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by C. A. Low, Jr.
Lewis Research Center
Cleveland, Ohio 44135

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Charles A. Low, Jr.
Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

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Abstract

The major objective of this program was to define the exact role of an on-board spacecraft computer in the control of ion thrusters. An initial computer control system with accurate high speed capability was designed, programmed, and tested with the computer as the sole control element for an operating ion thruster. The command functions and a code format for a spacecraft digital control system were established. A second computer control system was constructed to operate with these functions and format. A throttle program sequence was established and tested. A two thruster array was tested with these computer control systems and the results reported.

INTRODUCTION

The digital computer has been successfully employed as an on-board control element in several spacecraft systems.(1) Rapidly advancing technology has reduced weight and improved reliability of computers to such an extent that their inherent advantages of flexibility and ability to handle complex logic functions can be effectively exploited. Some 16 bit central processing units have been reduced to single microcircuit chips.(2)

Some of the more complex planetary space missions can utilize the ion thruster as the prime propulsion system to a definite advantage. Such future electric propulsion spacecraft will have an on-board computer to control many of the functions of the spacecraft. The optimization of the control of an ion thruster over a large throttling range and operation including start-up over a wide environmental range suggests that the computer could be used to perform this complex control problem. The test and development program in the last few years at Lewis Research Center has been aimed at exploring the capabilities of digital computer control with the objective of determining the best role of the computer and its limitations.

It is the object of this paper to indicate the progress towards that goal of better defining the proper role of the digital computer in a spacecraft thruster control system. The efforts to date have been principally centered on control of a 30 cm thruster, but control of the 8 cm thruster while note the express objective of this effort, has been carfully updated and made into a compatible system. Therefore, simultaneous thruster operation from similar computer programs and interfaces is possible.

The initial computer control system was designed to have maximum speed and resolution of input data and output power supply elements, so that the computer program operation itself was the complete control and limiting element. Thus, it was possible to assess the maximum capability for computer control in contrast to previous work(3-5) which incorporate a computer into an existing system. This paper describes the system and its capabilities and details of several methods of high voltage isolation. The important features of the computer system itself are also given.

The system has proved to be a high speed, very accurate, and flexible data acquisition and automated test facility for ion thrusters. Many of the programs and formats created for thruster testing are indicated. In practice three major programs indicated the appropriate roles and limitations of computer control. These were: Beam Current and Discharge Voltage Control, Start-Up of Thruster, and Recycle Recovery from Arcs. The details of these particular programs are given as being representative of the limitations and complications that may be encountered in a typical digital control application.

Many of the conclusions as to the role of the computer for thruster control were incorporated into a 16 bit command word format for interfacing to an advanced spacecraft power processor unit (PPU) design. A typical spacecraft input/output transmission system was employed. The resulting command code is given and discussed as it forms the basis for further testing of computer control systems.

An existing LeRC power supply console was modified to accept this command format in order to simulate as nearly as possible the spacecraft power processor. A current technology level thruster operating from this power supply console was installed in the vacuum facility. The operation of this current technology thruster and control system will be described including observations with two thrusters in operation simultaneously. The programming and operation of this thruster system over a throttle map from 0.4 to 2.4 A beam current will be described and discussed. The conclusions from this work suggest a basis for the definition of the areas of further investigation and test programs.

This paper attempts to indicate: the basis of an initial test and design program, the operation and results of that initial program, the criteria for establishment of a command code and its format, the preliminary operation of a thruster using this command code, and finally the direction of future programs to resolve current problems or provide exact implementation of current designs. The role of the computer as an ion thruster control element has been defined in a large measure by the tests and observations described, but the final evolution of the optimum design is still subject to further testing and operational experience.

Initial Digital System Design and Facility Capabilities

The philosophy of the initial approach to digital control was to create a laboratory system with minimum design restrictions; thereby, making the digital computer system a very flexible tool for investigating thruster control problems. In addition, this approach has the feature of making the computer and software the limiting item, so that the maximum opportunity for success is afforded.

The use of a relatively large vacuum tank with high pumping capacity, for instance, guaranteed that facility limitations would not be a factor in 30 cm ion thruster operation. While modified commercial power supply systems were employed wherever practical, the minimum control response time, commensurate with realistic costs, was specified. Still several specially designed power supplies were required to meet the expected response requirements, i. e., that of having the computer control the limiting item. High speed data input systems were designed and constructed, so that the characteristic thruster operational parameters could be measured directly. This system was capable of measuring transient or oscillation conditions in order to better define the exact thruster control requirements. An area of real concern in the overall system was the isolation of the input or output signals from and to the computer from the high potentials at which many of the signals exist. Thus, several types and methods of high voltage isolation were employed, partially for evaluation of each type's usefulness. The computer itself was chosen with somewhat more memory, programming software, and input/output capability than was estimated to be necessary in order that these features which are not basic limitations of a digital control system did not become overriding factors. Thus, an extremely versatile and accurate high speed control system has been created.

Physical Layout and Mechanical Designs

Figure 1 shows the overall layout of the facility. The thruster is mounted on the centerline of a 3 meter diameter vacuum tank. Adjacent is an air conditioned control room where most of the power supplies, all the control and measuring circuitry, the computer and high voltage interfaces, and the computer itself plus its paper tape peripherals are located. The two high voltage power supplies for the screen and accelerator voltages are located in the test cell due to space considerations and the fact that their high speed regulation is achieved through dissipation in high power vacuum tubes which would present excess heat load in the air conditioned area. The power leads to the thruster run directly from the thruster to the power supplies in as short a path as possible. This short cable run coupled with the fact that all thruster potentials are measured via a separate pair of leads directly from thruster components serves to minimize effects of power lead and connection impedance. The arrangement of the system components in the control room racks, with the low voltage and low noise computer equipment at one end progressing to the high voltage and high noise power supply components at the other end, was done to minimize the cross coupling of thruster noise and transients to the noise sensitive computer systems. This approach proved effective in prevention of this problem. A standard mercury feed measuring system was located on the side of the vacuum facility along with three ice reference junctions for thermocouples. These thermocouples were isolated and could be attached to the thrustor components at the three major floating voltage potentials, i. e., screen voltage, accelerator voltage, and neutralizer common voltage.

Vacuum Facility Description. The vacuum facility utilized in this program is identified as tank 7 at LeRC. The initial design and operation was reported by Keller and Wise.(6) However, this program is its first use as a mercury ion thruster test facility.

The tank is a 1.6 cm thick stainless steel cylinder 3.1 meters in diameter and 6.5 meters long. One end is flanged at the full diameter with a movable end bell which rolls back on a carriage. Both ends have large flanged openings. Additional smaller access ports are located on the sides and top of the tank.

The high vacuum system consists of six high speed diffusion pumps with a pumping capacity of 50 000 liter per second (l/s) each at the operating pressure of 10^{-6} torr. The foreline of these diffusion pumps is evacuated by a roots blower with a capacity of 2340 l/s backed by two mechanical pumps, having capacities of 145 l/s. Internally each diffusion pump is protected by a cheveron liquid nitrogen baffle. A mercury condensing liquid nitrogen baffle extends along the entire cylindrical wall and across the target end of the tank opposite the thruster. In order to conserve liquid nitrogen only the portion of the liquid nitrogen baffle across the target end of the tank is used for thruster testing.

The tank pressure without the thruster operating is nominally 3×10^{-7} torr or better. Satisfactory tank pressures are achieved during thruster operation with only the target end baffle cold. Tank pressure increases with thruster beam current. Fig. 2 shows that tank pressure is nearly a linear function of the total beam current from several different thrusters operating individually or together. The pressure data representative of normal operation of this vacuum facility over the past four year period.

As a consequence of its size, pumping speed, and overall performance this vacuum facility presents no restriction for the testing of 30 cm ion thrusters either individually or in multiple operation.

Thruster Description. The 30 cm mercury ion thruster used in these initial control studies was of the design reported by Bechtel.(7) No attempt was made to modify it or to improve performance for the initial programming and control tests. However, the fact that the thruster system had no mercury feed line isolators did contribute to additional high voltage isolation requirements for the control system. The long thermal time constants associated with the thruster body and vaporizer system probably helped control stability. The only major disadvantage of this thruster to the test program was the lack of a magnetic baffle for throttling purposes. This lack did impact somewhat the completion of a successful start up to an arbitrary thrust level. In general, however, the thruster proved adequate for the initial phases of testing; but, its performance characteristics and data would indicate that much superior thrusters are now readily available in the form of the LeRC 30 cm Engineering Model Thruster (EMT).(8,9)

Power Supply System

The basic design premise was to employ commercially available analog programmable power supplies wherever practical. As fast a response time as was realisticly and economically feasible was specified for all cases. However, response requirements on the discharge current and keeper current supplies dictated special design and construction. The high voltage isolation for the cathode tip heater and vaporizer plus the main vaporizer was achieved with chopper inverters. These are also representative of flight power processor characteristics.

The computer outputs a 12 bit digital control word to each supply to specify a regulation point for voltage or current output. Several different methods of control isolation and digital to analog conversion were used partially as a test to evaluate the usefulness of each method.

Power Supply Capability. The output capabilities of the various supplies is shown in Table I. All are voltage regulated with respect to the input set point except the main discharge, the cathode keeper, and the neutralizer keeper supplies. The indicated power output capacity of most supplies has proved to meet or exceed thruster requirements; however, the keeper current supply originally designed for 1 A was upgraded to a 2 A size, commensurate with current thruster operating practice. The frequency response shown in Table I is that corresponding to a square wave input. These approximate response values are to serve only as a guide and indication of system capability.

Control Isolation Methods. A basic problem for control of thruster power supplies is that the analog control circuit is often at high potential. Therefore, the interface to the computer must be isolated for these voltages. The desired response speed is a major factor in the choice of method. Three different types of control or power supply isolation were employed in this system. Table I shows the supplies associated with each type of isolation method.

The first and most common method was to use a resistance programmable power supply floated or isolated at the high voltage. A binary resistance string was controlled by the contacts of 12 relays, the coils of which were at the ground potential and engaged by a binary word from the computer interface. An isolation voltage of up to 10 000 volts was provided by the insulation between the coil and contact assembly, and only one electrical breakdown failure occurred in operation. The fatigue wear of cycled reed relays was of concern, but preliminary tests showed at least 50 million cycles gave little degradation. In practice only two failures of this type were evidenced. So, the overall performance was adequate; however, the speed of these devices was quite low. With a square wave signal applied a limit was reached between 250 and 1000 cycles per second. Nevertheless, this was adequate for the applications where this method of isolation was employed.

A second method of providing digital control of an isolated power supply was used for the cathode tip heater, the cathode vaporizer, and the main vaporizer supplies. This technique was to use a commercial digitally controlled dc supply to provide an input power to a transistor chopper operating at 8000 Hz. The resultant ac square wave was transformer coupled and isolated to serve as input to a rectifier circuit at the high potential. These simulate to first order the inverter systems of flight power processors. The chopper-inverter output voltage tracked the input voltage within two percent. Reliability was excellant, with a limit of 100 to 250 cycles output for a square wave input without appreciable distortion. This is completely adequate for these heater type supplies where the thermal time constants are on the order of seconds.

The third method of input isolation utilized was employed for the discharge supply plus the neutralizer and cathode keeper supplies. This method provided 12 bits of digital data at the high common voltage of the supply by using a photodiode in each signal line to transmit a light signal to a phototransistor receiver operated at the floating potential. The input digital signal is converted to an analog input for the power supply by a commercial DAC package.

These three supplies regulate current to the mercury plasma which requires fast response for stability. Supplies were constructed for this purpose which had analog sine wave frequency response to 50 000 Hz. The response to a digital input square wave of 10 000 Hz was excellant with little distortion for a resistive load. The thruster load produced considerable noise spikes which occasionally affected the input DAC set.

The discharge supply was controlled by use of a transistorized dissipative regulator following a commercial dc power supply. This special circuit with its fast frequency response at 25 A output was especially successful.

The design and implementation of the isolation methods and special power supplies described in this section was done by E. H. Kramer of LeRC.

Direct Metering and Manual Control

The voltage and current parameters for all the thruster power circuits are directly metered within ±1 percent by meters situated in control area racks. These meters are of the light pointer illuminated scale type and are connected directly in the high voltage leads. There is sufficient voltage insulation between the meter circuit and the case which is at ground potential. Thus, a rapid scan can be made by eye to ascertain the thruster operating conditions.

Since operation independent of the computer is sometimes desirable, provision has been made to individually switch each supply to a manual control or to the computer control. The voltage and currents can be set manually by ten turn potentiometers.

Optical ADC Input System

The accurate measurement of many thruster parameters suggests measurement of the voltage or current in the leads to the thruster itself. However this requires that the measuring device be floated at the high potential. A system capable of accurate performance under these conditions was designed by R. R. Robson at LeRC. It consists of a commercial analog to digital converter isolated at the high potential with its own separate power supply. The resulting digital data is transmitted by twelve light emitting diodes via optical coupling to phototransistors at ground potential, which are appropriately connected to the digital input interface of the computer. A single optically isolated circuit from ground to the converter initiates the conversion cycle, the completion of which provides a flag to enable the computer system to input the data.

Sixteen channels of high speed thruster data are provided to the computer by this system. Eight channels have 12 bit resolution with unipolar input and eight channels have 10 bit reolution with a bipolar input. While the 10 bit devices have a slightly shorter conversion time, both units return data about 14 μsec after the encode initiation. Thus, resolution and accuracy are better than 1 part per thousand with a possible sample data rate up to 50 000 samples/sec.

Multiplex Input System

There are numerous thruster parameters of interest whose time variation is not rapid or important. Thirty two such signal parameters are sampled and converted to digital data by a commercial multiplexer system. The frequency response for each channel is less than 100 cycles with a scan rate of 125 μsec/channel of input. The major feature of this system is that each input is transformer isolated individually using a small signal chopper technique. With a common mode capability of 2500 V ac or 4000 V dc, at a 20 millivolt full scale signal the system has a -160 dB common mode signal rejection. This input system allows the direct input of thermocouple outputs in the low millivolt range for which the computer can calculate the corresponding temperature. Half of the thirty two channels are reserved for thermocouple inputs with the rest of the inputs being electrical parameters with slow time variations. Again the entire system has an accuracy of 12 bits or 1 part in 4096.

Computer and Input/Output System

The appropriate characteristics of a computer commensurate with operation a thruster control application are too numerous to evaluate; however, several important factors did emerge from study of these requirements. First, use of a commercial production computer would allow realistic investigation of all control situations with less cost than for any existing flight type equipment. Secondly, while not all spacecraft computers use 16 bit words, the commercial minicomputer industry was rapidly adopting this as standard. Third, the availability of supporting software, such as FORTRAN compilers, assemblers, editors, and a linking loader was of major significance. Fourth, the input/output system had to be compatible with a large number of devices and convenient interface circuits had to be commercially available. Fifth, transfers and storage of numbers had to be convenient; thus, a machine with two or more accumulators is virtually necessary for a high speed control application where these are the most repetitive operations. Sixth, a convenient multilevel interrupt system had to be available. A commercial Hewlett Packard 2100A machine meeting these requirements was obtained having sixteen thousand words of core memory with a 16 bit word length. Forty five input/output locations are provided for interfacing to devices with a separate interrupt assigned to each location. The machine cycle time is 2 μsec for all 80 instructions. An extended arithmetic unit permits rapid hardware multiply and divide operations.

Auxiliary System Devices

Two commercial timing devices have been incorporated into the system. One, a digital time of day clock, provides the current day, hour, minute, and second and is utilized to create a complete data record. The second, an interval timer, can either time a period in microseconds between two computer start-stop instructions or create a computer varied preset delay and is utilized as a tool to evaluate some of the timing criteria for control.

Computer Peripheral Equipment

Paper tape is the medium used to program and load the computer. A high speed photoreader reads this 1 inch wide paper tape at 500 characters per sec. A high speed paper tape punch capable of punching 120 characters per sec provides the tape output. An ASR-35 teleprinter at 10 characters/sec is provided for the typewritten output of data or for keyboard input of same. The paper tape system has been very reliable and adequate for this application; however, the relatively slow speed type out of data has often proved to be a limiting factor in operation, and is an area for future improvement.

Initial System Programming and Test Results

The initial programming concept was to set up an operational system which was as flexible as practical, so a series of program subroutines were written to control or service each hardware input/output element independently. Then, each element could be linked together by a master program to perform the desired test. Since a time of 1 msec for a control loop appeared feasible, the slow teleprinter must utilize programs where one line at a time is rapidly stored in a buffer location, and printout occurs via an interrupt operation. This repeated looping in and out of a program to print or output large quantities of data must be done if the loop time per control cycle is short.

These system operating programs form a basic library of available routines and are described. A few specific test programs are discussed in detail and the results indicated as examples of the capabilities. Finally the overall conclusions from the initial operations of this system are given.

Program Subroutine Library

A series of program subroutines was developed for general purpose use. These fall into four major classes: first, there are the device input/output service routines for the thruster data or power supply control. These subroutines are written in assembly language (identified by a three letter mnemonic code). Second, there are the data output routines, which format and print the data on the teleprinter or output data to tape punches, strip chart recorders, digital displays and such. These are usually written as FORTRAN subroutines (identified by a four letter mnemonic code). Third, there are groups of FORTRAN subroutines to convert data into engineering units; to calculate temperatures from thermocouple measures; to calculate power, efficiency, ev/ion, thruster, and other derived parameters; and to compute mercury flows from manually input data. Fourth, there are a group of system control functions, such as time delays, input of switch register control of program flow, etc. Thus, a very flexible system was established. A complete list of these library functional subroutines are shown in Table II. The use of the LIST program produces the page listing shown as Fig. 3 which illustrates the full capability of the programming as a data acquisition system.

In actual practice a relatively small fraction of the library saw the majority of service. Use is a indicator of the value of a subroutine. In general, data output via LINE routine on the teleprinter saw the most use along with digital displays via DEC and OCT. The conversion of input data into engineering units is absolutely necessary, but further calculations of thruster performance were not routinely done. As for data input it became rapidly apparent that a scan of all data once per control loop was an effective input philosophy, which was then extended to control data output by use of the OUTP program. Operating experience rapidly indicated those features which are of maximum value in investigation of the thruster control characteristics.

High Voltage Recycle Program

On each data or control cycle having a one second period the recycle program is entered. Four parameters are sampled over an average of 16 measurements in 16.7 msec. These are: screen voltage, accelerator voltage, beam current, and accelerator current. If any one meets the following criteria, a recycle is initiated: screen voltage <200 volts, accelerator voltage <100 volts, beam current >3.0 A, or accelerator current >50 mA; otherwise the program is exited. The original set points of the discharge current and high voltages are stored if recycle is indicated.

A recycle is initiated by setting both high voltages to zero with the discharge current reduced to some low value for a period of time. Both this OFF time and the set value of discharge current were varied.

Next the three parameters are ramped back to their previous values in about 1 sec with 100 steps. The screen voltage was delayed over the application of the accelerator voltage. Initial turn on of the high voltages was at 500 and 250 V for the screen and accelerator respectively.

Evaluation of High Voltage Recycle

The program sequence has been detailed. The success and lack of difficulties with this simple approach indicate that it merits some consideration as to the reasons for its effectiveness. In 95 to 98 percent of all arcs, a single recycle restored the thruster to normal operation. In all other cases observed, two recycles only occurred before restoration to normal thruster operation. Of course, it is possible to have repeated recycles in abnormal thruster operating modes, but the reliable correction of arc faults during normal operation is the real criteria for judgement of success or failure of a recycle sequence.

There are several factors peculiar to the system used which are important constraints upon the recycle mode. First, the screen and accelerator power supplies were of a design such that little energy was available for arc discharge with very rapid (1 msec of less) crossover control to current limits of 3.0 and 0.5 A, respectively. This low dissipation of energy with rapid current limiting feature permitted a slow (1 sec) computer response to an arc condition without any apparent grid damage. Second, the choice of 2.0 A as the value to which the discharge current was reduced during the recycle depends on the ability of the accelerator supply to produce sufficient current not to go into current limit on reapplication of its voltage. With a 0.5 A capacity available the particular supply used in this test did not present as serious a restriction as perhaps flight type power conditioners which may require further reduction of discharge current. Third, in this control program the various vaporizer currents remained at their last updated value during the entire recycle. Thus, the vaporizer drifts encountered during recycle with systems utilizing analog control loops were not present in this program which held all parameters, except the two high voltages and the discharge current, constant during a recycle.

Some modification of the timing of the recycle program was done, but the previously described program appeared to perform the best. The time that the high voltages were held off was varied from about 50 msec to 10 sec. For reasons that may have as much to do with discharge stabilization at the lower current as with the time of high voltage off itself, a delay of between 250 msec and 1 sec produced the best results. For times shorter than 100 msec the probability of a second recycle following the first increased rapidly. For off times greater than 2 sec it appeared that thermal effects caused by the low discharge power began to affect recovery in a smooth manner. Thus, one second, which also corresponded to a normal control loop cycle time was employed.

Prior tests[10] had indicated that the accelerator voltage should be reapplied before the screen voltage was applied. A delay of about 50 msec in screen voltage over accelerator voltage worked acceptably, so that parameter was fixed and further variations were not investigated.

The reapplication of the high voltages at lower values, those set for operation at the time of arc, significantly reduced the likely prospect of second and third recycles. Any voltage less than one-half of the original screen voltage appeared to be a sufficient reduction. A constant screen to accelerator voltage ratio of two, which was commensurate with the normal grid operation, was arbitrarily chosen. Thus, on reapplication the screen was set to 500 V and the accelerator to 250 V.

The two high voltages and the discharge current were linearly increased in a number of steps to their former operating value to complete the recycle. The rate of increase and/or the number of steps were varied. It was difficult to determine the best rate, but an increase in less than 1/2 second brought more additional recycles while ramp up times longer than 2 sec seemed to again increase the thermal problems associated with low discharge powers. Thus, a 1 sec 100 step ramp up these parameters seemed appropriate.

The criteria used in these tests for evaluation of recycle programming was to produce the recycle sequence which was both reliable and minimized additional recycles. Long (>3 sec) recycle times eschew additional thermal problems, while short (<250 msec) recycle times increase the likelihood of additional recycles. However, the program presented has operated for several hundred hours and has adequately handled virtually all breakdown arc recycle under a variety of operating conditions, and it is consistent with previous recycle experience.[10]

Two Vaporizer Control Program

The basic evolution of 30 cm thruster control done at LeRC[7] has indicated that the beam current can be controlled by the main vaporizer flow, while the cathode flow could be used to control the discharge voltage. In a similar manner the neutralizer keeper voltage may be controlled by neutralizer vaporizer flow. The use of the digital computer as the control element as a substitution for two analog loop system was investigated. The control sequence being: the sampling of the beam current and the discharge voltage data, and then comparison with desired set values with output of a new power to the respective vaporizer. A variety of different control algorithms were utilized with various gains and sample rate times. The algorithm most extensively evaluated was the simple uniform increment or decrement of the vaporizer voltage depending on whether data sample was above or below reference value. This is equivalent to an integrator type analog system. Another program tested was an algorithm equivalent to proportional control where correction applied is proportional to magnitude of the reference value error. Phase shift compensation was also attempted. A digital control program was not developed for the neutralizer system in these initial tests, since modifications to the EMT neutralizer operating mode were being implemented.

Evaluation of Digital Control of Two Vaporizers

Figs. 4 and 5 show the typical hunt error for a uniform increment program for both main and cathode vaporizer control loops at a beam current of 1.50 A and a discharge voltage of 35.0 V as the reference set points. A control loop time of 1 sec was used in these representative tests with data recorded every 10 sec. Stable operation for 50 hours was obtained at this particular operating point.

This simple uniform increment or decrement of power to the respective vaporizer as a correction with respect to data versus reference value error proved to be the most useful of the control algorithms tested. A primary reason for this was the ability to achieve control regardless of the thermal response or initial conditions. However, the increment size commensurate with one percent beam control was one part per 4000, which made large changes of reference values a slow process. The required increment size for discharge voltage control to 0.1 V was one part per 1000. Data resolution of at least one part per 2000 was also needed for the control via computer to function properly. Thus, a serious disadvantage of using the computer as the complete control element is the relatively high resolution input/output devices required.

Control and loop times of less than 1 sec to sample data and output corrections resulted in appropriate increments smaller than the setting resolution of the output devices. Thus, no advantage was gained by use of these short loop times. Much slower control loop times of 5 and 10 sec introducted larger errors due to thermal response time now becoming comparable to these loop cycle times. Thus, 1 sec control loop times were established for all subsequent testing with this thruster system.

Attempts to introduce appropriate phase shifts in the control algorithm helped reduce the magnitude of the error amplitude at a specific operating point. However, at a different operating point the phase shift was often inappropriate and increased the error amplitude. A zero phase correction seemed to work best for the largest number of conditions; thus, the initial simplest control algorithm emerged as the best choice for general operation of vaporizer control loops.

While the results of this test program clearly indicate that the computer can be reliably utilized as the control loop element, two serious disadvantages are very apparent. First, the input/output system elements must have high resolution capability such as 12 bits. Secondly, the appropriate sample loop times of about 1 second require that the computer be dedicated full time to this single application. These requirements are probably not compatable with use of this mode in conjunction with a general purpose on-board spacecraft computer.

Thruster Start-Up Program

This program was written as a first attempt at start-up sequencing, and the timing was deliberately chosen very slow, so that it would be easy to observe performance. By the time this program was written a 1 cycle per second vaporizer control loop time had become standard. Thus, the program is reentered once a second, a single start-up step is accomplished, and the program is exited. The program steps pass progressively through five stages: turn on and preheat, ignition of neutralizer, ignition of cathode, ignition of discharge, and extraction of beam.

In the first step of the preheat stage the following supplies are sequentially turned on and set to zero output: main vaporizer, cathode vaporizer, neutralizer vaporizer, distributor heater, cathode tip heater and neutralizer tip heater. Each succeeding preheat step then increases the voltage output by 1 percent of a specified final value. Thus, after 100 sec each heater or vaporizer is at the prescribed set operating point. For another 200 steps or 200 sec the program remains in this stage at these heat levels.

In the first step of the neutralizer ignition stage, the neutralizer keeper supply is turned on and set to regulate at 0.5 A. In each succeeding entry the neutralizer keeper current and voltage are sampled and averaged. The ignition criterion is: the keeper voltage <25 V; and the keeper current >0.2 A for 100 consecutive steps. If the system did not ignite in 300 steps, the neutralizer vaporizer and heater voltages are increased by 1 percent and the step counter reset. Thus the tip and vaporizer are slowly increased until ignition is achieved. When ignition is successful, the neutralizer tip heater voltage is reduced by 10 percent and the neutralizer vaporizer voltage by 20 percent. If a later reentry to the program indicates the neutralizer discharge has extinguished, control reverts to the ignition phase; otherwise, control passes to the next phase.

The cathode ignition phase is identical to the neutralizer ignition phase with the exception that the ignition criterion is: a keeper current >0.3 A; and a keeper voltage <30 V on keeper. A regulated keeper current of 0.5 A is established on initiation of the cathode keeper discharge.

The first step of the discharge ignition phase is the turn on of the discharge supply set to regulate at 5 A emission current. Again the ignition criteria must be met for 100 steps, with a no discharge condition for 300 steps increasing the main and cathode vaporizer voltages by 1 percent. The ignition criteria used is: a discharge voltage <50 V; and a discharge current >2.0 A. On completion of the discharge ignition phase, the distributor heater and cathode tip heater voltages are set to zero. Furthermore, the main vaporizer voltage is reduced 10 percent, the cathode vaporizer voltage is reduced 20 percent, and the discharge current is reduced to 2 A. The thruster is held at this condition 2 to 5 minutes. Then, the control passes to the beam extraction stage.

The initial step of beam extraction stage turns on the accelerator and screen voltages set at 250 and 500 V. A beam current >100 mA for 100 steps completes this stage.

Evaluation of Thruster Start-Up

A sequential turn on of each supply may not be required. Since all tip heater and vaporizer supplies were voltage controlled, a slow voltage increase was necessary to eliminate the requirement for excessive power before the resistance of these heaters had thermally stabilized. This difficulty alone is sufficient to require that all heater and vaporizer supplies be controlled by the computer on a current not a voltage basis. This approach is employed in all present and future power processor designs. The thruster of the earlier LeRC design employed in these tests required 15 to 20 minutes of this preheat stage to get to reasonable thermal temperatures. Newer 30 cm thrusters such as, the 400 series(9) and the Engineering Model Thruster(10) have better thermal response which may appreciably reduce this preheat time.

The ignition of both the cathode and neutralizer discharge was then accomplished by applying the keeper voltages. If no keeper discharge was detected the tip heater current was increased by about 1 percent every 300 sec until ignition was obtained. The slow increase was chosen to achieve the neutralizer and cathode discharge ignition at as low a tip temperature and heater current as possible. While in most cases the discharges finally lit before the heater current reached a preset maximum, two difficulties with this sequencing became apparent. First, if flow of mercury was restricted or a very cold initial thruster temperature encountered, the program advanced the tip current to high levels when keeper discharges did not ignite. Secondly, each successive ignition tended to be a little slower than the previous one, which incurred a correspondingly higher tip current.

Thus, the program tended to increase repeatedly the required tip current toward the maximum. Later studies have indicated that a fixed tip heater current high enough for positive ignition is a solution to this problem inherent in the original program.

After ignition of both neutralizer and cathode the keeper currents were established at 0.5 A and both tip heaters and vaporizers were reduced in current to levels which maintained a stable discharge. An alternative procedure is to raise the keeper current to 2 to 3 A which provides sufficient heat to eliminate the need for tip heater current. This was not done with this initial system since at the time of the tests the keeper supplies were not of adequate current capacity. Another argument in favor of using keeper rather than tip heater power is that less range of set points is needed with respect to tip heater supplies. Later tests use the keeper power and turn off tip heater as a standard procedure.

The program sequence could accomodate a cathode or neutralizer discharge that did not remain lighted during start-up. There was no occasion when this was required during the approximately 100 start up sequences observed. The implication of this fact is that the criteria for determining that the respective discharge was lit and stable was adequate and reliable. The conditions were that the keeper current be continuously above 0.25 A and the keeper voltage be continuously below 25 V for 60 to 100 sec. When this condition was met, the ignition was considered complete and tip heater and vaporizer currents reduced for stable operation.

The next stage of start-up sequence was the ignition of the discharge. Application of the discharge voltage usually brought immediate transfer of the cathode discharge to anode and subsequent ignition of the main discharge. The optimum physical baffle for throttled operation of the early LeRC thruster was not commensurate with an easy transfer from cathode keeper to main discharge. If the discharge did not transfer immediately the program sequence increased the main vaporizer heater to effect discharge ignition. When the main discharge did ignite the excessively high mercury flow from the main vaporizer caused condensed mercury to accumulate causing a "flooded" condition. The lack of immediate discharge ignition happened only 5 to 10 percent of the time and ignition always took place. Newer thrusters with magnetic baffles can avoid this problem; therefore, no further effort was expended to find an interim solution. A discharge current of over 2.0 A and a discharge voltage below 50 V for 1 minute established ignition of discharge and turned off the cathode tip heater, and reduced main and cathode vaporizers to establish a stable discharge at a low current of 2.0 A.

After the main discharge had been established for 2 to 5 minutes, the next program sequence was to apply the screen and accelerator voltages to extract a minimum beam. For this initial turn-on 250 V was applied to the accelerator grid and 500 V to the screen grid. The reasoning for this procedure is that in a minimum power situation it is necessary to initially extract a beam whose power is less than that available from the solar all array, and this condition also requires that the low discharge power not exceed that limit. The initial extraction of the beam turned out to be very reliable as long as the discharge current was at least 2.0 A. At lower currents the discharge would occassionally extinguish, but never at 2.0 A. Thus, with a minimum beam of about 0.2 A extracted at a minimum accelerator voltage of 250 V at a minimum screen voltage of 500 V with a minimum discharge current of 2 A, a start up at minimum power could be achieved as per mission requirements. The fact that this was reliably done nearly 100 times lends confidence to this approach.

It was planned to simply increase discharge current and high voltages to produce a minimum operating point at 1/4 power. However, implementation proved difficult and no final program was established; however, this transition is clearly identified as a problem area for further work.

General Conclusions and Observations from Initial Test Program

The high speed of the data input system in general became a liability rather than an asset. Noise and ripple fluctuations are significantly large on many parameters that either filtering or data averaging of multiple readings was necessary. The average dc value is of interest for most control or data purposes. It is impossible to respond to these rapid fluctuations, so averaging is necessary especially with respect to the high frequency random noise. Thus, a much slower data input system would be adequate for all flight applications.

The data input and output should be a multiplex scan once each cycle for optimum efficiency, since single inputs or interrupt inputs waste both time and memory to implement with no apparent advantage for control of ion thrusters. The interrupt system should be reserved solely to indicate to the computer a possible or actual malfunction and should not be used for routine operation.

In actual control operation of the thruster many of the input parameters remain at or near a fixed value under a variety of conditions. Thus, the ability to set any value is unnecessary, and a few fixed values are adequate. The ability to have variable control serves no actual control function; therefore, the complexity of having these functions as controllable over an entire range is unwarranted.

Thus, this initial phase of testing with computer control demonstrated the validity of the system as an investigative tool, and better defined of the role of the computer through actual experience.

Command Code for Flight Power Processor

Evolution of Code

The basic conclusion that the operation of a thruster can be achieved with a relatively small number of fixed set points for most power supplies reduces the complexity of the interfaces between the computer and power processor. Nevertheless, some sort of communication scheme must be established for control. A basic digital 16 bit command word structure had been determined for a previous spacecraft control system design by JPL. This 16 bit format was used as the basis for constructing a command word set for thruster control. Table III gives the general format of this code. The input/output system uses the first or low order bit as a parity check bit with add parity being required for entire word. Thus, a separate bit is required for this purpose alone. The number of spacecraft devices which can be addressed by the JPL input/output system is 32 using the upper bits, nos. 12 to 16. A specific code was selected for eight PPU/thruster systems as given in Table III.

The three bits nos. 9-10-11 are used to specify a particular function for the PPU/thruster control system to perform. Table IV gives the coding for these function specifications. The seven functions are: data interrogration, discrete set points, power supplies on-off, beam current reference set, magnetic baffle current set, discharge current set, and screen voltage set.

For interrogation of the thruster/power system for data return, 6 bits no. 3 to 8 are used to address or select up to 32 channels of input with bit no. 2 being used to select either an analog to digital convertion or direct digital data measurement. The input data is restricted to 7 bit resolution by the proposed input/output system. In practice only 24 analog data channels and 4 channels of digital data are required.

There are several power supplies which require a limited number of set points for either current or voltage. Analysis of running and start up needs indicated that in no case were more than 8 set point points required. Thus, only 3 bits were required for each of these discrete functions, and bits no. 2-3-4 are utilized to indicate these actions. This leaves bits no. 5-6-7-8 available as additional subfunction address codes, so that up to 16 different discrete functions can be accommodated as shown in Table V. This number can easily provide all the required discrete set points.

The turn on or off of all the 12 power supplies independently of each other is not possible in one word with only 7 bits for selection available. However, two groups of 6 bits are possible with the bit no. 8 being used to identify a low voltage group consisting of heater and vaporizer supplies or a high voltage group consisting of the screen, accelerator, keeper, discharge, and magnetic baffle supplies. The specific power supply coding given in Table IV. Thus, a single command can turn any of all of a single group on or off and only two commands are required for complete control of power supply status.

The resolution requirements for those parameters which must be continuously variable over the throttling range are indicated by mission control requirements. A 1 percent of full power in power or beam was dictated by mission analysis. For a full power beam of 2 A increments of 20 mA were indicated. Since there are 75 steps between the low beam of 0.5 and 2 A, the lowest binary bit combination which could be used was 7 bits or 128 steps. These steps constitute the resolution for the beam current reference word. Three other parameters were considered necessary to be continuously variable over the throttle range. They are: magnetic baffle current, screen voltage and discharge current. These also have 1 part in 128 resolution. As a consequence of the above there are 4 command words which require 7 bits of data output. These are given in Table IV. By these procedures a complete set of command functions were developed for control of the thruster, and Tables III to V form a complete reference for the established bit patterns. Operational experience will determine the adequacy or insufficiency of this command code set.

Internal Power Processor Functions

The use of an on-board general purpose computer suggests that except for short periods time the computer should not be dedicated to control of thrusters. The two vaporizer control loop studies presented earlier indicate that this would be necessary if the computer were the complete and only control element. Thus, the command code provides for external control of slow speed functions while the more rapid or continuous control functions are assigned to internal power processor control. The control of the three vaporizers are relegated to internal analog control loops within the power processor. The recycle for high voltage arc recovery is in the same category and is handled as an internal hardwire power processor function. Also reduction of tip heater power on ignition is accommodated internal to the power processor. Response to loss of neutralizer is also an internal circuitry provision. Thus, all functions requiring fast response to protect the power processor are done by internal circuitry.

There is a method of having immediate computer service of a specific problem within a few microseconds. This interrupt technique is used to handle conditions which can be or become serious where 1 sec or response is adequate. The 1 sec criteria was selected on the basis that any rapid corrective actions are handled internally. The conditions which cause interrupt are: neutralizer failure, beam current out of limits, excessive arcs, high accelerator current, low screen voltage, and low input voltage. The interrupt location or status is given in the first digital data or status word. The exact algorithms and implementation of interrupts is an area that is not within the capability of any presently operating Lewis power processor control system, so that final definition must be reserved for later studies.

Comments on Code Format

The code set and format given in Tables III, IV, and V will acceptably provide the necessary control functions for an ion thruster. A similar code has been established for 8 cm thruster/power processor with compatible addresses for similar functions. This was done to provide the most commonality in programming for a system incorporating both 8 and 30 cm thrusters in a single spacecraft such as the proposed SERT III.

Certain restrictions on format resulted from the desire to accomodate an already existing JPL input/output system design. From a computer storage and manipulation point of view a 16 bit word easily breaks up into two 8 bit bytes or four 4 bit bytes. Table VI shows a proposed command code format based on this division. The 7 bit commands and data require the space of an 8 bit byte. Thus, 8 bit data and set point formats would better utilize storage and in addition provide a little resolution margin not available in the present 7 bit format.

The four 4 bit bytes easily suggest a 4 bit power processor identification code, which can easily accomodate 8 power processor/thruster systems plus 8 other spacecraft systems. This number is perhaps the maximum number of systems commensurate with a single computer or input/output system in any case. The next 4 bit byte becomes the function code, which allows now 16 rather than 8 function address; this serves to relax an limitation which is somewhat restrictive when 8 and 30 cm power process processors/thruster systems are intermixed.

Finally, the parity bit is only necessary for the transmission scheme. The storage and software generation of parity have clearly proved to be a nuisance; thus, it is recommended that the parity check be done only internally to the transmission system to power processor but not be a part of the computer generated code. With the elimination of the parity bit the lower half of 16 bit word can conveniently contain the 8 bit reference words or the 4 bit discrete addresses plus a 4 bit set point code, which allows a greater flexibility in programming.

The format of Table VI could be easily derived from the orginal format with only small changes required. Increased ease of programming, more effective use of storage, increased resolution, better accommodation of mixed 8 and 30 cm systems, and more set point flexibility make this 4 and 8 bit byte breakup of the command word format desirable.

Current Test System and Program

At the time the command word format was being established, it was recognized that a computer program should be written to control a thruster using the new format. In addition if this were to serve as a useful tool in the future, the output and input of data to the power processor and its internal control functions should as nearly as possible simulate the envisioned flight power processor functions. The LeRC thruster was remounted about 50 cm below the centerline of the tank, where it can be operated by the existing system either manually or under computer control. Another separate, existing 30 cm power supply console was modified to accept the command word format and was interfaced to a single computer input/output slot of the same computer. A modified 400 series thruster[11] having operating characteristics compatible with current EMT[8,9] designs was mounted on the centerline of the vacuum facility supported from the movable end bell flange.

The programming plan and progress to date is indicated in the next section. The implementation of the command code format is of course of prime concern, but the first really operational program in this new format has been a beam or power throttle profile over the entire range of thruster output.

Power Supply Console Features and Modifications

A power supply package originally designed for digital control was modified in order to accommodate analog control loops, a new recycle sequence, manual analog inputs, and conversion of the digital command word format into appropriate analog set points. A new command receiver and decoder was designed especially to interface to the computer and accept the established command word format. The commands are then converted into appropriate analog signals. Each of the set points can be adjusted individually with a potentiometer. This feature enables these set points to be varied until the proper thruster operation point is found. The analog signal from either the computer set point or reference word command or the manual analog control is then converted and transmitted to the power supply as the original digital format. A continuous update at a 2 msec rate provides both the commmand transmission and data return for control.

In the data system individual modules handle each signal channel with an analog to digital converter isolated at the floating potential. All these modules transmit the 8 bit data to ground by use of the optical coupling technique described earlier, but use serial transmission to reduce the number of isolation channels required. All channels are simultaneously updated in 128 μsec with the scan of all data channels requiring 2 msec. The command code is used to directly access the data system. The flag return to computer is delayed to 10 msec to better simulate the slower spacecraft system.

The power supplies themselves are all commercial 60 cycle ac to dc supplies with the exception of the discharge supply which is of the same special design as described for the original computer control system. The initial design and modifications for this power supply console were done by R. R. Robson at the LeRC.

Thruster Specifications

These tests were performed with a thruster whose operating characteristics were representative of current technology. A 400 series thruster[11] was updated with a cathode system from a 700 series thruster.[12] The modifications included a cathode pole piece, a 7 1/2 turn magnetic baffle, a cathode assembly, and a cathode vaporizer-isolator assembly from the 700 series. A Lewis dished grid set S/N 29 with a 0.63 mm spacing having a screen grid with

1.9 mm diameter apertures and an accelerator grid with 1.5 mm diameter holes completed the modifications. Test operation at 1.00 and 2.00 A beams indicated performance compatible with state of the art technology as indicated in Table VII.

Programming for the Current System

The establishment of the command code format suggested that all programming effort utilize that code. The exact input/output driver program must accomodate existing hardware, but its input and data return should simulate the contemplated flight system. All the rest of the programming in assembly language can be representative of that required for an actual spacecraft computer control system.

All control programs were written so that control of up to 8 thrusters could be accommodated. The simultaneous operation or start up of one thruster should be possible with other thrusters in all phases of operational modes, since this is the case in actual spacecraft applications. While this requirement imposes many additional restrictions over programming for a single thruster, it forces realistic accessment of the problems of multiple thruster control. The hope is that serious reprogramming effort might be avoided in later stages of development, when multiple thrusters must be operated.

A first requirement of complete system programming is to store all the current command, status, and data information for each thruster system as the commands are sent out and return data and status received. A program has been established to accomplish this. Stable operation over the entire throttling range must be achieved and a continuous throttle from the minimum power condition is required as the next step. Program implementation of this requirement has been completed.

The following subsections describe in detail the programs written to meet these goals and also the program established to print out data during their operation. Further programming for start-up to the minimum power point is currently in progress, but has not been tested in operation. Of course, much future programming effort will be required to establish a final flightlike system, but the current progress to date has formed an initial guideline basis for that effort.

Power Processor Output Program-PPU. This program would not be necessary in the final flight system, and only serves to make the output of a word in the command code format compatible with the present hardware system. It was indicated that each of 8 power processors could be interfaced to separate individual computer output locations, thus, it is possible to interface 8 different systems independent of basic programming of the control system. This program converts the power processor selection code portion of the command word format into an output slot allocation.

Since the particular LeRC power supply console first interfaced does not check parity, the PPU program checks parity. The appropriate error indication is returned for a parity violation.

The PPU program serves to make the command code compatible with the hardware interface; and while it is satisfactory for present operation, new interfaces with additional power processors or control consoles can be accommodated by simple revisions of this one program.

Command and Data Storage Program-EXC. In order to effectively operate and control several thrusters at once, it is necessary that the current status of the various input command functions along with the latest digital and analog data be available for each power processor/thruster system. The technique usually employed in computer programming is to relegate this information to a common memory block which in accessible to all programs. For a single thruster there are 16 discrete command functions, 4 reference command functions, 2 on-off command functions, and several timing status indicators necessary to completely specify the last or current status of the command input to each power processor/thruster system. Thus, 32 computer words are allotted for each thruster system, which requires a common block of 256 words for an 8 thruster system for storage of the current command information. There are 24 analog measurements and 4 digital status measurements, which represent the latest data update from each thruster. Thus, another 32 computer memory words per thruster system or a common block of 256 words is allocated for current data storage. Some further word packing might be possible in a final system to reduce memory requirements, but for an initial operation the 512 words reserved for this table are not an excessive requirement.

The EXC program has a principal function to store in the appropriate common memory location each command as it is executed by the thruster power processor and each element of digital or analog data as it is returned from the thruster power processor. While this is the most important function of the EXC program several other management functions are also performed by this program. The input to this program consists of two words stored in the accumulator registers of the computer. The first input word is a command code word to be output to the power processor; however, if second word is not zero but a power processor identification code, the two words are merged to form an output command code. Thus, a single function code can be easily used for several power processors. Also the proper parity is generated before the command word is output to the power processor. In addition a complete scan or average of 1024 data readings is executed in response to an appropriate input command. The program detects input command errors and stores these error indications along with error indications returned from the thruster/power processor in response to input commands. The final steps of this routine stores the command executed in the prime accumulator and the last input data or error indication in the second accumulator.

The EXC program has proven satisfactory in operation, and no revisions or changes are suggested for near term needs. The reduction of memory requirements is an indicated improvement for a final flight computer version.

Throttle Operation Program-TAB. The stable efficient operation of the thruster at all thrust or power levels requires the optimization of the thruster operating parameters at each specific level. For the worst case it would be necessary to store in memory a complete set of input parameters for each throttle level. It has been indicated that a step size of about 1 percent in beam or power is appropriate for throttle operation on deep space missions. Therefore, a table or map of 128 operating points was established as a basic requirement for throttle operation. Variations between thrusters in performance characteristics cannot be accommodated, but a single set of input parameters for each thruster power level must be adequate for every thruster. Differences or variations between thrusters must be relatively small for a single throttle program to be effective with multiple thruster operation.

Four reference functions and up to 16 discrete set point functions suggest a very large set of information must be stored for each throttle point if the optimum number of input variable possibilities are maintained. However, further examination of a reference function command word reveals that only the last 8 bits are necessary information. The upper 8 bits are simply the power processor and function selection which would be the same for each entry of the throttle map. In the case of the discrete functions only the lower 4 bits specify the configuration, with the upper 12 bits indicating the power processor, the function, and the discrete set addresses. These would be the same for each entry in the table. Only 8 bits need be stored for each reference function and only 4 bits need be stored for each discrete function to completely specify the input configuration for each throttle point. A table entry format of eight 16 bit words was chosen to accommodate each table or operating point and is shown in Table VIII. Each of the four reference words is stored as 8 bits in the lower half of the first four 16 bit words. These are representative of a 30 cm thruster, the upper 8 bits are reserved for a possible 8 cm map. The sixteen 4 bit discrete functions are packed into the final four 16 bit words of a table entry with 4 discrete functions stored per word.

The entire set of 128 operating points can be stored in a table of 1024 sixteen bit words. The table storage size given here is a maximum and is commensurate with the greatest flexibility and number of operating combinations that can be contemplated. In practice many of the options may not be required or even desired and much further packing of the words could easily be done to reduce significantly the memory storage required. The memory storage requirements for an optimum throttle map are not the prohibitive factor in the throttling program.

Given a specific operating point, the TAB program unpacks these table bits, combines them with the command function codes, and merges the proper power processor identification. Then the resulting 20 command words are output to the proper thruster through the EXC and PPU programs to establish operation at the selected point.

For convenience in testing, the TAB program can punch the eight table words for each operating points on paper tape or read the same into the computer from tape. In flight operation with a finalized table, this program punch/read feature would be eliminated.

There is one function which is not specified in the throttle table. This is the on-off command function for the various power supplies. This was omitted for two reasons. First, it should not be required for throttle operation. Second, continuous sending of this command with each throttle charge is not desirable for single bit errors can have unwanted consequences. This on-off capability was the only command function not accommodated in the throttle table storage.

Furthermore, it must be possible to transition smoothly from one operating point to another. Without use of a step by step method to go from one throttle level to another, it would be impossible to establish by ground testing that every transition between all throttle levels results in a stable or acceptable operating mode and power profile. The TAB program has the feature of being able to accept a new operating point and to increase or decrease by one table location on each entry to the program until the new operating point is reached. The time per point of 10 sec has been employed in initial tests, but this can be varied.

The specific nature of the TAB program allows its use for another important phase of thruster testing. The accurate mapping of thruster characteristics requires operation at a large number of preselected conditions and the accumulation of data after stable operation is established at these specific conditions. If each point of the table is loaded with the desired input conditions, stepping through the table would establish operation at the test conditions. By using one step per half hour and taking data every 10 minutes a complete map of thruster operating characteristics could be obtained. Such an automated test program at this facility can be used to test several of the EMT's in order to establish the divergence in thruster characteristics with a fixed input conditions.

Data Output Program-DATA. A program in FORTRAN has been written, which outputs the data for each power processor converted to engineering units with appropriate lables being printed out with the data. A data scan for one thruster is typed on a single page by the teleprinter in about 1 minute.

The initialization phase of this program allows identification numbers to be entered for each thruster and power processor, selection of any data sample averaging to 10 000 samples/point, and selection of a separate time delay after each thruster data printout up to 10 000 minutes.

This program is a test implementation requirement and would not be part of a flight system software; however, the collection of a data record of the system has been satisfactorily accomplished by routine looping through this program with delay time times of 10 minutes between samples being chosen for extended operating periods.

Performance of Throttle Program

As was indicated earilier the accurate establishment of a throttling map is a considerable task of detailed optimization at each point. An initial approach was to manually operate the thruster at various beam levels to find combinations of parameters where the thruster operated stably. Fortunately some simple relationships between the reference function parameters appeared adequate for stable operation. Table IX gives the initial choice of thruster parameter relationships for operation of the TAB throttle program.

This specific throttle profile was operated with about 10 minutes of stable operation at each point and the data recorded at each beam level between 0.4 and 2.4 A. Some calibration difficulties were apparent, especially with respect to maintaining the accurate control of the proportional loops at the exact set points and in the accurate control of discharge current. Nevertheless, each table point produced a stable operation of the thruster at that set point. While clearly not the optimum operating values, the initial actual operation of a throttle table was successful demonstrating that the technique and program were appropriate.

With the choice of each point in the throttle map indicating stable operation, the next test was to change from one beam value to another new value at a fixed step rate. Only a rate of 10 sec per step has been tested to present. For all beam changes attempted the transition was stable and the beam current overshoot was less than 50 mA. However, the beam current lagged the set point by more than 1 minute for all increasing transitions. In decreasing beam situations to set points below 0.8 A beam the lag was much greater.

The establishment of a unique stable path connecting all throttle points is important evidence that such a method is a feasible reality, not merely a theoretical paper plan. The initial implementation of this throttle program was successful at every operating condition between 0.4 and 2.4 A beam; thereby, the general validity of the method has been demonstrated. Only the simple optimization of the set points, the minor improvement of control electronics, and the investigation of power profiles and throttle rates on transitions remain to be completed.

Two Thruster Operation

Two thrusters were simultaneously operated as a test for interactions between their beams. The LeRC thruster was mounted 50 cm below the tank centerline with the newer 400 series thruster positioned on the tank centerline. The grids were located in the same plane with beam axis parallel. The LeRC thruster was operated in a manual mode for all dual thruster tests and at a stable beam current of 1 A. Both thrusters were operated with a screen voltage of 1100 V at an accelerator voltage of 500 V. The neutralizers were positioned 180° apart on the outside edge of each thruster.

With the LeRC thruster operating, a manually controlled start up of the 400 series thruster was completely normal and uncomplicated. The initial operation of the 400 series neutralizer did not couple to the existing beam of the LeRC thruster. In operation the neutralizer common voltage was changed by less than 2 V due to operation of the other thruster. The throttle operation of the 400 series thruster between 0.4 and 2.4 A beam was apparently unchanged by the presence of another operating thruster. Repeated operation of an induced recycle of the 400 series thruster with both thrusters operating has been done 200 times with no apparent effect.

In general it appears that no major interaction problem exists for simultaneous operation of 30 cm ion thrusters in close proximity to each other.. The initial premise that each thruster can be treated as an independent module for control purposes appears correct. More data on Multiple Thrustor Array (MTA-Ref. 14) operation is needed before this conclusion is completely justified; however, these initial two thruster tests have generated an optimistic view of the interaction situation with respect to control of multiple thruster arrays.

Future Plans and Tests

The current progress and status of the digital control tests effort has been given, but a responsible program must look to the future. The overall goal of establishing a practical computer control system is clear, but the specific near term effort plans are of prime importance in achieving that goal.

An area of prime concern is the program to start up to the minimum power point, which must accommodate one to eight thruster in all operating modes including start-up. Start-up sequencing to full beam power has been established for a single thruster; however, the transition to stable operation on application of the high voltages is of real concern if the available solar array power is not to be exceeded when near the minimum array power condition. After an acceptable start-up program is established, it must be operated through several hundred cycles to establish its reliability.

The optimization of the throttling set points and test operation of the same for stability are also needed. In addition the power profiles and other characteristics of transition methods and rates must be thoughtly investigated before acceptable performance can be guaranteed. The start up and throttle operation must be done with several different thrusters operated singly or in multiple configurations to demonstrate that thruster/power processor independent programming is adequate.

An area that has not been addressed at all is the handling of interrupts as a result of off normal operation. A routine must be programmed for each case. Only the simplest responses can be accommodated without excessive memory requirements. The various options must be carefully evaluated and an appropriate selection made. Testing in some cases is difficult, for the corresponding thruster operating condition is not a normal situation; nevertheless, each interrupt must be programmed and tested.

When flight like power processors become available to the program, interfacing and operation of these systems with the computer control system is contemplated. As development of a flight system progresses, the selection and actual programming of an flight type computer must be integrated into the program. At this point optimization of the programming, especially with respect to memory utilization, becomes a significant effort.

Summary and Conclusion

The on-board digital computer forms an important and integral part of the control system for the sophisticated and complex spacecraft commensurate with the use of ion thrusters for prime propulsion. The object of the computer control effort at the LeRC has been to define the exact role of the computer system in the control of ion thrusters.

A high speed, highly accurate, and extremely flexible system was designed and operated with the computer as the sole control element. This initial system permitted the evaluation of many hardware and software techniques. While it was shown that the computer could completely control a thruster, there are certain high speed repetitive control loop functions which are very costly in terms of both computer time and memory requirements. The slower functions, such as, throttling over the operating range and start up sequencing are the best use of the computer capabilities. An initial thruster start-up program was created and successfully tested but several technique changes were indicated for improved reliability. The initial control system proved to operate dependably as a very accurate high speed thruster data acquisition system. The real problems and limitations of computer control became readily apparent during testing.

On the basis of the above work, independent thruster/power processor control efforts, and spacecraft system requirements the command and data func-functions which provide the most effective use of the computer capability were established. The decision to incorporate certain fast internal logic within the power processor reduced the computer speed and memory requirements. The exact computer functions were established along with indication of set point choices and referenceeresolution requirements. A full set of computer command functions was developed and the output word format specified for a system of several thrusters.

With this format dictated, a shift in program emphasis to the use of these commands alone to control a thruster/power processor was executed. A power supply console was modified to accept the command word format and an updated thruster installed and coupled to this new power console. Programming in this flight like context has been initiated to control this presently representative system. Initial testing of a throttle program has verified the program technique and system operation, but optimization of the program will require much further effort. In conjunction with these tests two thrusters were operated in close proximity to each other with no serious interaction effects.

Future efforts must include establishment of start-up routines, specific testing for thruster characteristic variations, cyclic reliability tests of all programs, and establishment of interrupt fault service routines and criteria. These programs must be applied to control of a Multiple Thruster Array and flight representative power processor systems. Finally, the programs must be optimized to the flight computer selected for the spacecraft.

The most effective role of the on-board spacecraft computer has been evolved from the initial efforts and the specific command functions have been defined for a representative thruster control system. Present test programs have indicated the general validity of an approach to computer control and have suggested the particular role of the computer for future electric propulsion spacecraft design. Additional programming and testing is required to fully specify the optimum and most reliable digital control for ion thruster system. The initial objective of this work has been achieved and a clear path of action defined to insure that the final objective of optimum system performance can accomplished.

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12. Poeschel, R. L., King, H. J. and Schnelker, D. E., "An Engineering Model 30 Cm Ion Thruster," AIAA Paper 73-1084, Lake Tahoe, Nev., 1973.

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Table I Digital control system - power supply capability

Power supply identification	Output capacity of power supply	Manual control function	Computer control function	Type of control isolation	Limits of response to square wave
Screen	2000 V - 3.0 A	V	V	Relay	200/500 Hz
Accelerator	2000 V - 0.5 A	V	V	Relay	200/500 Hz
Discharge	100 V - 25.0 A	J	J	Optical DAC	10 000 Hz
Main vaporizer	10 V - 5 A	V	V	Chopper/Inv.	100/250 Hz
Main isolator	10 V - 10 A	V,J	V	Relay	250/1000 Hz
Cathode vaporizer	7 V - 7 A	V	V	Chopper/Inv.	100/250 Hz
Cathode isolator	10 V - 10 A	V,J	V	Relay	250/1000 Hz
Cathode keeper	400 V - 100 MA				
	80 V - 1A	J	J	Optical DAC	10 000 Hz
Cathode tip heater	10 V - 10 A	V	V	Chopper/Inv.	100/250 Hz
Neutralizer vaporizer	10 V - 10 A	V,J	V	Relay	250/1000 Hz
Neutralizer tip heater	10 V - 10 A	V,J	V	Relay	250/1000 Hz
Neutralizer keeper	400 V - 100 MA				
	80 V - 1 A	J			
	50 V - 1 A		V	Optical DAC	10 000 Hz
Neutralizer bias	±150 V - 3.5 A	V	none	Relay	250/1000 Hz
Magnetic baffle	25 V - 20 A	J	J	Relay	200/500 Hz
Distributer heater	10 V - 10 A	V,J	V	Relay	250/1000 Hz

V = Voltage regulation; J = Current regulation

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Table II Thruster control computer library package

Mnemonic name	Octal memory locations	Description of the function and purpose of subroutine
FRMTR	02000 - 03777 00300 - 00477	Provides for input and output functions of octal, integer, and floating point numbers. Makes conversions to ASCII for teletype. Is Hewlett-Packard routine with array and E-formats removed.
BCS-LIB	04000 - 04777	FORTRAN library routines needed for thruster program. Floating point arithmetic and conversions to integer. FORTRAN operating routines. Is Hewlett-Packard package with mathematical and array functions removed
ADC	05000 - 05521	Provides for input from high speed ADC units. Either as single input, average of 16 points in 16.7 msec, or scan of all units.
MUX	05522 - 05777	Provides for input from multiplexer either as scan or single input of one channel.
DEC	06000 - 06007	Output to decimal display.
DVS	06010 - 06107	Output to a selected digitally controlled Hewlett-Packard power supply.
INV	06110 - 06427	Output and input of time as integers to interval timer. Provides for control functions of start, stop, and reset; plus selection of operating mode.
MPR	06430 - 06567	Provides output to selected channel of multiprogrammer.
OCT	06570 - 06577	Output of integer to octal display.
PWR	06600 - 06777	Provides for turn on or off of relays controlling AC power to supplies. Either individually or in sequential order.
DAC	07000 - 07077	Output to high speed digital to analog converters which control voltage and current of discharge and cathode keeper current.
OUTP	07100 - 07777	Provides for output limits on each unit. Provides for output to all or selected groups of devices in order by calling proper driver subroutines.
TAPE	10000 - 10503	Provides data output as punched paper tape record in several formats.
ASC	10504 - 11130	Provides the ASCII character labels for tables and headings of teletype output.
LIST	11131 - 11777	Prints on teletype a complete table of all data in engineering units with labels and heading. Done one line of buffer data at a time via interrupt.
TYPE	12000 - 12777	Provides for input of data to octal or integer memory locations in several formats
CALC	13000 - 13777	Does the calculation of powers, plus does calling of TEMP and FLOW routines and calculation of other derived parameters of thruster performance.
FLOW	14000 - 14377	Allows teletype input of flow data and does calculations required to convert height readings per unit time to equivalent flows.
TEMP	14400 - 14777	Converts thermocouple readings in millivolts to centigrade temperatures for three types of thermocouple: iron-consantan, copper-consantan, and platinum-platinum, (13% rhodium)
VDIS	15000 - 15377	Provide for visual display of selected data on octal and decimal units. Converts floating point number to decimal with four most significant digits.
PENS	15400 - 15777	Provides for presentation of selected data channels and scale factors on strip chart recorder.
CLK	16000 - 16177	Provides for input as integer numbers the days, hours, minutes, and seconds shown on digital
CONV	16200 - 16777	Converts the integer data from MUX and ADC readings into engineering units with the proper scale factors.
SAMP	17000 - 17137	Provides for scan of ADC's and MUX with several selected modes of averaging for the ADC units.
A1K	17140 - 17277	Provides the average of 1000 readings for a selected channel of MUX or ADC with proper time delays for accuracy
PAGE	17300 - 17357	Brings teletype paper to top of page. Has 2 second wait for action to complete.
XNK	17360 - 17477	Conversion between the number of input channel and the number of the data position in tables of engineering units.
TIM	17500 - 17537	Provide time delays in milliseconds up to 32.768 seconds total
SWR	17540 - 17557	Input of data from bits 0 through 5 of switch register if bit 15 set.
XJK	17560 - 17677	Provides correspondence between input channel numbers and output channel numbers for same device.
ITR	17700 - 17777	Space allocation for links to interrupt routines for single channel trip functions.
LINE	20000 - 21777 End of library package	Prints a single line of data on teletype in octal or engineering units in several preselected formats. Also prints heading and ASCII code for selected data channels at top of page.

Table III Command word General Format and Thruster/Power Processor System Coding

Descriptive Command Action	Command Word Bit Pattern No. 16 = Most Significant Bit No. 1 = Least Significant Bit				
	16-15-14-13-12	11-10-9	8-7-6-5-4-3-2		1
General Command Formats	Device or PPU Identification Code	Function Specification	Reference Word Set		Parity
			Measurement Address		
			Discrete Sub Function	Discrete Action	
1st Thruster/Power System	10001	As given in Table IV and Table V			
2nd	10010				
3rd	10100				
4th	10111				
5th	11000				
6th	11011				
7th	11101				
8th	11110				
All Thruster/Power Systems	10101				

Note: Bit no. 1 is always generated so that sum of all 16 bits in command word is odd.
Any device code other than those listed do not apply to thruster power systems.

Table IV Command word format for function specifications of thruster/power processor system (bits 11/10/9 = function specification code)

Command word bit pattern												Descriptive command action
16 15 14 13 12	11	10	9	8	7	6	5	4	3	2	1	
Any PPU code shown in table III	0	0	0	X	X	X	X	X	X	X	P	This function code not used
	0	0	1	X	X	X	X	X	X	X	P	Beam current reference function
				B7	B6	B5	B4	B3	B2	B1	P	B1 through B7 = seven bit set value**
	0	1	0	X	X	X	X	X	X	X	P	Discrete set point function
				E4	E3	E2	E1	X	X	X	P	See table V for these 16 subfunctions - 0/0/0/0 through 1/1/1/1 = E4/E3/E2/E1
	0	1	1	X	X	X	X	X	X	X	P	Magnetic baffle reference function
				G7	G6	G5	G4	G3	G2	G1	P	G1 through G7 = 7 bit set value**
	1	0	0	X	X	X	X	X	X	X	P	Measurement request function
				X	X	X	X	X	X	0	P	Digital (discrete) measurement request
				26	25	24	23	22	21	0	P	21 through 26 = address (only first 4 used)**
				X	X	X	X	X	X	1	P	Analog (conversion) measurement request
				A6	A5	A4	A3	A2	A1	1	P	A1 through A6 = address (only first 24 used)**
	1	0	1	X	X	X	X	X	X	X	P	Discharge current reference function
				D7	D6	D5	D4	D3	D2	D1	P	D1 through D7 = 7 bit set value**
	1	1	0	X	X	X	X	X	X	X	P	Power supply on off function
				0	AC	SN	DV	MB	CK	NK	P	High voltage supplies* Bits 2 through 7
				1	IS	MV	CV	NV	CT	NT		Low voltage supplies* 1/0 = on/off of supply
	1	1	1	X	X	X	X	X	X	X	P	Screen voltage reference function
				S7	S6	S5	S4	S3	S2	S1	P	S1 through S7 = 7 bit set value**

*In the power supply on/off function the various power supplies are indicated by: AC = Accelerator, SN = Screen supply, DV = Discharge, MB = Magnetic baffle, CK = Cathode keeper, NK = Neutralizer keeper, IS = Isolator heaters, MV = Main vaporizer, CV = Cathode vaporizer, NV = Neutralizer vaporizer, CT = Cathode tip, and NT = Neutralizer tip.

**Where X1 through Xn is used, the least significant bit is X1 with Xn being the most significant bit

X's indicate that the bit represented by the X does not specify the particular function or action indicated.

P's indicate the approporiate parity bit to make the complete 16 bit word have odd parity.

Table V Command word format for discrete set point function (bits 11-10-9 = 010) only - (bits 8-7-6-5 = discrete subfunction code)

Command work bit pattern										Descriptive command action
16 15 14 13 12	11 10 9	8	7	6	5	4	3	2	1	
Any PPU code shown in table III	0 1 0	X	X	X	X	X	X	X	P	Discrete set point function
		0	0	0	0	X	X	X	P	This subfunction code not used
		0	0	0	1	X	X	X	P	Accelerator system
						A3	A2	A1	P	A2/A1 = 0/0, 1/0, 0/1 = 3 voltage set points; A2/A1 = 1/1 proportional control A3 = 0 or 1 = ON or OFF of accelerator current interrupt
		0	0	1	0	X	X	X	P	Neutralizer keeper voltage
						F3	F2	F1		F3/F2/F1 = 0/0/0 through 1/1/1 = 8 voltage set points
		0	0	1	1	X	X	X	P	Discharge voltage
						V3	V2	V1	P	V3/V2/V1 = 0/0/0 through 1/1/1 = i voltage set points
		0	1	0	0	X	X	X	P	Neutralizer vaporizer current N2/N1 = 1/0, 0/1 = two set points N3 = 1 or 0 = ON or OFF of proportional control
		0	1	0	1	X	X	X	P	Neutralizer keeper current
						J3	J2	J1	P	J2/J1 = 0/0 through 1/0 = 4 set points J3 = 1 or 0 = OFF or ON of neutralizer interlock
	See table IV for other function specifi-cations	0	1	1	0	X	X	X	P	Neutralizer tip heater
						X	T2	T1		T2/T1 = 0/0 through 1/1 = 4 set points
		0	1	1	1	X	X	X	P	Neutralizer vaporizer proportional control
						X	X	X	P	Y2/Y1 = 0/0 through 1/0 = 4 configurations 1/3 = 0/1 = normal/redundunt loop
		1	0	0	0	X	X	X	P	Cathode vaporizer
						C3	C2	C1	P	C2/C1 = 1/0 and 0/1 = two set points C3 = 0 or 1 = OFF or ON of proportional control
		1	0	0	1	X	X	X	P	Cathode keeper current
						X	K2	K1		K2/K1 = 0/0 through 1/1 = 4 set points
		1	0	1	0	X	H2	H1	P	Cathode tip heater
						X	H2	H1	P	H2/H1 = 0/0 through 1/1 = 4 set points
		1	0	1	1	X	X	X	P	Cathode vaporizer proportional control
						X	X	X		X2/X1 = 0/0 through 1/1 = 4 configurations X3 = 0/1 = normal/redundant loop
		1	1	0	0	X	X	X	P	Main vaporizer
						M3	M2	M1	P	M2/M1 = 0/1, 1/0, 1/1 = 3 set points
		1	1	0	1	X	X	X	P	Back up systems
						Q3	Q2	Q1	P	Q1 = 1/0 = ON/OFF screen module Q2 = 1/0 = ON/OFF discharge module Q3 = 1/0 = ON?OFF grid clear
		1	1	1	0	X	X	X	P	Isolator heaters
						X	R2	R1	P	R2/R1 = 0/1, 1/0, 1/1 = 3 set points
		1	1	1	1	X	X	X	P	Main vaporizer proportional control
						W3	W2	W1	P	W2/W1 = 0/0 through 1/1 = 4 configurations W3 = 0/1 = Normal/redundant loop

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Table VI Proposed general format for improved thruster/power system control command code

<table>
<tr><th colspan="4">Command Word Bit Pattern</th></tr>
<tr><td>16-15-14-13</td><td>12-11-10-9</td><td>8-7-6-5</td><td>4-3-2-1</td></tr>
<tr><td rowspan="2">4 bit PPU or other device ID code</td><td rowspan="2">4 bit command general function code</td><td>4 bit discrete command sub function code</td><td>4 bit set point or action code</td></tr>
<tr><td colspan="2">8 bit reference word or data request address</td></tr>
</table>

Note: No parity bit
No code for all device response

Table VII Typical 30 cm thruster operating characteristics (Hughes S/N 402 with Lewis grid S/N 29)

Thruster Parameter	At 1.00 A beam	At 2.00 A beam
Screen potential, V	1100	1100
Accelerator potential, V	500	500
Accelerator current, mA	2.0	4.4
Discharge potential, V	37.0	37.0
Discharge current, A	5.0	10.0
Magnetic baffle potential, V	0.12	0.24
Magnetic baffle current, A	2.00	4.00
Isolator heater potential, V	3.6	1.7
Isolator heater current, A	2.00	1.00
Main vaporizer potential, V	5.5	6.3
Main vaporizer current, A	1.00	1.10
Floating potential, V	12.4	10.4
Cathode tip potential, V	0.0	0.0
Cathode tip current, A	0.0	0.0
Cathode keeper potential, V	6.8	4.3
Cathode keeper current, A	0.50	0.50
Cathode vaporizer potential, V	3.6	3.5
Cathode vaporizer current, A	1.48	1.45
Neutralizer tip potential	0.0	0.0
Neutralizer tip current	0.0	0.0
Neutralizer keeper potential, V	15.0	15.0
Neutralizer keeper current, A	1.5	1.5
Neutralizer vaporizer potential, V	3.12	2.88
Neutralizer vaporizer current, A	1.40	1.28
Main vaporizer mercury flow, mA	1084	1960
Cathode vaporizer mercury flow, mA	112	136
Neutralizer vaporizer mercury flow, mA	75	55
Beam power, W	1087	2179
Discharge power, W	185	370
Total power, W	1334	2616
Electron volts 1 ion, eV/ion	185	185
Electrical effeciency, %	81.5	83.3
Propellant utilization efficiency, %	83.6	95.4
Electrical specific impulse, sec	3288	3291
Electrical thrust, mN	67.5	135.1

Table VIII Data storage bit pattern for TAB program at table entry point = N

Table Entry N		Word Bit Pattern			
Word number	Table location	Bit no. 16-15-14-13	Bit no. 12-11-10-9	Bit no. 8-7-6-5	Bit no. 4-3-2-1
1	N	Spare A		Beam current reference value	
2	N + 128	Spare B		Magnetic baffle current reference value	
3	N + 256	Spare C		Discharge current reference value	
4	N + 384	Spare D		Screen voltage reference value	
5	N + 512	Discharge voltage set pt.	Neut. keeper voltage set pt.	Acc. system conf.	Not used
6	N + 640	Neut. vaporizer p. control conf.	Neut. tip heater set pt.	Neut. keeper current set pt.	Neut. vaporizer current set pt.
7	N + 768	Cathode vaporizer p. control conf.	Cathode tip heater set pt.	Cathode keeper current set pt.	Cathode vaporizer current set pt.
8	N + 896	Main vaporizer p. control conf.	Isolator heaters current set pt.	Back up systems conf.	Main vaporizer current set pt.

Table IX Thruster operating parameters for throttle map table

Table point, N	0 to 24	25 to 49	50 to 127
Screen potential, V	1100	1100	1100
Accelerator potential, V	500	500	500
Discharge potential, V	37	37	37
Beam current, A	.02 N	.02 N	.02 N
Discharge current, A	.1 N	.1 N	.1 N
Magnetic baffle current, A	.04 N	.04 N	.04 N
Isolator heater current, A	4.0	2.0	1.0
Neutralizer keeper potential, V	15.0	15.0	15.0
Neutralizer keeper current, A	2.0	2.0	1.5
Cathode keeper current, A	0.5	0.5	0.5
Neutralizer tip current, A	0.0	0.0	0.0
Cathode tip current, A	0.0	0.0	0.0

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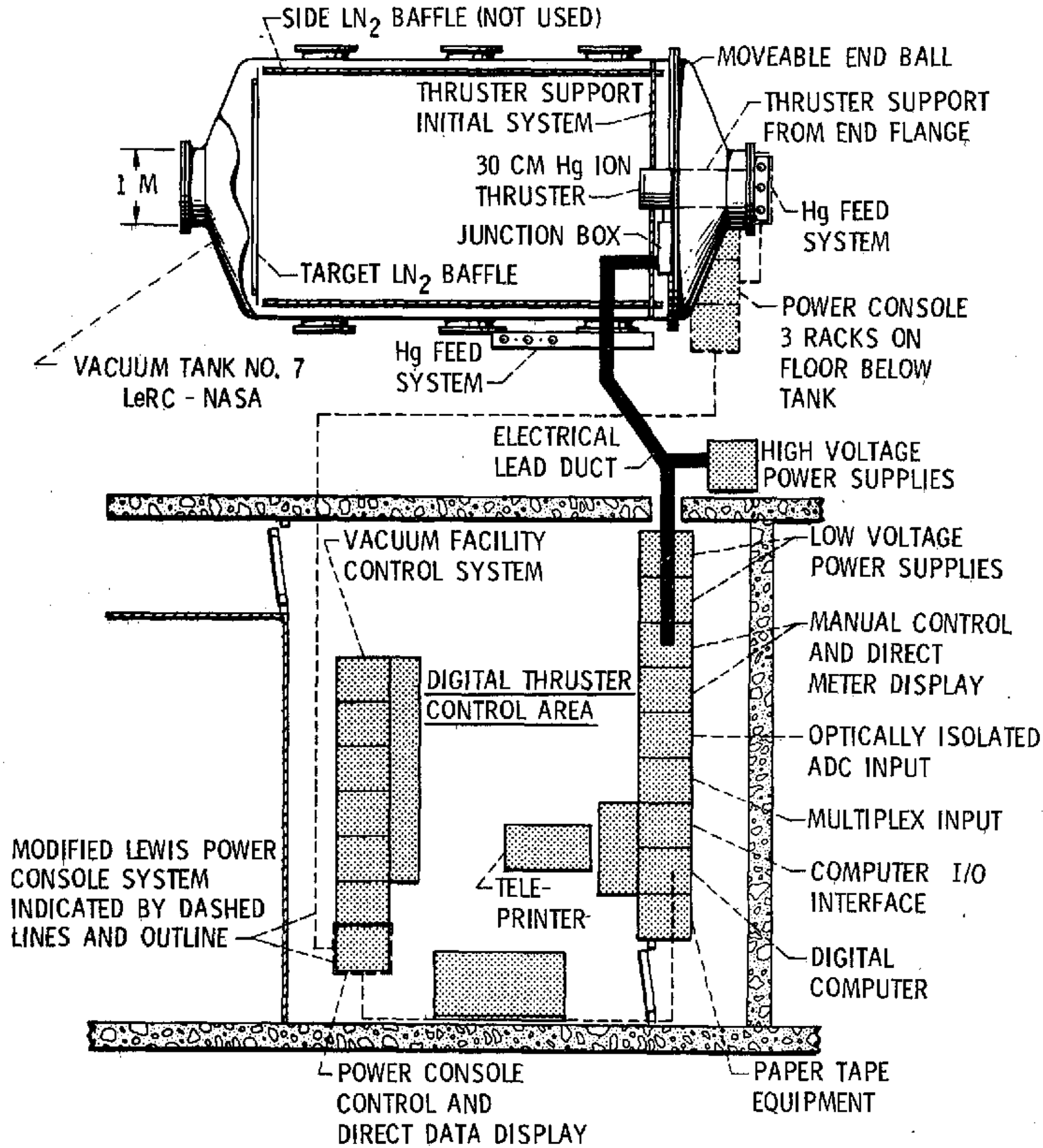

Figure 1. - Plan view digital control and ion thruster test facility LeRC.

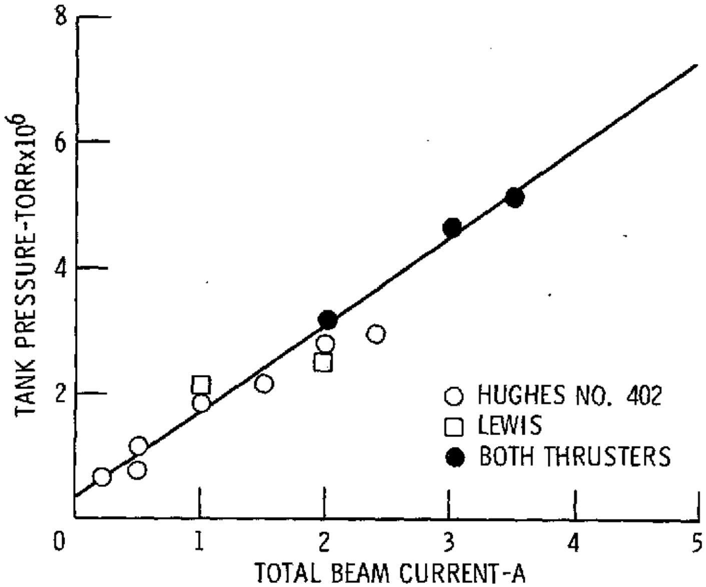

Figure 2. - Vacuum as a function of beam. One or both 30 cm thruster - 1100 V on screen grid - 500 V on accelerator grid.

LEWIS RESEARCH CENTER - TANK 7 EPRB - COMPUTER CONTROL - 30 CM THRUSTER

TEST NO. - 1234 : DATE - 365/1975 : DATA LIST- 987 : TIME - 11:22:33

VAZ=	500.02	JAZ=	4.22	PAZ=	1.05	RTO=	67.43
VSZ=	998.92	JSZ=	1005.00	PSZ=	1003.91	ESI=	3232.90
DVI=	37.51	JEZ=	5.05	PDG=	189.38	EVI=	189.37
VIZ=	1035.45	JIZ=	6.07	PWR=	1280.39	EFF=	80.05
VGZ=	10.47	JBZ=	1000.00	PBZ=	1024.98	ETZ=	65.27
VMV=	5.75	JMV=	1.20	PMV=	6.90	TMV=	300.12
VMI=	4.02	JMI=	1.05	PMI=	4.22	TMI=	246.72
VCV=	1.60	JCV=	3.84	PCV=	6.14	TCV=	275.01
VCI=	4.02	JCI=	1.12	PCI=	4.50	TCI=	250.67
VCT=	2.60	JCT=	1.25	PCT=	3.25	TCT=	1205.13
VCK=	6.72	JCK=	510.86	PCK=	3.43	PTK=	2.07
VNB=	0.01	JNE=	1001.16	PNB=	0.00	TBB=	-187.02
VNV=	2.64	JNV=	1.41	PNV=	3.72	TNV=	283.05
VNT=	2.25	JNT=	1.20	PNT=	2.70	TNT=	986.14
VNK=	16.11	JNK=	1501.00	PNK=	24.18	IC1=	-0.00
VDH=	6.02	JDH=	4.01	PDH=	24.14	TEB=	157.16
VMG=	1.12	JMG=	2.56	PMG=	2.87	IC2=	-0.00
HHM=	87.60	JOM=	1125.00	DHM=	3.32	PUF=	77.95
HHC=	36.14	JOC=	97.75	DHC=	1.15	TSI=	2520.04
HHN=	25.23	JON=	60.01	DHN=	0.75	TEF=	62.40
ARC=	15.00	JOT=	1282.76	MIN=	252.00	TZZ=	65.00

PROVISION FOR ADDITIONAL ENTRIES TO A TOTAL OF 120 ITEMS PRINTED OUT

Figure 3. - Typical complete printout on teleprinter of measured and computed thruster parameters using LIST program.

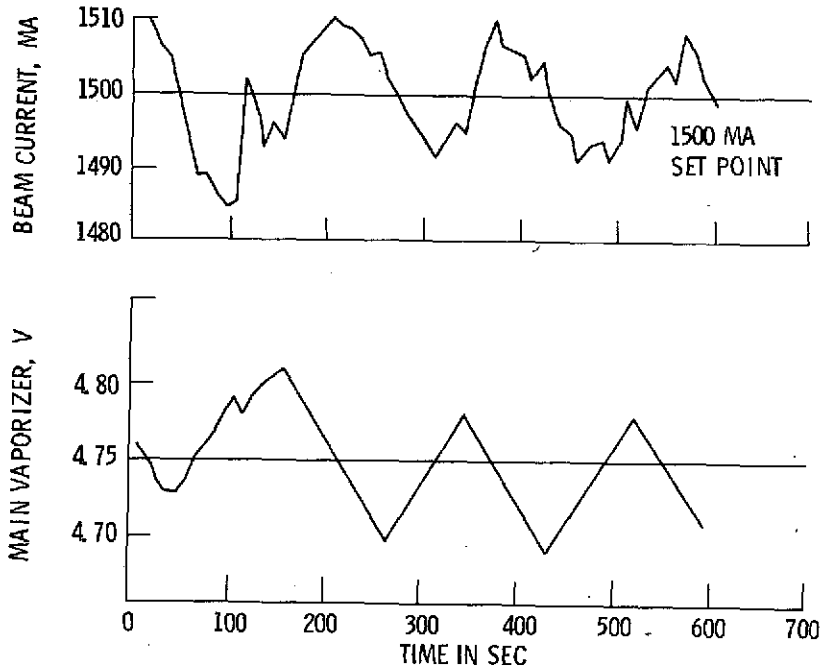

Figure 4. - Control response of beam current by main vaporizer voltage incremented with step function integrator updated once per second. LeRC thruster 10 A discharge; 1000 V screen; 500 V accelerator; 35 V discharge.

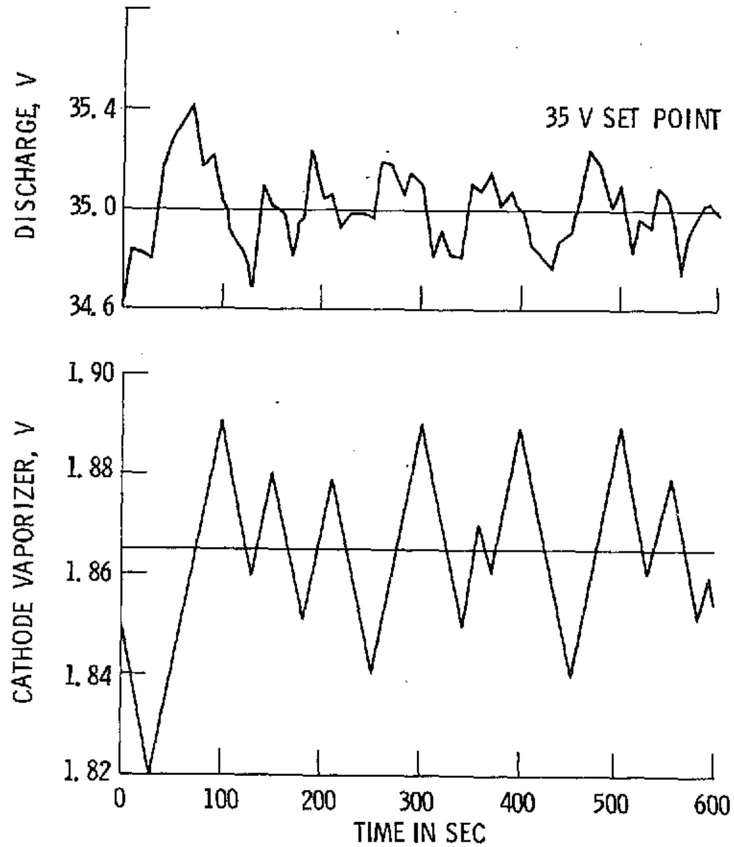

Figure 5. - Control response of discharge voltage to cathode vaporizer voltage incremented with step function integrator updated once per second LeRC thruster; 10 A discharge; 1500 MA beam; 1000 V screen; 500 V accelerator.