NASA TECHNICAL MEMORANDUM NASA TM X- 71775

NASA TM X- 71775

(NASA-TM-X-71775) POWER PROCESSING FOR ELECTRIC PROPULSION (NASA) 22 p HC $3.25 CSCL 21C

N75-29172

Unclas

G3/20 31419

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TECHNICAL PAPER to be presented at
Electronic and Aerospace Systems Conference (EASCON)
sponsored by the Institute of Electrical and Electronics Engineers
Washington, D.C., September 28 - October 1, 1975

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E-8429

ABSTRACT

The potential of achieving up to 30 percent more spacecraft payload or 50 percent more useful operating life by the use of electric propulsion in place of conventional cold gas or hydrazine systems in science, communications, and earth applications spacecraft is a compelling reason to consider the inclusion of electric thruster sytems in new spacecraft design. The propulsion requirements of such spacecraft dictate a wide range of thruster power levels and operational lifetimes, which must be matched by lightweight, efficient, and reliable thruster power processing systems. This paper will present electron bombardment ion thruster requirements; review the performance characteristics of present power processing systems; discuss design philosophies and alternatives in areas such as inverter type, arc protection, and control methods; and project future performance potentials for meeting goals in the areas of power process or weight (10 kg/kW), efficiency (approaching 92 percent), reliability (0.96 for 15,000 hr), and thermal control capability (0.3 to 5 AU).

INTRODUCTION

Space flight has been a reality for less than a score of years, yet in that time enormous technological strides have been made. Unmanned exploration of the inner and some outer planets is a reality. The Mariner, Explorer, and Pioneer series spacecraft are yielding a wealth of knowledge about the nature of the solar system. Satellites in geosynchronous orbits have become a practical reality, providing us with physical data about the Earth and with worldwide services in communication and navigation.

To date, virtually all propulsion systems for planetary or Earth orbital applications have been chemical devices. As man progresses in space, however, the missions will become more extensive and difficult to accomplish with only chemical propulsion.

This paper describes one type of propulsion system that offers promise of filling a wide range of propulsion needs - an ion-thruster propulsion system. The mercury-bombardment ion thruster of this system has evolved to the point of flight readiness with a propellant specific impulse of 3000 seconds. This impulse is approximately six to eight times that of the best chemical rocket systems. As is shown later, the mass of the required electric powerplant does not permit a corresponding six- to eightfold increase in the velocity increment imparted to the spacecraft, but the gains are substantial. Power processing technology is being pursued vigorously to optimize these gains.

ION PROPULSION THEORY

The principal elements of the ion-thruster propulsion system are shown in figure 1. The Sun provides energy, which is converted into electric power by solar cells. The power is then conditioned to the current and voltage needed by the ion thruster. Propellant is ionized in the thruster and electrically exhausted to produce thrust. For many missions, the power source can serve the dual roles of providing both thruster power and power for mission objectives subsequent to the thrusting period. The thruster will be of appropriate size to satisfy the thrust requirements for the particular propulsion task.

The main advantage of using electric propulsion is that the electric energy added to the exhaust propellant greatly increases its velocity, or specific impulse, and hence more thrust is produced with the same propellant flow rate. The mass of propellant required to produce a given thrust decreases with increasing specific impulse, as shown in figure 2. The saving in propellant mass, however, is offset by the increasingly massive powerplant required to accelerate the exhaust to higher velocities. This increase in powerplant mass is shown in figure 3. The maximum payload of a spacecraft is achieved at the optimum specific impulse, where the sum of the propellant and powerplant mass is a minimum, as shown in figure 4.

Figure 4 indicates that at low specific impulse the propellant mass can be excessively large, while at high specific impulse the powerplant mass becomes excessive. Between these two extremes is a broad useful range where sufficient payload remains for design of a practical spacecraft. As defined by figure 4, payload includes the mass of the spacecraft itself and the useful payload. The optimum value of specific impulse to maximize payload usually is between 2000 and 5000 seconds, and thus the optimum value of exhaust velocity is between 20,000 and 50,000 meters per second. This range of exhaust velocity is easily achieved with ion thrusters.

ION-THRUSTER OPERATION

The first electron-bombardment thruster was conceived and tested by Dr. Harold R. Kaufman in 1959 at the NASA Lewis Research Center. This thruster operates by flowing a gaseous propellant into a discharge chamber. The propellant may be any gas, but mercury, cesium, and the noble gases are the most efficient for propulsion applications. Propellant atoms are ionized in the discharge chamber by electron bombardment in a process similar to that in a mercury arc sunlamp. This ionization occurs when an atom in the discharge loses an electron after bombardment by an energetic (40-eV) discharge electron. The electrons and the ions form a plasma in the ionization chamber. The electric field between the screen and the accelerator draws ions from the plasma. These ions are then accelerated out through many small holes in the screen and accelerator electrode to form an ion beam, as shown in figure 5. A neutralizer injects an equal number of electrons into the ion beam. This beam of electrons allows the spacecraft to remain electrically neutral and is a requirement for successful thruster operation.

POWER PROCESSING FOR AUXILIARY PROPULSION

Thruster System

Geosynchronous spacecraft often require careful control of their position and orientation over long periods of time. This is especially true of the highly directional antennas presently being used. Electric propulsion is ideal for the stationkeeping and attitude-control functions of geosynchronous satellites because of their high specific impulse, which results in considerable propellant weight savings over chemical propulsion systems.

The most important application of auxiliary-propulsion ion thrusters is north-south stationkeeping. Gravitational forces of the Sun and Moon tend to increase the inclination of the geosynchronous orbit, as shown in figure 16. Through the use of proper thrusting, centered about the nodal crossings, as indicated in figure 6, the geosynchronous orbit will not incline and will remain in the equatorial plane. The duration of thrust each day depends on the spacecraft mass and thrust level and on how closely the thrusters can be alined with respect to a north-south line and still have a thrust direction through the center of mass of the spacecraft. Typical thruster orientations on a spinner spacecraft are shown in figure 7.

Auxiliary electric propulsion employing an Hg ion bomb can represent a profit when used in place of other types of auxiliary propulsion for geosynchronous spacecraft. Figure 8 compares weights of a mercury ion-thruster system for north-south stationkeeping with those for a hydrazine system. As can be readily seen, the use of electric propulsion can provide a significant weight saving on a long-mission-life spacecraft. A typical 347-kilogram (765-lb) geosynchronous 7-year spinner spacecraft could save 51 kilograms (112 lb) by substitution of mercury ion thrusters for a hydrazine north-south stationkeeping system.

A typical 1 millipound auxiliary propulsion ion thruster is shown in figure 9. Power processing for two ion thruster systems are described in the following section.

SIT-8 Thruster Power Processing System

The Hughes Aircraft Company under contract to the NASA Lewis Research Center initiated, in mid-1973, development of a power processing system for the 8-cm electron bombardment Hg ion thruster. To date this effort has encompassed the implementation of a thermal-vacuum breadboard (TBVV) unit and the design of an Engineering Model (EM) power processor based on the earlier breoadboard circuitry.

The TBVV has successfully undergone substantial static load and thruster evaluation ground testing and is presently being operated in a life test with an 8-cm thruster at LeRC. Fabrication of the EM system is scheduled to be completed in late 1975. This will be followed by an extensive program of qualification testing.

System electrical description. - The 8-cm thruster requires nine independently controllable power supplies to achieve and maintain steady-state thruster operation. A listing of the supply specification currently incorporated in the Engineering Model power processor design is given in table 1 and a functional block diagram depicting the power processor's electrical system configuration is shown in figure 10.

Input power to the power circuitry is derived from a 70 V ± 20 V solar panel bus. At the 1 mlb (445 dynes) thrust level the total input power required is approximately 150 W. Sufficient input filtering has been incorporated in the design to limit the current ripple to less than 1 percent at this power level. Additional bus protection in the form of a power monitor limits (under any conceivable set of anomalous conditions) the maximum power drawn to 200 W.

Two basic power conditioning techniques are used to condition the input power to meet the voltages and currents required by the thruster. The screen and discharge supply are each mechanized using a 10 KHz pulse width module (PWM) parallel transistorized DC/DC converter configuration. This standardized power stage incorporates current feedback to maintain efficiency over a wide power range and derives its PWM control with the use of a small-signal magnetic amplifier in the transistor base drive circuitry. Isolation between the control circuitry and the rectified and filtered output is achieved with magnetics.

The remaining supplies are implemented using an AC distribution approach. The line voltage is down converted to 48 V by the switching line regulator and is then used by the AC inverter to generate 96 V AC across its autotransformer output for distribution to the seven supplies. The inverter power stage uses the same basic design as employed in the screen and discharge supplies. The heater, vaporizer, and keeper supplies each contain self-saturating power magnetic amplifiers with RMS current control loops and output power transformers to properly match the thruster load impedances and to provide load-source isolation. Additional output rectification and filtering is used in the keeper supplies. Because the accelerator supply has a very low steady-state output level, a very simple actively current-limited dissipative regulator was selected for use in this supply.

Each of the supplies provide 0 to 5 V DC analog signals proportional to its output voltage and current, and in turn, each output level is porportional to an input reference signal in the range 0 to 5 V DC. These signals establish the point of electrical interface between the power circuitry and the control circuitry portions of the power processor. Because these signals are analog, low-level, and relatively slow varying, filtering and isolation can be effectively incorporated at this interface to eliminate power transients and thruster noise from reaching the low-level digital and analog control circuitry.

The digital interface unit represents the major subsection of the power processor. It receives, decodes, and stores serial digital commands; converts 0 to 5 V DC analog supply data into the proper serial digital format for transmission upon command; performs closed-loop control of thruster operating parameters based on sensed analog supply data and stored reference commands; and undertakes various automatic sequential logic operations associated with thruster start-up and restart, fault clearance, and system protection functions. This unit also contains the housekeeping inverter which provides circuit bias power for receiving commands and converting data and AC drive signals to synchromize the line regulator and AC distribution inverter. Also housed in the digital interface unit is the logic and power circuitry for driving the thruster gimbal motors to achieve 2-axis thrust vectoring via input commands to the power processor.

The present power processor achieves an electrical efficiency of 80 percent when operated from the nominal 70 V bus at an output power level corresponding to 1 mlb of thrust. The electrical component weight associated with this electrical design is 8 pounds (3.6 kg).

System mechanical design. - The packaging concept which has been selected for the EM power processor is depicted in figure 11. The unit is subdivided into 17 modular sections; six modules contain the power circuitry and the remaining 11 narrower modules house the digital interface electronics. The dimensions of the unit are 23×11×50 cm and its total weight is 16 pounds (7.3 kg).

Each power module holds a discrete functional portion of the power electronics (e.g., one or two complete supplies, AC distribution inverter plus line regulator, etc.). This simplifies fabrication and test of the individual modules and allows a complete checkout of each prior to integration into the overall system. The digital interface unit modules are constructed with much the same approach as used for the power. The power electronic portion of the power processor is built up by bolting the tightly fitting modules together and interwiring between modules and output connector as required. A center web gives the module structural strength and provides a good conductive thermal path to the outer portions of the module which form the skin of the power processor.

Power flow in the power processor is from the digital interface unit through the power circuitry to the output power connectors. The system harness is separated into two bundles which run the length of the power processor outside the module structure and beneath the removable harness cover (fig. 10 backside). This minimizes coupling between the power and low-level control and telemetry interwiring.

The relative placement of an ion thruster on a spacecraft can be highly dependent on the overall spacecraft configuration. From a propulsion system standpoint it is desirable for the power processor to be located near the thruster. Thermal and structural design constraints have therefore been placed on the power processor packaging which considers location of the unit either interior of the spacecraft body on an equipment shelf or exterior on a thermally isolated appendage.

The current EM design assumes that when the unit is mounted to an external appendage that the on-orbit sun line is perpendicular to the harness cover. With this additional constraint the thermal radiation properties are sufficient to maintain satisfactory upper operating temperature at its nominal power rating. In addition, the unit should encounter no low temperature difficulty in maximum eclipse even when unpowered in the preceding orbital pass. Mounting the unit in the interior of the spacecraft represents by comparison little thermal difficulty.

ATS-6 Thruster Power Processing

The ATS-6 ion thruster system, shown in figure 12, was designed to produce 1 mlb of thrust, 6 hours a day, for 3 years at synchronous altitude. The thruster receives power through a 30.5-cm-long shielded cable from its power conditioning unit. The system was conceived as a demonstration of north-south stationkeeping and of general spacecraft compatibility on an operational geosynchronous satellite. The primary consideration in the design of the power processor, therefore, was reliability.

System electrical description. - The spacecraft supplies a nominal 150 W at 28 V DC ± 2 percent. The thrustor can accept this tolerance on each of the voltages supplied to it; therefore the power conditioner provides no active regulation other than for the vaporizer control loops.

A block diagram of the power processor is shown in figure 13. A total of 16 power outputs is required by the thruster. These are supplied by a total of four converters, with the organization determined by thruster operating requirements. The converters are of the parallel 100 percent duty-cycle type, and operate at 10 KHz.

The heart of the system is the master converter. It is a two-transformer self-excited type which provides the base drive for the other three converters as well as low-voltage housekeeping power and several outputs to the thruster, both 10 KHz and DC. The housekeeping supplies provide about 2 W to power the 13 dual command circuits and the 12 dual telemetry circuits.

The largest of the converters is the high-voltage converter, which supplies power to the beam, nominally +550 V DC at about 0.5 mA; and the anode and cathode vaporizers, about 8.0 and 6.0 W, respectively. The current drawn from each of these supplies can be much larger than nominal during certain phases of thruster operation; the beam supply overload trip point is 200 mA and the trip point for the accelerator supply is 20 mA. If either of these levels is exceeded, the base drive to the high-voltage converter is interrupted for about 50 milliseconds. A short circuit condition will result in continuous cycling with "on" periods which are effectively less than 1 millisecond.

The discharge, or "arc", converter supplies power to the plasma anode, nominally +16 V DC at 1.6 A. and the boundary anode array, nominally +3 V DC at about 200 mA. The plasma anode supply is referenced to the beam potential, +550 V DC from ground; the boundary anode supply is referenced to the plasma anode supply.

The plasma anode current is sensed by means of a current transformer in series with the converter transformer secondaries, and the trip point is 4.0 A. Exceeding this current causes the 28-V input to the arc converter to be interrupted for about 6 seconds, by means of a series PNP transistor. This transistor is part of a special circuit commonly called an "arc dipper" which is also used to lower the 16 V DC discharge voltage to 12 V DC during overload cycles of the high-voltage converter. This reduces the plasma density in the thruster and facilitates re-establishing high voltage on the thruster electrodes.

The fourth converter is the neutralizer start converter, whose output, +150 V DC supplied through a 4000-ohm current-limiting resistor, is used to initiate the neutralizer discharge. A low-voltage keeper supply maintains the discharge during normal thruster operation, and the neutralizer start converter is then inoperative. Its efficiency, therefore, is of little significance.

All three of these externally driven converters incorporate a technique to prevent collector current overlap. This consists of a negative feedback winding on the converter output transformer which includes series diodes such that the external drive power to the base of transistor 2 is shunted through the negative feedback winding until the stored charge in the base of transistor 1 is completely removed and its collector voltage rises. This has been found to be effective in reducing both transistor power dissipation and current spikes on the +28 V supply bus.

Deflection of the thruster ion beam is produced by slight shifting of the accelerator electrode by means of electrically heating the appropriate pair of its eight support legs. There are thus four deflection supplies; these receive processed power from the master converter.

System mechanical design. - The power conditioning package is approximately 25×25×11.4 cm and weighs 7.3 kg. It consists of an upper chassis which houses all the command, control, and telemetry circuitry in the form of encapsulated plug-in modules. It also houses the connectors which interface with the spacecraft, and the EMI filters. The lower chassis contains all the power conversion circuitry and the connector which interfaces with the cable to the thruster. All heat-generating components are mounted directly on the floor of the package for maximum heat transfer.

All magnetic devices in the system are toroids and are unencapsulated to allow them to outgas completely. They are partially embedded, however, in Solithane, which provides a tough, flexible mechanical interface between the toroid and its mounting surface, without sacrificing heat conductivity.

The design is very conservative throughout. All components operate at or near 50 percent of rated voltage and/or 25 percent of rated power; nonsaturating transformers are designed to operate at 50 percent of rated saturation flux density; and great attention was given both mechanical ruggedness and thermal path lengths. All components underwent burn-in; magnetic components were opated in a thermal-vacuum environment for 2 weeks.

Performance. - The performance of the power conditioning unit is summarized in table 2; a weight breakdown is provided in table 3. Two views of the unit are shown in figures 4 and 5. Much of the power loss is a result of the large number of components required to perform functions other than power conditioning per se; the converters are reasonably efficient. The high-voltage converter exhibits an efficiency of 91 percent in steady-state system operation; a "bare" version, with no low-voltage vaporizer power, has exhibited 94 percent.

One prototype and three flight units were delivered to Goddard Space Flight Center. During the entire test program, including flight acceptance testing with operating thrusters, no component or functional failures were encountered. The largest measured internal temperature rise, at full power operation, was 10° C.

Two of the units are in orbit and have been exercised; one has accumulated 100 hours of operation. The only operating anomaly has been a tendency of the deflection command registers (low-power TTL) to respond to the occasional 1100-V thruster transients.

Future. - The system described here represents the technology of 1970 in a relatively low-power application, in which reliability had first priority, efficiency second, and weight third. Practical experience with the system had generated considerable confidence in the basic approach.

Future versions of this system would benefit from weight and power loss reductions stemming from increased use of integrated circuits and from a greater degree of mechanical and thermal integration with the spacecraft. A switching preregulator was proposed in 1972, which, if combined with an improved version of the ATS-6 power conditioner, allow operation from an unregulated solar panel bus with a net efficiency if 84 percent and a weight of under 12 pounds (5.5 kg).

POWER PROCESSING FOR PRIMARY PROPULSION

Electric propulsion for primary spacecraft thrust is of interest for both near-Earth and interplanetary missions. Near-Earth applications include spiralout maneauvers from low to high orbit and Earth escape. Once at high orbit the thruster may also be used for stationkeeping applications. Interplanetary missions include flights out of the ecliptic and flyby past or rendezvous with asteroids, comets, and planets. A primary electric propulsion stage could offer large payload advantages as a commercial tug in conjunction with the space shuttle.

One way to compare the capability of an electric propulsion spacecraft with that of a chemical system is to consider the total impulse delivered by two such systems. A 1500-kg electric propulsion spacecraft with 500 kg of propellant can deliver slightly more total impulse than a 2914 Delta rocket stage, which has a mass of 5500 kg, including 4500 kg of propellant. To explain more fully the characteristics of a primary electric propulsion system, the major elements are discussed in the following section.

Thruster

Intensive study and development have been under way at the NASA Lewis Research Center, the NASA Jet Propulsion Laboratory, Hughes Research Laboratory, and the NASA George C. Marshall Space Flight Center in the area of primary-propulsion applications. The candidate thruster for use on all proposed missions is the 30-cm thruster (fig. 16). This thruster operates at a nominal input power of 2.75 kW at a thrust of 30 mlb and a specific impulse of 3000 seconds. Thruster efficiencies in excess of 71 percent are achieved at full thrust, but there is some decrease at throttle conditions. The thruster has been designed to throttle over more than a 4:1 range of input power and has a design goal lifetime in excess of 10,000 hours.

The thruster has been qualified both mechanically and thermally and is compatible with the launch environment of boosters ranging from Thor/Delta to Titan with a variety of upper stages. It is able to operate in the thermal environment associated with in- and out-bound interplanetary missions ranging from about 0.3 to 5 AU. As verified in the SERT II flight, this thruster is capable of very long-term space storage and has highly reliable multiple-restart capability.

Transistorized Power Processing System for 30-cm Thruster

A 15 KW Solar Electric Propulsion (SEP) spacecraft for Earth orbital or inteplanetary missions must condition and control 12 kW of the total power to operate the primary propulsion thrust subsystem. These processes must be lightweight, efficient, and capable of thermally self-radiating to space. One of the concepts is discussed here; a modularized transistorized design.

The Hughes Aircraft Company recently completed a program to develop a 30-cm thruster thermal vacuum breadboard (TVBB) power processor. This program, sponsored by the NASA Lewis Research Center, concentrated on the implementation of a high-performance power processor system based on a transistorized bridge inverter power stage.

Prior to delivery of the hardware it was extensively tested on a static load and operating thruster. The electrical efficiency achieved by the TVBB power processor exceeded the program goals and represents a significant flight power system technology accomplishment. At the rated nominal output power the efficiency was 91.6 percent and 91.9 percent for input bus voltages of 200 and 400 V, respectively. The associated total electrical component weight is less than 35 pounds (16 kg).

System electrical description. - The 30-cm thruster TVBB power processor which is nominally rated at 3 kW is composed of 12 controllable DC output supplies and an interface/control subsystem. Specifications of the individual supplies are given in table 4. The maximum and nominal power supply ratings are listed together with the type of internal regulation (constant voltage on current) and the system potential to which the outputs of the supplies are referenced.

The interface/control subsystem established, by issuing an analog reference signal, in the 0 to 5 V DC range, the output voltage or current levels of each supply. The number of setpoints listed in table 4 correspond to the number of discrete reference levels which can be issued by the control electronics.

The system configuration employed is indicated in figure 17. Prime power to the system from the 200 to 400 V solar array bus is distributed directly to the screen and discharge supplies. Distribution of power to the remaining supplies is via the switching line regulator which down converts the line to 180 V. The heater, vaporizer, keeper, and magnetic baffle supplies are implemented with standardized self-saturating magnetic amplifier current-feedback controllers. The output of each of these supplies is transformer isolated and following rectification, filtered by a single L-C stage. The accelerator supply employs a single-ended energy-flyback scheme to convert it's 180 V input to meet the listed thruster requirements.

The screen and discharge supplies produce the bulk of the system's conditioned output power during normal thruster operation and represents the power circuitry area where most of the technology effort was directed during the development program. These supplies use a standardized transistor bridge inverter module in their design.

The screen supply is configured with five inverter modules (four operating and one standby) which have their DC output connected in series to achieve the necessary output voltage. Each inverter module has a nominal power rating in excess of 600 W and a peak short-term capability of approximately 1200 W. Incorporation of high-voltage, high-frequency switching transistors, ultra fast-recovery output rectifiers, and a low-loss ferrite output transformer has lead to overall low specific weights and high efficiencies. By staggering the phase of the pulse width modulated logic drive signals to individual inverter modules which operate at 10 KHz the fundamental power ripple frequency appearing at the supply input and output filters is 80 KHz. This has substantially reduced filter weight penalties.

A single operating inverter module is used in the discharge supply. This is supplemented with a standby inverter which has its DC output connected in parallel with the operating inverter at a point prior to the final L-C output filter stage. In the event of a failure the pulse width modulated inverter drive signals are automatically transferred to the standby inverter to bring it on line. Post development evaluation of the component stress levels actually occurring in the TVBB discharge supply indicates that the redundant inverter (and its weight) could be eliminated from future systems with little detrimental impact on total system reliability.

Reliable, high-performance operation of the transistorized bridge inverter from the 200 to 400 V bus has required careful attention to drive and stress control circuitry. The finalized designs in these areas, while sophisticated in concept, have proven to be simple in their implementation and highly effective over an extreme range of load conditions.

The interface/control subsystem contains the low-level system electronics associated with digital command reception and storage, A/D supply data conversion and transmission, closed loop thruster operating parameter control, and various automatic system sequencing and protective operations. Communication between the power processor and external command and data subsystems is by photo-isolated data links using a strobed 16-parallel bit format; communication between the interface/control subsystem and the individual supplies for supply reference control and for voltage and current data collection is accomplished with 0 to 5 V DC analog signals.

System mechanical description. - The packaging concept used in fabricating the TVBB power processor is reasonably evident from the photograph of the backside of the delivered unit shown in figure 17. Individual module plates (each containing a separate electrical function or set of functions) are bolted to a gridded aluminum frame forming a rigid planar package with extremal dimensions of 24.5×54×4.5 cm. Each module area is sized to maintain a worst-case plate temperature of 50° C under conditions of radiating to deep space from the front side (only) with no solar incidence.

To minimize noise coupling between the power and low-level signal wiring, routing of harnesses has been given careful attention. The control and data signal harness between the interface/control unit (fig. 18. box with vertically mounted circuit cards) and the various supplies is routed along the horizontal center line; input and output power cabling is routed along the perimeter of the power processor frame in an enclosed channel.

The use of many standardized low-power circuit functions in both the power circuitry and control circuitry make the use of hybrids in these areas attractive for implementing this class of power processor in the future. In addition, the size of electrical components and the homogeneous distribution of power losses are well suited to more compact system packaging concepts now being considered which use heat pipes for thermal control.

CONCLUDING REMARKS

Flight power processing for electric propulsion presents the designer with difficult problems and constraints. The concepts discussed here are representative of the approaches taken to satisfy the unique requirements of the device and its mission function.

The ATS-6 power system was designed for unit simplicity and reliability which consequently restricts its flexibility to address in-flight thruster malfunctions. The 8- and 30-cm PPU's discussed here represent a philosophy of system reliability through in-flight readjustment of operating conditions. This requies a sophisticated logic and control system which, while operationally simple, is complex and requires a computer logic interface.

All units described have successfully demonstrated the difficult design features of high efficiency, low weight, and the ability to operate an ion thruster.

Advances in electronic device technology should allow further reduction in system size and weight with improved system reliability.

TABLE 1. - 8-CM THRUSTER POWER PROCESSOR SUPPLY SPECIFICATIONS

Supply	Maximum power	Nominal power	Regulation type & ± %	Output reference potential	Type control input
1. Main vaporizer	6 V at 3 A	5 V at 2 A	I, 5	Spacecraft	8 fixed setpoints and loop control with D/A variable reference
2. Main cathode heater	8 V at 4 A	6 V at 3 A	I, 5	Screen	8 setpoints
3. Main keeper	25 V at 0.5 A	15 V at 0.36 A	I, 3	Screen	4 setpoints
4. Neutralizer vaporizer heater	4 V at 2 A	2 V at 1 A	I, 5	Spacecraft	Variable reference and loop control with D/A variable reference
5. Neutralizer cathode heater	8 V at 4 A	7 V at 3 A	I, 5	Neutralizer common	8 setpoints
6. Neutralizer keeper	25 V at 0.5 A	20 V at 0.36 A	I, 3	Neutralizer common	4 setpoints
7. Main discharge	50 V at 1 A	40 V at 0.5 A	I, 3	Screen	D/A variable reference
8. Screen	1200 V at 0.090 A	1180 V at 0.072 A	V, 1	PPU common	Single setpoint
9. Accel	-500 V at 0.008 A	-300 V at 0.001 A	V, 1	PPU common	Single setpoint

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TABLE 2. - (ATS-6 PPU) ELECTRICAL PERFORMANCE, STEADY STATE

High Voltage Converter	Volts	Amperes	Watts
Beam	560	0.111	62.16
Accelerator	560	.001	.56
Cathode vaporizer	4.44	1.11	4.93
Anode vaporizer	5.96	1.49	8.88
Total converter power			76.53
Arc Converter			
Plasma anode	16.00	1.65	26.40
Boundary anodes	3.00	.08	.24
Total converter power			26.64
Master Converter			
Anode heater	2.14	1.95	4.17
Cathode heater	1.65	1.51	2.49
Neutralizer heater	2.13	1.94	4.13
Neutralizer vaporizer	5.08	1.27	6.45
Neutralizer keeper	4.90	.02	.10
Total converter power			17.34
Total power delivered to thruster			120.51
Total power consumed			143.70
Net power conditioner efficiency			83.86%

TABLE 3. - (ATS-6 PPU) POWER CONDITIONING UNIT WEIGHT BREAKDOWN

	Weight, lb
Plug-in welded modules (command, TM, control)	2.50
Terminal welded modules (power, rectifier, control)	1.35
Magnetics (transformers, inductors, magnetic amplifiers)	2.56
EMI filters (total of 57)	.70
Power components (semiconductors, capacitors, etc.)	.80
Wiring	.70
Miscellaneous hardware	1.00
Chassis	5.00
Connectors	.14
Circuit boards	1.25
Total	16.00 (7.3 kg)

TABLE 4. - 30-CM THRUSTER POWER PROCESSOR SUPPLY SPECIFICATIONS

Supply	Maximum power	Nominal power	Regulation type & ± %	Output reference potential	Type control input
1. Main vaporizer	10 V at 2 A	7 V at 1 A	I, 5	Spacecraft	4 setpoints and loop control with D/A variable reference
2. Cathode vaporizer	10 V at 2 A	3.5 V at 1 A	I, 5	Spacecraft	4 setpoints
3. Cathode heater	15 V at 6 A	9 V at 4.5 A	I, 5	Screen	4 setpoints
4. Main isolator and Cathode isolator	10 V at 2 A	4.5 V at 1 A		Screen	4 setpoints
5. Neutralizer heater	10 V at 5 A	8.5 V at 4.2 A	I, 5	Neutralizer common	4 setpoints
6. Neutralizer vaporizer	10 V at 2 A	3.5 V at 1 A	I, 5	Spacecraft	4 setpoints and loop control
7. Neutralizer keeper	25 V at 3 A	12 V at 2 A	I, 5	Neutralizer common	4 setpoints
8. Cathode keeper	60 V at 1 A	10 V at 0.5	I, 1	Screen	4 setpoints
9. Discharge	45 V at 14 A	37 V at 13 A	I, 1	Screen	D/A variable reference
10. Accelerator	1000 V at 0.1 A	500 V at 0.008 A	V, 2	PPU common	Single setpoint
11. Screen	1100 V at 2.2 A	1100 V at 2 A	V, 1	PPU common	D/A variable reference
12. Magnetic baffle	2 V at 5 A	2 V at 4 A	I, 5	Screen	D/A variable reference

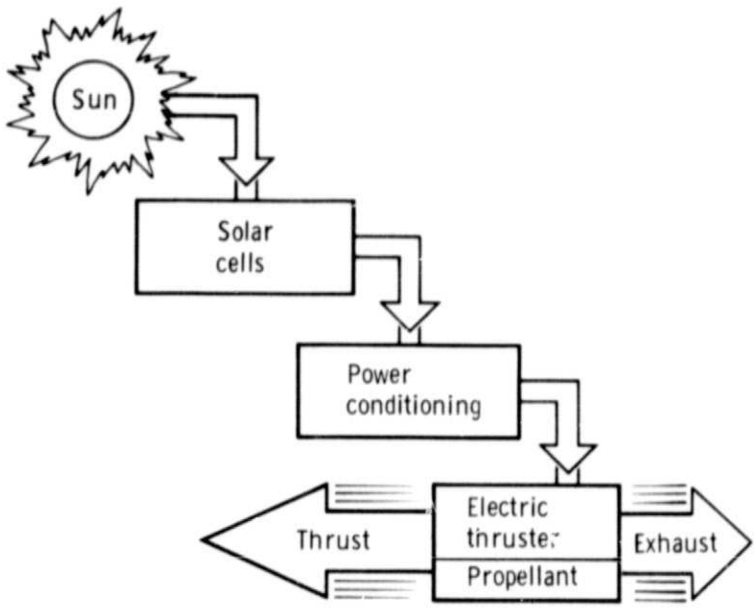

Figure 1.

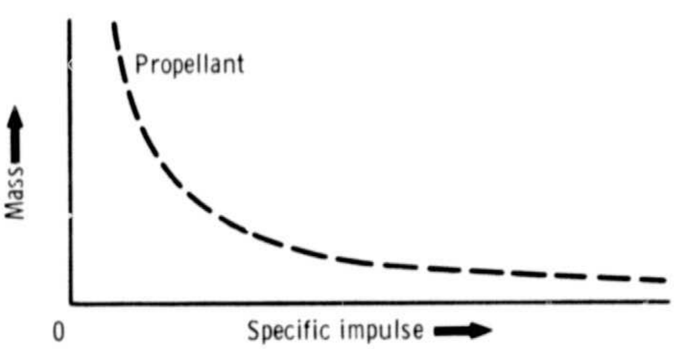

Figure 2.

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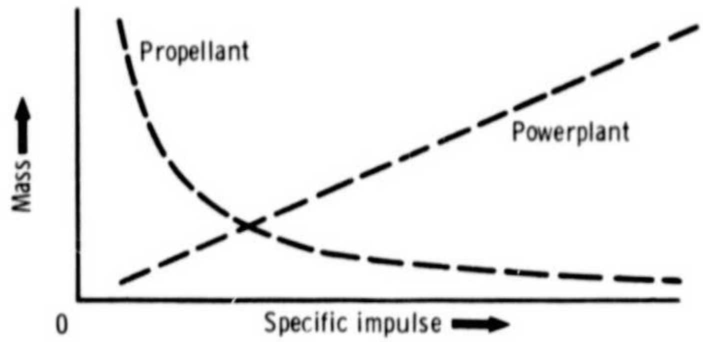

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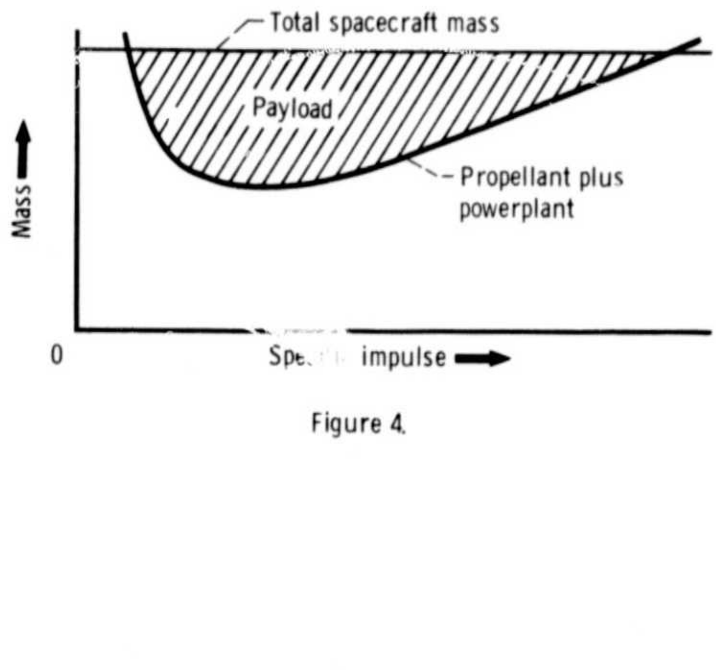

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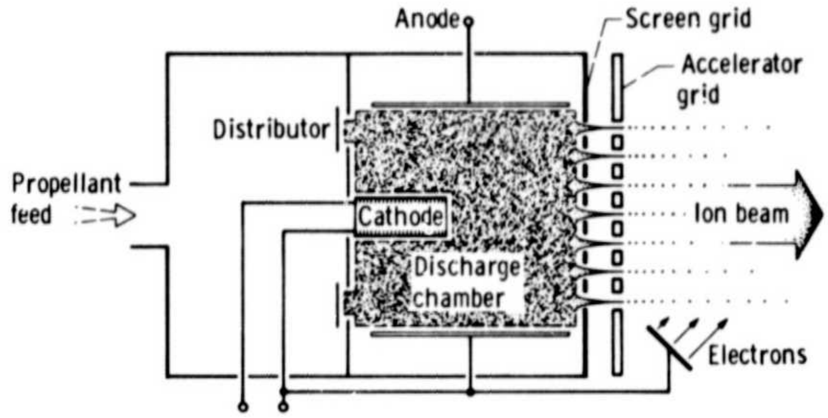

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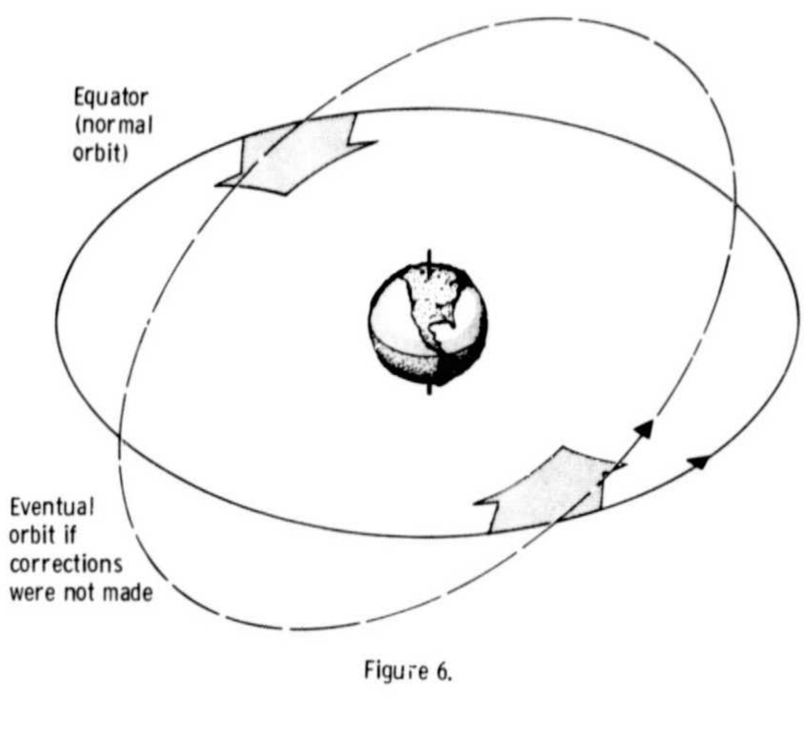

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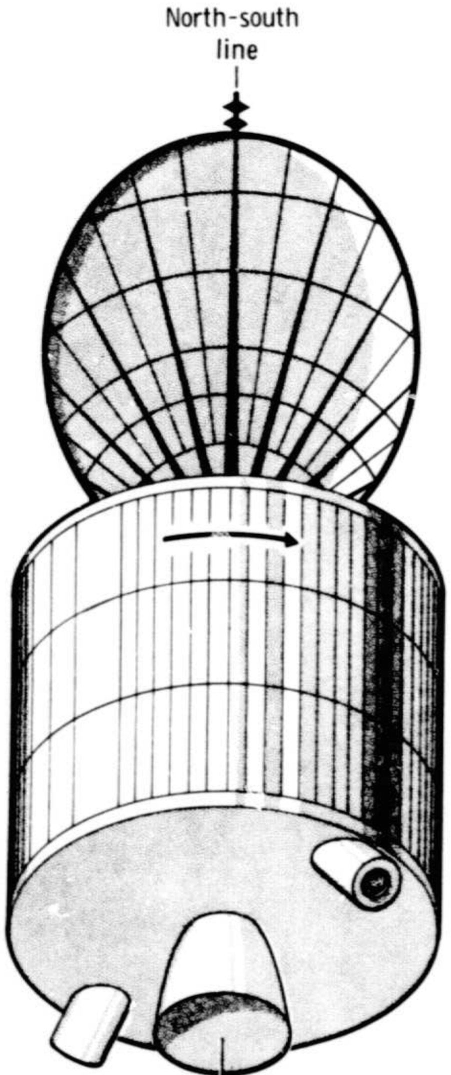

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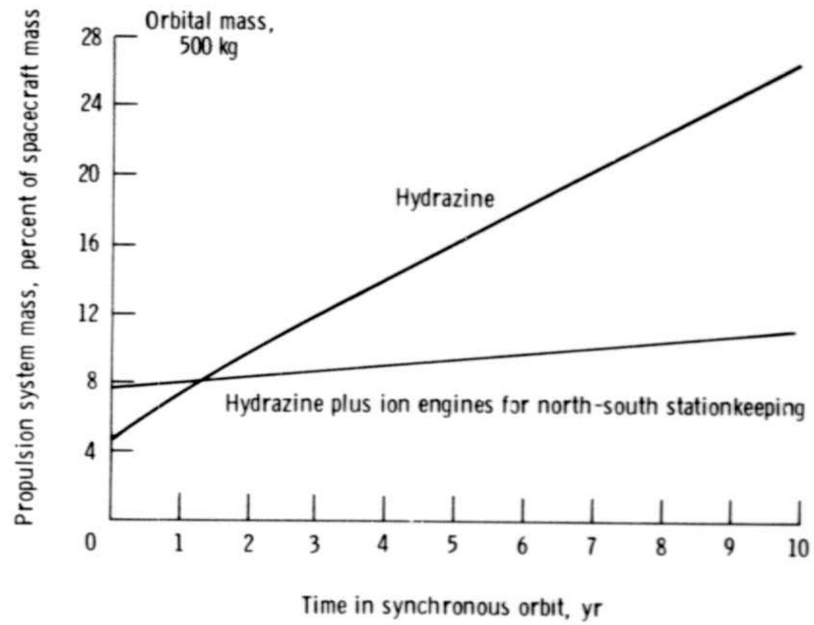

Figure 8.

C-74-1308

Figure 9.

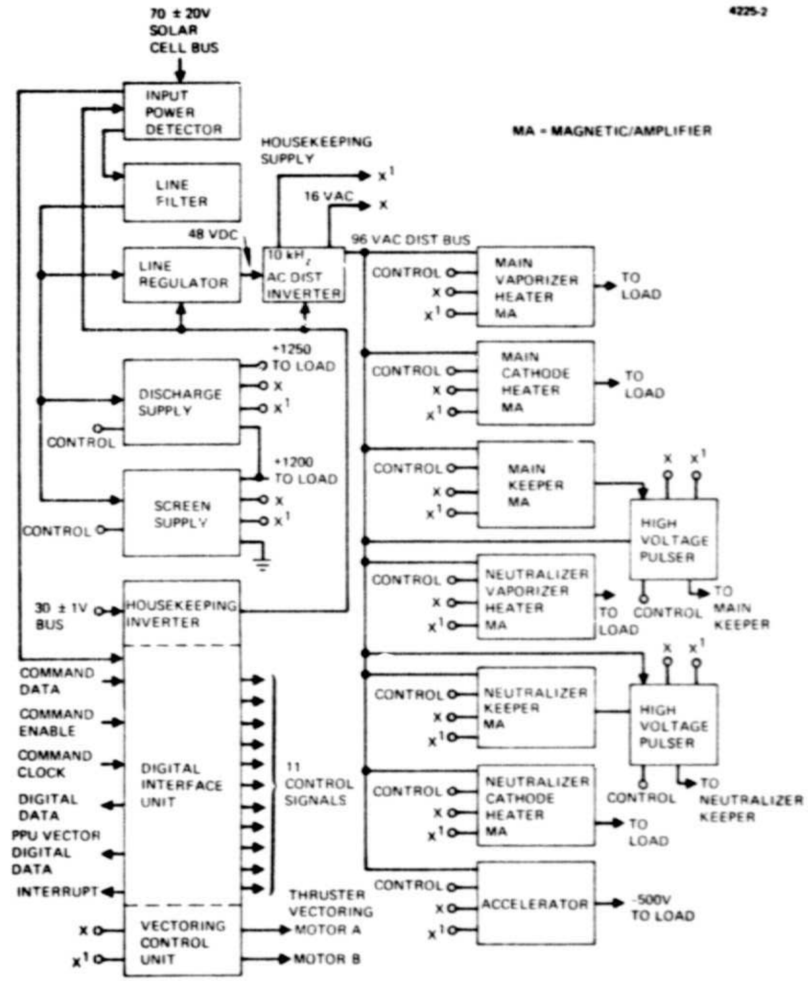

Figure 10. - 8-Cm ion thruster EM power processor functional block diagram.

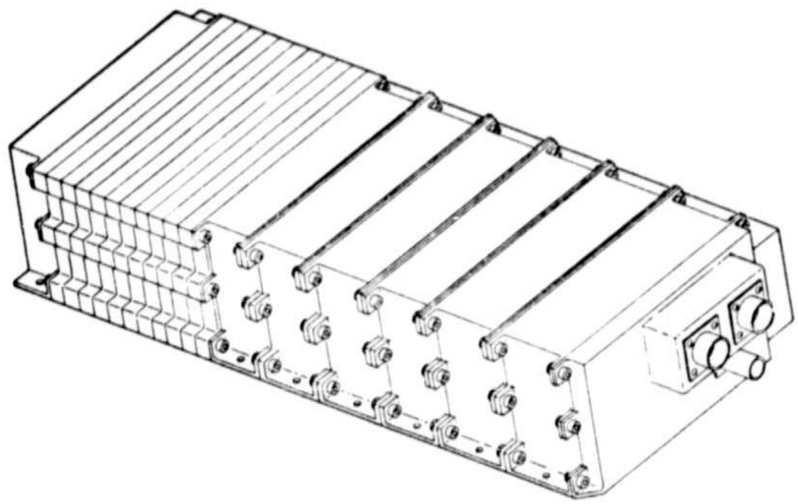

Figure 11. - 8-Cm ion thruster EM power processor package.

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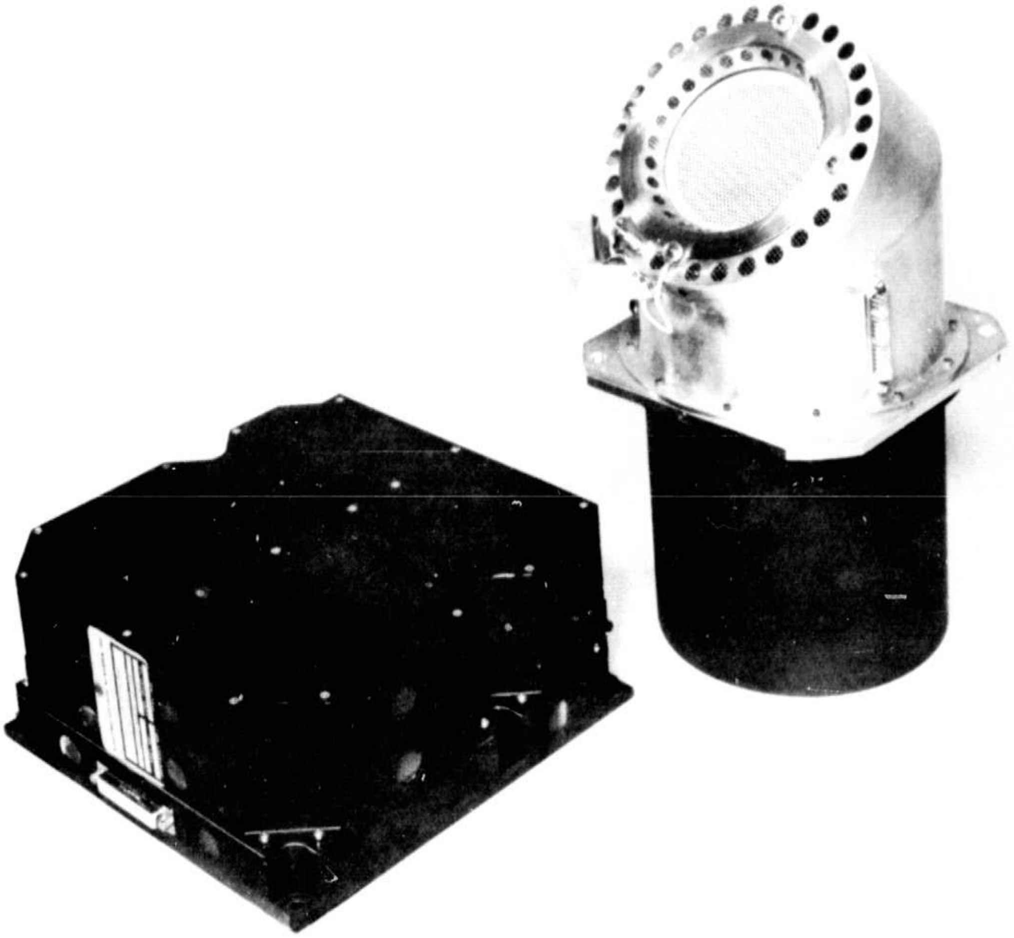

Figure 12.

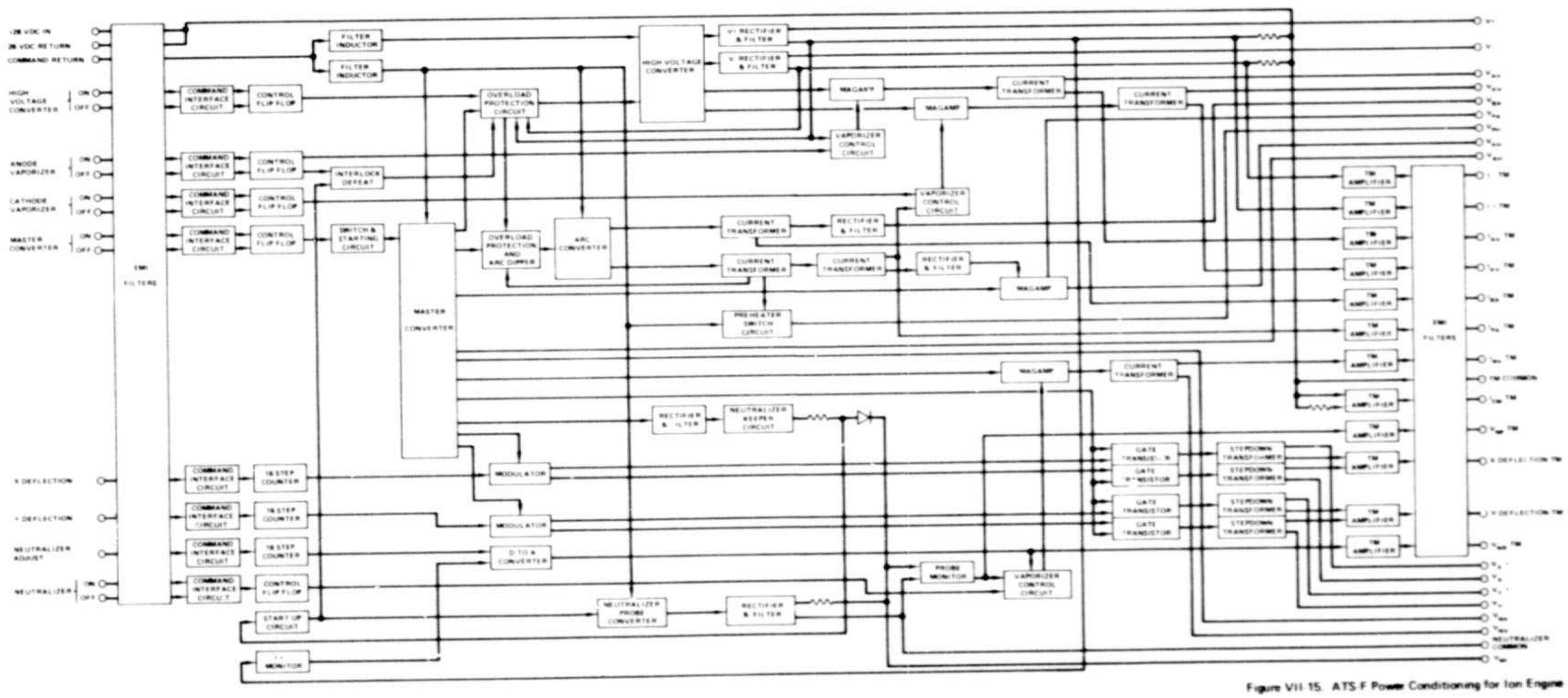

Figure VII-15. ATS-F Power Conditioning for Ion Engine

Figure 13.

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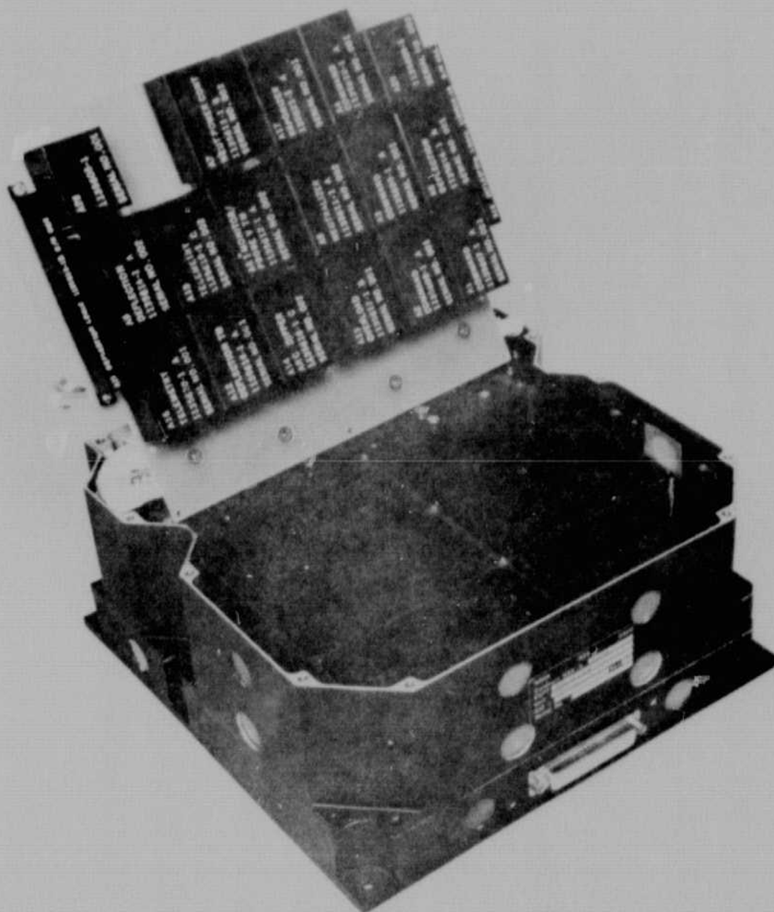

Figure 14.

Figure 15.

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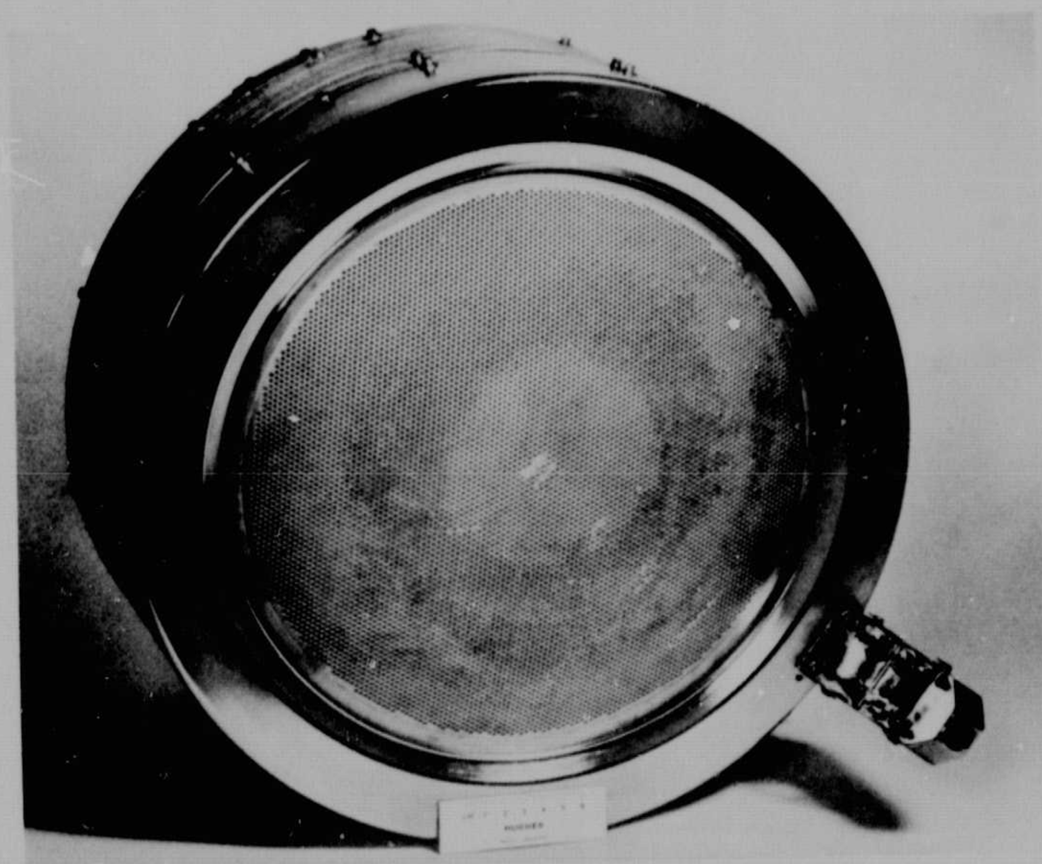

Figure 16.

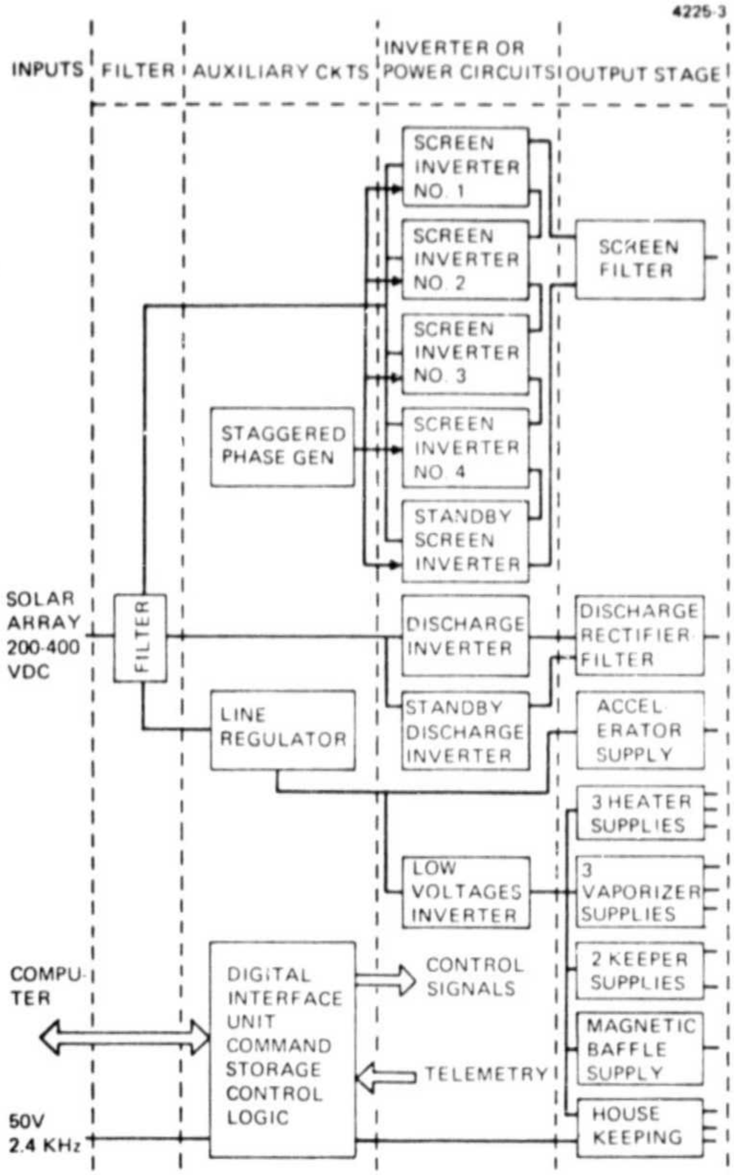

Figure 17. - Cm-30 ion thruster transistorized TVBB power processor functional block diagram.

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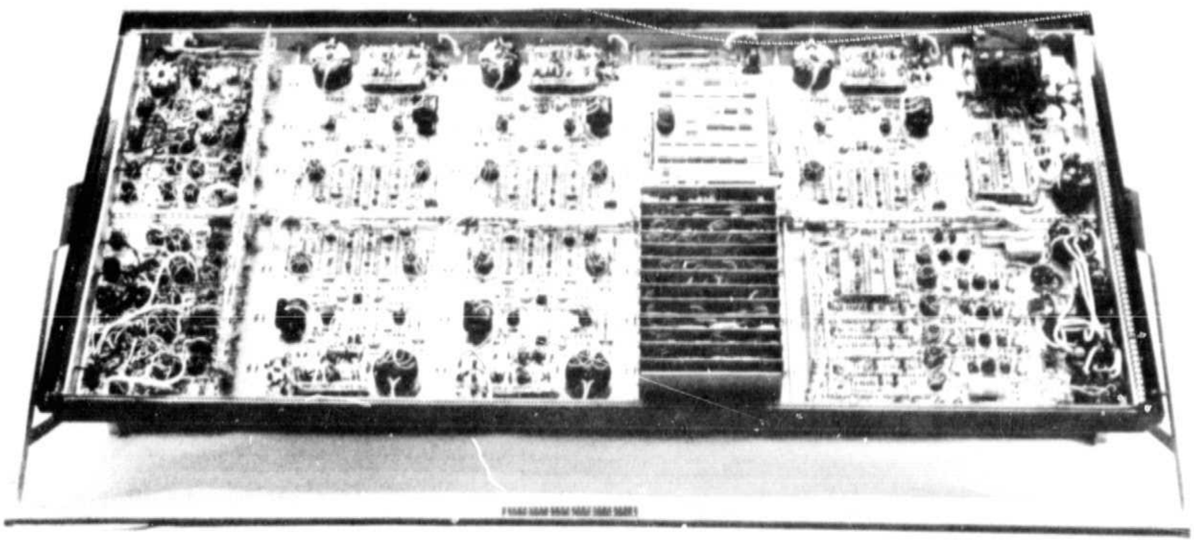

Figure 18.