RHETT/EPDM
POWER PROCESSING UNIT

Peter T. Skelly and Robert J. Kay
PRIMEX Aerospace Company
Redmond, WA

Abstract

Russian Closed Drift Hall Effect electric propulsion technology has become available for use on satellites throughout the world. While the Stationary Plasma Thruster (SPT) has a history of successful flight application in both the former Soviet Union and Russian space programs, no flight configuration power processor has existed for the Thruster-with-Anode-Layer (TAL). The RHETT II and subsequent EPDM programs were developed with the objective to demonstrate a TAL propulsion system on orbit. As part of this effort, PRIMEX Aerospace Company (PAC) designed and developed a Power Processor Unit (PPU).

Introduction

Electric propulsion technology uses electric energy to increase the velocity of thruster exhaust. The increase of the exhaust velocity enables more efficient use of propellant on orbit. The three main types of electric propulsion include electrothermal devices such as resistojets and arcjets, electromagnetic devices such as elctroplasmadynamic thrusters, and electrostatic engines such as Ion engines[1] and Closed Drift Hall Thrusters.

Commercial satellites such as the General Electric Astrospace series 5000 have used Resistojets since the 1980s. They are being used for orbit insertion on the Iridium constellation. A PAC 1.8 kW hydrazine arcjet system with a specific impulse of about 500 seconds is operational on Lockheed Martin series 7000 GEO comsat spacecraft.[2-3] The Lockheed Martin A2100 series GEO comsat spacecraft use a new PAC 2.2kW, 585 second specific impulse hydrazine arcjet system[4].

The power processing unit requirements for resistojets are straightforward and consist of controlling the power applied to a resistance heater used to heat the propellant as it exits the thruster. The power processing unit requirements for arcjets are significantly more complex due to the dynamics of the electric arc. An Arcjet load is not resistive and the power supply must be capable of stable operation while powering a highly variable reactive load. In addition, the thruster requires an ancillary high voltage supply for starting. In general, as the performance of electric thrusters increases, the complexity of the power processors also increases.[5-6] PPU architecture and operating parameters is critical in achieving the high potential for spacecraft mass reduction obtainable with electric propulsion systems. In order to operate a TAL, the PPU must accomplish the tasks of providing system telemetry, cathode heater power, starter (ignitor)/keeper power and inner and outer magnet power, in addition to the main discharge power.

The Russian Hall Effect Thruster Technology phase II (RHETT II) program provides Hall system hardware to the Naval Research Laboratory (NRL) Electric Propulsion Developement Module (EPDM) flight. EPDM will be the first Western flight of a Hall thruster system with a mix of Russian and US technologies.[8] A Thruster-with-Anode-Layer (TAL) from TSNIIMASH was chosen for this demonstration. PAC, used a combination of BMDO and internal funding, to develop and qualify the Power Processing Unit (PPU) shown in Figure 1. The PPU is a principal component of the RHETT II/EPDM TAL interface shown in Figure 2.

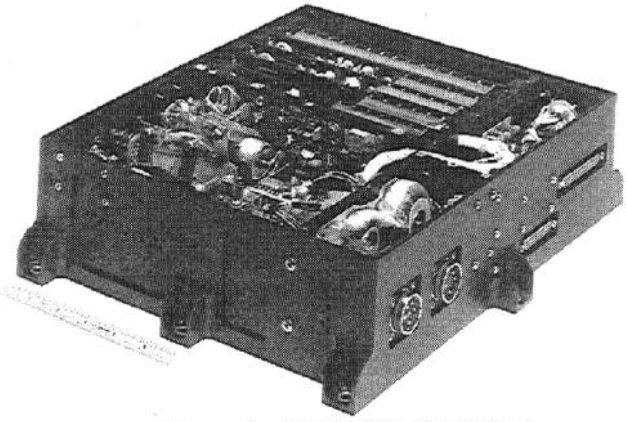

Figure 1. PAC PPU, PN 1077-1

The RHETT II/EPDM program had some extremely aggressive schedule constraints. The PPU design and qualification testing efforts were to be completed in the last quarter of 1996. System integration issues extended the overall activity to the first quarter of 1997. In all, the PPU was developed and qualified for flight in approximately 15 months.

The RHETT II/EPDM design objective called for a simple single set point feed system and battery power for the demonstration. Taken together, the constraints of battery power and non-adjustable propellant flow limited the demonstration to 850 watts maximum input to the PPU. This condition corresponds to 40 A. maximum at minimum battery voltage and maximum propellant flow. Propellant flow from the pressure regulated, orifice feed system varies slightly with temperature. The nominal operating point of 700 watts is set by the propellant flow rate at nominal temperature.

PPU Design Requirements

The TAL placed several basic requirements upon the PPU. In this application five separate but interrelated power supplies were used, as shown in Table 2.

The other required functions of the PPU are:

- Sequencing of the supplies for the various modes of TAL system operation
- Receive and act upon commands from the Auxiliary Interface Unit (AIU) for PPU ENABLE/DISABLE, Cathode Heater current level SET, Cathode Heater ON/OFF, TAL ON/OFF
- Provide telemetry to AIU for all supply output currents and voltages
- Provide status to AIU of all received commands
- Provide indication of Anode supply overcurrent
- Provide isolation of the PPU from the effects of the anode current perturbations inherent in hall thrusters

The following list includes additional RHETT II/EPDM key requirements and objectives.

- PPU capable of Anode (discharge) power of 1350 watts
- Input voltage range, 22V to 34V
- Efficiency of Anode (discharge) supply of >90%
- Capable of typical launch vehicle dynamic environmental (vibration, shock) levels
- Non-operating temperature range of -55°C to +125°C
- Operating temperature range of -40°C to +70°C. All components shall meet standard spacecraft temperature derating limits
- Standard spacecraft component stress derating (voltage, current) levels apply
- Electromagnetic compatibility shall be assured by use of MIL-STD-461C as a design guide. PPU shall be tested to MIL-STD-461C CE01, CE03, CS01, CS03, RE02, and RS02
- Unit shall be designed for a GEO mission of 15 years plus a 50% design margin
- Design Radiation environment, 100kRads (Si)

PPU Design Development

Critical to the success of the PPU development was the characterization of the load parameters of the various supplies. A review of the open literature revealed that the discharge current of the TAL anode was nearly independent of anode voltage and was proportional to propellant mass flow rate. For this reason, the anode supply was configured as a constant voltage regulated supply, with anode current determined by the propellant system. The anode load characteristics were also a function of both inner and outer magnet currents. One unusual aspect of the anode discharge current of closed drift hall thrusters is the presence of high levels of current perturbations. For the TAL, these perturbations are a function of the magnitude and the ratio of the inner and outer magnet currents to the anode current. Independent inner and outer magnet supplies enable adjustment of currents to minimize the undesired perturbations.

Previous PPUs designed for Hall Current Thrusters utilized an external LC or RC filter or a matching network between the anode and the anode supply. These filters were added to dampen the current perturbation and to decouple the anode supply control loop from the affects of the current perturbations. For the RHETT II program the anode supply design has internal output filtering sufficient to dampen the current perturbations and to have a control loop robust enough to properly control the supply during the perturbations.

The cathode used on the RHETT II program is nearly identical to the cathode developed for the international space station plasma contactor. The load requirements were determined from the work done by NASA LeRC[7].

PPU Design Description

The PPU functions are shown in the block diagram, figure 2. The PPU external electrical connections are in figure 3.

Anode Supply (Discharge supply)

The anode or discharge supply accounts for the majority of power developed within the PPU. The power converter is a buck derived push pull design operating at a switching frequency of 55kHz. Current mode control maintains the main power transformer centered on its B-H curve and provides pulse by pulse current limiting. The topology and frequency were chosen to build on the success of previous flight PPUs developed for arcjets at similar power levels[5]. For the RHETT II/EPDM design, the anode supply was designed to provide an output of 300 volts at up to 1350 watts. For the EPDM mission, the anode power was limited to about 850 watts to keep the input current under a spacecraft imposed maximum input current draw of 40 A.

One design issue inherent with this topology is the requirement to maintain tight coupling between two primary sections of the main power transformer. Any leakage inductance between the two sections of the primary traps parasitic energy which is not recovered. This problem becomes more acute for a 28 volt design because the primary current and hence parasitic energy increases with decreasing input voltage. Special winding techniques and a copper foil primary winding were used to reduce leakage inductance and improve magnetic coupling. The main power transformer was wound on a tape-wound Supermalloy core which was encapsulated in thermally conductive potting compound and bonded to the chassis for cooling.

Previous PAC PPUs developed using this technology used custom power hybrid FET switches. These switches have very low on resistance resulting in high efficiency. For the RHETT II/EPDM design, standard RAD HARD multiple paralleled power FETs provided the low on resistance required as well as a more schedule effective solution. A low inductance planar interconnect method connected the FETs to the main power transformer, minimizing component stresses and losses.

High output voltages present a design challenge in the selection of rectifier diodes. High voltage diodes have much higher forward conduction loss and reverse recovery losses than lower voltage diodes, which impacts PPU efficiency. The reverse recovery characteristics of the high voltage diodes also causes high voltage turn off spikes on the diodes which could damage them. Clamping the spikes to a safe level prevented this problem. An active snubber returned the energy back to the input and increased PPU efficiency by about two percent to approximately 92 percent.

Cathode Heater Supply

The cathode used on the RHETT II program was derived from the NASA design for the Plasma Contactor developed for the Space Station. For this reason the cathode heater supply was based on the buck derived push pull design developed for the Plasma Contactor heater supply[7]. The cathode heater is a resistive element with positive temperature coefficient. Constant current is used to drive the heater to reduce life limiting turn-on power surges.

The purpose of the cathode is to emit electrons when heated. The emission efficiency of the cathode is enhanced by special coatings on the cathode surface. The emission efficiency is easily ruined by contamination of the coatings. The possibility of contamination is reduced by conditioning the cathode after it is in a vacuum, before use of the thruster. The conditioning is accomplished by bake-out at reduced cathode heater currents. The cathode heater supply is set to the desired current level in response to commands from the spacecraft. The two lowest current levels are used only for initial cathode conditioning and the highest level is used for heating the cathode to induce electron emission prior to starting the TAL.

Magnet Supplies

Separate constant current supplies were developed for the inner and the outer magnets for the RHETT II TAL. This allows setting the magnet current to different levels if required. The two magnet supplies were identical in design and were based on the same buck derived push pull design developed for the cathode heater supply.

Keeper/Ignitor Supply

The keeper/ignitor supply developed for this application was a single switch dual output forward/flyback design. The "forward" output produced 600 volts for the ignition of the keeper, while the "flyback" output produced 30 volts for the steady state operation of the keeper. The two outputs were then combined through isolation diodes and applied to the keeper electrode. The converter was operated at constant duty cycle in discontinuous mode such that output was a constant power output, producing an output current approximately proportional to 1/Vout. The high voltage output current was limited by a series 100kOhm resistance. The Keeper/Ignitor supply was only used to start the cathode emitting and was turned off after the discharge supply was on.

Commands to the PPU

The command interface to the PPU on RHETT II, consists of the five level commands shown in Table 3.

Telemetry and Status from the PPU

Telemetry was provided for the functions in Table 4.

Sequence of Operation

The PPU sequence of operation is shown in Figure 4. The operation of the cathode heater is independent of the operation of the other supplies within the PPU and is determined by ground commands. The sequencing of the magnet supplies, the keeper/ignitor supply and the discharge supply is controlled by logic within the PPU.

Test Results

Nominal measured efficiency of the PPU Discharge Supply is presented in Table 5. The PPU completed its qualification test regimen in March of 1997. The tests included vibration and shock, EMI emissions, thermal vacuum cycle testing, electrical performance over temperature and input power variation. Although issues were identified during qualification which required design modifications and some limited mission operational constraints, the PPU successfully performed all the functions associated with TAL operation. The final thruster integration tests performed at LeRC were successful. No persistent, steady state instabilities or oscillations were observed. Startup and general operation of the TAL were achieved without difficulty. Some operational anomalies (oscillations) did occur at TAL low temperature extremes. These oscillations were relatively quick to damp out once warm-up of the thruster occurred. Straightforward modification of the PPU design can correct these low temperature deficiencies.

The PPU design is thermally limited at the +70°C operating temperature, to a maximum continuous output power operation of about 900 watts at low input voltage. Additional thermal enhancements would be required to accommodate operation at the 1350 watt power level. With the spacecraft constraint of no more than 40 A. from the power bus, the resultant output power level, at the 90% efficiency, was limited to about 850 watts. This limitation was not considered to be an impact to success of the Rhett II/EPDM program.

Conclusions

The PAC PPU was designed, built and qualified in a 15 month period starting in January 1996. The unit demonstrated an efficiency > 90% by utilizing an enhanced proven design topology. With the successful completion of the PAC PPU program, all RHETT II/EPDM subsystems are now qualified for flight on the first scheduled demonstration of Hall Effect propulsion on a western spacecraft. This on orbit demonstration is scheduled for the 4th quarter of 1997.

References

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Table 1. Input/Output Power Requirements

Vin	24V to 34V
Iin	less than 40 A.
Pin	less than 1020 watts
TAL Discharge Power	550 to 850 watts

Table 2. PPU Power Supplies

SUPPLY	Voltage	Current	Type
Anode (discharge)	300 Volts	1.83 to 2.83 A.	Constant Voltage
Inner Magnet Supply	less than 8 Volts	2.5 A.	Constant Current
Outer Magnet Supply	less than 8 Volts	2.5 A.	Constant Current
Cathode Heater Supply	less than 12 Volts	Three commandable levels: 3.85 A., 7.20 A., 8.50 A.	Constant Current
Keeper/Ignitor	600 Volts to start 5 to 30 Volts to sustain	Capacitor Output, Start ~ 1 A. 1.0 to 6 A. to sustain	

Table 3. PPU Command Interface

COMMAND	EFFECT when TRUE	EFFECT when FALSE
PPU_ENABLE	Required for operation of PPU	All PPU outputs off
TAL_ON	Begins TAL RUN sequence	TAL OFF
CATHODE_HEATER_ON	Cathode heater on at level determined by CATHODE_CMD_A and CATHODE_CMD_B	Cathode heater OFF
CATHODE_CMD_A	Part of a two bit binary representation of cathode heater current. Three of four possible levels used.	
CATHODE_CMD_B	Part of a two bit binary representation of cathode heater current. Three of four possible levels used.	

Table 4. PPU Telemetry and Status

CHANNEL	FUNCTION
Vd	Discharge Voltage Telemetry
Id	Discharge Current Telemetry
Vmi	Inner Magnet Voltage Telemetry
Imi	Inner Magnet Current telemetry
Imo	Outer Magnet Current Telemetry
Vch	Cathode Heater Voltage Telemetry
Ich	Cathode Heater Current telemetry
Vin	Input Voltage Telemetry
Vfloat	Float Voltage Telemetry *
PPU Temp	PPU Temperature Telemetry
Discharge Overcurrent	Discharge Overcurrent Status
PPU_ENABLE_STATUS	PPU_ENABLE Command Status
TAL_ON_STATUS	TAL_ON Command Status
CATHODE_ON_STATUS	CATHODE_ON Command Status

* The Float Voltage is the voltage difference between the Discharge Return or Cathode potential and Spacecraft Ground.

Table 5. Discharge Power Supply Efficiency

V_{in}, V.	I_{in}, A.	P_{in}, Watts	V_{out}, V.	I_o, A.	Po , Watts	Efficiency , %
24.02	40.36	969.45	302.5	2.94	889.35	91.7
28.49	35.33	1006.6	301.8	3.04	917.47	91.1
32.44	29.24	948.5	300.18	2.89	867.52	91.5

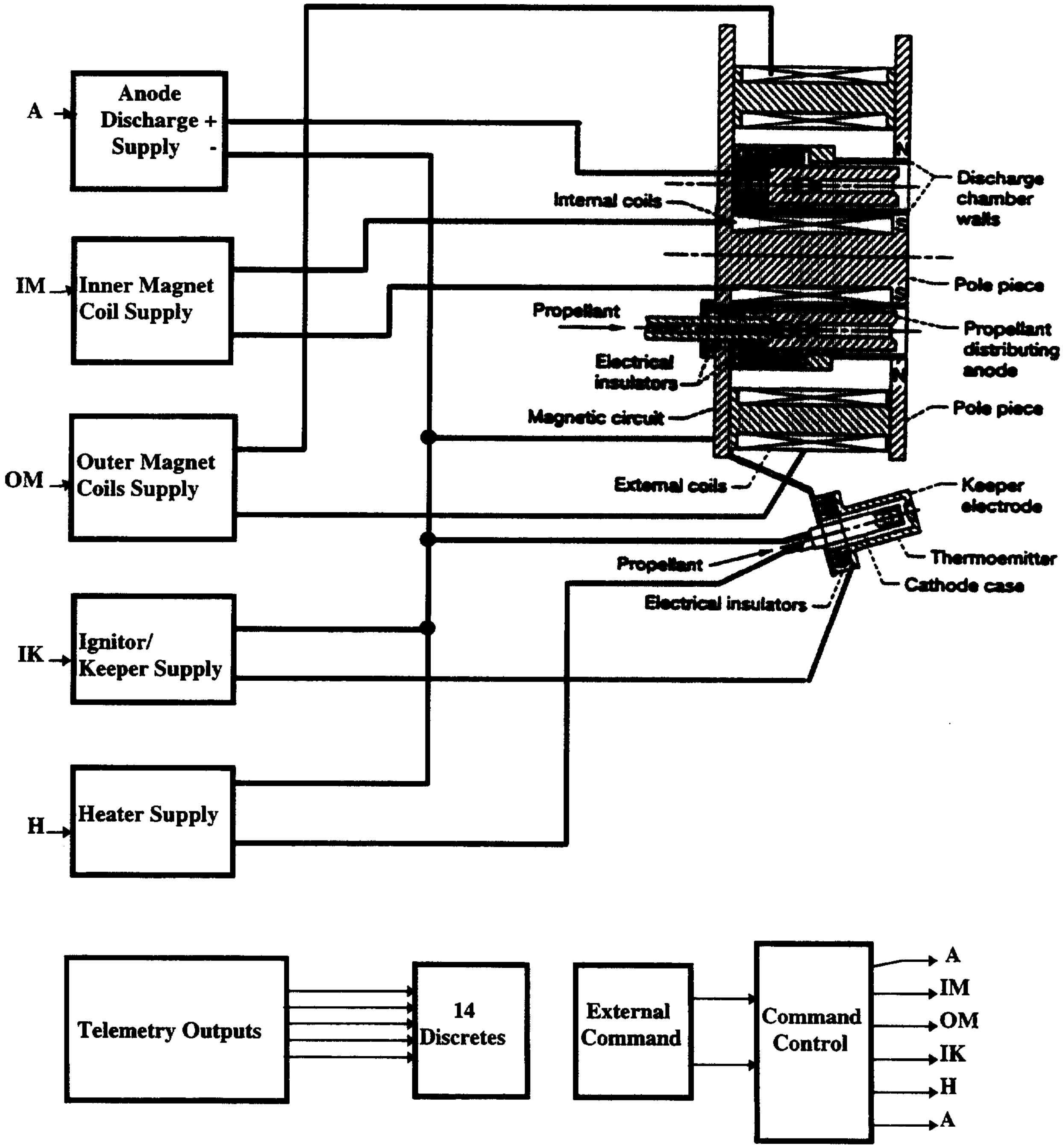

Figure 2. TAL/PPU Interface

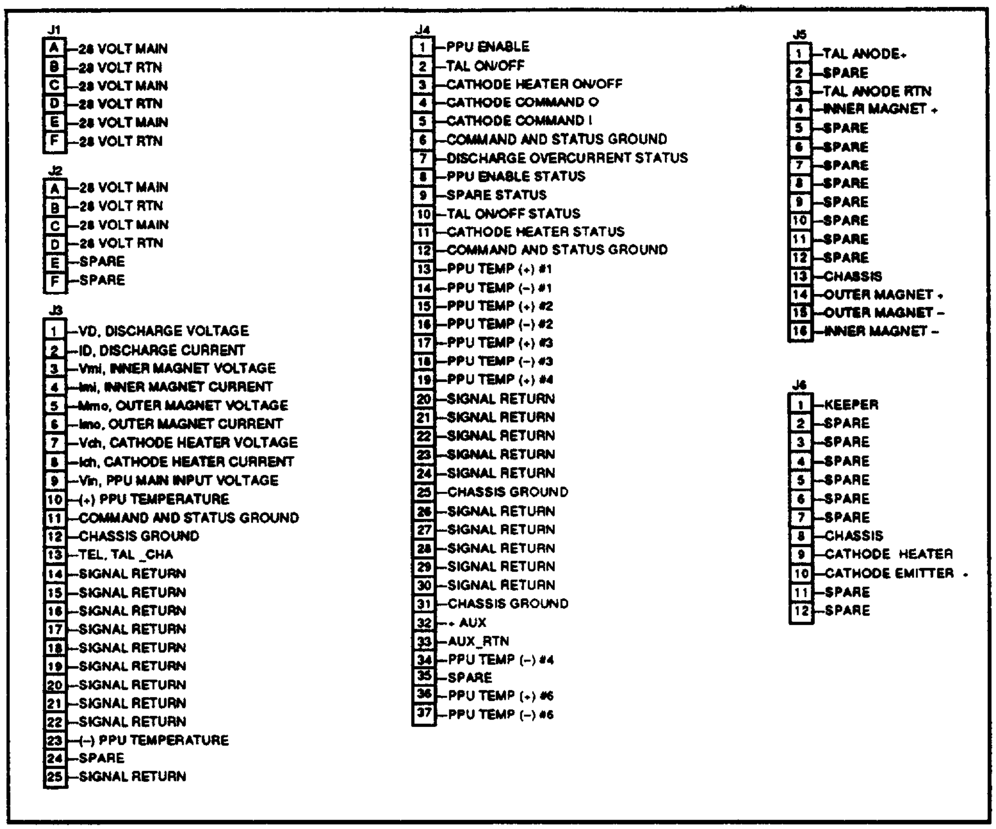

Figure 3. External Connections

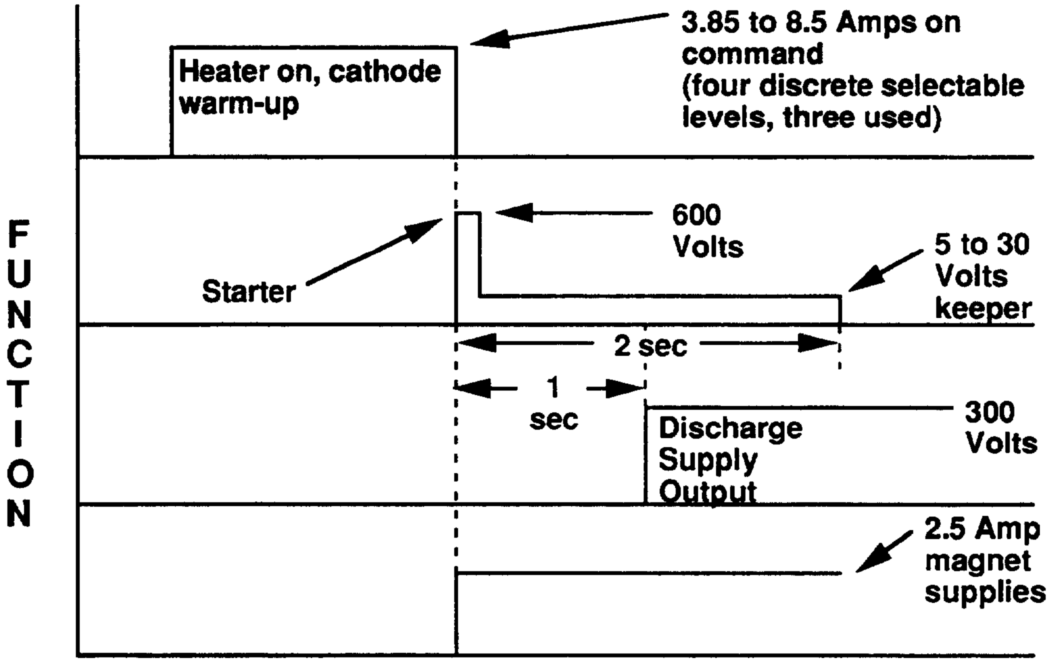

Figure 4. PPU Supply Sequence of Operation