922

LM CATHODE THRUSTER SYSTEM

4 JANUARY 1970 through 4 APRIL 1970

QUARTERLY PROGRESS REPORT NO.3, PHASE II

CONTRACT JPL 952131

by

J. HYMAN, JR., J.R. BAYLESS,
J. SIMPKINS and J.W. WARD

15 APRIL 1970

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This report contains information prepared by the Hughes Research Laboratories under JPL subcontract. Its content is not necessarily endorsed by the Jet Propulsion Laboratory, California Institute of Technology, or the National Aeronautics and Space Administration.

ABSTRACT

A 20 cm LM cathode thruster system is being developed for operation at beam currents $I_B = 0.5$ A to 1.0 A and a beam voltage $V_B \overline{<} 2$ kV. The thruster employs a thin-screen high-transparency (70%) ion-extraction system and an LM cathode which is thermally integrated with the thruster body. Assembly of all elements of the system is complete, and optimization-testing is under way. Currently, a beam current $I_B = 825$ mA is produced with a total source energy per ion $V_S =$ 345 eV/ion at a mass utilization efficiency $\eta_m = 85\%$. The liquid mercury feed system with its associated power conditioning circuits is now undergoing bell-jar testing prior to integration and testing of the complete thruster system. Thermal analysis has been completed which demonstrates the capability of the LM cathode thruster to operate in close-packed linear arrays and which examines the influence of the external anode connector on thruster operation.

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SECTION I

INTRODUCTION

For detailed mission analysis or comparative evaluation of alternative thruster types, it is necessary to know the operating characteristics of an entire thruster system, including the subsystems for propellant feed, ion beam neutralization, and power conditioning. The development of each of these components for the LM cathode thruster system has now reached a stage where a laboratory-type thruster system (not involving flight-type power supplies) can be built based on existing technology. As a first step in the construction of this system, a thermally integrated 20 cm LM cathode thruster has been constructed and is now being tested for operation at beam currents I_B = 0.5 to 1.0 A. A mercury feed system has also been assembled which consists of a hydrogen-bubble high-voltage isolator followed by an electromagnetic (EM) pump, a liquid-mercury flowmeter, and a single-capillary flow impedance. These components combine to provide liquid mercury to an LM cathode which is thermally integrated with the 20 cm thruster. The feed system will be enclosed ultimately within the ground-screen shroud of the thruster and operated as part of a complete thruster system. The resulting LM cathode thruster system (designated the LMT-20-II system) requires only a mercury supply and the appropriate electrical power for its operation. No neutralizer cathode development is planned under this effort.

Programs for research and development of the LM cathode, the thruster, and various elements of the liquid-mercury feed system have been carried out as separately funded projects. Through coordinated guidance of the over-all program, however, these separate projects have produced the necessary devices and technology which are now being employed for the development of a reliable and useful laboratory-type thruster system.

The feasibility of LM cathode thruster life in excess of 10^4 hours was demonstrated at Hughes Research Laboratories (HRL) under Contract NAS 3-6262; a 20 cm thruster equipped with a circular LM cathode was successfully tested for an accumulated 4,000 hours. No erosion of the molybdenum cathode structure was evident following this test, and there was no degradation of cathode performance. Development of high-temperature LM cathodes began at HRL under Contract NASW-1404 after it became apparent from thermal analysis that combining thrusters in peripheral or clustered arrays places a constraint on the operation of <u>any</u> electron-bombardment ion thruster unless the temperature of the thruster shell can be allowed to exceed a value on the order of 200°C.

The demonstrated feasibility of system life in excess of 10^4 hours, combined with a demonstrated capability for operation of a high-temperature LM cathode in an efficient thruster, prepared the way for the construction of a 30 cm thermally integrated thruster under the first phase of the current contract. This thruster has now demonstrated efficient performance at a specific impulse $I_{sp, eff} = 4,100$ sec; a beam current $I_B = 1,400$ mA is produced at a beam voltage $V_B = 2$ kV with a source energy per ion $V_S = 270$ eV/ion* at a mass utilization efficiency $\eta_m = 90\%$. At this power level, the thermally integrated LM cathode achieves an equilibrium body temperature $T_K = 200°C$; it rejects the heat from the discharge along a tapered aluminum endplate to the outer thruster shell, from which the heat is radiated to the walls of the vacuum chamber.

In a related contract effort (Contract NAS 7-539), the design of liquid-mercury feed systems was explored in detail. A number of unique components were built so that their operating characteristics could be established and the various systems which were considered could be properly evaluated. Two of these components, an EM pump and a high-voltage isolator, were incorporated into a breadboard flow system which was operated under the first phase of the current contract for a final demonstration of the proper operation of each of the components and of the mutual compatibility of all of the components of the system. The feed system consisted of (1) a gas-pressurized positive-expulsion mercury reservoir, (2) the liquid-mercury high-voltage isolator, (3) the EM pump, (4) a single-capillary flow impedance, and (5) a high-temperature LM cathode which was thermally integrated with the 30 cm electron-bombardment thruster. Successful operation of the 30 cm LM cathode thruster with the breadboard liquid-mercury feed system led to the present development of the LMT-20-II thruster system.

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*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.

SECTION II

THE LMT-20-II THRUST CHAMBER

The thermally integrated LMT-20-II performed this quarter with satisfactory efficiency in its initial experimental operation. Thruster performance data obtained from this operation are plotted in Fig. 1. With an ion beam current I_B = 776 mA, the source energy per ion was V_S = 278 eV/ion* at a propulsion utilization efficiency η_m = 80%. With the same neutral flow rate and a propellant efficiency η_m = 85%, a beam current I_B = 825 mA was produced at a total source energy per ion V_S = 345 eV/ion. These data correspond to operation at a beam voltage V_B = 2 kV and an accel voltage V_{Ac} = - 2 kV; at η_m = 85% the drain current to the accel electrode was measured at 0.36%. Under equilibrium operating conditions, the thruster endplate reached a temperature of 140°C, which is 20°C higher than had been predicted by thermal analysis for operation at that power level. This apparent discrepancy seemed to result from a decrease in the spectral emissivity of the thruster surface from the initial value of 0.85 (obtained by use of a surface coating) to a value close to 0.7. A decrease of this magnitude is consistent with an observed deposition of metal which was backsputtered from the walls of the vacuum chamber and partially coated the thruster surfaces. This occurred because the thruster was operated without the usual sputter-prevention shield in order to facilitate visual observation of all parts of the thruster during initial operation.

For this test, thruster operation was implemented with single-capillary fed LM cathode K-51 and a piston-driven liquid mercury feed system. The LMT-20-II feed system (including an electromagnetic pump, high-voltage isolator, and liquid mercury flowmeter) is currently undergoing check-out testing prior to integration and operation with the thruster. A cathode-cup pole piece was employed which is 4.2 cm long and 5 cm in diameter with a 0.051 cm wall thickness. This cup is penetrated by 32 post-cathode propellant diversion apertures of 0.79 cm diameter, which are covered with 50% transparent wire mesh.

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*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.

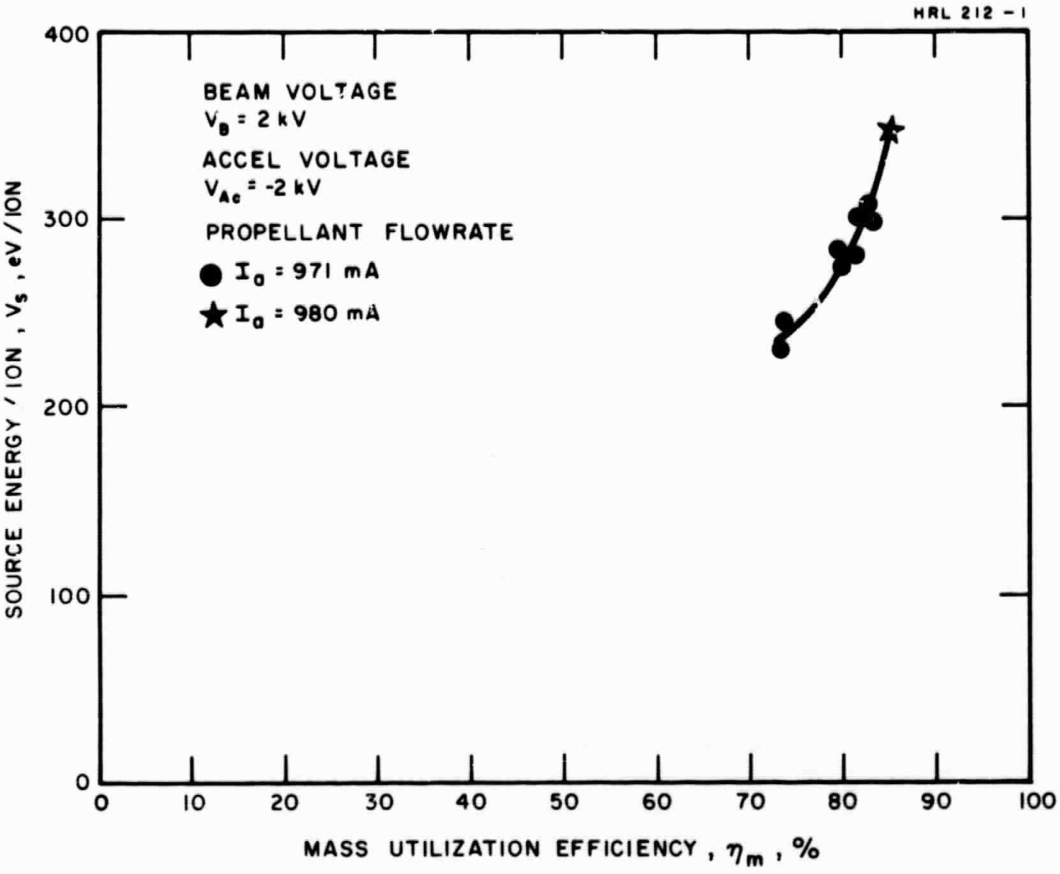

Fig. 1. Performance of the LMT-20-II thruster.

At the conclusion of initial testing, the cathode mounting arrangement was modified for better conformity with the final design configuration, and several thrust chamber modifications were carried out to advance the flexibility of thruster operation and to develop suitable control characteristics. A stainless steel shield was installed to shadow the cylindrical thruster surfaces from backsputtered material, and the high-emissivity thermal coating was renewed. To provide a suitable base for the new coating, the thruster had to be disassembled and sandblasted to prepare the aluminum surface prior to application of the water solution of a mixture of potassium silicate and titanium dioxide in a dry weight ratio of four to three.

For experimental flexibility, a second LM cathode K-25-V has been modified to have the same exterior dimensions as LM cathode K-51. The two cathodes are now physically interchangeable, and both are similar to the new LM cathode K-54 which is currently being tested as part of the LMT-20-II liquid mercury feed system. The cathode mounting arrangement has been modified to the thermally integrated configuration. In this configuration, the location of the cathode and the cathode-cup pole piece is moved slightly downstream with respect to the thrust chamber (by removal of a gas-cooling flange which separates the cathode mounting plate from the thruster endplate). This modification is significant not only as a step toward the final design configuration, but also because of a demonstrated sensitivity of thruster performance to the detailed nature of the magnetic field at the cathode location.

SECTION III

THE LMT-20-II LIQUID MERCURY FEED SYSTEM

Bell-jar testing of the LMT-20-II liquid mercury feed system prior to its integration with the 20 cm LM cathode thruster has begun. This system contains all of the elements necessary to provide mercury propellant to the thruster in a measured and controllable manner. The elements of the system module are shown in Fig. 2. In order of flow sequence, the liquid-mercury feed system includes a mercury shutoff valve, the hydrogen-bubble high-voltage isolator,[1] the EM pump,[1,2] the mercury flowmeter,[2] and a single-capillary impedance[3] to regulate the mercury flow to LM cathode K-54.[2] A titanium reservoir for pressurized hydrogen gas and a bubble injector element are associated with the high voltage isolator. Bell-jar operation of an LM cathode discharge under conditions of high-voltage isolation, and calibration of the liquid mercury flowmeter are scheduled.

The feed system is supplied with mercury by a gas-pressurized mercury reservoir. Pressurized nitrogen is applied above a piston pressing on the mercury surface to serve as the driving force. The piston position is indicated by a dial indicator (calibrated to 0.001 in. or 0.0001 in.) which contacts the top of the piston shaft, and its displacement as a function of time serves as an indication of mercury consumption and yields an accurate measure of the flow rate which supplements the instantaneous value obtained from the flowmeter. The shutoff valve permits handling of the thruster system outside the vacuum environment with no loss of mercury or atmospheric contamination of the stored mercury. The high-voltage isolator permits operation of the thruster at a potential which 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 the electromagnetic pump; the single-capillary flow impedance establishes a mercury flow rate which is linearly related to the applied pressure.

An important aspect of feed system assembly involves the interface formed at the vacuum chamber endplate. Endplate connections have been arranged to permit versatility of system operation both for thruster experiments conducted within the 5 ft diameter vacuum chamber and for check-out tests conducted within a 1 ft diameter bell jar. The system is shown in Fig. 3 assembled for bell-jar testing with LM cathode K-54. Vacuum feedthroughs have been provided to permit movement within the vacuum of electron and neutral flow baffles and positioning of the igniter electrode, and to permit propellant flow to the thruster system from an externally mounted reservoir. The propellant feed line

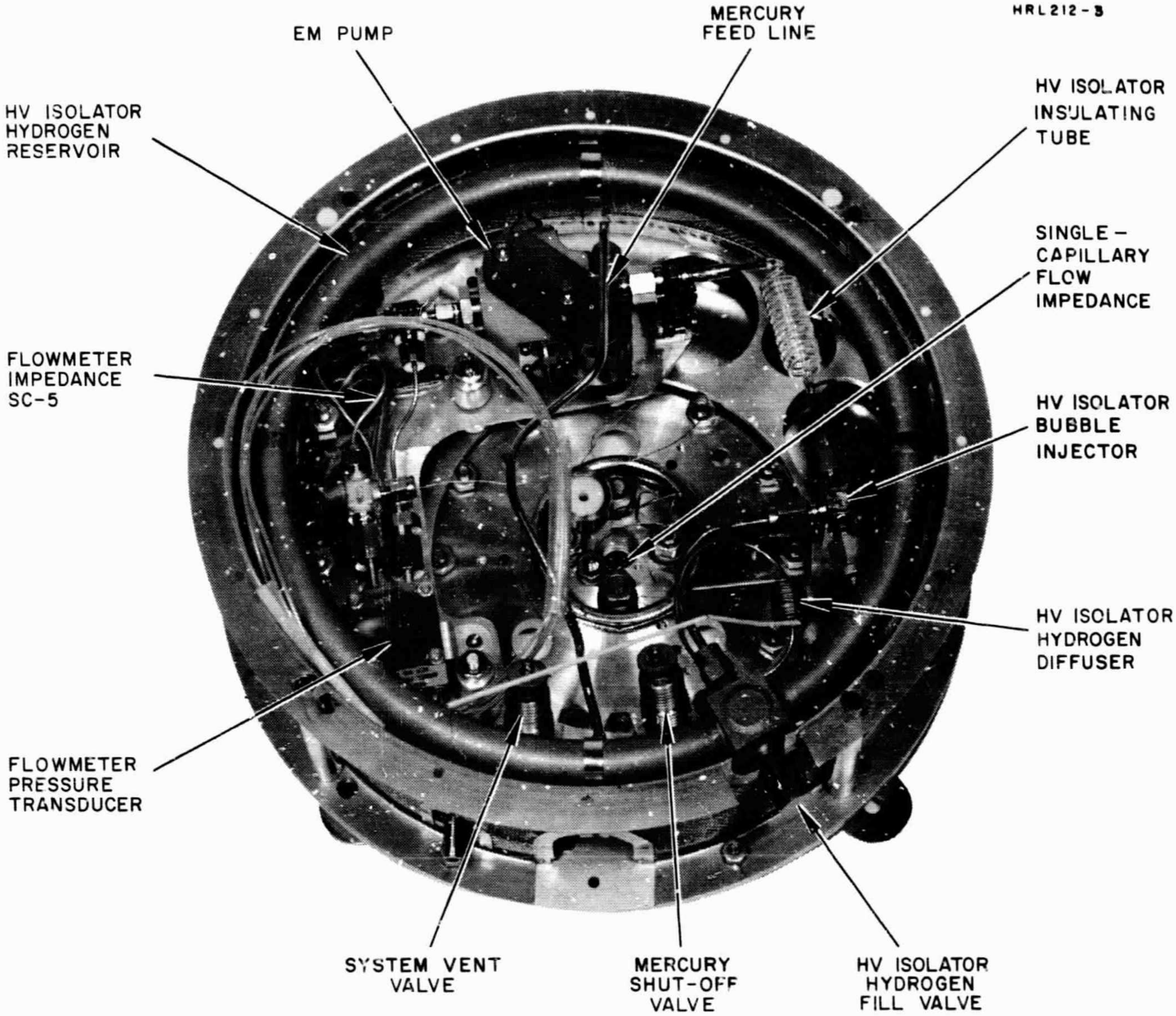

Fig. 2. The LMT-20-II liquid mercury feed system.

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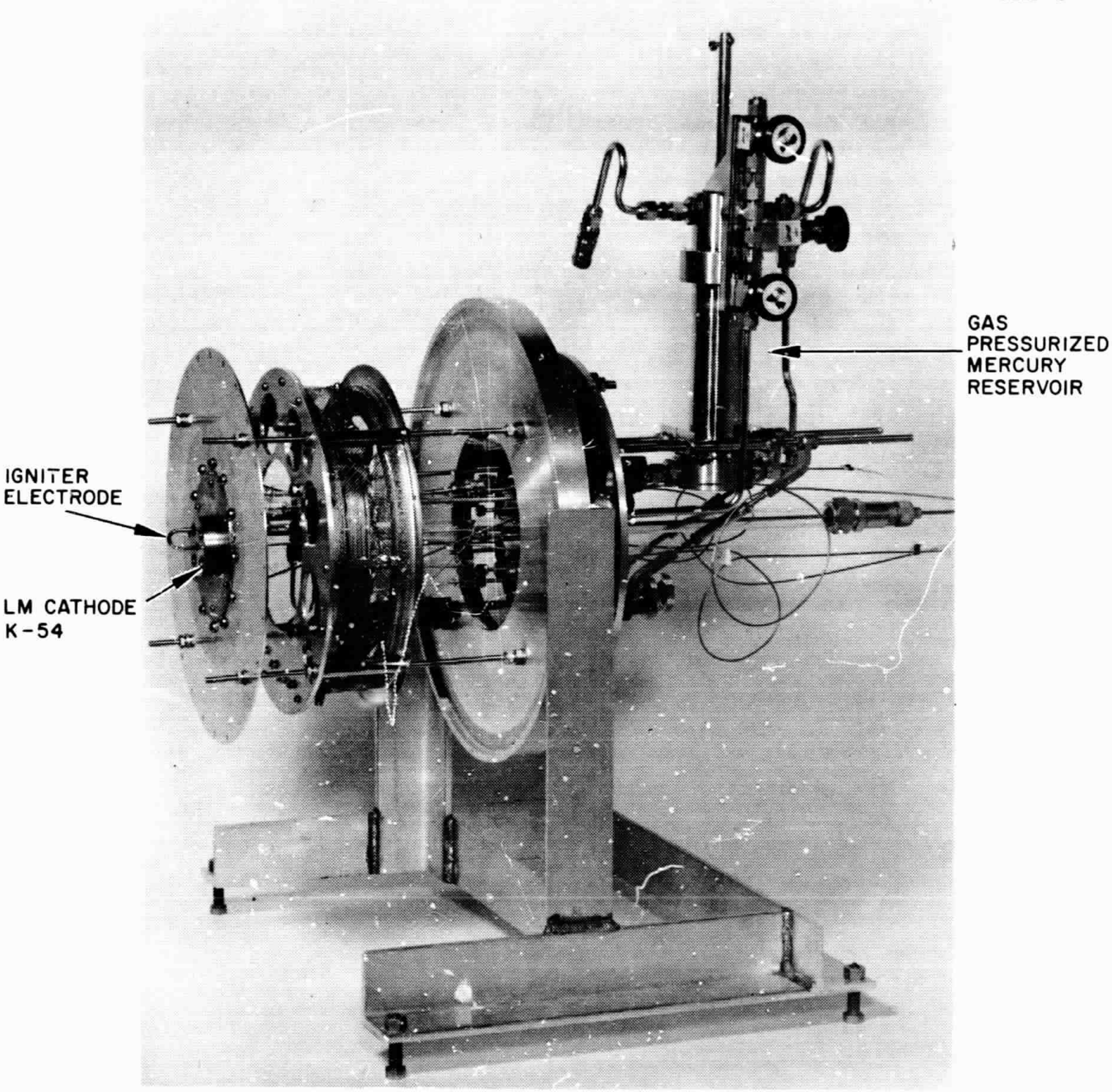


Fig. 3. LM cathode K-54 and the liquid mercury feed system mounted for bell-jar testing.

can be opened to the vacuum by a remotely actuated valve. This permits venting, prior to system operation, of gas which enters the feed line during disassembly of the thruster system during experimental testing.

The titanium reservoir of the high-voltage isolator has been filled with hydrogen gas at a pressure of 400 psi, and the propellant reservoir has been filled with mercury by vacuum distillation at a pressure of 5 x 10^{-7} Torr. Initial testing uncovered a liquid mercury leak in a section of flow line which could not be tested prior to assembly. Another mercury pressure leak occurred as the result of a faulty rubber "O" ring seal in the Whittiker P109 D pressure transducer, which is part of the liquid mercury flowmeter. This transducer had not been used in earlier flowmeter evaluations, and the leak was not revealed in the prior inspection with a helium leak detector. The faulty flow line has been replaced and new "O" rings have been installed in the pressure transducer. Check-out testing was resumed only after the entire flow system was disassembled and emptied of mercury (except for the reservoir) to permit all elements to be outgassed thoroughly under vacuum before liquid mercury was reintroduced into the flow lines. This procedure is essential to insure that no gas bubbles are trapped within the feed system.

SECTION IV

POWER CONDITIONING

An all-solid-state power conditioning subsystem has been completed which contains the electronic circuitry necessary to provide appropriate power inputs (from a solar array power source) for the EM pump, and the high-voltage isolator of the LMT-20-II feed system. The subsystem consists of a solar panel simulator, a voltage regulator, a 10 kHz converter, a power control circuit for the EM pump, and a power controller for the high-voltage circuitry. Each part of the subsystem is built as a separate module. A circuit diagram is given in Fig. 4, which shows each of the circuits along with the cable connections which join them. The solar panel simulator provides an output voltage of 60 to 90 V dc (dependent on load) to simulate a solar panel operating in space. The voltage regulator provides a 60 V dc output which is regulated to within ±2%. From this signal, the converter produces plus and minus 15 V dc voltages for use by the EM pump power system and 60 V square-wave power at 10 kHz for use by both the EM pump and high-voltage isolator systems.

The ultimate output of the EM pump power system is a variable dc voltage in the range -0. 1 V to + 0. 1 V; its magnitude and polarity are determined by the magnitude and polarity of a control signal which can be either a reference signal or the feedback command input provided by the liquid-mercury flowmeter which was developed under this contract. The isolator system provides 6 V, 1. 5 A pulses of 10 kHz power to drive the heater, which is located in the iron diffuser element of the hydrogen-bubble high-voltage isolator. The time between pulses is 30 min, and the pulse width is variable from 10 sec to 2 min.

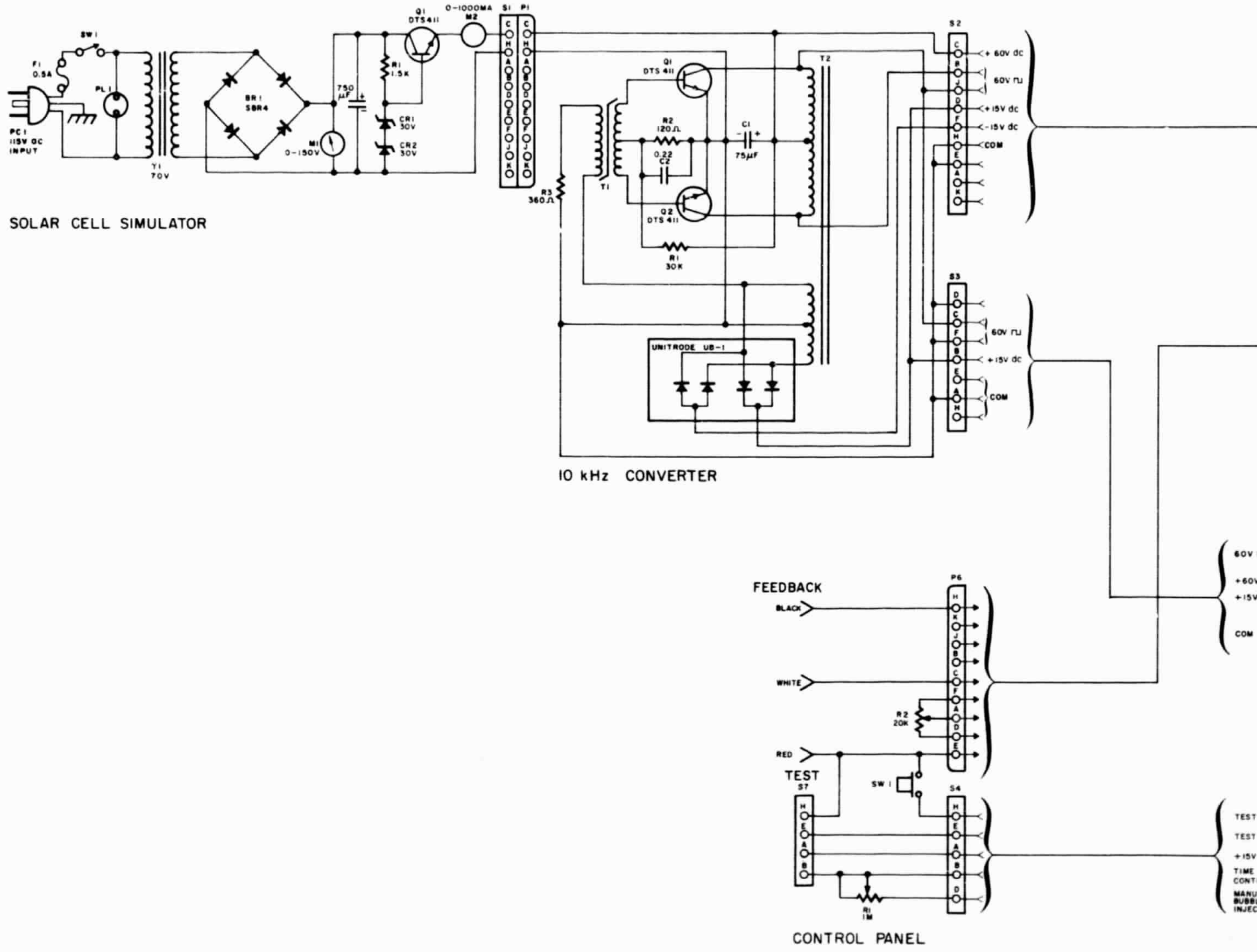
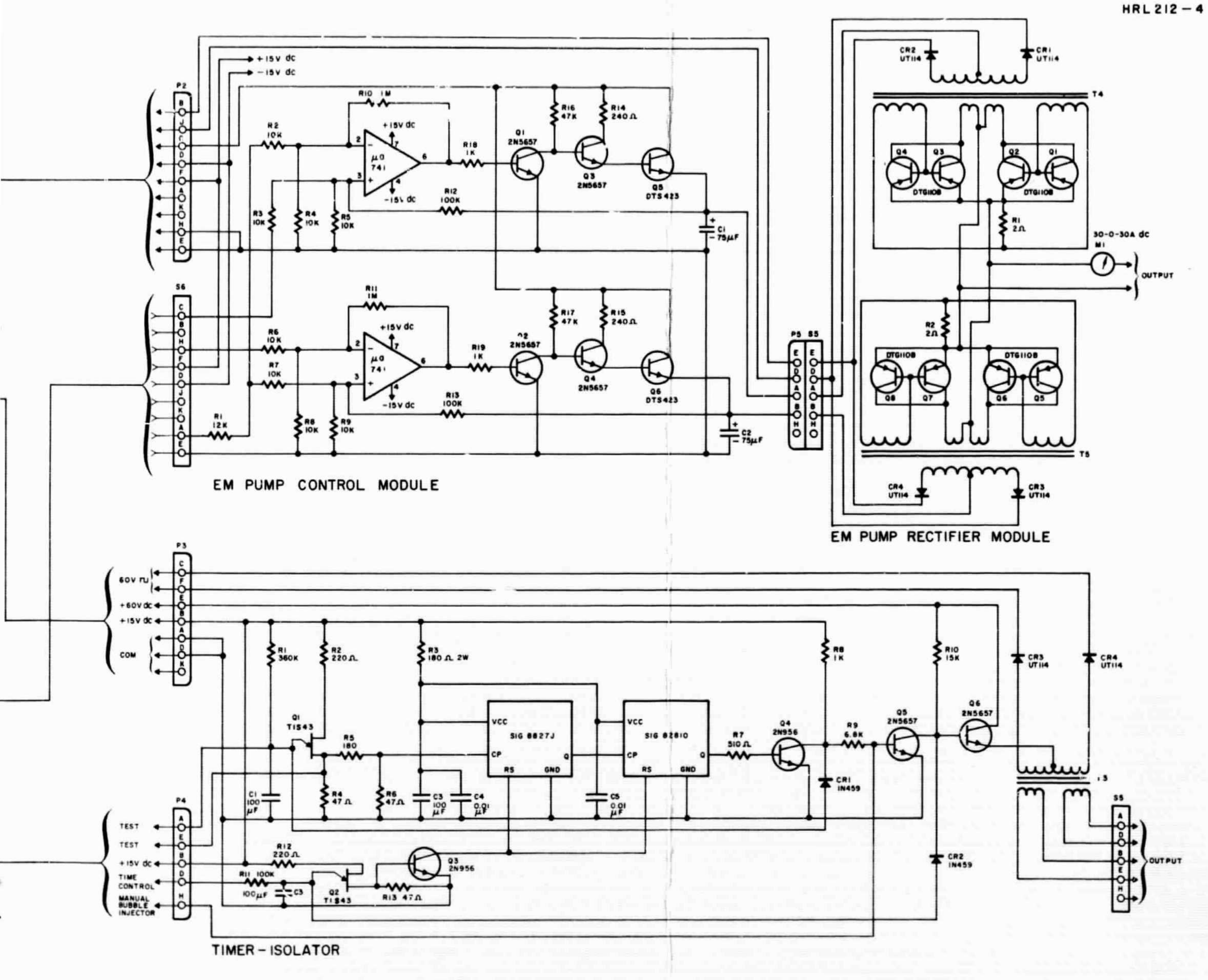


Fig. 4. Power-conditi



wer-conditioning circuit diagram.

SECTION V

THERMAL ANALYSIS

Detailed thermal analysis is required to determine the operating characteristics and to establish accurate quantitative design criteria for the lightweight, thermally integrated LM cathode thruster. Thermal simulation of the LM cathode thruster, which was undertaken as part of the present effort, has now been completed with the analysis of two final configurations of the LMT-20-II system. The first is that of an infinite linear array of identical thrusters, and the second is that of a single thruster which does not employ an outer anode connector.

An infinite linear array of identical thrusters was analyzed for the case in which the thrusters are placed directly against one another. To simulate this configuration without introducing the complexity of azimuthal asymmetry, a model is used in which the lateral environment of an individual thruster is made to be uniform with an emissivity which is the average of the emissivities appropriate for a thruster in a linear array. An average emissivity of 0.67 is obtained by using the simplifying approximation that each incremental area on the lateral thruster surface radiates only in the radial direction. In this case, two thirds of the lateral thruster surface radiates to space, which has unity emissivity, and one third of the surface radiates to an identical operating thruster which can be represented by a surface with an emissivity of zero. In this analysis the operating conditions of the LMT-20-II thruster are taken to be

Beam current $I_B = 1$ A

Mercury flow rate equivalent $I_a = 1.18$ A

Discharge current $I_K = 7$ A

Discharge voltage $V_A = 40$ V

Source energy per ion $V_S = 280$ eV/ion

Mass utilization efficiency $\eta_m = 85\%$

Specific thermal load $V_{K'\,th} = 4$ W/A*

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*To facilitate this calculation, the specific thermal load for the LM cathode $V_{K\,th}$ (which depends on the cathode temperature) is given a constant value close to the anticipated self-consistent value.

For these parameters, the computer-simulated thermal model predicts a cathode temperature of 164°C. This is within the desirable operating temperature range of the LM cathode thruster, and thus the feasibility of operation in a close-packed linear array is established.

The second configuration to be considered was that of a single thruster which operates without an external anode connector. While confirming the effectiveness of the LMT-20-II design, which includes the outer anode connector, this analysis indicates that a still more efficient design (without an anode connector) may be possible if the degree of thermal isolation between the anode and the thruster shell can be increased by the use of heat shielding above a critical level. An important part of the current experimental program will be to determine whether this degree of isolation can in fact be achieved by the lightweight heat shielding now employed with the LMT-20-II thruster. If no outer anode connector is employed, analysis indicates that the interior of the discharge chamber attains a relatively high temperature (600 to 750°C) and the discharge heat is dissipated by radiation through the apertures of the ion extraction system rather than from an external anode connector. Table I compares the cathode temperature calculated both with and without an anode connector for two values of the effective emissivity ϵ_e, which is associated with multiple heat shields placed between the anode and the thruster shell. For the lower value of ϵ_e (a higher degree of insulation), the cathode temperature is lower for the geometry which does not employ an outer connector.

TABLE I

Effect of the Outer Anode Connector on Cathode Temperature T_K as a Function of the Effective Emissivity ϵ_e

Effective Emissivity ϵ_e	0.006	0.06
Cathode Temperature T_K (With Outer Anode Connector)	130°C	159°C
Cathode Temperature T_K (Without Outer Anode Connector)	80°C	173°C

Recent experiments with the LMT-20-II thruster have been conducted with heat shielding placed between the anode and thruster shell which consists of eleven layers of aluminum foil. The thermal isolation afforded by this configuration has been found to be quite effective at least for the short duration of the current experiments. The effective emissivity ϵ_e* of this configuration has been calculated to be $\epsilon_e = 0.006$ with the assumptions that the surface of the heat shields retains the characteristic of clean aluminum $\epsilon_{Al} = 0.1$ and that conductive and convective heat transfer can be neglected between adjacent heat shields. At this level of thermal isolation, the outer anode connector is no longer useful and the cathode temperature is actually increased by conduction or radiation from the outer connector to the thruster shell. However, a higher value of the effective emissivity may be more characteristic of the actual experimental situation if the assumptions are not satisfied either initially or after deterioration as a result of prolonged thruster operation. A value $\epsilon_e = 0.06$ would result if the assumption of low heat transfer between adjacent heat shields were invalidated, or if the individual aluminum heat shields lost their characteristic emissivity and approached a gray condition with $\epsilon = 0.5$. If the low value of effective emissivity cannot be maintained, the usefulness of the outer connector is apparent from the relative values of cathode temperatures which correspond to the higher value of effective emissivity.

Until the long-term characteristics of multiple heat shielding have been determined experimentally, the thruster configuration which employs an outer anode connector represents the more conservative design. For moderately effective heat shielding, this configuration results in the lowest cathode temperature, and in all cases results in the lowest internal thruster temperatures. Furthermore, when the outer anode connector is employed, the cathode temperature is seen to be less sensitive to variation or deterioration in the effectiveness of multiple heat shielding.

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*The effective emissivity ϵ_e is the emissivity of two closely spaced parallel surfaces which exchange the same radiant power as two parallel surfaces of emissivity ϵ between which a number n of heat shields are placed.

$$\epsilon_e = \frac{2\epsilon}{(2-\epsilon)(n+1)+\epsilon}$$

SECTION VI

CONCLUSIONS

Construction of the 20 cm LM cathode thruster system (designated the LMT-20-II system) is completed, and check-out testing of the thrust chamber, power conditioning, and liquid mercury feed system is underway. Integration of these elements with the remainder of the power conditioning system (consisting of laboratory power supplies) will complete the LMT-20-II thruster system. Optimization and testing of the completed thruster system will continue for the remainder of the contract effort. The program of analysis and over-all evaluation of the thermal characteristics of the LM cathode thruster system has been completed.

Accomplishments under the current phase of this contract include the following:

1. The experimental LMT-20-I thruster was optimized for operation at a beam voltage V_B = 2 kV with beam currents in the range I_B = 0.5 A to 1.0 A in order to predetermine optimization modifications which will be useful with the LMT-20-II thruster. The best performance was achieved at a beam current I_B = 950 mA with a total source energy per ion V_S = 383 eV* /ion and a mass utilization efficiency η_m = 88%.

2. Construction of the LMT-20-II thrust chamber is complete, and satisfactory efficiency was obtained in the initial experimental configuration. At a beam current I_B = 825 mA, the total source energy per ion is V_S = 345 eV/ion at a mass utilization efficiency η_m = 85%.

3. A prototype model of a liquid-mercury flowmeter has been tested and shows promise of a measurement accuracy of ±1%. The flowmeter will operate with a power expenditure of 1 W.

4. An electromagnetic pump using molybdenum electrodes has been operated for over 800 hours at a pressure rise of ±0.6 atm with a power expenditure of 2 W.

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*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.

5. A high-voltage isolator has been developed and has been operated reliably and repeatably for over 500 hours. The average power expenditure is 0.4 W when operated in the pulsed-only heating mode.

6. An all-solid-state power conditioner subsystem has been completed which contains the electronic circuitry necessary to provide appropriate power inputs (from a solar array power source) for the EM pump and the high voltage isolator of the LMT-20-II feed system.

7. The thermal profile of the LMT-30-I thruster was calculated by analytical techniques and shown to agree with the experimentally measured profile. This correspondence confirms the validity of the analytical approach.

8. A program of thermal analysis has been completed in which the thermal properties of the LMT-20-II thruster were determined using the same analytic techniques that were verified experimentally with the LMT-30-I thruster. The analysis indicates that the temperature of the LMT-20-II thruster will remain within acceptable limits when operated within the design current range. No constraint is imposed by arranging groups of thrusters in a closely packed linear array. Groups of thrusters operated in infinite planar clusters will achieve satisfactory thermal balance by self-radiation alone, so long as the separation between thrusters is equal to at least twice the thruster diameter.

SECTION VII

RECOMMENDATIONS AND FUTURE PLANS

During the next quarter, completion of the efforts begun under the second phase of this contract is planned as follows:

1. Testing and optimization of the LMT-20-II thruster for operation in the range $I_B = 0.5$ A to 1.0 A will be completed.
2. Testing of the LMT-20-II liquid mercury feed system in combination with its associated power conditioning equipment will be completed.
3. All elements of the LMT-20-II thruster system will be integrated. The completed system will be optimized and tested.

SECTION VIII

NEW TECHNOLOGY

A. FIRST QUARTER

During the first quarter of the current phase of this contract, an invention which is believed to be patentable was reduced to practice. Accordingly, the following patent disclosure was submitted to the Patent Department of the Hughes Aircraft Company.

PD 69419, Sensitive Liquid-Metal Flow Meter, by Julius Hyman, Jr.

The principles upon which this invention is based are reported to NASA on pp. 21-23 of the First Quarterly Report, 15 May 1968, covering Phase I of this contract. Further details concerning the operation of this device are contained on pp. 35-37 and in the Appendix of Quarterly Progress Report No. 1, 15 October 1969, covering Phase II of this contract.

B. SECOND QUARTER

No reportable items of new technology were identified during the second quarter of the subject effort.

C. THIRD QUARTER

No reportable items of new technology were identified during the third quarter of the subject effort.

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