isolator power P_{is}, w	0.7	0.7
EM pump power P_{EM}, w	1.0	1.0
Flowmeter power P_F, w	1.0	1.0
Total system power[b] P_T	2372	1423
Total power efficiency $\eta_{p,T} = P_B/P_T$,%	84	70
Total mass utilization efficiency $\eta_{m,T} \sim \eta_m - \eta_{m,N}$,%	86	86
Total thruster efficiency $\eta_T = \eta_{p,T}\eta_{m,T}$,%	72	60

[a] No neutralizer was operated with the LMT-20-II system, but neutralizer losses have been estimated from data obtained in earlier operation of the LMT-30-I system.
[b] This value has been determined assuming the use of permanent magnets. During experimentation, bar electromagnets were used to achieve greater operating flexibility. Approximately 16 w was consumed by these magnets.

§ This transducer has since been replaced in the LMT-20-II system by a Whittiker P109D transducer which was preferred for its lower mass.

System Efficiency

Data obtained from operation of the LMT-20-II system provide a basis for comparative evaluation with other electron bombardment thruster types. Typical discharge-chamber performance data are shown in Fig. 8 for operation of the LMT-20-II system over the range of beam current from I_B = 0.5 to 1.0 amp. At the maximum ion-beam current $I_B = 1.0$ amp, the source energy per ion is $V_S = 315$ ev/ion¶ at a thruster propellant utilization efficiency $\eta_m = 89\%$. The total efficiency of the over-all thruster system is evaluated in Table 1 for operation at $I_B = 1.0$ amp; no separate tabulation is listed for operation at reduced beam current, because differences in performance are small. The over-all efficiency reaches its maximum value $\eta_T = 72\%$ for operation at the design impulse $I_{sp,\,eff} = 4040$ sec, and decreases to a value of $\eta_T = 60\%$ for operation at a specific impulse $I_{sp,\,eff} = 2710$ sec.

Power-Conditioning Subsystem

Only slight modification is required for electrical integration of the LMT-20-II system with the power conditioning and control circuitry presently used with SEPST III system. Special circuits which are particular to the LMT-20-II system have been incorporated into an all-solid-state power conditioning subsystem which provides the appropriate power inputs (from a solar array power source) for the EM pump and the high-voltage isolator. The subsystem consists of a voltage regulator, a 10 kHz converter, a power control circuit for the EM pump, and a power controller for the high-voltage isolator. Each part of the subsystem is built as a separate module. A solar panel simulator provides an output voltage of 60–90 v.d.c. (dependent on load). The voltage regulator provides a 60 v.d.c. output which is regulated to within $\pm 2\%$. From this signal, the converter produces plus and minus 15 v d.c. power for use by the EM pump power control module, and 60 v square-wave power at 10 kHz for use by both the EM pump rectifier module and high-voltage isolator power controller.

The output of the EM pump rectifier module is a variable d.c. voltage in the range -0.1 v–0.1 v; its magnitude and

¶ V_S, the total source energy per ion, is the discharge energy per ion, because no heater, vaporizer, or keeper power is required with the LM cathode.

polarity are determined by the control signal which can be either a reference signal or the feedback command input provided by the flowmeter. The isolator power controller provides 15-v pulses of 10 kHz power to drive the heater which is located in the iron diffuser section of the high-voltage isolator. The time between pulses is 30 min and the pulse width is variable from 10 sec to 2.8 min.

The elements of the power-conditioning circuitry that are associated with the discharge chamber and the ion-beam extraction system are expected to be virtually interchangable for LM and hollow-cathode thrusters due to the similarity of their electrical characteristics. With respect to other elements of the circuitry, there are significant differences between the two systems. For instance, the LM cathode does not employ a vaporizer. The role of the vaporizer in the hollow-cathode system for use in propellant flow control is replaced in the LMT-20-II system by the EM pump in conjunction with the single-capillary impedance. Ignition of the main discharge and neutralizer discharge is obtained automatically by a high voltage (40 kv) spark igniter.[3] This igniter consumes no power during normal thruster operation. Since no heaters are required for LM cathode operation, the SEPST III power supplies associated with these functions will not be needed.

Control System

To optimally achieve the goals of a specific propulsion mission, the elements of the LMT-20-II system must be combined with logic and control circuitry to maintain efficient operation and to regulate and control the thrust schedule as determined by mission requirements. Though no hardware has been built for automatic control of the LMT-20-II system, a general control scheme has been developed. A schematic diagram is presented in Fig. 9 which shows how the elements of the thruster system are operated by the power-conditioning and control circuitry. By reliance on direct measurement and control over the mercury flow rate, a significant advance can be achieved in the direction of stable and accurate control over the thruster operation.[8] The system employs one control loop in which the cathode current is varied in order to control the ion-beam current. This control is based on a sensitive and single-valued relationship, because the beam current I_B increases almost linearly with discharge current I_K for a constant value of propellant utilization efficiency. By means of a second control loop, the propellant utilization efficiency η_m is held at the desired value by control of propellant flow rate. The flow rate measured by the flowmeter is expressed as an equivalent electrical current I_{Hg} which, when multiplied by the required value of mass utilization efficiency, is compared with the required beam current to produce an error signal which can be used to drive the EM pump. High feedback gain is possible in the flow-control loop since this loop is expected to be extremely stable by virtue of the viscous damping forces derived from mercury flow through the single-capillary impedance.

This control scheme should exhibit an added measure of stability beyond that which is now employed for control of the SEPST III hollow-cathode thruster system. In that system, the beam current is controlled by varying the mercury flow rate through the main propellant vaporizer. The desired value of propellant utilization efficiency is obtained only indirectly by reliance on a functional relationship between the beam current and the cathode discharge current. Unfortunately, this relationship is not entirely single-valued for operation of highly optimized thruster systems (above a certain maximum value, the beam current is reduced by increases in propellant flow rate), and system control is lost if thruster operation occurs beyond prescribed limits.[8] Though definite and repeatable functional relationships between beam current, discharge current, and propellant utilization efficiency also exist with the LM cathode thruster, reliance in this system on the direct measurement and control of the liquid-

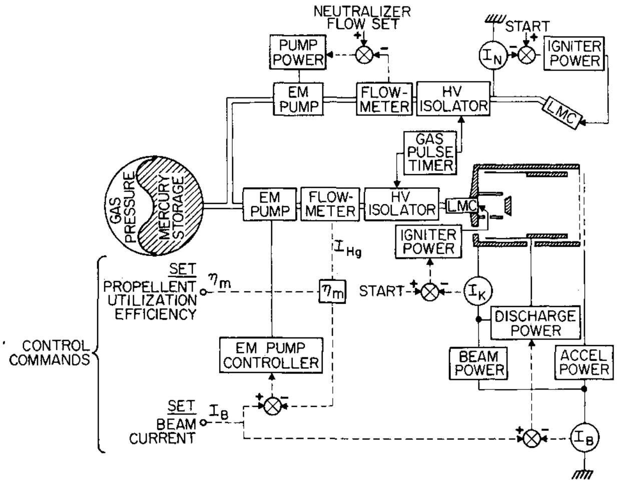

Fig. 9 Control logic for LMT-20-II thruster system.

mercury flow rate is expected to provide sufficient information for unambiguous control over all relevent parameters.

Conclusion

Efficient performance has been demonstrated in operation of a flight-type 20-cm electron-bombardment mercury ion thruster which utilizes a liquid metal (LM) cathode which is thermally integrated with the aluminum body of the thrust chamber. The thruster system, designated LMT-20-II, operates over a design range of beam current from $I_B = 0.5$ to 1.0 amp at a nominal beam voltage $V_B = 2$ kv. At full beam power, the cathode temperature is held at a value $T_K = 200°C$ by a balance between discharge heating and cooling by radiation from the outer walls of the thrust chamber. Discharge chamber performance is essentially unchanged for operation at an effective specific impulse $I_{sp,\,eff} = 2710$ sec. The LMT-20-II system includes a liquid mercury feed system with the capability for automatic flow measurement and control and high-voltage isolation between the thrust chamber and the propellant reservoir. Direct control of the propellant flow rate is expected to result in the design of a stable thruster control system which does not rely on the details of the thruster electrical characteristics.

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