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Power Console Development for NASA's Electric Propulsion Outreach Program

Luis R. Piñero, Michael J. Patterson, and Vincent E. Satterwhite
Lewis Research Center
Cleveland, Ohio

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POWER CONSOLE DEVELOPMENT
FOR NASA'S ELECTRIC PROPULSION OUTREACH PROGRAM

Luis R. Piñero*, Michael J. Patterson**, and Vincent E. Satterwhite***
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Abstract

NASA Lewis Research Center is developing a 30 cm diameter xenon ion thruster for auxiliary and primary propulsion applications. To maximize expectations for user-acceptance of ion propulsion technology, NASA LeRC, through their Electric Propulsion Outreach Program, is providing sectors of industry with portable power consoles for operation of 5 KW-class xenon ion thrusters. This power console provides all necessary functions to permit thruster operations over a 0.5 - 5 KW envelope under both manual and automated control. These functions include, discharge, cathode heater, neutralizer keeper, and neutralizer heater currents, screen and accelerator voltages, and a gas feed system to regulate and control propellant flow to the thruster. An electronic circuit monitors screen and accelerator currents and controls arcing events. The power console was successfully integrated with the NASA 30 cm thruster.

Introduction

Ion propulsion systems, which enable spacecraft mass savings, are being developed and flight tested in the United States, Japan, and Europe.[1-3] Due to solar array and battery technology the power level of interest is between 0.5 and 5 KW for maneuvering, repositioning, orbit transfer, and planetary missions. NASA Lewis Research Center (NASA LeRC) is focused on the development of a 30 cm xenon ion propulsion system for these applications.[4] The U.S. industrial experience with this technology is limited. Technology transfer is therefore imperative to maximize expectations of user-acceptance of ion propulsion. To facilitate this, NASA has an Electric Propulsion Outreach Program promoting electric propulsion technology transfer to US industry. Through this program, NASA will provide 30 cm xenon ion thrusters and portable power consoles so that an experience-base of key technologies and operations of ion propulsion systems can be established. Potential candidates receive these systems through Space Act Agreements. This paper documents the development of the power console and discusses aspects of its integration with a 30 cm ion thruster.

Background

In an ion propulsion system, thrust is generated by a combination of three mechanisms. These mechanisms are ion generation, ion acceleration, and beam neutralization. A block diagram which shows the functions of the NASA 30 cm ion propulsion system is shown in Figure 1. The cathode and neutralizer heaters are energized and raise the temperature of the discharge and neutralizer hollow cathode inserts to prepare them for ignition with a regulated current. A potential across the discharge cathode and thruster anode is established by the discharge supply, and another potential is established across neutralizer cathode and neutralizer keeper, provided by the neutralizer keeper supply. The electrons from the discharge cathode ionize the xenon gas, are collected by the anode, and are recirculated via the discharge power supply. Ions produced in the discharge preferentially drift toward the grids,

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* Electrical Engineer, On-Board Propulsion Branch

** Aerospace Engineer, On-Board Propulsion Branch, Member AIAA

*** Electronic Systems Mechanic, Energy and Spacecraft Branch where they are electrostatically focused and accelerated by the screen and accelerator grid potentials to form a well-collimated ion beam. The ion beam is charge neutralized by the presence of electrons supplied by the neutralizer. The neutralizer keeper power supply is used to maintain the neutralizer cathode discharge, and does so under varying conditions of emission current demand.

A total of six electrical functions are needed on the NASA 30 cm thruster. These electrical functions are discharge cathode heater, discharge, neutralizer cathode heater, and neutralizer cathode keeper currents, and screen and accelerator high voltages. All these are required during steady state operation except for the heaters which are only needed during thruster start up.[5] A breadboard power processing unit (PPU) is in the design stage at NASA LeRC in support of the NASA Solar Electric Propulsion Technology Application Readiness Validation Program (NSTAR). This PPU will consist of a total of three power supplies that will provide the six electrical functions for the thruster.[6] For comparison purposes in this publication, we define a power supply as any device with DC or AC input which regulates one independent or two or more simultaneous output parameters. Also for system comparison purposes, only main electrical function power supplies are considered, so high voltage ignitors or housekeeping power supplies are not considered. There are a number of ion thruster systems under development for station keeping like the UK-10/T5, the Hughes 13 cm, the ETS-VI, and the RIT-10.[2,7-10] Table 1 compiles thruster and power interface requirements for these systems and the NASA 30 cm thruster.

Apparatus

Power Console

A photograph of a NASA's power console and a block diagram are shown in Figures 2 and 3, respectively. The power console provides, via six separate power supplies, the six electrical functions needed for the NASA 30 cm thruster. The use of separate power supplies was chosen in order to allow more flexibility to the user of the power console. Provided in addition are cathode ignition high voltages, recycle control, and regulated gas flow for the discharge cathode, neutralizer cathode, and main discharge. The recycle control function used to extinguish arcs is provided by an electronic circuit in the power console, and is described in a later section. The control unit contains all the isolated telemetry needed to evaluate thruster performance and an isolated interface for computerized data acquisition and control. The computer interface facilitates data storage, control of the power supplies, and shutdown capabilities for long duration testing.

The power console also contains a xenon propellant feed system. A typical feed system is shown in Figure 4. This feed system provides flow regulation and control of the xenon propellant to the thruster, as well as containing provisions for eliminating contaminants in the xenon propellant and feed system which may negatively impact cathode emitter lifetime. The NASA 30 cm thruster requires three separate propellant flows. Approximately 10% of the total propellant flow is required for the discharge and neutralizer cathodes to maintain their emission while the remaining flow goes to the discharge chamber through a main plenum. These flows determine the thruster performance and its load characteristics to the power supplies. Each of the three propellant flows in the power console feed system are provided by three separated feed lines to the thruster. Each of the lines incorporate individual commercial mass flow transducers which measure the flow rates, with each transducer calibrated using a primary standard. The contamination control provisions in the power console feed system include use of low outgassing components, feed system bake-out and leak-rate instrumentation, and use of an active gettering compound to reduce oxygen and water vapor in the propellant delivery. The feed system is customized to the end-user and is typically mounted on, or in close proximity to, the vacuum test chamber.

Thruster

The thruster used to integrate and test the power console and to define recycle control requirements was a laboratory-version 30 cm diameter thruster with ring-cusp plasma discharge operating on xenon propellant. The effective beam, or ion extraction, diameter was 28.2 cm. The thruster incorporated a segmented-anode geometry consisting of three segments of stainless steel, with an exterior chamber of 0.76 mm thick cold-rolled steel. The thruster used a distributed 'reverse-injection' propellant system for the main flow. A reverse-feed system was employed to improve the discharge propellant efficiency. The magnetic circuit design employed used samarium-cobalt permanent magnets arranged to form a ring-cusp field boundary. Conventional hollow cathodes were employed in the discharge and neutralizer. The cathode tubes consist of a refractory metal alloy and an orifice plate. The orifice diameters of the discharge and neutralizer cathodes were 1.52 mm and 0.51 mm respectively. Porous tungsten inserts, impregnated with a low work function compound were used as the electron emitters.

Testing was conducted with a two-grid ion optics set using a titanium mounting system.[11] The molybdenum electrodes had a nominal thickness of 0.38 mm, with 1.91 mm and 1.52 mm diameter circular screen and accelerator apertures, respectively. The open-area-fraction for the screen and accelerator electrodes was 0.67 and 0.43, respectively. A minimum electrode cold-gap of 0.48 mm was set. The performance of this thruster has been documented operating with conventional laboratory power supply systems.[12]

Facility

Thruster / power console integration testing was conducted in the Tank 5 vacuum chamber facility at NASA LeRC. The chamber is 4.6 m in diameter by 19.2 m in length. The pumping characteristics of the facility include a nominal 110 kl/s xenon pumping speed, a no-load pressure of $\leq 6.7\times10^{-5}$ Pa, and an operational pressure of $\leq 1.0\times10^{-3}$ Pa. Additional tests to quantify recycle requirements were conducted at NASA LeRC Tank 1 facility. Tank 1 is approximately 1.5 m in diameter by 4.5 m in length and has a nominal 30 kl/s xenon pumping speed, a no-load pressure of $\leq 6.7\times10^{-5}$ Pa, and an operational pressure of $\leq 1.0\times10^{-2}$ Pa.

Power Console Design

Several technical goals where imposed on the power console design. It was required to provide all the electrical, propellant flow control, and telemetry functions for the NASA 30 cm thruster. It had to be capable of operating at multiple setpoints over a power envelope of 0.5 to 5.0 KW under manual or automated control for thruster performance characterizations. Autonomous capabilities of detecting fault conditions during unattended, long-duration lifetesting where also needed since power consoles will be used during the ground test phase of the NSTAR Program. Finally and importantly, the power consoles will be used by a broad group of costumers, it was required to be transportable, have user-friendly interfaces, be very flexible, and be simple to maintain and repair.

Control mode

Ion propulsion systems are being developed using both open loop and closed loop feedback systems.[13] The selection of a control mode is one driver that can determine system and thruster performance. Open loop systems operate according to the load characteristics of the thruster. These systems are simpler and lighter than closed loop systems which require isolation, amplification, and filtering, which can dramatically increase parts count, mass, and cost of the PPU and can decrease system reliability. On the other hand, closed loop systems do allow for operational control and accommodation of changes in thruster load characteristics with time. The Hughes 13 cm PPU operates in an open loop and single setpoint mode. These limited requirements permitted the development of a very light and simple PPU. The ETS-VI and UK-10/T5 systems operates with multiple feedback loops.[13-14] Three of these loops are common to both systems. A thrust control loop maintains a constant beam current and thus thrust level by regulating the main discharge flow. A discharge cathode loop regulates cathode flow to keep a constant discharge voltage in the ETS-VI system and a constant keeper voltage in the UK-10/T5 system. A neutralization loop regulates neutralizer keeper voltage by regulating neutralizer flow. The UK-10/T5 system has a fourth loop in which the cathode keeper to anode voltage (ΔV) and thus propellant utilization efficiency is kept constant by regulating magnet current.

NASA's power console operates in an open loop mode. There are no feedback loops on any thruster electrical parameters. The only control offered by the power console is the recycle sequence for grid arc extinction.

Power Supplies

The power console is contained in a portable standard 48 cm (19") wide rack, and consists of two parts, the power supplies and the control unit. The input requirement for the rack is 3 phase 208 V / 50 A. The discharge and cathode heater supplies are electrically isolated by an isolation transformer and mechanically isolated from the rack to allow them to float above screen potential. The rest of the power supplies are referenced to neutralizer common. A bi-directional 75 volt zener clamp between neutralizer common and ground eliminates the need for isolation of these power supplies. The high voltage ignitor circuit used for discharge and neutralizer cathode ignition is shown in Figure 5. A small isolation transformer isolates the 120 V_{AC} input which then is rectified and filtered to generate a maximum of 350 V_{DC} @ 100 mA. A blocking diode is used to protect the discharge and neutralizer keeper power supplies and the instrumentation from the ignitor high voltage. The output of the rack to the thruster consists of seven power leads, one for each power supply (except the screen), and one each for discharge cathode and neutralizer cathode common.

Control Unit

The control unit contains all the electronic circuit boards and instrumentation needed to perform the control and telemetry functions of the power console, and has a user interface on its front panel. Photographs of the control unit and the circuit boards are shown in Figures 6 - 8. The plug-in edge connector design of the electronic circuit boards and the use of modular components facilitates repair and maintenance of the control unit. Potentiometers generate voltage signals used to control the output of the power supplies. To avoid grounding problems, these signals are isolated using the circuit shown in Figure 9. This circuit consists of a DC to DC converter that generates isolated power for the output side of six isolation amplifiers that isolate each control signal. The current and voltage outputs of each power supply are measured in the control unit by the circuit shown in Figure 10. Currents and voltages are measured using Hall Effect sensors and voltage dividers respectively. The isolated current outputs of the Hall Effect sensors are dropped across resistors to obtain voltage signals that are displayed on voltmeters on the front panel. The outputs of the voltage dividers are isolated by the circuit shown in Figure 11. This circuit works like the isolation circuit of Figure 9, except that the isolated power outputs of the DC to DC converter are used on the input side of the isolation amplifiers. The isolated signals are also displayed on the front panel meters.

The recycle logic circuit, shown in Figure 12, consists of voltage comparators that detect when the screen or accelerator currents rise above a reference value. Two Hall Effect sensors are used to monitor the screen and accelerator currents. This triggers six one-shots connected in series that are used to control the length of each event of the recycle sequence. The length of each event can be adjusted by potentiometers on the circuit board, and the sequence can be altered by changing jumpers. In case of a grid-to-grid or grid-to-ground arc, the recycle logic circuit controls the high voltage power supplies and reduces the discharge current to a preset value on the front panel. The length of the recycle is limited by the response time of the power supplies. Recycles are described in detail in a later section.

An isolated analog interface provides representative low voltage signals of thruster parameters, and remote control of the power supplies. A computerized data acquisition and control system, shown in Figure 13, was developed to perform these functions. The system uses a laptop computer, a commercially available data acquisition and control software package, a 16-channel multiplexer, a 16-channel analog to digital (A/D) converter, and two 4-channel digital to analog (D/A) converters. The system displays and stores thruster data in the laptop computer and sends the required signals to control the power supplies instead of using the potentiometers in the control unit's front panel. For lifetesting purposes, this system offers a shutdown capability. In the event of off normal thruster conditions, the power to the console will be automatically turned off and the test will be terminated.

Thruster Integration

The power console depicted in Figure 2 is actually a product of several iterations in design. Three different versions of power consoles were built successively during the development process to test various components and concepts, and all three have operated the 30 cm thruster over various power envelopes under steady state conditions. The first power console, designated in Table 2 as #1, was used as a proof of concept. Results obtained from its testing verified the telemetry, isolation, and high voltage ignitor circuitry designs. Additionally, problems related to the recycle control circuit, which is described in a following section, were identified.

Information derived from console #1 lead to the design of console #2. This incorporated a modular control unit, as shown in Figure 6 and 7, which utilized wire wrapped breadboard circuits. This unit had several test objectives including defining the recycle control technique, recycle and accelerator (accel) power supply requirements, and demonstrating thruster operations up to 2 kW. Additionally, extended-duration testing on a thruster load to demonstrate unattended operation was conducted. These tests resulted in the selection of the baseline recycle control technique, demonstrated steady state operation of the thruster at power levels up to 2 KW, and included two 50 hour tests of the thruster and power console at power levels of approximately 0.6 and 1.5 KW.

Another outcome of testing the second console was the demonstration of thruster operations over varied test environments. This was attained by testing in two different facilities, Tank 5 and Tank 1, with different pumping speeds. This resulted in different thruster load dynamics at the same nominal thruster operating conditions, due to substantial differences in the accelerator grid impingement currents. This test was crucial as the test environment (primarily, the vacuum facility pumping speeds) will vary greatly among the sites which will use the power consoles.

Power console #3 is the first of several consoles which are being built in duplicate fashion, and will be used and transferred to industry under the Electric Propulsion Outreach Program. Modifications from the second console design include printed electronic circuit boards, and a capability to run the thruster at power levels up to 5 kW.

The following sections describe in more detail the results of the power console / thruster integration tests.

Power Supply Configuration

There are two possible points to which the positive side of the screen power supply can be connected to operate an ion thruster, as shown in Figure 14. In the first option, the tie point is at discharge cathode common. In this configuration, the discharge power supply regulates the anode current, which is the sum of the cathode emission current and the beam current. The second option is to tie screen potential to the positive side of the discharge supply and thruster anode. In this case, the discharge supply regulates the cathode emission current only.

Electron backstreaming during recycles can present a problem in the first configuration. This is because the neutralizer common can become electrically connected to the anode through the conductive plasma. Since the thruster does not have a cathode keeper, the discharge cathode can be extinguished due to the replacement of the cathode emission component of the anode current, which is being regulated by the discharge supply, with current from the neutralizer. Additionally, during backstreaming the output of the discharge and screen power supplies are paralleled which may result in damage to the discharge supply. In the second configuration, the discharge will not be extinguished by electron backstreaming since the cathode emission current is regulated. However in the second configuration, grid-to-grid arcing may result in the full output voltage of both the screen and accel power supplies being paralleled with the discharge power supply with resultant damage to the power supply. This can be avoided by electrically isolating the screen grid from cathode potential and permitting the grid to float. An additional advantage to isolating the screen grid is increased grid lifetime, as this configuration reduces the incident discharge ion energies which impinge on the grid. For these reasons the selection of the second configuration, where the positive side of screen supply is tied to the positive side of discharge supply, with an electrically isolated screen grid, was selected as the basic approach for the power console.

Recycle

Once the propellant flows and the desired outputs of the power supplies are set, the start up sequence can be initiated. First, the cathode heater power supplies are activated to condition the cathodes. When conditioning is finished, the neutralizer cathode keeper and discharge power supplies can be activated, and they should provide open circuit voltages. If the open circuit voltages do not ignite the cathodes, the high voltage ignitors can be used. After both cathodes are in operation, the cathode heater supplies can be turned off and the high voltage power supplies can be activated using a single switch in the front panel of the control unit.

During normal thruster operations, a high voltage arc can occur between the grids in the ion optics or from the grids or other high voltage surfaces to ground. A recycle sequence is initiated when high voltage arcing is detected, and it is used to extinguish the arc to preclude damage to the thruster or power electronics and to reestablish normal thruster operation. This recycle sequence consists of a controlled set of sequential changes to the power supply outputs. An investigation was conducted to define and verify the conditions and requirements for arc detection and control that would be required for the power console to operate the NASA 30 cm thruster over a power envelope of 0.5 to 5.0 KW. While the output characteristics of some of the commercial power supplies used in the power console are different than that envisioned for the breadboard PPU development, it was anticipated that this exercise may provide preliminary requirements, limits, and guidelines that may be employed in the PPU recycle approach.

There are several requirements to complete a recycle sequence. In order to extinguish arcs, the high voltage inputs to the thrusters must be removed. Also, to reduce the accelerator grid impingement current and facilitate high voltage restoration, the plasma density in the discharge chamber has to be minimized prior to restoring the high voltage input by reducing the magnitude of the discharge current from its nominal value. Additionally, to avoid electron backstreaming from the neutralizer to thruster anode, the accelerator voltage should remain on while the screen voltage magnitude goes to zero. During the high voltage restoration, the accelerator voltage should also precede the screen voltage in order to avoid electron backstreaming[15-16]. Finally, the discharge supply input current should be increased to its nominal value only after the high voltage have reached its nominal value. Details of these requirements can vary depending on the power supply output impedance, and the thruster load characteristics and power level.

Two different control techniques were investigated for recycle control. The first approach used was a comparator circuit. The circuit monitored screen and accelerator currents to detect arcs. Then, it sequenced the recycle by monitoring the screen and accelerator voltages and comparing them to their nominal values or zero magnitude to trigger the different events in the recycle sequence. This approach was not very successful because under several thruster conditions, the events could easily get out of synchronization.

The second recycle approach consisted of a circuit that sequentially timed the events of the recycle sequence. A total of five events were used for the sequence, as shown in Figure 15. Assuming nominal operation, the first event after arc detection is the turn-off of the screen supply and reducing the discharge current. Limitations on discharge current imposed by the accel power supply are discussed in the Appendix. Then, after a short period of time, the accel supply is turned off. Then the high voltage is restored by turning on the accel supply ahead of the screen supply. Finally, the discharge current rises to nominal value. The length of each event can be adjusted according to the load characteristics of the thruster and the response time of the power supplies. This approach was chosen for the power console and used during the integration tests with the NASA 30 cm thruster. Details about the recycle sequence can be found in the Appendix.

Implications on PPU Development

The integration tests of the power console with the NASA 30 cm thruster have brought out many issues which may impact the PPU design approach. The power range of operation is a first order consideration as it determines the size and mass of critical components in the power supplies like transformers, transistors, rectifiers, and output filters. The control technique and the number of setpoints required are also critical elements in design because they not only affect the thruster and the PPU, but also the propellant management system. The power supply configuration impacts the PPU design in terms of protection during off-normal conditions during recycles. The configuration chosen for the NASA 30 cm ion PPU is with the positive side of the screen supply tied to the positive side of the discharge supply, with an electrically isolated screen grid.

The recycle requirements identified with the power console may be necessary for successful recycles with the PPU under development. Successful recycles with the power console were found to require separate control over the outputs of the screen and accel power supplies. The proposed PPU combines the screen and accel supplies on the same transformer[6] which makes proper control of the screen and accelerator high voltages difficult. The ability to use a single transformer may require modifications to the recycle concept used herein and / or the use of circuitry to allow independent control over the screen and accelerator high voltages.

Another issue is the need of a discharge current cut-back during a recycle. A current of 3 A is a minimum for stable discharge cathode operation, and under these conditions, a peak accelerator current of 200 ma occur during recycles at beam currents up to about 1.6 A. This accelerator current requirement will increase with increasing discharge cut-back current and thruster power levels.

Status

The first of several power consoles is completing final thruster integration tests, and will be incorporated at an external site in early 1994. Four additional power consoles are in various stages of build-up, two of which will be used to support the NSTAR ground test program. These additional consoles are being built using screen power supplies with a 5 kW (nominally, 1.5 KV at 3.3 A beam current) capability. Additionally, investigations of recycle dynamics at various power levels and their effects on the breadboard PPU requirements are continuing at NASA LeRC.

Summary

An Electric Propulsion Outreach Program to transfer ion propulsion technology to industry is on going at NASA. NASA 30 cm xenon ion thrusters, propellant management systems, and power consoles with all the functions needed to run a thruster will be provided to demonstrate the technology. The power console was built using commercial power supplies, with open loop / manual or automated multiple setpoint operation, and with an adjustable recycle sequence. It was integrated with a NASA 30 cm ion thruster. Design criteria used on the power console and integration data including recycle dynamics, screen supply connection, and accel supply requirements, were discussed. These have implications on the PPU design and will be studied in more detail.

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Appendix

The power console recycle sequence was tested using both a resistive load and the NASA 30 cm thruster. Initially, testing was restricted to a power envelope of 0.6 to 1.8 KW with a 0.8 to 1.8 A beam current because the output of the available screen supply was limited to 1.0 KV @ 2 A. A plot of a recycle of each case is shown in Figure A1. It is desirable to obtain the fastest possible recycle, to make the recycle duration negligible compared to thruster operation. However, the total length of the recycle was limited by the response time of the power supplies, and was approximately 2.3 seconds in length, The recycle starts when an arc occurs and the screen , accelerator, or both currents increase above the recycle reference values. The typical values for the references used during this test were 1.8 A for the screen current and 0.5 A for the accelerator current which are below the maximum current output of the respective power supplies to avoid a collapse off their output voltage or triggering protection mechanisms in the power supplies. In the first event of the recycle sequence, the screen voltage is removed and the discharge current is reduced. The accel supply remained on for approximately 300 milliseconds after which time it is commanded off and its output drops to zero. The screen power supply remains off for a duration of approximately 1.5 seconds. This length of time is dictated by a protection mechanism in the specific commercial power supply used. Using a power supply without this feature would permit more rapid restoration of the high voltage. Then, the accelerator voltage is restored to its nominal value. Approximately 150 milliseconds later, the screen voltage is restored. The combined rise time of the accelerator and screen voltages is nearly 400 milliseconds and after a safety margin of about 100 milliseconds the discharge current is commanded to its nominal value. The difference between the accelerator voltage in the plot of the resistive load test and the thruster test is due to the slow time constant of the resistive load compared to the thruster dynamic load during the recycle and the difference in the discharge current magnitude is due to the power handling capability of the resistive load.

The NASA 30 cm thruster does not have a cathode keeper. The result of which is that during a high voltage recycle, the discharge must be maintained via a cathode-to-anode discharge. This discharge invariably requires a higher current, and thus generates a higher plasma density than a keeper discharge. This imposes particular requirements on the accel power supply. The steady state accelerator current for the NASA 30 cm thruster is approximately 10 mA, but during a recycle it can increase by more than an order of magnitude. This is due to impingement current during the transients of the recycle, and whenever the magnitude of the accelerator voltage is considerably greater than the screen voltage. The magnitude of the impingement current is a function of the ion density in the discharge chamber. A high accelerator impingement current can exceed the current capability of the accel power supply causing its output voltage to collapse which can result in electron backstreaming. An example of this can be seen in Figure A2. Screen and accelerator voltages and discharge current are shown during a recycle sequence. During the high voltage turn-off, the accelerator voltage should stay on for a short period of time but, due to the limited current capability of the accel supply used for this test and the high impingement current, the accelerator voltage drops. This impingement current experienced during a recycle can be reduced by decreasing the magnitude of the discharge current. There is however a minimum discharge current at which the discharge cathode can be run without extinguishing its emission. This condition then defines a minimum accelerator current requirement. It was found that it was possible to complete a recycle by reducing the discharge current to 3 A, but an accelerator current of more than 100 mA is needed for beam currents greater than 0.8 A, and more than 200 mA is needed for 1.6 beam current.

The UK-10/T5, ETS-VI, and Hughes 13 cm thrusters have a cathode keeper.[2-3] This allows turning off the discharge power supply during a recycle. This decreases the current requirements on the accel supply and increases the probability of getting through the recycle by minimizing the ion density in the discharge chamber. On the other hand, a cathode keeper adds to the parts count of the system and by being in proximity to the discharge cathode, may be susceptible to high erosion rates.[5]

Thruster	NASA 30 cm	UK-10/T5	ETS-VI	Hughes13cm	RIT-10
Power (KW)	0.5 - 5	0.653	0.600	0.427	0.586
Number of power supplies	6-Power console 3-Simplified PPU	7	6	7	5
Number of electrical functions	6	8	7	7	5
Minimum number of power leads	7	10	8	8	7

Table 1. Thruster / power interface requirements

Power console	Test objectives	Test results	Load	Facility
#1	* Proof of concept	* Verifiaction of isolation and telemetry approach * Verification of high voltage ignitor circuitry	* Resistive load * 30 cm lab model thruster	* Tank 5
#2	* Define recycle requirements * Demonstrate thruster operation up to 2 KW * Demonstrate operations under varied test environments * Demonstrate extended duration testing	* Selection of timer recycle control * Quantification of accel power supply current requirements * Steady state operation to approximately 2 KW completed * ~ 50 hr tests performed at 0.6 and 1.5 KW * Demonstration of thruster operation under high background pressure conditions	* Resistive load * 30 cm lab model thruster	* Tank 5 * Tank 1
#3	* Demonstrate electronic circuit boards operation * Demonstrate thruster operation up to 5 KW	* In progress	* Resistive load * 30 cm functional model thruster	* Tank 5

Table 2. Power console development stages

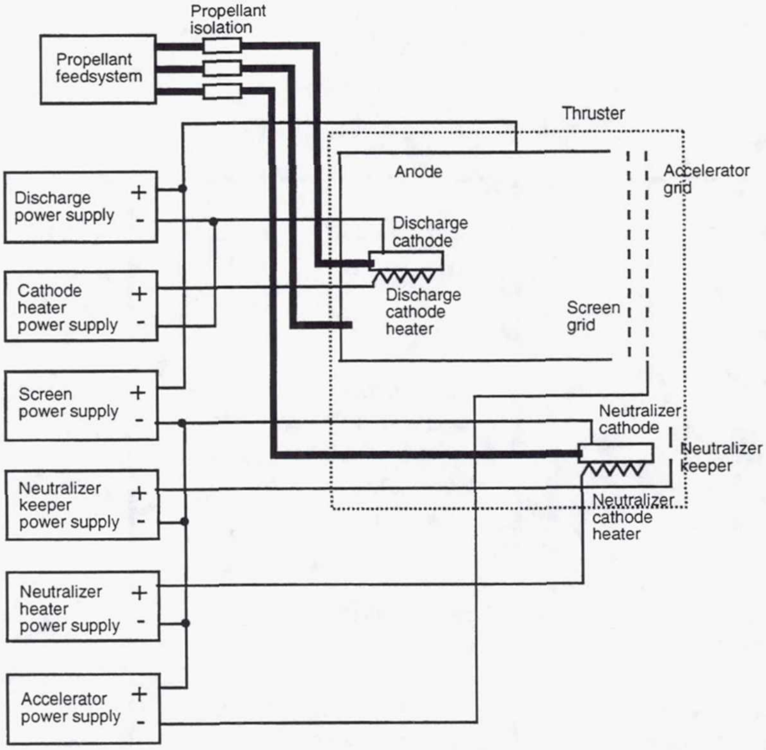


Figure 1.—NASA 30 cm ion propulsion system.

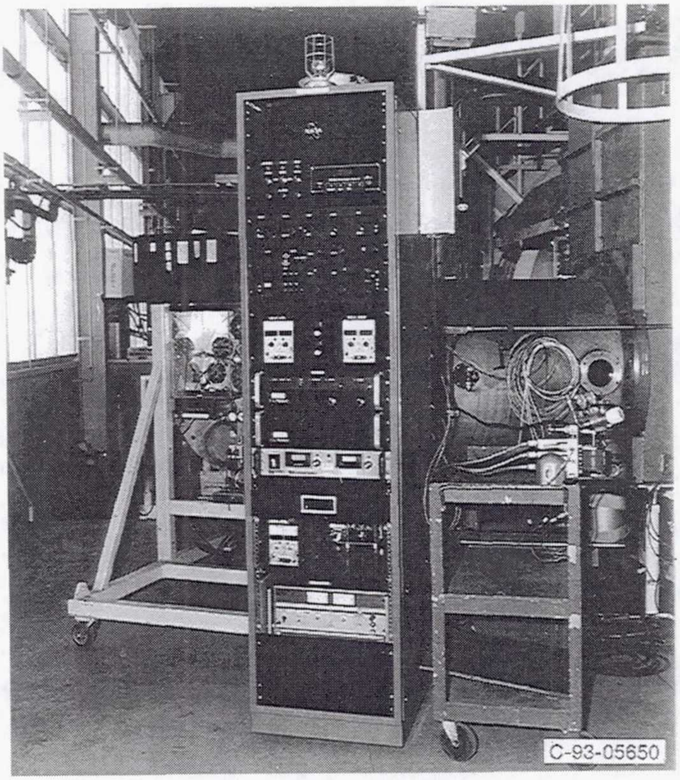


Figure 2.—5 KW power console.

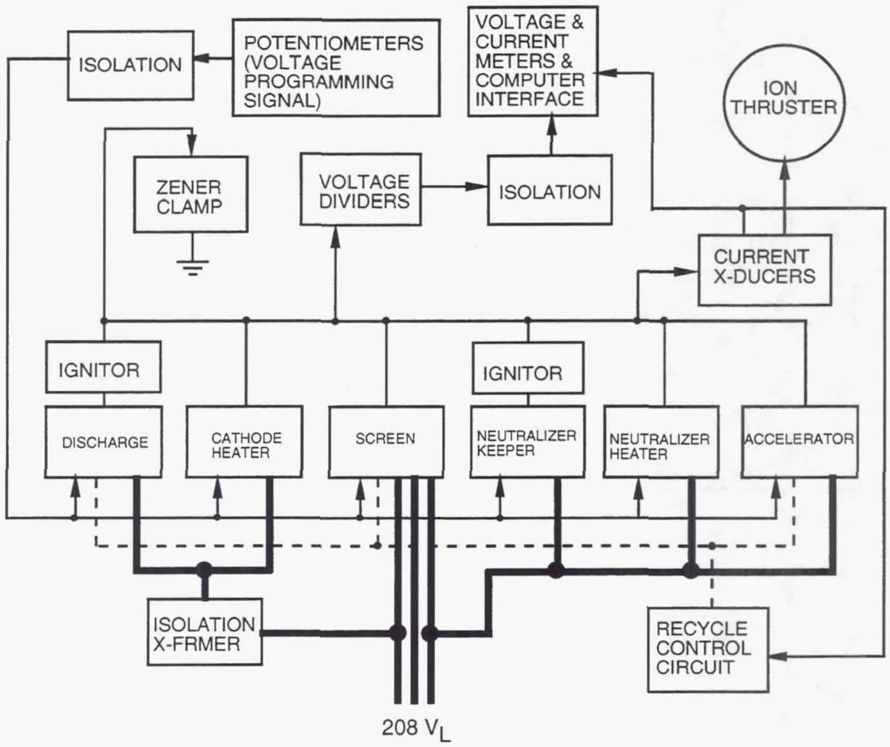


Figure 3.—Power console block diagram.

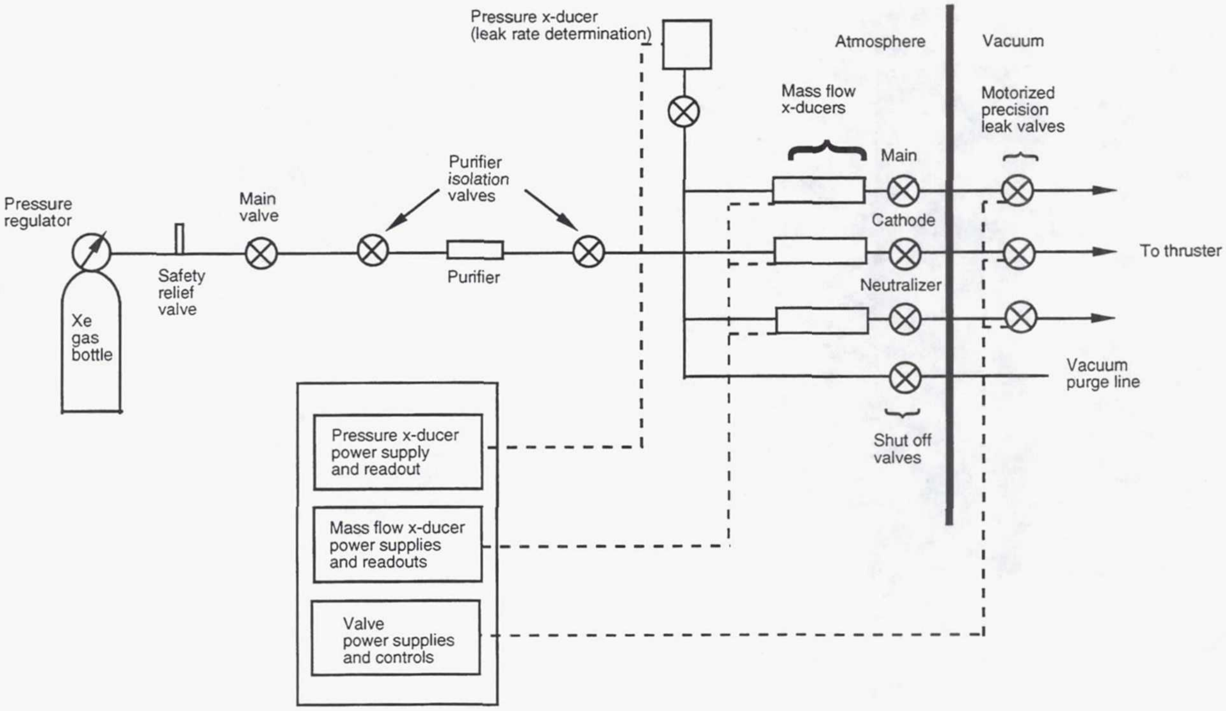


Figure 4.—Power console feed system.

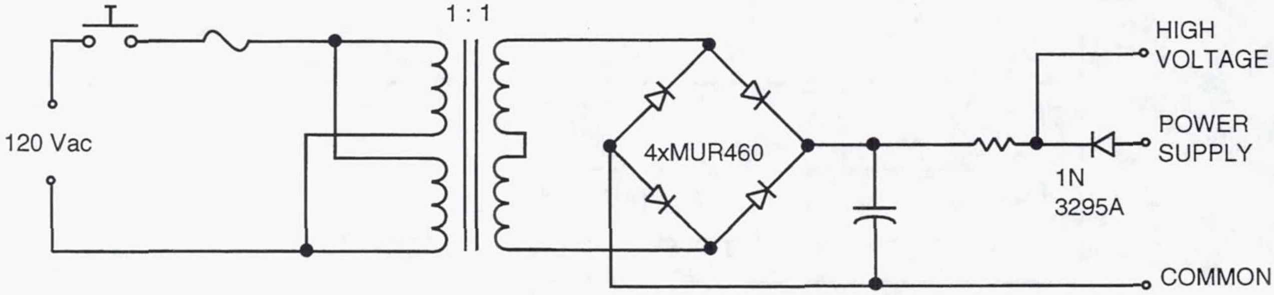


Figure 5.—Cathode ignitor schematic.

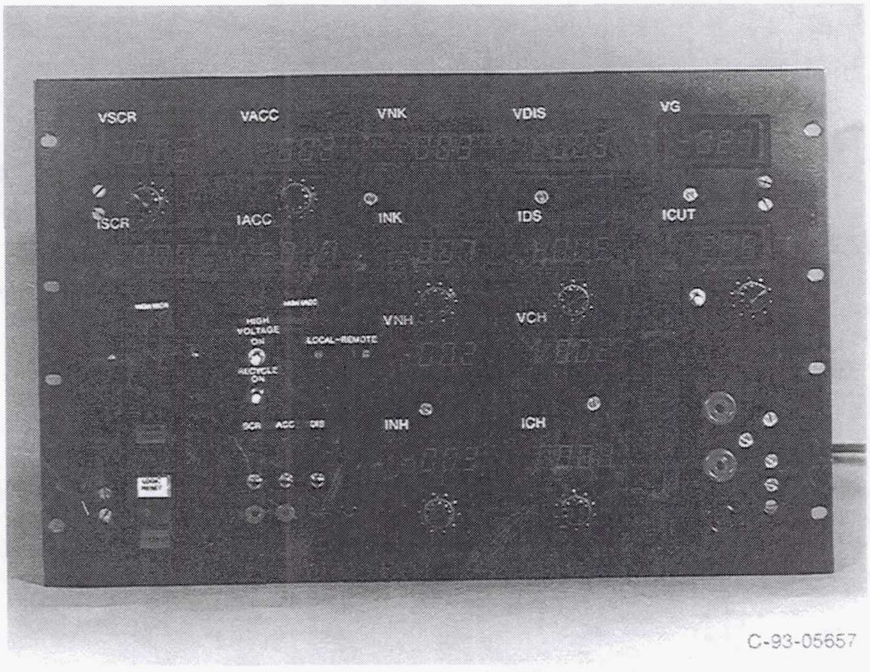


Figure 6.—Power console control unit front panel.

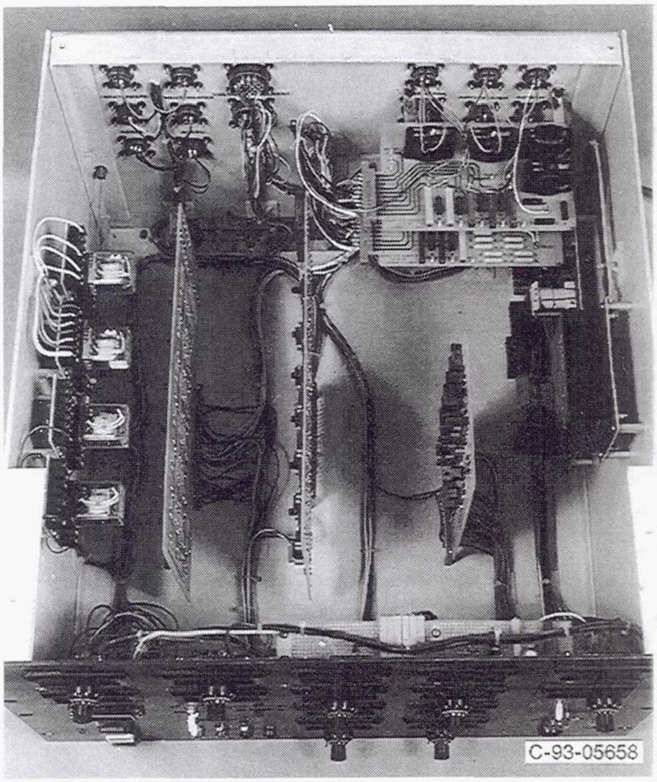


Figure 7.—Power console control unit.

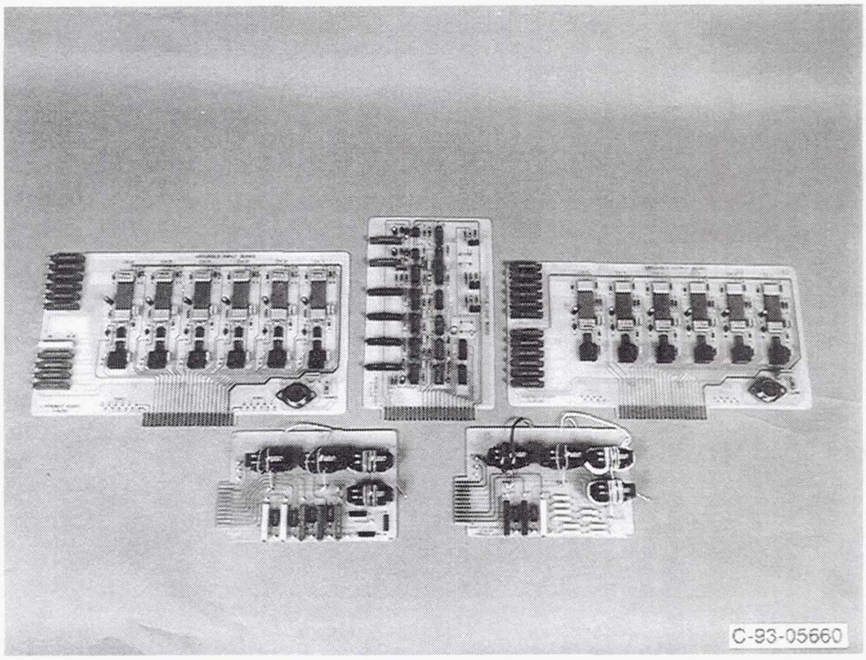


Figure 8.—Electronic circuit boards.

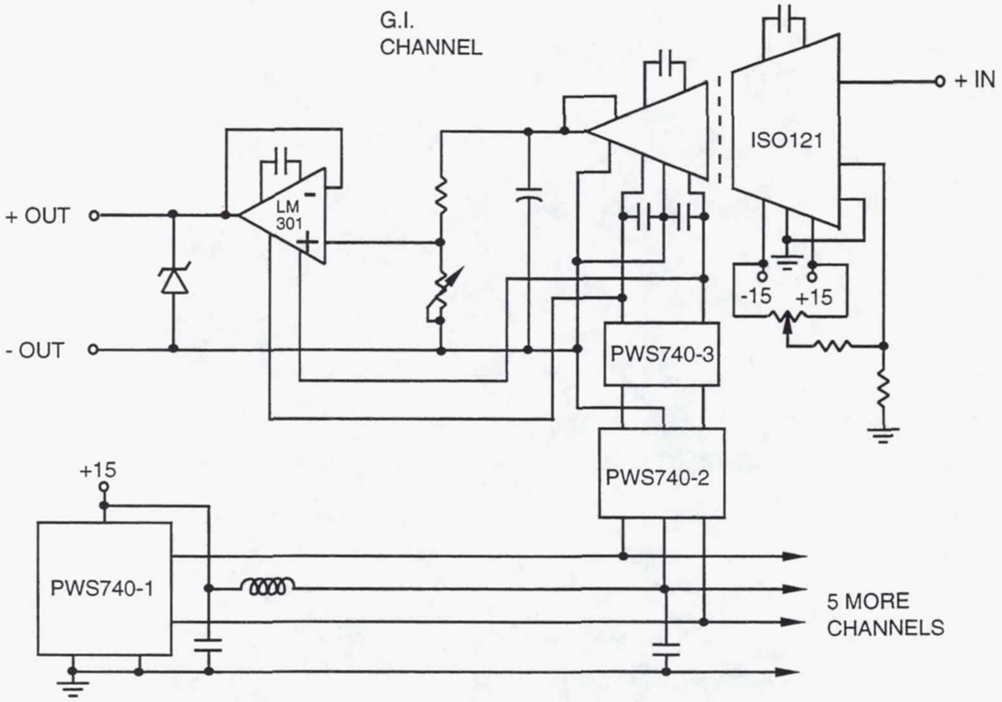


Figure 9.—Grounded input isolation circuit schematic.

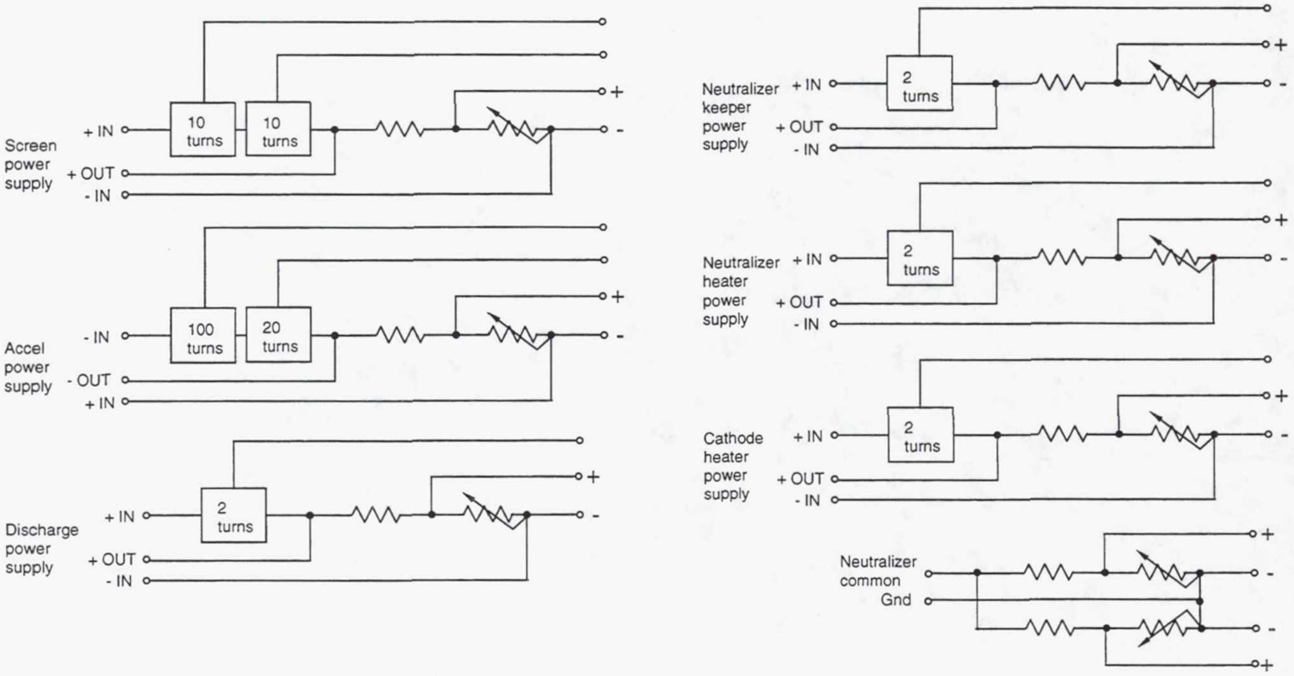


Figure 10.—Voltage and current sense circuit schematic.

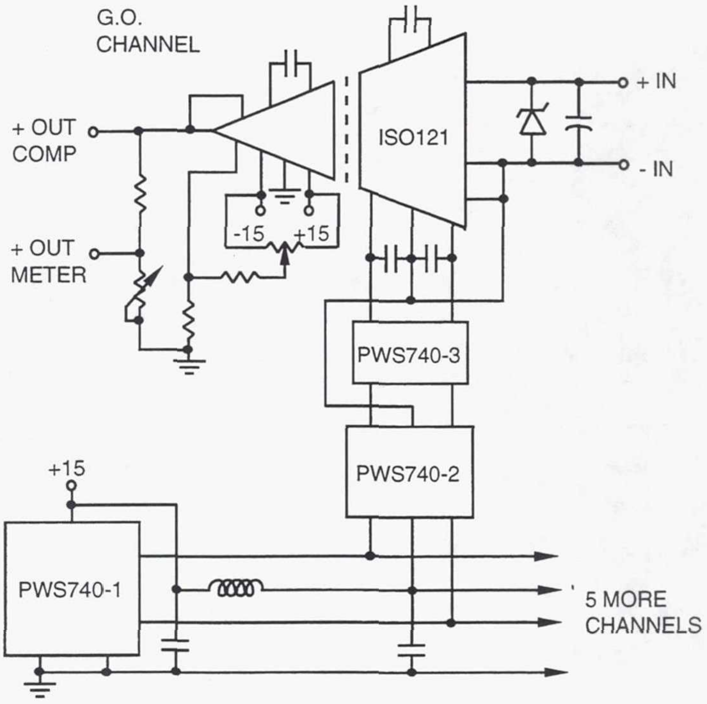


Figure 11.—Grounded output isolation circuit schematic.

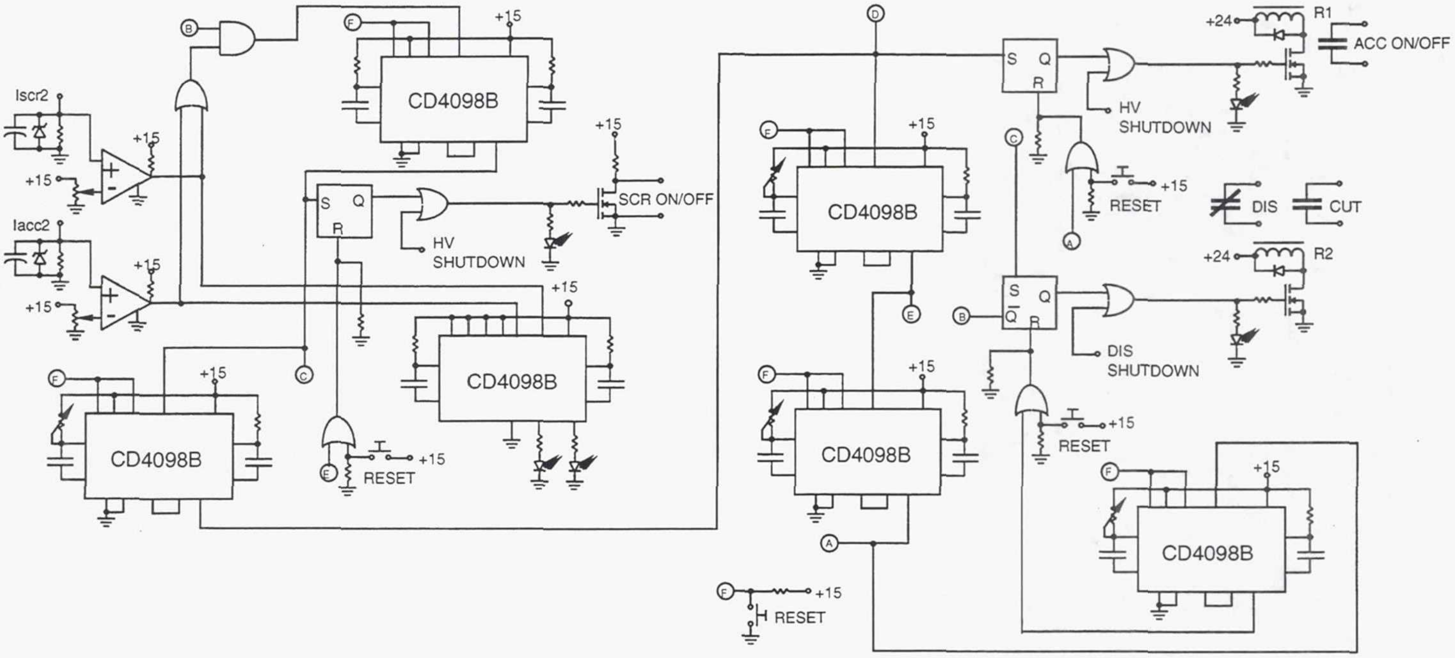


Figure 12.—Recycle logic circuit schematic.

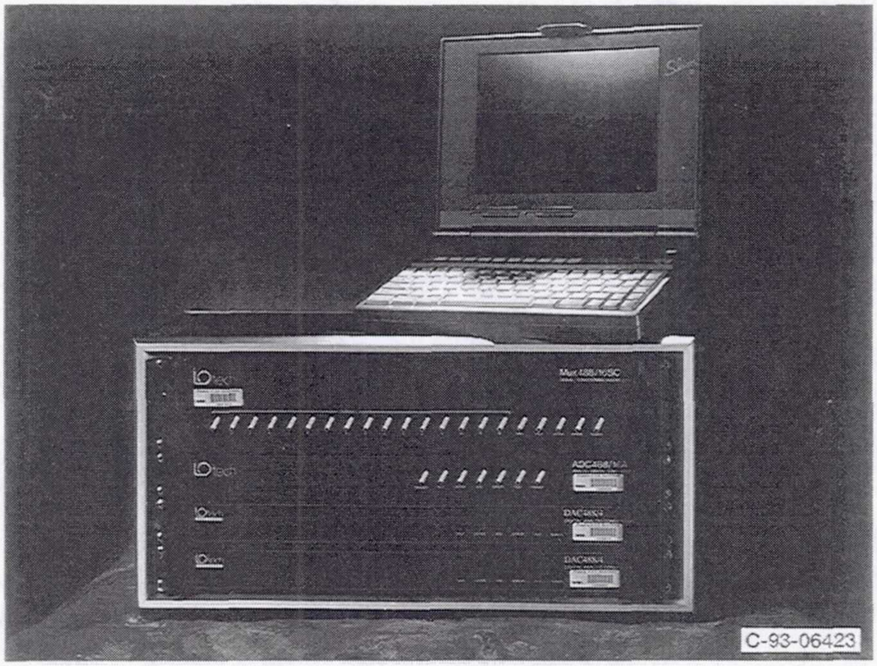
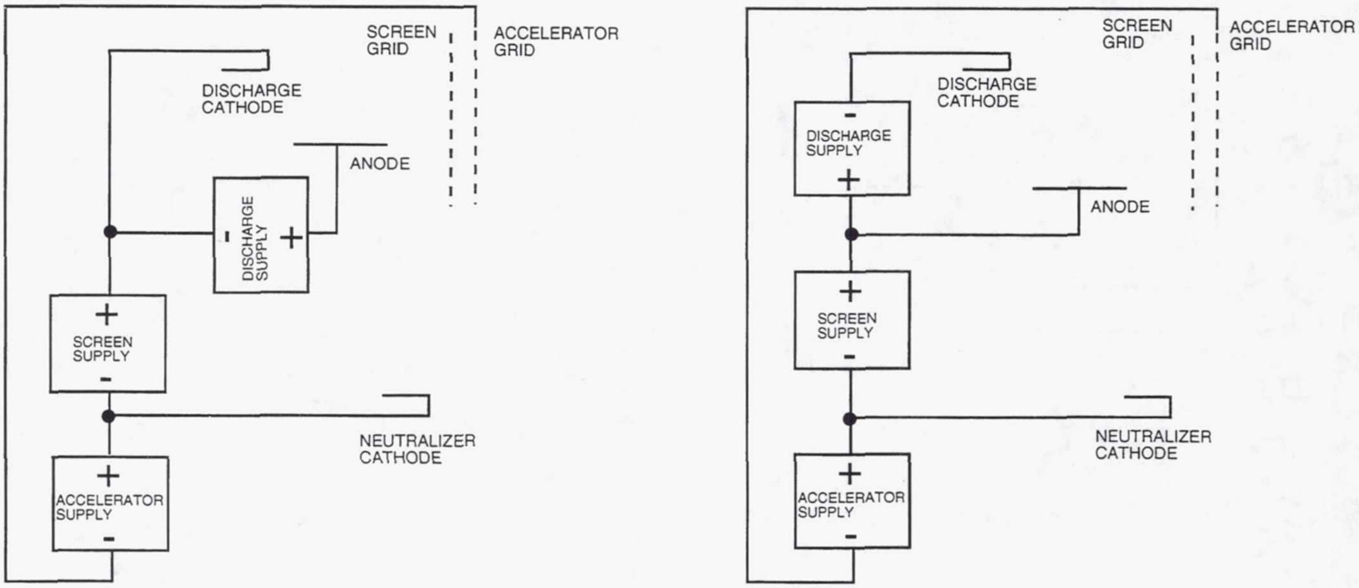


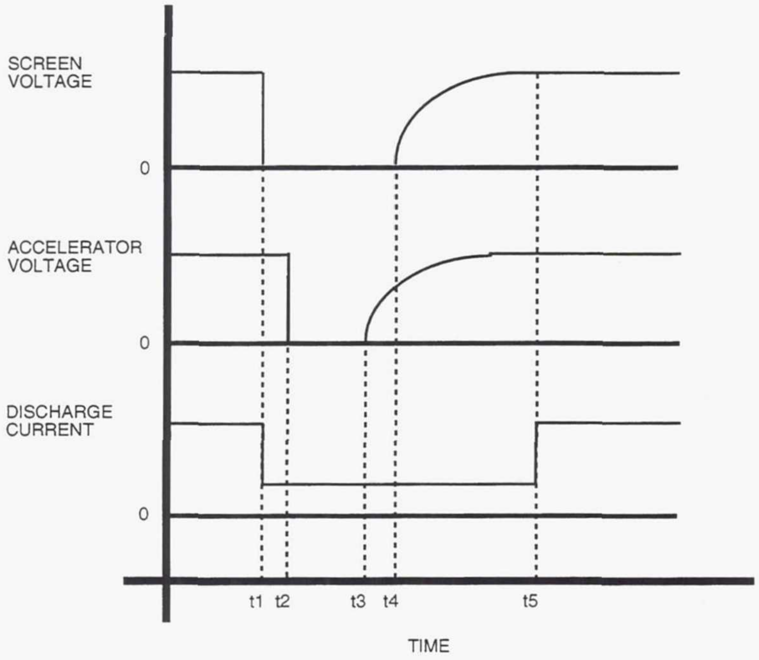
Figure 13.—Computerized data acquisition and control system.



a) Positive side of screen supply to negative side of discharge supply

b) Positive side of screen supply to positive side of discharge supply

Figure 14.—Power supply configurations.



t1 - Screen off, discharge cut-back

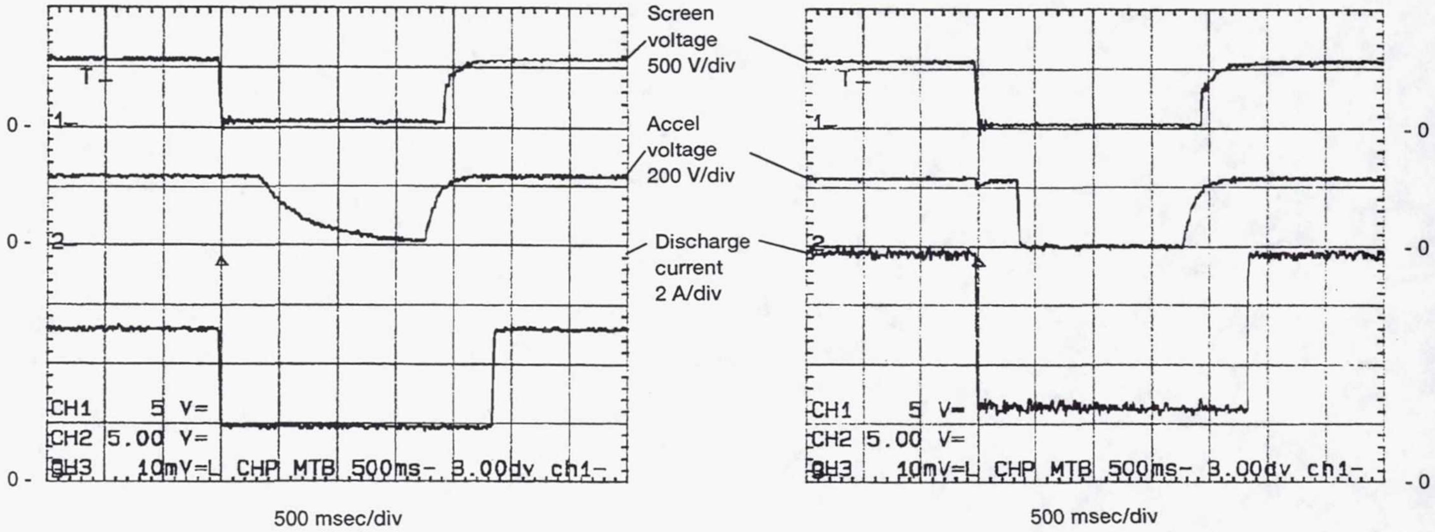
t2 - Accel off

t3 - Accel on

t4 - Screen on

t5 - Discharge nominal

Figure 15.—Recycle sequence.



a) Resistive load.

b) NASA 30 cm thruster.

Figure A1.—Recycle sequence test.

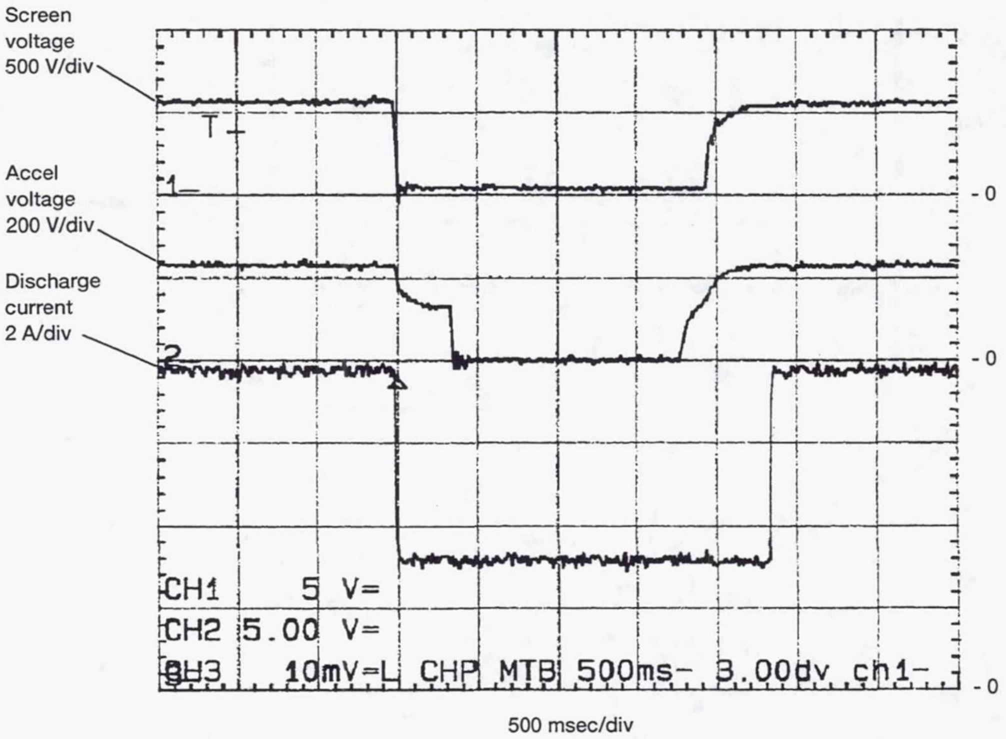


Figure A2.—Recycle sequence on NASA 30 cm thruster showing collapse of accelerator voltage due to excessive accelerator current.

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Luis R. Piñero, Michael J. Patterson, and Vincent E. Satterwhite

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13. ABSTRACT ***(Maximum 200 words)***

NASA Lewis Research Center is developing a 30 cm diameter xenon ion thruster for auxiliary and primary propulsion applications. To maximize expectations for user-acceptance of ion propulsion technology, NASA LeRC, through their Electric Propulsion Outreach Program, is providing sectors of industry with portable power consoles for operation of 5 KW-class xenon ion thrusters. This power console provides all necessary functions to permit thruster operations over a 0.5 - 5 KW envelope under both manual and automated control. These functions include, discharge, cathode heater, neutralizer keeper, and neutralizer heater currents, screen and accelerator voltages, and a gas feed system to regulate and control propellant flow to the thruster. An electronic circuit monitors screen and accelerator currents and controls arcing events. The power console was successfully integrated with the NASA 30 cm thruster.

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Lewis Research Center
21000 Brookpark Rd.
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