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*Technical Memorandum 33-705*

# *Power Processor Design Considerations for a Solar Electric Propulsion Spacecraft*

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(NASA-CR-140842) POWER PROCESSOR DESIGN CONSIDERATIONS FOR A SOLAR ELECTRIC PROPULSION SPACECRAFT (Jet Propulsion Lab.) 67 p HC $4.25 CSCL 21C N75-12064 Unclas G3/20 03570



JET PROPULSION LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

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# PREFACE

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## ABSTRACT

This document describes the work performed during 1973 on the study of the propulsion power processor design options as part of the Solar Electric Propulsion System Integration Technology (SEPSIT) program. This propulsion power processor would generate the regulated dc voltages and currents from a solar array source of a solar electric propelled spacecraft. The power processor consists of 12 power supplies that provide the regulated voltages and currents necessary to power a 30-cm mercury ion thruster, that is applied in this study to a 1980 Encke Comet rendezvous mission.

This report includes: the study of the design options for processing the 200 to 400 V unregulated solar array power; the design options for generating this regulated power required by each supply; the technical approaches utilized in the developed design; and the technological limitation of the identified design options. Alternate approaches for delivering power to a number of mercury ion thrusters (eight for the Encke Comet rendezvous mission) and methods of optimizing are also described.

The study identified a number of viable design options for processing and generating regulated power by each power supply and a proposed power processor configuration that has advantages over the current design approach. It was concluded that this proposed power processor design should be considered for the application in solar electric propulsion missions of the future.

## I. INTRODUCTION

Solar electric propulsion as a propulsive technology has been in the process of development for many years. As the probability of flight application increases, new factors need to be considered beyond that normally required for basic technology development.

The actual application of a new technology to a flight spacecraft brings into focus the requirement that the new technology must operate in a particular environment. Namely, in an environment where other spacecraft subsystems are present and capable of introducing new requirements and interfaces which may not have been previously considered during the technology development period. The basic fact that many of the other "existing" spacecraft subsystems must directly interface and/or interact with the new technology introduces a new set of technology questions. For example, how is the new technology best integrated into the spacecraft design? This question prompts an investigation into the basic functional requirements and design techniques used in the new technology development, its supporting hardware, and the additional interfaces that must be established.

This report documents the design trades and options which were taken into consideration in attempting to apply a power processor design in a solar electric spacecraft for its first flight application in a rendezvous class of mission.

Mission selection and its accompanying mission requirements have the tendency to reflect upon the stress placed on a particular technology. The comet Encke rendezvous mission for the 1981 apparition was selected as the study basis because of its possibility of actual flight application and the additional fact that it should give the spacecraft designer and power processor designer a reasonably good stress of the technology application.

## II. DESIGN REQUIREMENTS AND CONSTRAINTS

The power subsystem of a Solar Electric Propulsion (SEP) module, (which is a part of solar electric propulsion spacecraft) generates, processes, and distributes all power necessary for the operation of the thrusters and other thruster supporting elements. In any solar electric propulsion mission, probably more than a single thruster will be required to produce the necessary spacecraft acceleration. However, independent of the specific number of thrusters, certain supporting elements will be required to provide power for the selection and control of thrusters in operation, the control and orientation of the thruster output in a common direction, and the generation of data for the evaluation of the performance of the thrust subsystem.

The SEP propulsion module power subsystem is shown in Fig. 1. The solar array generates raw dc power which is delivered via the power distribution module to the thruster power processors and to the power conditioners of the thrust subsystem supporting subsystems.

A thrust profile (Ref. 1) for an Encke Comet rendezvous mission was selected for this design study. Such a mission would require the operation of 6 thrusters at the beginning and the end of the mission. These thrusters are of the 30-cm size with an $I_{sp}$ of 3000, developed by the Lewis Research Center. During the remaining portion of the mission the number of thrusters in operation is directly related to the available solar power. This level decreases to a design minimum of two thrusters operating below the 1/2 power at aphelion. The design level minimum of two operating thrusters was determined by attitude-control requirements of the spacecraft.

Mission reliability studies (Ref. 1) revealed that for a minimum weight, the mission reliability is optimized with the use of a switch and two spare thrusters. Figure 1 shows a block diagram with 6 power processors, a switch, and 8 thrusters based upon this reliability study. The function of the switch was to connect the output of a selected power processor to a selected thruster.

A switch study (Ref. 1) constrained by the identical mission assumptions, indicated that two desirable switching modes were possible candidates: (1) one in which every power processor is capable of switching to every thruster and (2) a single power processor capable of switching to a maximum of four thrusters.

Based upon an Encke rendezvous mission spacecraft design (Ref. 1) the following requirements were identified for the power processor from the determined interfaces:

(1) Solar array source and power subsystem

  (a) No reverse current to the solar array

  (b) Ripple noise and power transients to be within the limits specified for compatible operation with the spacecraft power subsystem

  (c) Automatic shutdown at input voltage below the maximum power point of the solar array

  (d) Electrical isolation between input and output power lines

(2) Data subsystem

  (a) Commands for start-up and shut-down

  (b) Reference signals for thruster operation

  (c) Telemetry signals for status

(3) Thruster

  (a) Power for operation

  (b) Overload protection

  (c) Overload tripping of high-voltage supplies during thruster recovery

  (d) Control loops between power supplies for thruster operation, control, and protection

## III. POWER PROCESSOR ELEMENT

An important and complex element of the SEP spacecraft power subsystem is the power processor. The power processor for a 30-cm thruster is required to deliver about 2.7 kW of regulated power, and at its design efficiency its power dissipation could be in excess of 260 W. This processor will require a radiator area in excess of 0.91 $m^2$ and will weigh in excess of 13.6 kg. These power values are approximately an order of magnitude higher than any known unmanned spacecraft power-conditioning equipment. A "typical" power processor, including power conditioners for the thrust support subsystem, is shown in Fig. 2. This block diagram represents the power processor developed by Hughes Aircraft Company (HAC) that utilizes a transistorized design for processing and conditioning most of the power. Another power processor developed by TRW utilizes a similar approach for processing the power. However, some differences do exist between these two designs and will be examined in the study of the individual supplies.

From the standpoint of power processing, the specific power requirements of the thruster, both developed designs recognized the existence of four major power supply groups as follows:

(1) Screen power supply

(2) Arc (discharge) power supply

(3) Acceleration power supply

(4) Heater power supplies

The screen power supply processes the majority of the power required by the thruster at relatively high voltages. The discharge power supply processes a relatively high power for one of the elements of the thruster. The acceleration power supply processes relatively low power at relatively high voltages. The heater supply power group processes a relatively low power required by a number of elements of the thruster such as heaters, vaporizers and keepers. The thruster start-up power requirement is 168 W for the heater supply group. The thruster operating power requirements at full thrust is about 2.7 kW and the heater supply group heater power requirement is 52 W.

In addition to supplying regulated power to the various thruster elements, the power processor is required to control and maintain the thruster throughout the various modes of operation: start-up, arc initiation, thrust output at set level, and breakdown of arcing. Control of these modes is accomplished by the power processor through control circuitry. Three major control loops have been identified in the block diagram (Fig. 2):

(1) The screen-vaporizer control loop to control the thrust output at the desired set level. A reference signal is received from the computer corresponding to the set level output.

(2) A discharge cathode vaporizer control loop which controls and maintains the discharge supply output voltage within the operating limits.

(3) Neutralizer keeper. Neutralizer vaporizer control loops which control the neutralizer vaporizer output current within the keeper operating voltage range.

To perform the various required operations, the power processor receives a number of command and reference signals. Sequential start-up is initiated by commands sent to the various power supplies and reference signals maintain the controls of the supplies to the desired characteristics.

The reference signals shown in Fig. 2 are:

(1) I Screen for setting the output screen current

(2) I Discharge for setting the output discharge current

(3) $I_{mag}$ baffle for setting the output magnetic baffle current

(4) E Screen for setting the output screen voltage above the 1100-V level (under consideration)

The power processor supplies are current limited to protect against overload and breakdown, and two of the supplies (the screen and acceleration) are equipped with tripping circuits. The tripping circuits shut down both supplies if either the screen or the accelerator output current rises to an overcurrent level. These circuits then restart the supplies within a set time period and with a desired sequence.

Based on the above described function a study of the various options of processing power for the 30-cm mercury ion thruster was initiated. The discussion of the design options follows.

# IV. SCREEN SUPPLY DESIGN

## A. DESIGN REQUIREMENTS

The screen supply provides the majority of the power required by a thruster. For the 30-cm thruster this supply is required to deliver power in the form of a regulated direct current voltage of 1100 V over an input voltage range of 200 to 400 Vdc. The output current of this supply is set by a reference and controlled by the screen-vaporizer control loop. The output design requirements are:

(1) Power output 2200 W

(2) Output voltage 1100 ± 1% (or set by reference)

(3) Output current 0.5 to 2.0 A

(4) Output voltage ripple 1% peak-to-peak

In order to provide the regulated power, the power supply interfaces with other elements of the power processor and receives the following:

(1) ON/OFF commands

(2) Telemetry signals

(3) Overload status of the accelerator supply

(4) Reference signals

The basic block diagram of the power supply is shown in Fig. 3. The major blocks are:

(1) A power regulator converter (PRC) that receives the raw power and generates the regulated output power

(2) A high-voltage filter that reduces the output voltage ripple and generates the telemetry signals

(3) A control module that accepts the commands, and references and provides the control signals to the PRC

This power supply trips when an overload is detected in the supply or in the accelerator supply.

## B. DEVELOPMENT STATUS

### 1. HAC-Developed Design

a. Low-Voltage Power Processor (LVPP) 53 to 80 V. The low-voltage power processor screen supply utilizes transistorized power conversion and pulse-width modulator technology. The power supply is capable of providing 2000 W from an output voltage of 53 to 80 V. The output voltage is 2000 ±1% V and the output current can be set by the reference from 0.5 to 1.0 A. This supply was designed for a 20-cm thruster. The block diagram of the screen supply is shown in Fig. 4.

The design utilizes 8 staggered phased converters to generate the output power; each converter generating 250 W at an output voltage of 250 V. The output of each converter was series added to produce the required 2000 W, at an output voltage of 2000 V. The staggered phased output of each converter is instrumental in reducing the size and weight of the output filter. Each converter is capable of generating higher power so that if one fails the remaining 7 could provide the 2000-W output. With this approach one converter failure could be tolerated with only a small increase in output ripple.

b. High-Voltage Power Processor 200 to 400 V. The high-voltage power processor screen supply utilizes a transistorized power conversion and pulse width modulation technology. This power supply is capable of providing 2200 W for an input voltage range of 200 to 400 V. The output voltage is 1100 V ± 1%, and the output current can be set by the reference from 0.5 to 2.0 A. A block diagram of a proposed transistorized screen power supply is shown in Fig. 5.

The design of the power supply is an outgrowth of the low-voltage power processor screen supply utilizing staggered phase converters. There are 4 converters, each capable of supplying 500 W. The output of each converter is series added to provide the 2000 W at an output voltage of 1100 V. A fifth converter is a standby unit ready to replace a failed converter thereby maintaining a four staggered phase system. In this approach the output ripple is not disturbed when a failure of a converter takes place.

### 2. TRW-Developed Design

The TRW-developed screen power supply utilizes SCR series resonant circuit power conversion technology. The power supply is capable of providing approximately 2400 W; 2200 W for the screen and a peak of 200 W for the accelerator from an input voltage range of 200 to 400 V. The screen output provides 1100 V ±1% at a current set by a reference from 0.5 to 2.0 A. The accelerator output provides -1000 V ±1% at 8 mA average. TRW elected to combine the screen and accelerator supplies into a single supply with two outputs because of the common functions. (Both supplies will trip when an overload occurs in either supply.) The block diagram of the TRW power processor screen power supply is shown in Fig. 6.

This power supply utilizes an SCR series resonant inverter to generate the power required. The regulator utilizes an analog-to-discrete-time-interval converter (ASDTIC) as the low-level amplifier to control the series resonant inverter.

## C. DESIGN OPTIONS

In the previous sections the design requirements of the screen power supply have been identified as well as the technical approaches utilized by HAC and TRW. In this section the stated design requirements for the screen power supply and the proposed technical approaches/options consistent with electronic technology will be discussed. The main goal is to examine the feasibility of the proposed technical approaches/options and to determine the best approach from the standpoint of flight project philosophy, mission requirements and spacecraft design constraints.

In the process of providing regulated power to the thruster there are a number of technical approaches/options for regulating the raw dc power from the source and for supplying power to the thruster. These options are summarized in the flow chart in Fig. 7. The discussion of the options follows.

1. Option 1: No Electronic Regulation

The projected solar array voltage swing of 200 to 400 V from 1.0 to 3.5 AU may be reduced by tilting the arrays off the sun at 1.0 AU. A preferable voltage swing of 300 to 400 V may be realized by tilting the arrays at 1 AU to some angle off the normal. Some power loss occurs in solar array power output when the arrays are tilted off the sun axis. Several advantages have been identified:

(a) Reduction in cable power loss and weight

(b) Increased power processor (PP) efficiency

(c) Reduction in power processor weight

However, the mission performance resulting from the reduced power at 1 AU were assessed, and this option was ruled out because of the power "loss."

2. Option 2: Switched Panels

This option is to maintain regulation or set the required voltage by switching segments of the two space vehicle arrays from series to parallel. Each array will have sections dedicated to supply power for the screens and is configured to produce 550 V at the maximum power point at 1 AU. Adding the two arrays in series will produce 1100 V. At higher AUs the voltage at maximum power point increases while the current decreases. As the AU distance increases and the maximum power point voltage reaches 1800 V, the arrays will be switched from series to parallel. At this point, the voltage of each array would be 900 V at the maximum power point. However, under load adjustment the required 1100 V could be obtained.

This option will produce variable thrust output. A feasibility study and more detailed analysis is required to determine the impact on guidance and trajectory.

This option was ruled out because the complexity of switching, weight penalty, and reliability of switches may offset any known advantages.

3. Option 3: Common Converter

Power requirements for 6 thruster configuration with a common supply is 6 × 2 kW = 12 kW. This common supply design can utilize 8 converters connected in series, each producing 1.5 kW. However, because of technical difficulties in the design of high power converters (1.5 kW), this option was eliminated from consideration. The technical problems considered in ruling out this particular option were as follows:

(1) The high power cannot practically be produced by the 8 converters (component limitation).

(2) High dissipation per converter would be difficult to radiate.

4. Option 3a: Common Converter per Two Thrusters

Based on attitude-control requirements, at least two thrusters must be continuously operating as a minimum. Supplying the power from a common supply for two thrusters would probably be feasible. However, it would require verification through testing that operating more than one thruster from a common supply is feasible. Such a screen supply would result in a weight reduction.

5. Option 4: Separate Converters With Common Bus

This option is similar to Option 3 except that more than 8 converters are used in a series-parallel combination to supply the power to a common bus. This design approach would reduce the power requirements per converter to a more reasonable level so that the design can be considered technically feasible (power-wise).

However, it has to be verified that operating more than one thruster from a common supply (hence common ground) is technically feasible.

6. Options 5, 6, 7, and 8: Separate Supplies per Thruster

These design options take into consideration redundancy within the supplies hardwired as opposed to switching to separate nonredundant supplies. The specific choice between Options 5, 6, 7 and 8 can only be made after system requirements are known (e.g., number of thrusters and PPs, the relative reliability of redundant PP circuitry, and the switching concept).

These above options suggested the need for a tradeoff study of redundancy versus system reliability that can be achieved with switching supplies or hardwired redundant supplies. Such a study was not performed as part of this activity.

# V. DISCHARGE SUPPLY DESIGN

## A. DESIGN REQUIREMENTS

The discharge supply provides moderately high power to the thruster. For the 30-cm thruster the supply is required to deliver power in the form of regulated dc current between 3.0 and 14 A, set by a reference, at a dc output voltage ranging between 37 to 42 V controlled by the cathode-vaporizer control loop. The output design requirements are:

(1) Power output 560 W.

(2) Output current 3 to 14 A set by reference and regulated to ±1%.

(3) Output voltage 37 to 42 V.

During start-up the power supply must be capable of providing 60 V at approximately 20 mA. The power supply interfaces with other units of the power processor and receives the following:

(1) ON/OFF commands

(2) Telemetry signals

(3) Overload status of screen and accelerator supplies

(4) Reference signals

(5) Feedback to cathode vaporizer supply

The basic block diagram of the discharge power supply is shown in Fig. 8.

The major blocks are:

(1) A power inverter that receives the raw dc power and provides the regulated power output,

(2) The rectifier filter unit that rectifies and filters the output of the inverter, generates the telemetry signals, and provides feedback to the cathode vaporizer.

## B. DEVELOPMENT STATUS

### 1. HAC-Developed Design

a. LVPP, 53 to 80 V. The LVPP discharge supply utilizes transistorized power conversion and pulse width modulation technology. The power supply is capable of providing 378 W from a dc input voltage of 53 to 80 V. The output current is dc, set by a reference, between 3.0 and 9.0 A and is regulated to ±1% at each set value. The dc output voltage varies between 37 to 42 V and is controlled by the output current of the cathode vaporizer supply control loop. The power supply was designed to provide the start-up requirements of 60 V at 20 mA. The power supply was designed for a 20-cm thruster. The block diagram of the discharge power supply is shown in Fig. 9.

The power supply utilizes transistorized power regulator inverter electronics that connect to an output power transformer through a mechanical switch. There are two power regulator inverter electronic circuits: a main and a standby. Drive from the staggered phase generator is used to drive both circuits. Switching from the main to standby is done by a sensing circuit which senses the output of the filter. The output current of the supply is set by the reference signal and is regulated by a control loop which senses the output current of the filter. The output voltage is used in the control loop of the cathode vaporizer to control the vaporizer output current.

b. High-Voltage Power Processor (HVPP) 200 to 400 V. The HVPP discharge supply also utilizes transistorized power conversion and pulse width modulation technology. The design is capable of providing 680 V. The output voltage is expected to vary between 37 to 42 V and output current to be set between 3.5 and 14 A by a reference. The output current would be regulated to ±1% at each set value. The power supply is designed also to satisfy the start-up requirements. The block diagram of this design is shown in Fig. 10. It consists of a main and standby converter with a filter unit.

This power supply design is similar to the LVPP except that the drive to each inverter is switched electronically from the main to the standby by a sensing network which senses the output of the filter. The output of each converter is isolated via the output diodes.

### 2. TRW-Developed Design

The TRW-developed design utilized the SCR series resonant circuit power conversion technology. The power supply is capable of providing the power requirement of 680 W with an input voltage of 200 to 400 V. The block diagram of the supply is shown in Fig. 11.

The regulator receives power from a multiple output inverter that supplies power to both the heater and keeper power supplies. The regulator utilizes SCRs and analog-signals-to-discrete-time-interval converter (ASDTIC) as the low-level amplifier to provide the regulated current at the set reference values.

## C. DESIGN OPTION

In the previous sections the design requirements of the discharge power supply have been identified as well as the technical approaches utilized by the two companies, HAC and TRW, to meet their design requirements, as part of the power processor technology development effort relating to solar electric propulsion.

In this section, the outlined design requirements and proposed design approaches/options consistent with technology will be discussed for the discharge power supply. The main goal of this section is to examine the feasibility of the proposed design approaches/options and to determine the best approach from the standpoint of flight project application, mission requirements, and spacecraft design constraints.

In the process of providing regulated power to the thruster, there are a number of technical approaches/options for regulating the raw dc power from the source output supplying power to the thruster.

The five options considered for the discharge power supply are summarized in a flow chart (Fig. 12).

1. <u>Option 1: Common Inverter</u>

A single inverter to power 6 thrusters with a single standby unit each having the capacity of $6 \times 680 = 4080$ W (Fig. 13).

The advantage of this option is the probable weight reduction.

The disadvantages are:

(1) Requirement of a switch to supply power to the operating thrusters.

(2) Interference with the operation of each thruster. Each thruster would require separate power for starting. In addition, during thruster breakdown condition, reestablishing of the arc will require ramping of the supply current which will affect the operation of the other thruster.

(3) Reduction of reliability.

This option is rejected because of the unique requirements of thruster operation for arc initiation and arc reestablishment after screen or accelerator supply breakdown.

2. <u>Options 2, 3, 4, and 5: Single Inverter per Thruster (Main With Standby, No Standby, Switching to Each Thruster, or Hardwired)</u>

These options require a tradeoff study of redundancy versus system reliability, with switching or hardwired supplies, to determine the best design approach.

## VI. ACCELERATOR SUPPLY DESIGN OPTIONS

### A. DESIGN REQUIREMENT

The accelerator supply provides relatively low power at relatively high voltage. For the 30-cm thruster this supply is required to deliver power in the form of regulated dc voltage of -500 V over an input voltage range of 200 to 400 Vdc. The output current of the supply is nominally at 8 mA but must be capable of delivering 20 mA in steady-stage operation and up to 100 mA for a duration not exceeding 1 s. The output design requirements are:

(1) Power output. 50 W peak, not exceeding 1 sec

(2) Output voltage. 500 V ±1%

(3) Output current. 8 mA nominal

(4) Output voltage ripple. 2% peak-to-peak

The interfaces with other power processor elements are as follows:

(1) ON/OFF commands

(2) Telemetry signals

(3) Overload status of the screen power supply

The basic block diagram of the power supply is shown in Fig. 14. The accelerator converter/regulator has the option of receiving: (1) either unregulated dc power directly from the solar array which needs to be regulated, (2) regulated dc power from a line regulator which needs to be further refined, or (3) regulated ac power from a regulated inverter which needs to be rectified and regulated. These three options have been applied in designs already developed. The accelerator/supply must also be designed to trip when a current overload is detected in output or in the output of the screen power supply.

## B. DEVELOPMENT STATUS

### 1. HAC-Developed Designs

a. LVPP, 53 to 80 V. The LVPP accelerator power supply utilizes transistorized power conversion and pulse width modulation technology. The output voltage is -1000 V and the output current is 10 mA for nominal operation and is capable of supplying 50 mA peak. The power supply was designed for a 20-cm thruster. The block diagram is shown in Fig. 15.

This supply receives regulated ac power from the heater inverter. This regulated power is rectified and was additionally regulated by a magnetic amplifier regulator.

b. HVPP, 200 to 400 V. The HVPP accelerator power design is similar to the LVPP design with the exception that it receives regulated dc power instead of regulated ac power. The output voltage of this design is -500 Vdc with an output current of 8 mA nominal. The block diagram of the power supply is shown in Fig. 16.

Regulated dc power is supplied to a dc-to-dc regulator-converter which additionally regulates the output voltage to the ±1% regulation requirement.

### 2. TRW-Developed Design

In this particular approach, the accelerator power supply is combined with the screen supply. It consists of a separate output transformer winding of the screen transformer followed by a regulator.

## C. DESIGN OPTION

In the previous sections the design requirements of the accelerator power supply have been identified as well as the technical approaches utilized by the two companies, HAC and TRW, to meet those design requirements, as part of the power processor technology development effort for solar electric propulsion.

In this section design requirements and proposed design options consistent with technology will be discussed for the accelerator power supply. The main goal of this section is to examine the feasibility of the proposed design approaches and to determine the best approach from the standpoint of flight project application, mission requirements and spacecraft design constraints.

In the process of providing regulated power to the thruster there are a number of technical approaches for regulating the raw dc power from the source and for supplying power to the thruster.

1. Option 1: Combine the Accelerator Power Supply With the Screen Power Supply

Under this option, the output of the accelerator power supply is switched to each thruster. In the TRW-developed design, the accelerator power supply was combined with the screen power supply by providing a separate output winding in the screen output transformer and providing a regulator for any additional regulation. This design approach would be feasible if the screen supply output voltage is required to be controlled by a reference. Switching to each thruster is a mission reliability assessment.

2. Option 2: Combine the Accelerator Power Supply With the Screen Power Supply Hardwired to the Thruster

Option 2 is similar to Option 1 except that the output of the power supply is hardwired to the thruster. As stated above, the mission reliability assessment will determine if switching is required.

3. Option 3: Provide Regulated dc or ac to a Converter-Regulator or Transformer Rectifier-Regulator for Additional Regulation and Switching to Each Thruster

The accelerator power supply output is switched to each thruster. This approach was utilized in the HAC design and is a feasible option. Switching the power supply output to each thruster is a matter of mission reliability assessment.

4. Option 4: Provide Regulated dc or ac to a Converter-Regulator or Transformer Rectifier-Regulator for Additional Regulation. The Accelerator Power Supply Output Is Hardwired to the Thruster

This approach is similar to Option 3 except that the output is hardwired to the thruster. As previously stated, the mission reliability assessment will determine if switching is required.

The four design options that have been proposed are shown in Fig. 17.

## VII. HEATER SUPPLY GROUP DESIGN

### A. DESIGN REQUIREMENTS

The heater supply group provides power to the thruster elements: heaters, keepers, and vaporizers. Regulated dc power at relatively low level is supplied to these elements. The design requirements of this power supply for a 30-cm thruster are listed in Table 1.

These supplies interface with other elements of the power processor, as follows:

(1) ON/OFF commands

(2) Telemetry signals

(3) Reference signals

(4) Feedback signals from screen and discharge power supplies for control loop operation

Because of the low power requirements, one technical approach would be to provide regulated ac power to individual transformer rectifier units with magnetic amplifier regulators for any additional regulations instead of supplying unregulated dc, from the solar array, to individual regulators. This approach will tend to be more efficient on a W/lb basis of regulated power produced. This approach was followed in the developed designs discussed in the following section.

## B. DEVELOPMENT STATUS

### 1. HAC-Developed Design

a. LVPP, 53 to 80 V. The LVPP heater supply group utilizes a line regulator and a power inverter to provide the regulated ac power to the heater supply. The block diagram of the heater power supply group is shown in Fig. 18. This heater power supply group does not include the main isolator and heater and the magnetic baffle heater power supplies, because it was designed for a 20-cm thruster. The heater supply group also accept the control signals, reference signals, and feedback inputs from the screen and discharge supplies.

b. LVPP, 200 to 400 V. The HVPP heater power supply group design is similar to the LVPP design with additional supplies for the main isolator cathode heaters and magnetic baffle heater for the 30-cm thruster.

### 2. TRW-Developed Design

The TRW-developed heater power supply group follows the same technical approach as the HAC design.

## C. DESIGN OPTIONS

In the previous sections the design requirements of the heater power supply group have been identified as well as the technical approaches utilized by the two companies, HAC and TRW, to meet the design requirements, as part of the power processor technology development effort for solar electric propulsion.

In this section design requirements and proposed design approaches/options consistent with technology will be discussed for the screen power supply. The main goal of this section is to examine the feasibility of prepared technical approaches/options and to determine the "best" approach from this standpoint of flight project philosophy, mission requirements, and spacecraft design constraints.

Since the heater supply group consists of 10 supplies, the number of cable interconnections to the thruster represents a strong design consideration. A look at the power transferring options, not only of the power processor, but of the entire SEP module is worth design considerations. The complete power processor would require 14 wires to deliver power to the thruster. With thruster redundancy, these power lines would require switching between spare thrusters. However, 11 of the 14 power lines deliver power generated by the heater supplies. Since all the designs developed followed the approach of providing regulated ac to the heater supplies, a viable option would be to switch only the two input ac lines to the heater supplies instead of the 11 output power lines. In this option the heater supplies would be hardwired to the thruster and the regulated ac power would be switched to energize the desired thruster. This approach reduces the total number of lines to be switched from 14 to 5. Three lines for the high-voltage outputs to the thruster as previously and 2 lines for the ac power to the heater supplies. This option will be discussed further in the power processor design option section.

In the process of providing regulated power to the thruster there are a number of technical approaches/options for regulating the raw dc power and supplying power to the thruster.

Five design options for the heater supply group were identified and are summarized in Fig. 19.

1. Option 1: A Common Line Regulator and Inverter With a Standby Inverter-Hardwired or Switched to the Heater Supplies (Control) Units

The control unit consists of transformer-rectifiers which are hardwired or switched to the thruster. This option has two switching points: (1) Switching is done between the inverter and power control units, and (2) Switching is done between the control units and thrusters.

Before examining the switching options, it is advisable to examine the design requirements of a common line regulator and inverter.

As assessment of the regulated ac power requirements of the thrusters and SEP module supporting subsystems for the mission was made. The power requirements are: (1) heater power for starting the thruster, (2) heater power during operation, (3) heater power for keeping the thruster warm when the thruster is non-operating, and (4) and power for the SEP module supporting subsystem during the mission flight phases. To limit the power requirements to reasonable levels, it was decided to limit the starting of the thruster to one at a time. This starting thruster approach was considered acceptable by the mission analysts. A common line regulator and common inverter for the thruster heater supply groups and the SEP module would reduce the overall weight of the thrust subsystem. The thruster starting, operating, and warm-up preliminary power requirements are shown in Table 2.

The assumed supporting subsystems preliminary power requirements for operating the designated number thrusters in each flight phase (starting with six thrusters operating to a minimum of 2 and also during thruster shutdown) are shown in Table 3.

The inverter design requirements are calculated below.

(1) Maximum Power Required

| | | |
|---|---|---|
| Starting one thruster | | 197 W |
| Operating 5 thrusters (5 × 38 W) | | 190 W |
| Supporting subsystems | | 160 W |
| | Total | 547 W |

ac power required by the users with an assumed transformer-rectifier (TR) efficiency of 90% is 547/0.90 = 610 W

(2) Minimum Power Required

| | | |
|---|---|---|
| 2 thrusters in operation (2 × 38 W) | | 76 W |
| Supporting subsystems | | 190 W |
| | Total | 266 W |

ac power required by the user with an assumed transformer-rectifier efficiency of 90% is 266/0.90 = 295 W

(3) Coast Period

Support subsystems and SEP module heaters = 424 W

ac Power required by the users with an assumed transformer-rectifier efficiency of 90% is 424/0.9 = 472 W

(4) Power Requirements of the Heater Inverter

Maximum = 610 W
Minimum = 295 W
Assuming that the output voltage of inverter is 200 V, then $I_{max}$ = 3.0 A

A common inverter can be designed to provide the ac power. A standby inverter to enhance this mission reliability is recommended. The design requirements of the inverter and lines regulator (Fig. 20) are summarized in Section IX-B.

2. Options 2, 3, 4, and 5

In these options each power processor contains the necessary units with or without redundancy and with or without switching at appropriate points.

In Option 2, a line regulator and an inverter with a standby inverter in each PP is switched to a power control unit with transformer rectifier outputs that are hardwired to the thruster.

In Option 3, a line regulator and an inverter with no standby is hardwired to power control units with transformer-rectifier in each PP, which outputs are switched to each thruster.

Option 4 is similar to Option 2 with no standby inverter.

Option 5 is similar to Option 3 except with a standby inverter.

A tradeoff study of redundancy versus system reliability is required to evaluate the need of redundant units as well as the options of switching at the input of the power control units instead of at the output.

## VIII. ELEMENT-DESIGN OPTION SUMMARIES

Based on the data generated the design options studied can be classified as follows:

(1) Ruled out, worth no further consideration

(2) Mission dependent

(3) Desirable in various degrees

The design options examined in each power supply and the conclusions reached are summarized in Tables 4, 5, 6, and 7.

A power processor block diagram showing the desirable options for power generation and distribution is shown in Fig. 21. The diagram shows a number of OR gates for processing raw solar array power and delivering power to the thruster.

The mission dependent modules which involves the need for redundant units are to be decided from specific mission reliability studies.

## IX. POWER PROCESSOR DESIGN OPTION TRADES

The results of the power supply design studies showed that two power processor designs have potential advantages:

Option 1: The power processor contains all the power supplies as a single unit. Each power processor then delivers power to a selected thruster via a switch as shown in Fig. 22. This is the present design and distribution concept (Ref. 1).

Option 2: Divides the option 1 power processor design mentioned above into two groups. The power generation and regulation (PGR) group and the power control (PC) group. The PGR group contains the screen, accelerator, discharge, and a power supply that provides ac regulated power for the PC group.

The PC group contains the heater power control units. Each group will have its own control circuits. The functions of this PC group are to receive the power from the PGR group and to provide all the controlled power required by the thruster. The PC group can be hardwired to the thruster. For an 8-thruster configuration, eight hardwired PC groups would be required. The number of PGR groups would be determined by the mission requirement. For example, the Encke Comet rendezvous mission will require 6 PGR groups, since only 6 thrusters are required for maximum thrust.

There are two technical approaches for the configuration of the PGR group. One of these approaches, classified as Option 2A is shown in block diagram form in Fig. 23.

The second approach, Option 2B, is similar to Option 2A but with the following changes:

(1) The regulated ac units of the PGR group are removed and become separate individual and redundant power conditioning units of the SEP module. The redundant line regulator and inverter will supply power through a separate switch to all power control units and to the SEP module support subsystems.

(2) The accelerator supply will be a part of the PC group because the screen supply output voltage is expected to be adjustable through a reference. However, grouping the accelerator supply with the screen supply would be advisable.

The block diagram of Option 2B is shown in Figure 24.

## A. COMPARISON OF OPTION 1 AND OPTION 2B

In order to examine the technical desirability between Options 1 and 2B a comparison was made for the following parameters: efficiency, weight and reliability. Because of certain previously outlined similarities, only Options 1 and 2B were selected for comparison. The results are summarized in Table 8.

The information shown in Table 8 was generated from the detailed analysis that follows:

### 1. Efficiency

No appreciable changes in estimated efficiency is expected, since both options use the same power supply designs.

2. Weight

The weight comparison was based on:

(1) The weight comparison of power processing units.
(2) The weight comparison of switches, and
(3) The weight comparison of cables for the two options

The power-processing units weight comparison data included all the power processing units of the SEP module: the power processing for the thruster, and the power conditioning for the support subsystem. Because the actual weight data exists for only the "low-voltage power processor," (a developed unit), the weight of the Options 1 and 2B power processor designs were based on that data. It should be mentioned that the weights are best estimates. The LVPP unit was developed under contract for JPL's SEPST III program in January 1970. This power processor was packaged on an eggcrate-modularized design (Ref. 3) and was designed to meet limited vibration requirements. The electronic components were mounted on a 40-mil magnesium chassis which served additionally as heat radiators. The power processor weight was 13.6 kg, including a shield cover of 0.9 kg. A comparison of the power processor weight for the two options is shown in Table 9.

In this study it was assumed that the spare or standby units are not essential. The total weight of the Option 1 power processor modules was calculated to be 12.3 kg. Adding to this weight of 12.3 kg, the weight of the 8th screen converter (0.8 kg) and the weight of the discharge standby inverter (0.5 kg), a total power processor weight of 13.6 kg is obtained. The weight of the Option 2B units is 9.6 kg for a PGR unit and 2.3 kg for a PC unit.

The breakdown of the power conditioning of the support subsystem is as follows: The estimated weight of Option 1 units is 7.4 kg composed of a single line regulator and 1 inverter.

The estimated weight of the Option 2 B units is 10.3 kg, consisting of a single line regulator and two inverters.

The comparison of the SEP module power unit for the two options utilizing the six power processors and power conditioning units for the SEP module support subsystem is as follows:

a. Option 1

| | |
|---|---|
| Propulsion power control, 6 units of 12.3 kg each | 73.8 |
| Power subsystem units | |
| One line regulator } One 2.4 kHz inverter } | 7.4 |
| Additional heater circuitry to keep thrusters warm during coast periods | 1.2 |
| Switches | |
| 6 units at 1.4 kg per unit (estimate) | 8.4 |
| Total | 90.8 kg |

b. Option 2B

| | |
|---|---|
| Power generator and regulator | |
| 6 units at 9.6 kg per unit | 57.6 |
| Power control | |
| 8 units at 5 kg per unit | 18.4 |
| Power subsystem units | |
| Line regulator | |
| 2.4-kHz inverter | 10.3 |
| (Additional heater circuitry not required. Thruster can keep warm by powering its own heaters) | |
| Switch (relays) 6 × 0.1 | 0.6 |
| Total | 86.9 kg |

A weight reduction in Option 2B system over Option 1 system can be calculated as:

$$\Delta = 90.8 - 86.9 = 3.9 \text{ kg}$$

The weight of the required switching concepts were estimates because of lack of data on the two proposed approaches; the 14 wire rotary switch versus the 3 or 4 wire relay or rotary switch.

No weight comparison of the cable weight was possible because the spacecraft configuration for the options was not complete. It should be mentioned that by separating the power processor into two modules it would be possible to locate the power control units closer to the thruster thereby reducing the lengths of the majority of the power delivering wires.

### 3. Reliability

The reliability comparison was based on observation instead of calculated data. It is expected that the 14-wire rotary switch will be more complex and, therefore, possibly less reliable. In addition, because of the lower number of wires to be switched, in Option 2B conventional-type switches or relays may be utilized. It is true that in Option 2B hardwiring of the heater supplies to the thruster introduces another series element in the reliability equation of the thruster which might reduce the thrust subsystem reliability. However these circuits process low power and can be designed to obtain very high reliability; so this penalty would be negligible.

The advantages that can be realized in 2B Option over Option 1 are:

(1) Possibility of "electronic tailoring" of each power control unit to each thruster, since the PC unit is a part of the thruster.

(2) In the case of standby thrusters, additional heaters will be required for temperature survival. The presence of a power control unit with each thruster will allow the turning on of the internal thrusters heaters as required.

(3) By combining the line regulator and inverter of each power processor and support subsystems into one unit it eliminates the separate power-conditioning units for the support subsystems.

A disadvantage of 2B Option over Option 1 is that by separating the present power processor design into two modules, separate control circuitry will be required that may add to the complexity of logic circuitry. However, such logic circuitry weight should be small.

B. PRELIMINARY FUNCTIONAL REQUIREMENTS OF THE OPTION 2B POWER PROCESSING UNITS

The preliminary functional requirements of the Option 2B power processor units are:

1. PGR Unit (Fig. 25)

(1) By command, turn ON the discharge supply and generate regulated dc current to ±1% corresponding to the received reference ($I_{ref}$) between 3.5 to 14.0 AU.

(2) By command, turn ON the screen and accelerometer supplies and generate regulated dc voltage of +1100 V ±1% and -500 V ±1%.

(3) Trip the screen and accelerometer supplies when an overload is detected at the output of the screen or accelerator supply and restart the supplies at the previous operating point after a predetermined time. If overload is repeated continuously after a predetermined number of trips, shut down the screen and accelerometer supplies.

(4) If screen supply is tripped due to overload, the discharge supply output current is reduced to a minimum (3.5 A) and is gradually increased to the previous operating point (ramping time to be determined after the screen supply is restarted.

(5) By command, turn off screen, accelerometer, and discharge supplies.

(6) Telemetry signals will be generated. The control circuit will be designed to control the supplied functions and accept the command and reference signals.

(7) The unit receives raw dc power, regulated ac power, timing signals, command signals, and reference signals.

2. Power Control Unit (Fig. 26)

(1) Receive regulated ac power for the transformer rectifier, regulator, heaters, and deliver the generated voltage and currents to the thruster.

(2) Receive from PGR units the regulated voltage, current of the screen and discharge power and deliver them to the thruster

(3) Turn on heaters as required by command

(4) Control the main vaporizer current by sensing the screen current and compare to the I reference

(5) Control the cathode vaporizer current by sensing the discharge voltage

(6) Control the neutralizer vaporizer current by sensing the neutralizer keeper voltage

(7) Provide isolated telemetry signals

(8) Accelerator TR trips on screen or accelerator overload

## C. PRELIMINARY POWER PROCESSOR PACKAGING CONSIDERATIONS

The method of packaging the LVPP power processor for SEPST III Program was by the utilizing of a single assembly containing all the various power and control units. Figure 27 shows the SEPST III eggcrate configuration upgraded for use for the SEPSIT Program (Ref. 1). These assemblies were to be mounted on the opposite sides of a structure with the power flowing in from the solar array at one end of the assembly and the power out to the thrusters at the other as shown in Fig. 28.

The study of power processing and distribution showed that it is desirable to have the power control and heater supplies as a separate assembly to be matched to each thruster. The screen and discharge supplies, where 86% of the power processor power dissipation occurred, will be packaged so that they could be switched to the selected thruster. This allowed a mixing of high-power and low-power units.

A method of packaging was proposed to effectively accomplish the widest range of possible combinations for a selected mission and/or multimission capability. Figure 29 shows the SEP module for the proposed combination of four power control units and three sets of screen and discharge supplies of the power generation and regulation units.

The packaging method proposed would utilize a Mariner/Viking size subassembly (Fig. 30) modified for use in a dual shear plate (DSP) configuration as shown in Fig. 31 (Ref. 2). This assembly has the same static and dynamic characteristics used for Mariner and Viking spacecraft and provides the flexibility of efficiently sizing for high or low dissipation subassemblies. Figures 32, 33, and 34 show a packaging arrangement that accommodates the volume and power requirements estimated in the power study.

For the study made, a 0.85 $m^2$ area for a 60°C temperature control surface assembly was used. A 2.6-kg weight savings per power processor was estimated for the DSP packaging over the eggcrate version for the same design requirements of resonant frequency and power dissipation. One factor was that the shear plate area would be considerably larger and possibly require heater power at some portion of the mission for the low dissipation portion in the eggcrate design.

The effect of thermal control or outer shear plate surface temperature on the power processor size is shown in Table 10 for two temperatures: 55 and 65°C. An estimate of the weight for the 55°C size of the power processor was 30 kg. The breakdown of the weight is shown in Table 11.

## X. CONCLUSION AND RECOMMENDATIONS

A brief study of the design considerations for processing and distributing power for a solar electric propulsion module have identified a number of interesting options. A solar electric propulsion module processes and distributes regulated power for the mercury ion thrusters and other SEP module supporting subsystems. A number of these options suggested a new design approach for such a power processor.

A brief comparison of a proposed design approach, Option 2B, to the present design configuration, Option 1, showed a number of advantages relative to weight and reliability for power processing and distributing power to the solar electric propulsion module. In addition, the proposed design approach generates new packaging consideration which may provide solutions to thermal and structural problems identified in the spacecraft configuration studies.

In contrast to these advantages, the question of control circuitry complexity for accommodating the new design approach was very briefly examined and not thoroughly analyzed.

This brief study of the design options has brought forward a proposed power processor design approach and deserves a closer in-depth consideration for its implementation into the solar electric propulsion mission of the future.

## REFERENCES


1. Gardner, J. A., Solar Electric Propulsion System Integration Technology (SEPSIT) Final Report, Technical Memorandum 33-583, Vol. II, Jet Propulsion Laboratory, Pasadena, Calif. Nov. 15, 1972.

2. Dawe, R. H., and Arnett, J. C., Electronic Assembly Packaging and Cabling for SEPSIT Rectangular Spacecraft, Report No. 900-623, June 29, 1973 (JPL internal document).

3. Hughes Aircraft Co., Development and Test of a Flight Prototype Power Conditioner for 20-cm Mercury Ion Bombardment Electric Thruster, Contract 952297, April 1, 1971.

Table 1. Power requirements of heater power supply group

| Component | Maximum ratings | | | Regulation |
|---|---|---|---|---|
| | $E_V$ | $I_A$ | W | |
| Main vaporizer | 10 | 2.0 | 20 | 5% (I) or loop with I screen |
| Cathode vaporizer | 10 | 2.0 | 20 | 5% (I) or loop with E discharge |
| Cathode heater | 15 | 6.0 | 90 | Current limited. ON during start, 5% (I) |
| Main isolator and cathode heaters | 10 | 4.0 | 40 | Current limited, 5% (V) |
| Neutralizer cathode heater | 10 | 5.0 | 50 | Current limited ON during start, 5% (I) |
| Neutralizer vaporizer | 10 | 2.0 | 20 | 5% (I) or loop with E neutralizer keeper |
| Neutralizer keeper | | | | |
| Start | 1000 | 0.02 | 20 | 5% (I). High voltage at initiation of discharge |
| Operate | 20 | 3.0 | 60 | |
| Cathode keeper | | | | |
| Start | 1000 | 0.02 | 20 | 5% (I). High voltage at initiation of discharge |
| Operate | 60 | 1.0 | 60 | |
| Magnetic baffle | 20 | 5.0 | 10 | 1% (I) current limited |

Table 2. Thruster heaters power requirements

| Heaters | Ratings, W | Startup power, W | Operating power, W | Warm-up power, W |
|---|---|---|---|---|
| Main vaporizer | 20 | 14 | 5.0 | 4.0 |
| Cathode vaporizer | 20 | 11 | 3.0 | 2.0 |
| Neutralizer vaporizer | 20 | 6 | 3.0 | 2.0 |
| Cathode heater | 90 | 62 | --- | --- |
| Neutralizer cathode heater | 60 | 42 | --- | --- |
| Main isolator and cathode isolator | 40 | 24 | --- | --- |
| Cathode keeper | 20 | 6 | 2.5 | --- |
| Neutralizer keeper | 60 | 24 | 18.0 | --- |
| Accelerator | 20 | 0 | 4.0 | --- |
| Magnetic baffle | 10 | 8 | 2.6 | --- |
| Totals | | 197 | 38.1 | 8.0 |

Table 3. Thruster supporting subsystem power requirements

| Subsystem | Thrusters in operation | | | |
|---|---|---|---|---|
| | 6 or 5 | 4 or 3 | 2 | 0 |
| | Power, W | | | |
| Interface unit | 18 | 18 | 18 | 18 |
| Propulsion power processors | 15 | 10 | 5 | 0 |
| TVC thrust vector control | 78 | 64 | 50 | 0 |
| Solar array pointing | 15 | 15 | 15 | 15 |
| Heaters | | | | |
| Power processors | 0 | 0 | 0 | 200 |
| Propellant distribution | 0 | 0 | 0 | 20 |
| Gimbal actuators | 10 | 20 | 30 | 40 |
| Thrusters, including spares | 24 | 48 | 72 | 96 |
| Miscellaneous heaters to keep the SEP module warm | 0 | 0 | 0 | 35 |
| Totals | 160 | 175 | 190 | 424 |

Table 4. Summary of screen power supply design options

| Option | Description | Conclusion | Decision based or required |
|---|---|---|---|
| 1 | Nonelectronic<br>Tilting arrays at 1 AU to limit voltage swing of the mission to 300 to 400 V | Ruled out | Excessive power loss at 1 AU |
| 2 | Switched panels<br>Switching panel from parallel to series at 1 AU and series to parallel later at other AUs. | Ruled out | Further study of mission profile to examine its feasibility is required. However, the switching complexity and weight penalty might be excessive |
| 3 | Common converter<br>Power for six thrusters ≈12 kW<br>Power for four thrusters ≈8 kW | Ruled out | Not technically feasible |
| 4 | Common converter for two thrusters<br>Power = 4 kW | Less desirable option<br>Added complexity | Operation of two thrusters from a common supply required isolation of power returns. Needs further investigation. Arc-over breakdown of one may also shut down the other |
| 5 | Separate converters with common bus<br>Parallel common converters | Less desirable option | Same as above |
| 6-9 | Separate converters per thruster with<br>Redundancy } switching<br>No redundancy } switching | Redundant units are mission dependent<br>Desirable option | High-power converters are susceptible to failure<br>Redundant units should be introduced where critical functions are performed |

Table 5. Summary of discharge power supply design options

| Option | Description | Conclusion | Decision based or required |
| --- | --- | --- | --- |
| 1 | Common inverter | Ruled out | Unique operational requirement of thruster (a) turn-on (b) arcover breakdown |
| 2-5 | Single inverter per thruster with | Mission dependent | High-power inverters are susceptible to failures |
| | No redundancy / Redundancy } and switching | Desirable | Redundant units should be selected on the basis of critical function |

Table 6. Summary of accelerator power supply design options

| Option | Description | Conclusion | Decision based or required |
| --- | --- | --- | --- |
| 1 | Combine with screen | Ruled out | If screen supply output voltage is variable |
| 2 | Input from heater inverter or line regulator | Desirable option | Present design |

Table 7. Summary of heater power supply group design options

| Option | Description | | Conclusion | Design based or required |
|---|---|---|---|---|
| 1 | Common line regulator on inverter with standby | | | Feasible supply design |
| | Maximum power | | Desirable option | No switching |
| | Start one thruster +5 operating | 387 W | | Heater power to each thruster as required |
| | SEP subsystem | 160 W | | |
| | Total | 547 W | | |
| | Minimum power | | | Power for SEP subsystem |
| | 2 thrusters operating | 76 W | | |
| | SEP subsystem | 190 W | | |
| | Total | 260 W | | |
| | Hardwired to power control unit and to thrusters | | | |
| All others | Line regulator and inverter — no standby in each PP | | The standby units are mission dependent | |
| | Line regulator and inverter — with standby in each PP | | | |
| | Switch to power control unit of each thruster | | Desirable option | 5 lines to be switched |
| | Hardwire the transformer-rectifier switch outputs to each thruster | | Less desirable option | (10 to 11) lines to be switched |

Table 8. Comparison summary of Options 1 and 2B

| | Option 1 | Option 2b |
|---|---|---|
| Estimated efficiency | Power overall efficiency = 91% | Power overall efficiency = 91% |
| | Screen supply 93%<br>Discharge supply 87%<br>Heater and others supply 80% | Screen 93%<br>Discharge 87%<br>Heater and others 80% |
| Weight | Power processor (Table 9) | A reduction of up to 3.9 kg for the system of 6 PPs to 8 thrusters and switches (see weight calculation) |
| | Cable weight: | |
| | 14 Wires to be switched | Only 3 or 4 wires to be switched |
| | | Additional reduction in cable weights can be realized by locating the power control unit in close proximity to the thruster |
| Reliability | Complex switching (14 lines) using a rotary switch | Switching of 3 or 4 lines can be done with conventional switches |
| | | The heater electronic circuits are connected directly to the thruster. However, these circuits are very low power and can be designed to obtain very high reliability |
| | No redundancy in inverter heater | Redundant heater inverters |

Table 9. Weight comparison of Options 1 and 2B

| Supplies | Option 1[c] Weight, kg | Option 2B[d] Weight, kg | |
|---|---|---|---|
| Screen supply[a] | 4. 8 | 4. 8 | Power generator and regulation 9. 6 kg No redundancy |
| Discharge[b] | 2. 3 | 2. 3 | |
| Staggered phase generator | 0. 4 | 0. 4 | |
| Frame | 1. 4 | 1. 4 | |
| Shield | 0. 9 | 0. 7 | |
| Accelerator | 0. 3 | 0. 3 | 2. 3 kg Power control |
| Low-voltage module | 0. 6 | 0. 6 | |
| Logic | 0. 3 | 0. 3 | |
| High-voltage module | 0. 5 | 0. 5 | |
| Frame (power control) | --- | 0. 4 | |
| Inverter | 0. 5 | --- | |
| Line regulator | 0. 3 | --- | |
| Isolation transformer | --- | 0. 2 | |
| Totals | 12. 3 | 11. 9 | |

[a]Screen supply, weight does not include a standby converter

[b]Discharge supply, weight does not include standby inverter

[c]Present power conditioner switches the outputs to the thruster

[d]Power generation and regulation unit switched to a power control unit per thruster

Table 10. Power processor sizing

| Subassemblies | Power dissipation,[a] W | Area, $m^2$ | | Shear plate length per subassembly based on footnote d | |
|---|---|---|---|---|---|
| | | Shear plate at 55°C[b] | Shear plate at 65°C[c] | 55°C | 65°C |
| High power | | | | | |
| Screen inventor (4) | 168 | 0.605 | 0.521 | 1.05 | 0.87 |
| Standby (1) | (42) | 0.151 | 0.130 | | |
| Discharge | 44.5 | 0.160 | 0.138 | 0.266 | 0.23 |
| Discharge output | 13 | 0.083 | 0.071 | 0.138 | 0.118 |
| Subtotal dissipation | 225.5 | | | | |
| Lower power units | | | | | |
| HV filter/ accelerator | 9.5 | 0.0342 | 0.0295 | 0.057 | 0.0492 |
| LV – power supplies | 13.0 | 0.0478 | 0.0403 | 0.080 | 0.0672 |
| Staggered phase generator/control | 12.5 | 0.0450 | 0.0397 | 0.075 | 0.0664 |
| Input filter | 8.5 | 0.0306 | 0.0263 | 0.051 | 0.044 |
| Subtotal dissipation | 43.5 | 0.1576 | 0.1358 | 0.263 | 0.2278 |
| Total dissipation | 279.0 | 1.056 | 0.8658 | | |
| Standby inverter | | 0.151 | 0.130 | | |
| Totals | | 1.207 | 0.996 | 2.01 | 1.66 |

[a]Operating at 2 A at 1 AU

[b]Using 0.0036 $m^2$/W normalized area at 1 AU

[c]Using 0.0031 $m^4$/W normalized area at 1 AU

[d]Assuming 0.6-m PP assembly shear plate width

Table 11. Estimated weight of power processor components at 55°C, 1 AU, 279 W dissipation (total area 1.207 $m^2$)

| Components | Weight, kg |
|---|---|
| Front and back shear plate | 8.5 |
| EMI and TC shielding | 0.9 |
| Louver support | 1.0 |
| Subassemblies (7 high-power subchassis, 4 low-power subchassis) | 9.0 |
| Harness and supports | 2.4 |
| Electronic components | 9.1 |
| TOTAL | 30.0 |

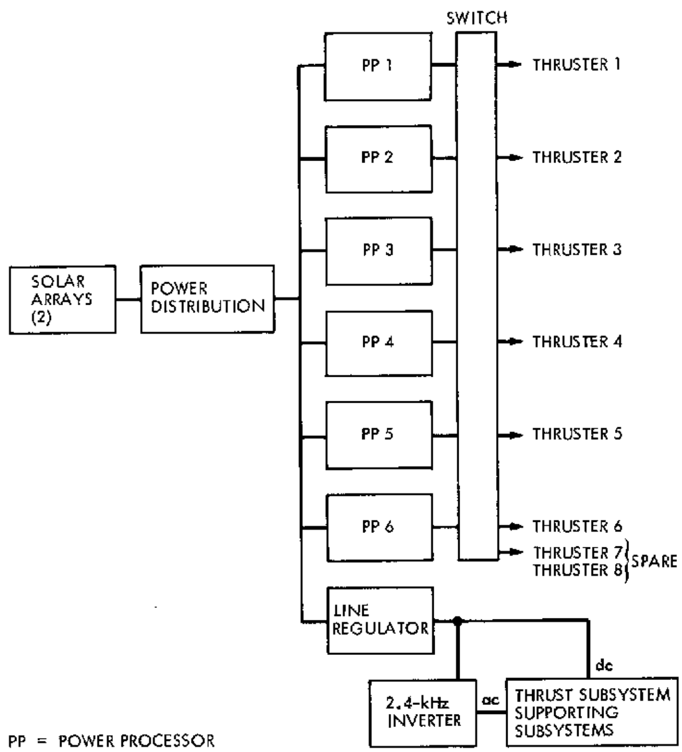


Fig. 1. SEP module power system block diagram

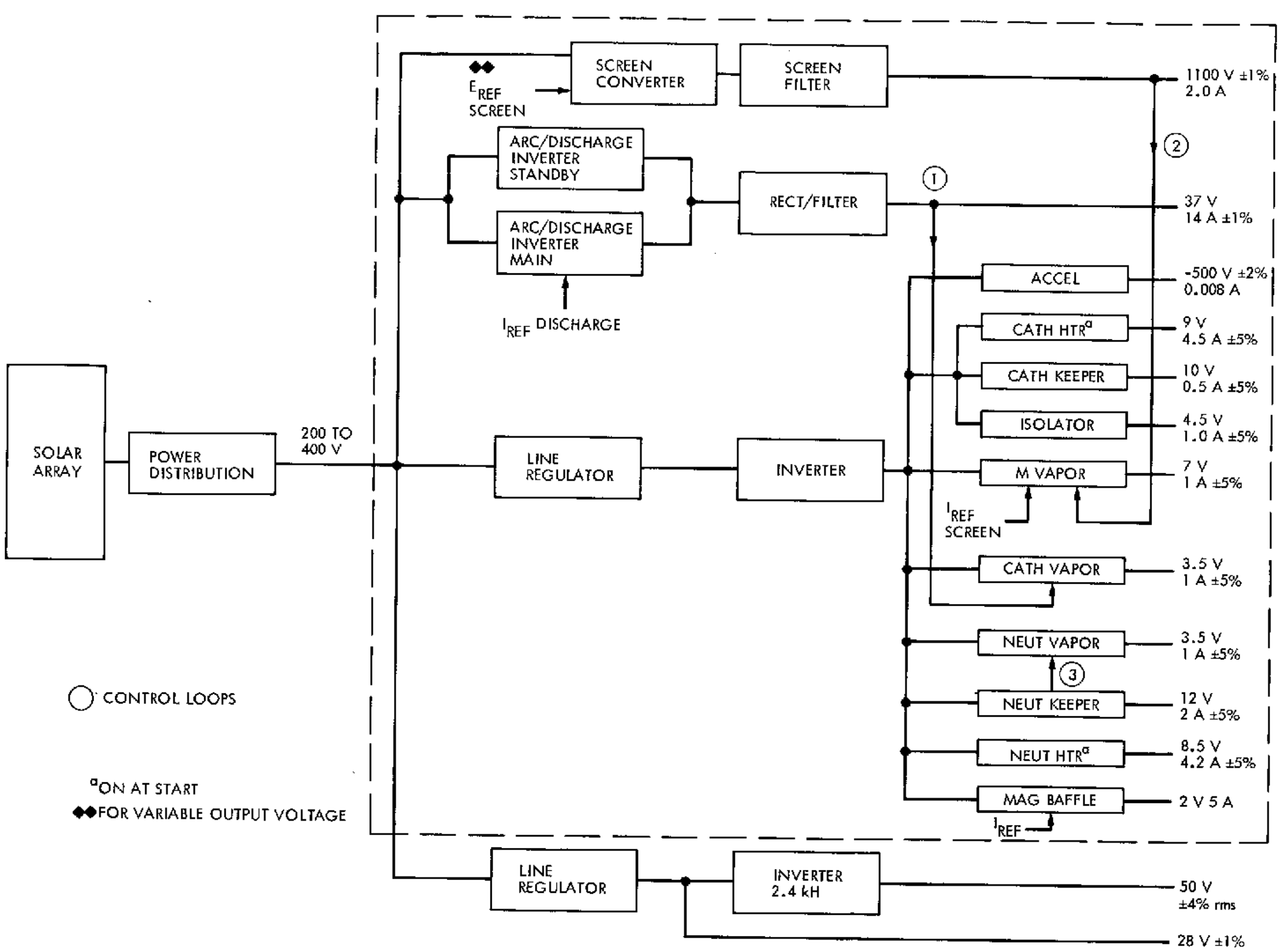


Fig. 2. Typical power processor (transistorized design) block diagram

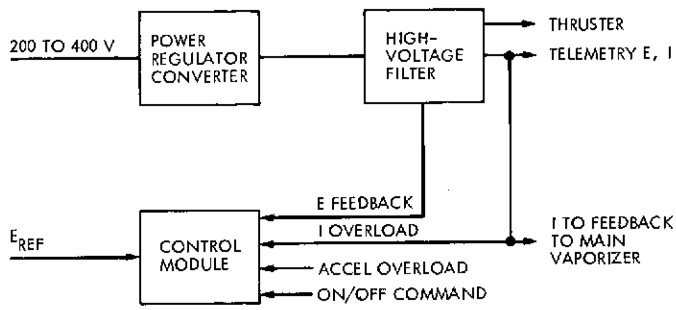


Fig. 3. Block diagram of screen power supply

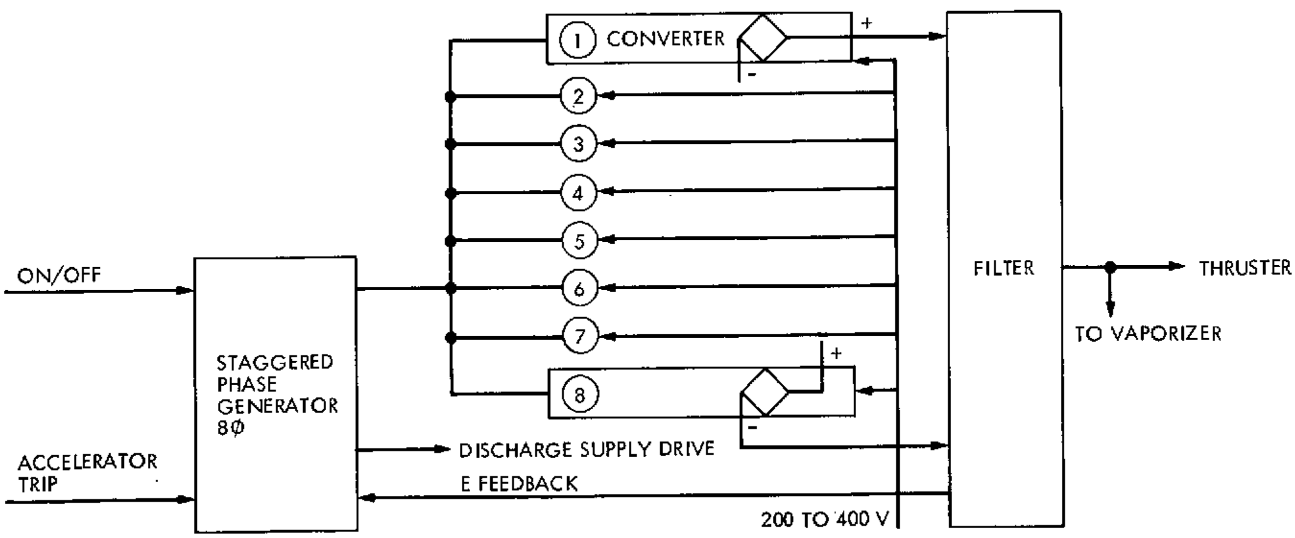


Fig. 4. SEPST III power processor screen power supply block diagram

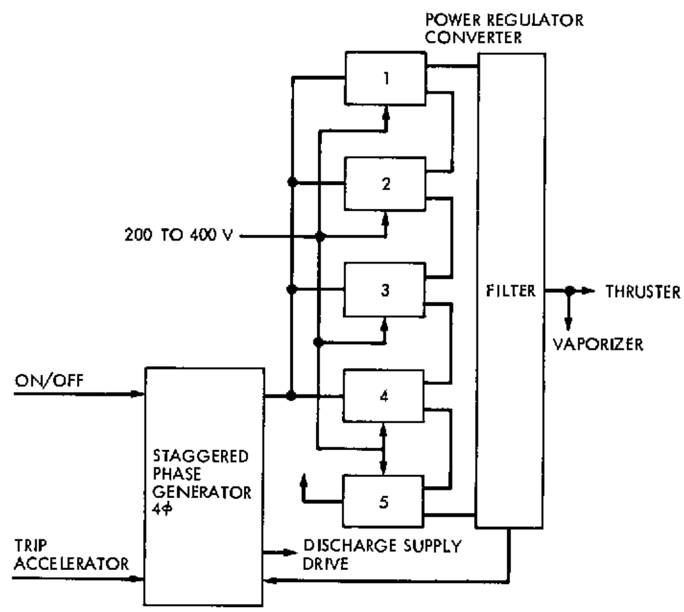


Fig. 5. 4-phase transistorized screen power supply block diagram

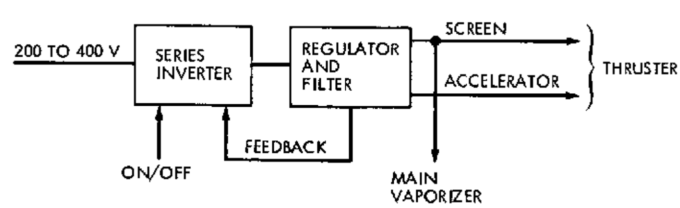


Fig. 6. TRW power processor screen power supply block diagram

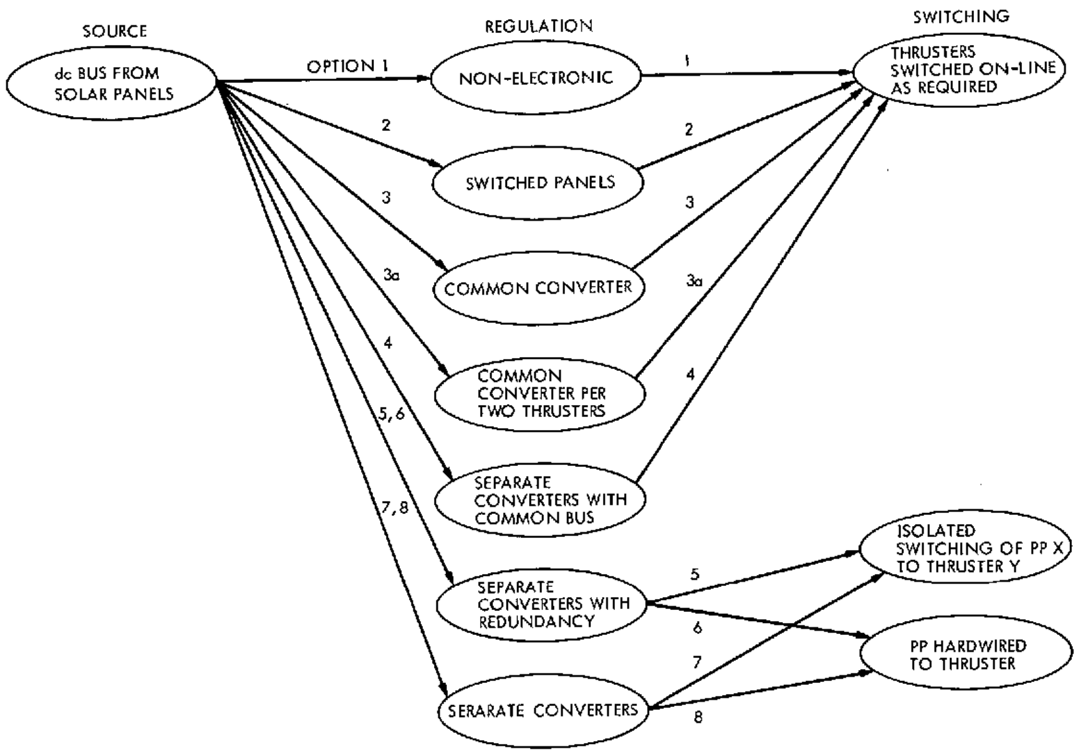


Fig. 7. Screen power supply design option

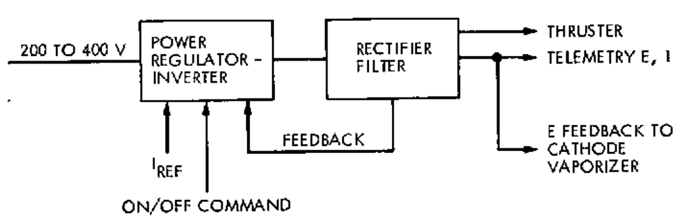


Fig. 8. Discharge power supply block diagram

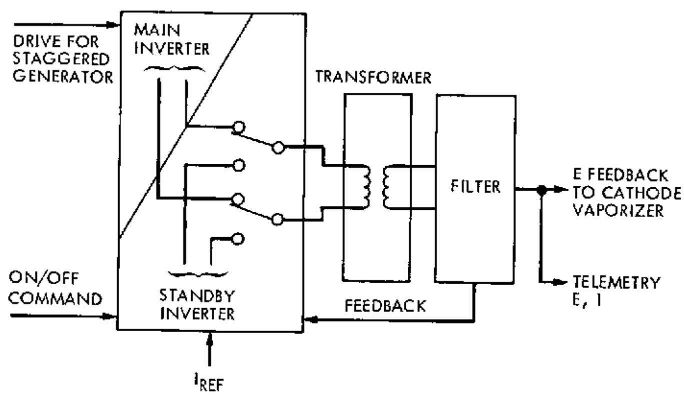


Fig. 9. SEPST III power processor discharge power supply block diagram

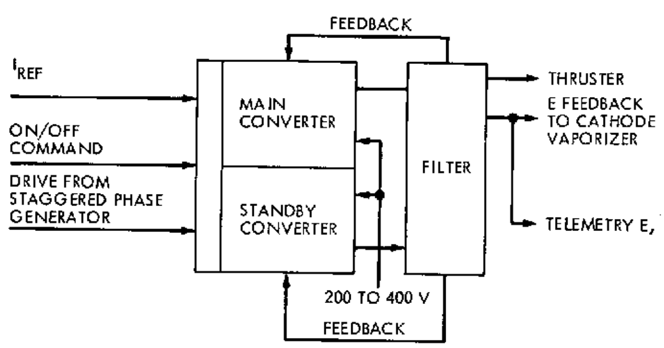


Fig. 10. Transistorized power processor discharge power supply block diagram

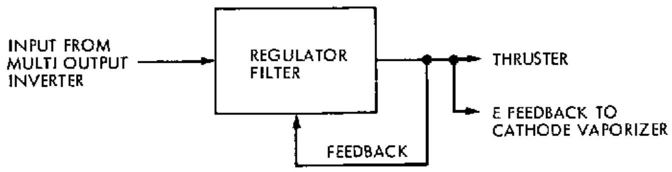


Fig. 11. SCR power processor discharge power supply block diagram

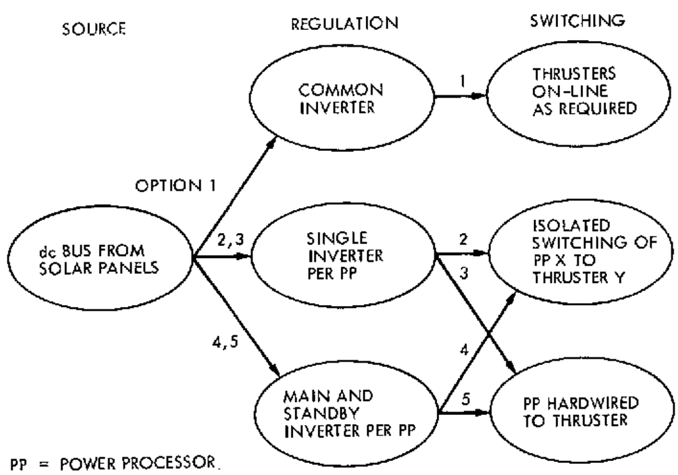


Fig. 12. Discharge power supply design option

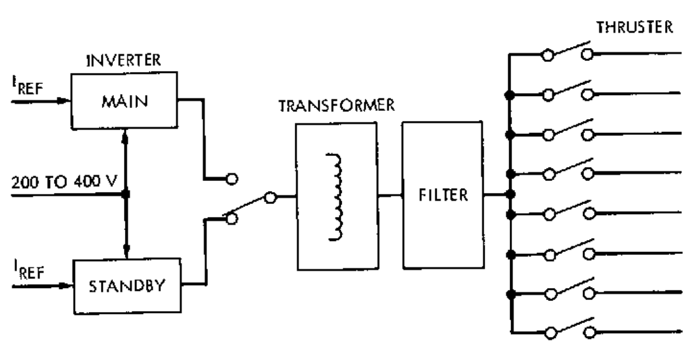


Fig. 13. Single inverter discharge power supply

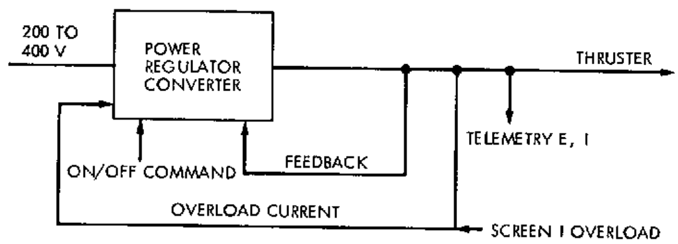


Fig. 14. Accelerator power supply block diagram

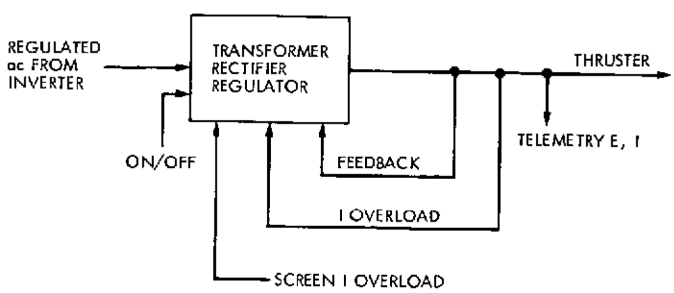


Fig. 15. SEPST III power processor accelerator power supply block diagram

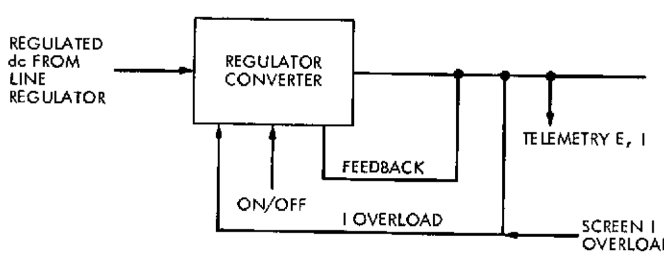


Fig. 16. Transistorized power processor accelerator power supply block diagram

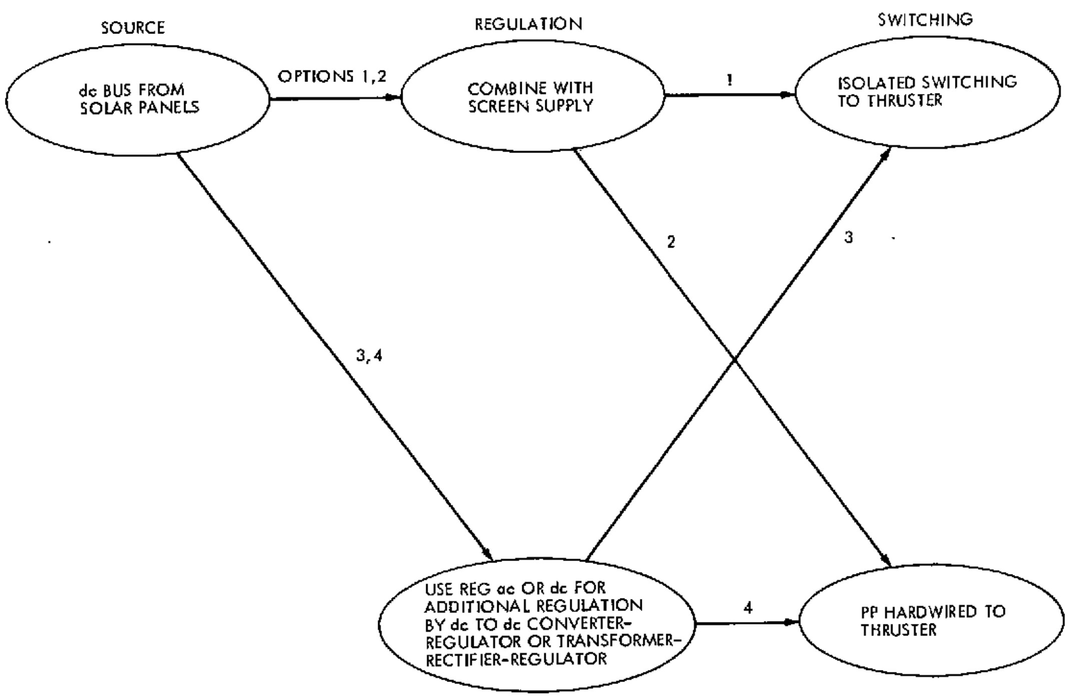


Fig. 17. Accelerator power supply design option

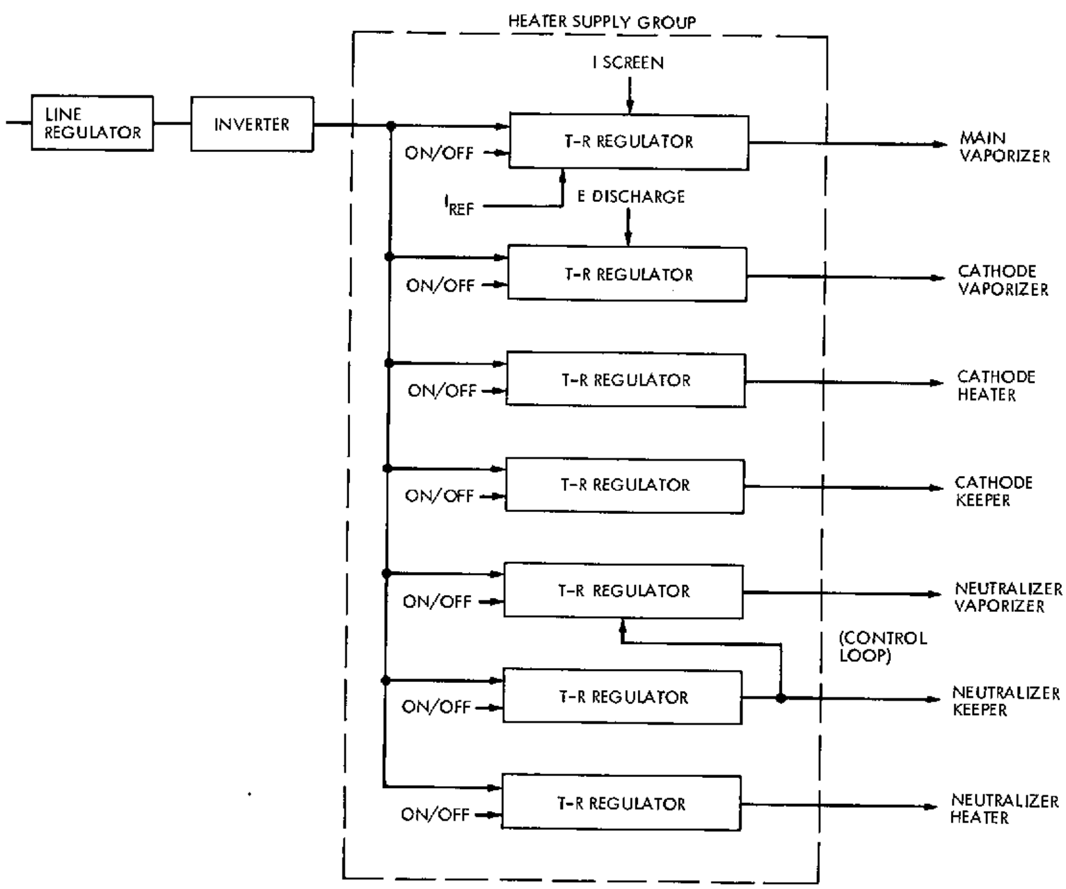


Fig. 18. SEPST III power processor heater power supply group block diagram

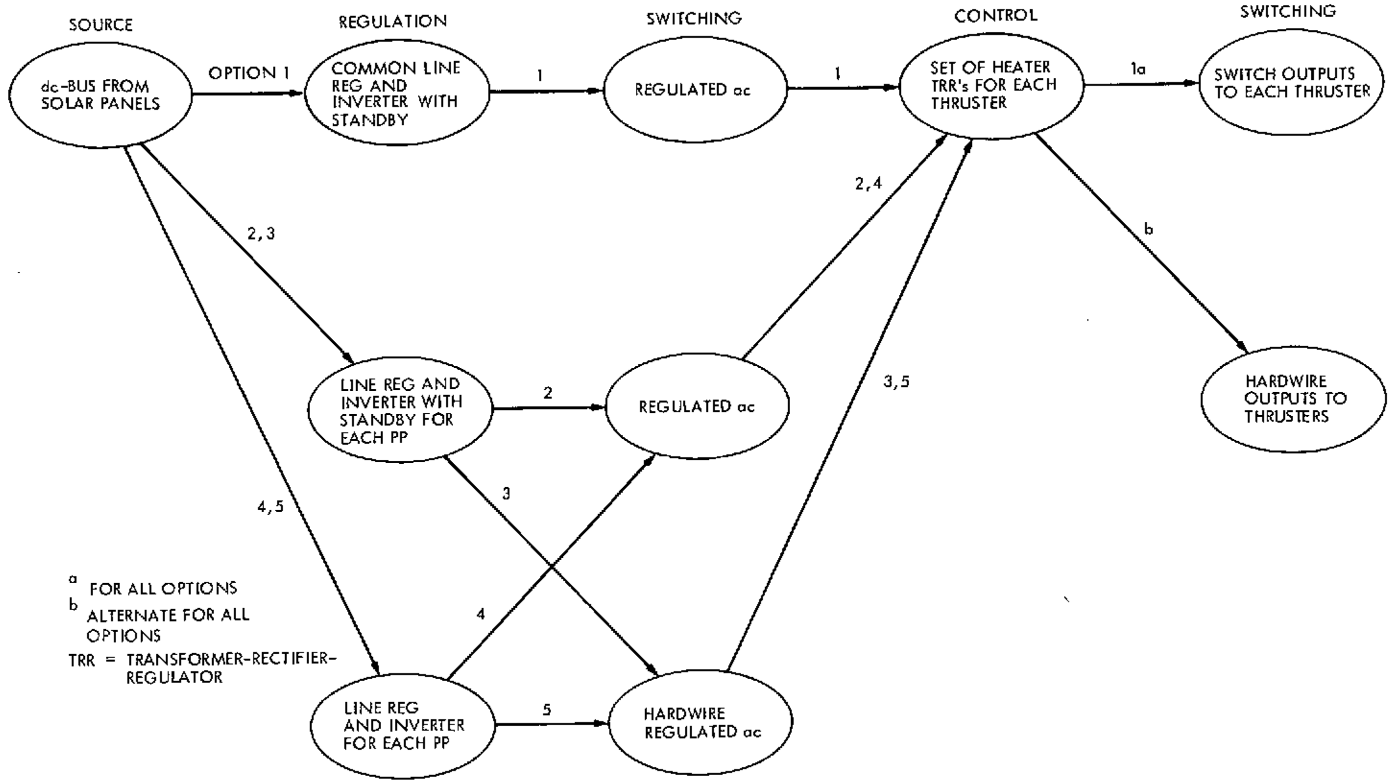


Fig. 19. Heater power supply group design option

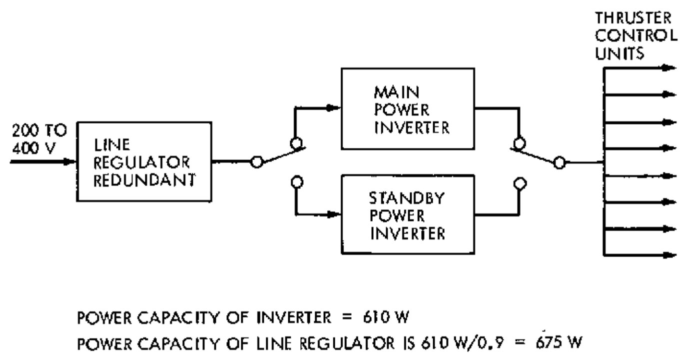


Fig. 20. Block diagram of the thruster power supply group ac input source

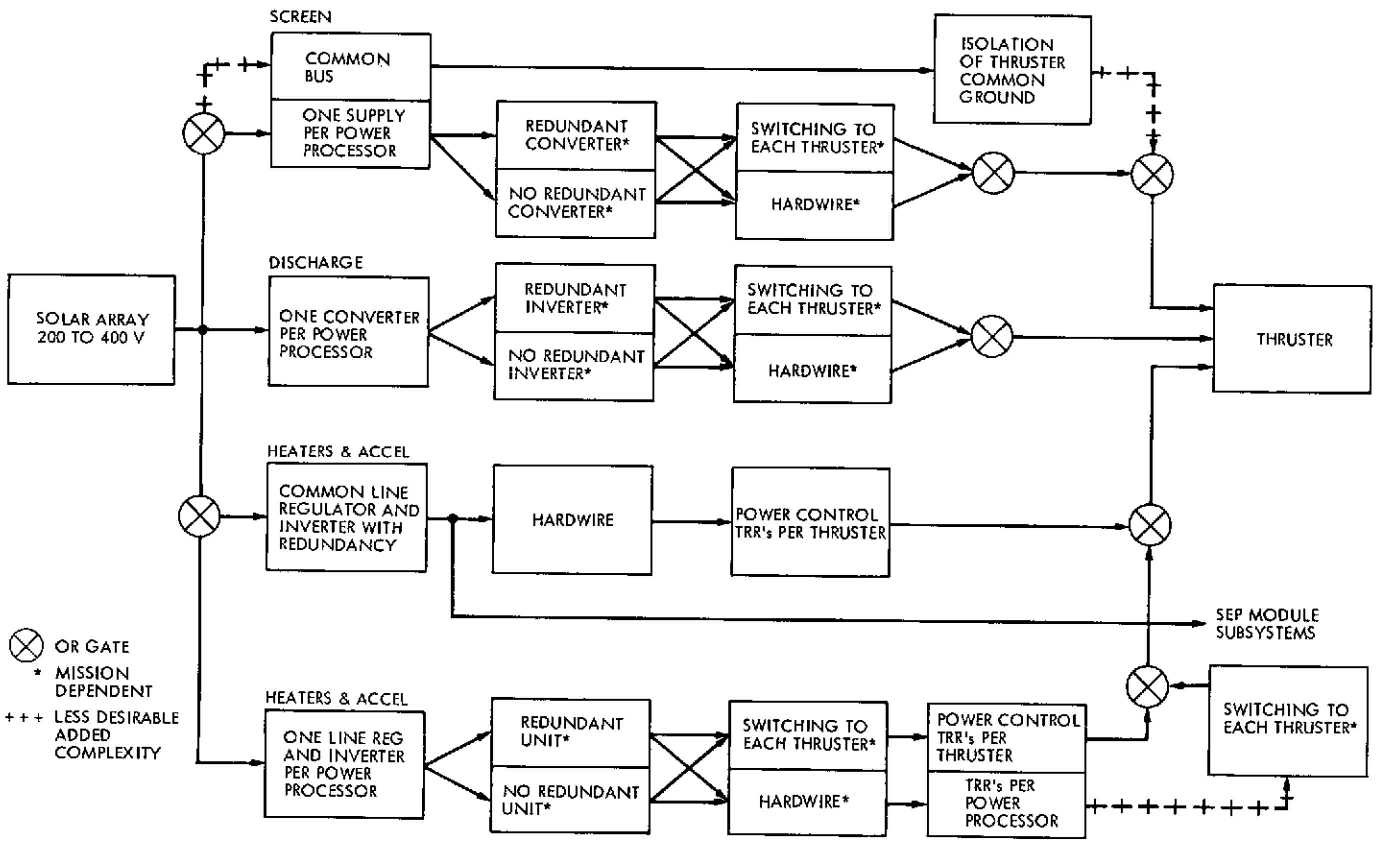


Fig. 21. Thruster power processor power distribution and conditioning options block diagram

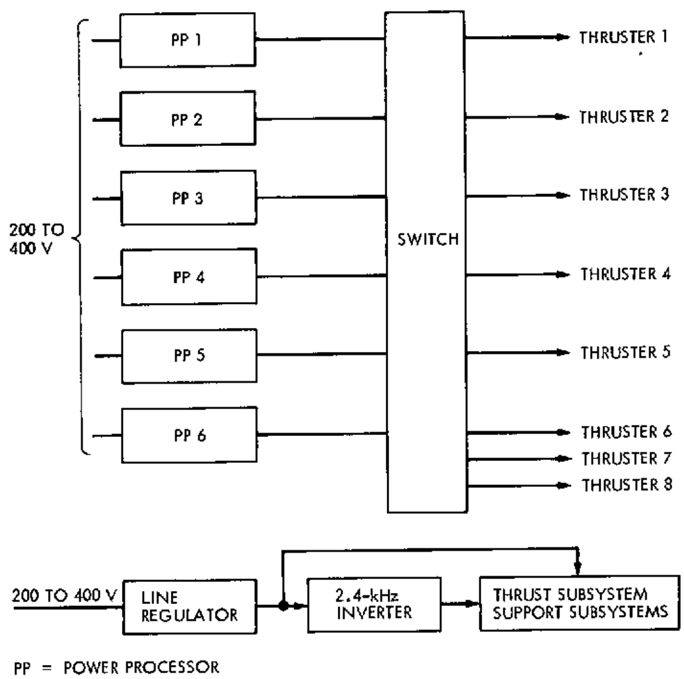


Fig. 22. Thrust subsystem configuration of Option 1

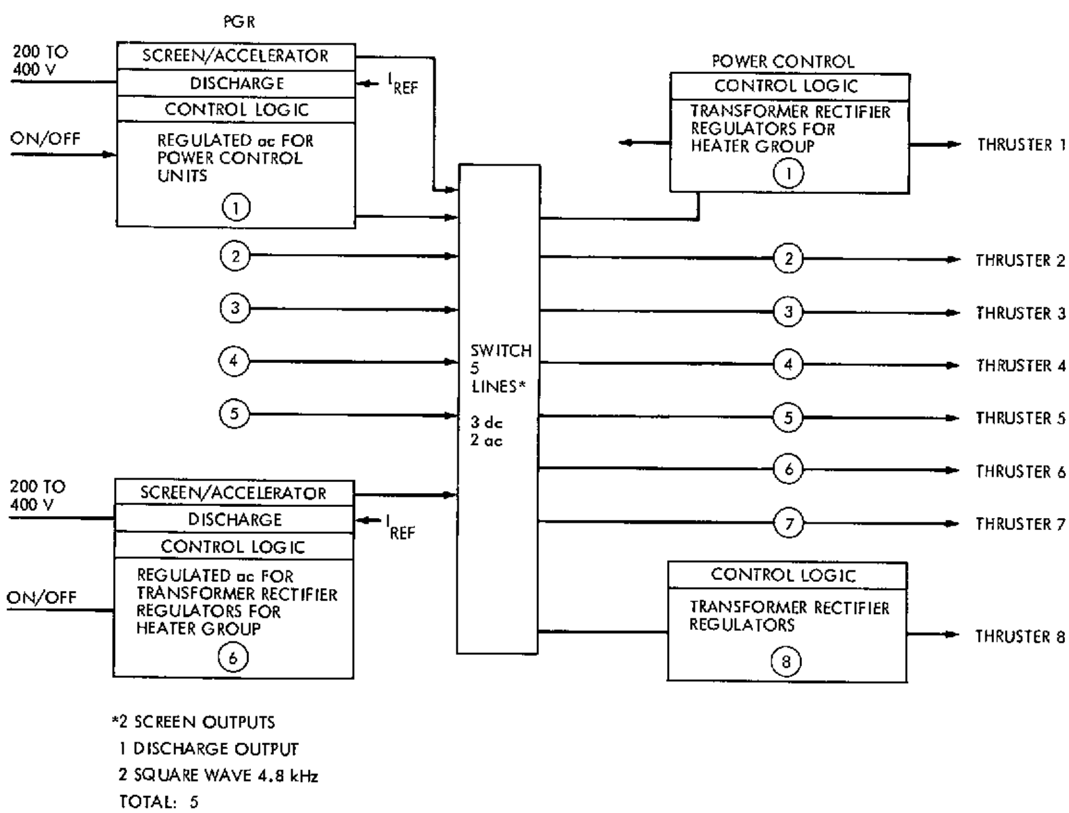


Fig. 23. Thrust subsystem configuration of Option 2A

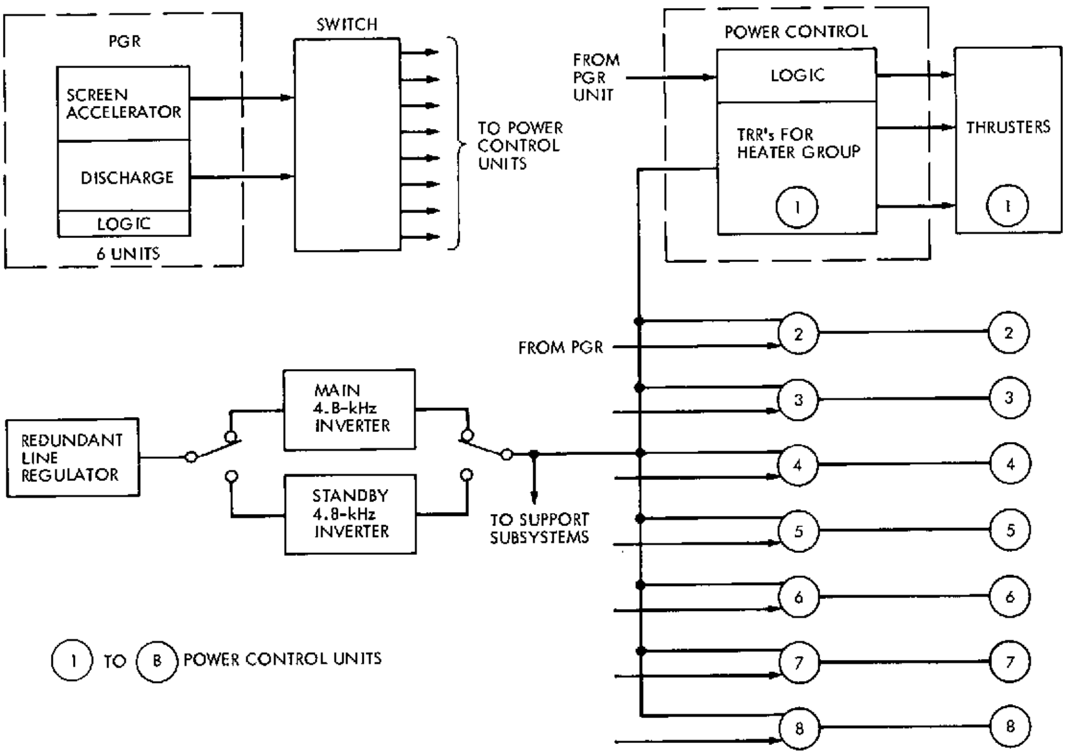


Fig. 24. Thrust subsystem configuration of Option 2B. Six PGR units and 8 power control units to 8 thrusters with separate power conditioners for ac power to control unit and support subsystem

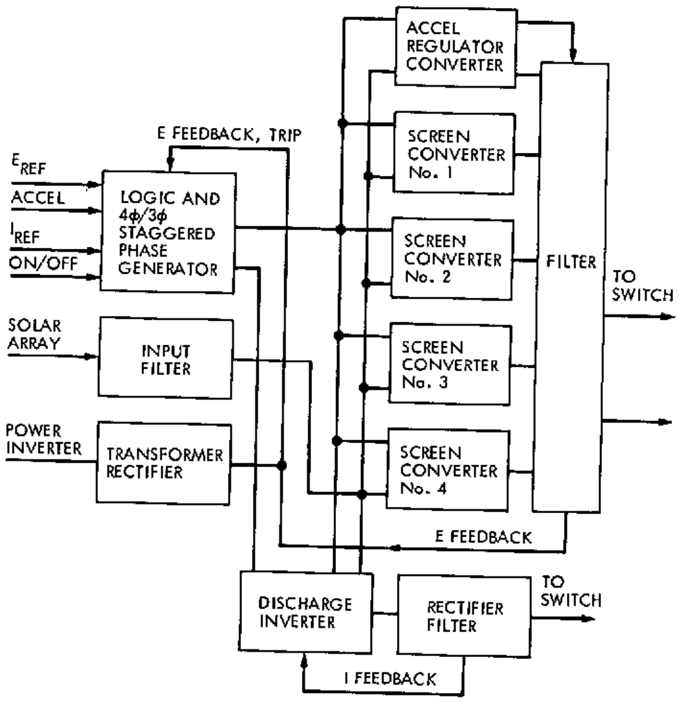


Fig. 25. Block diagram of a proposed power generation and regulation unit

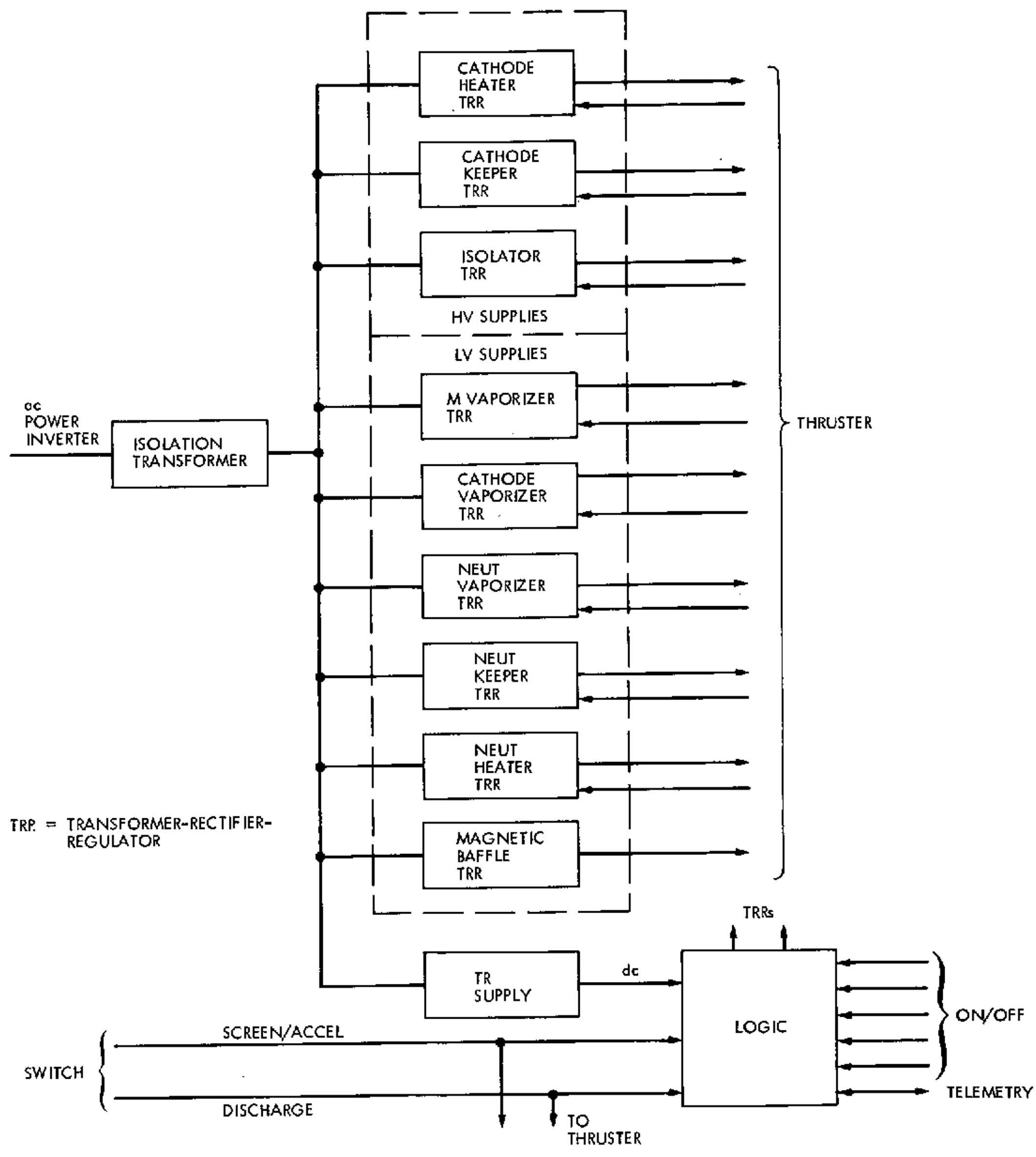


Fig. 26. Block diagram of a proposed control unit

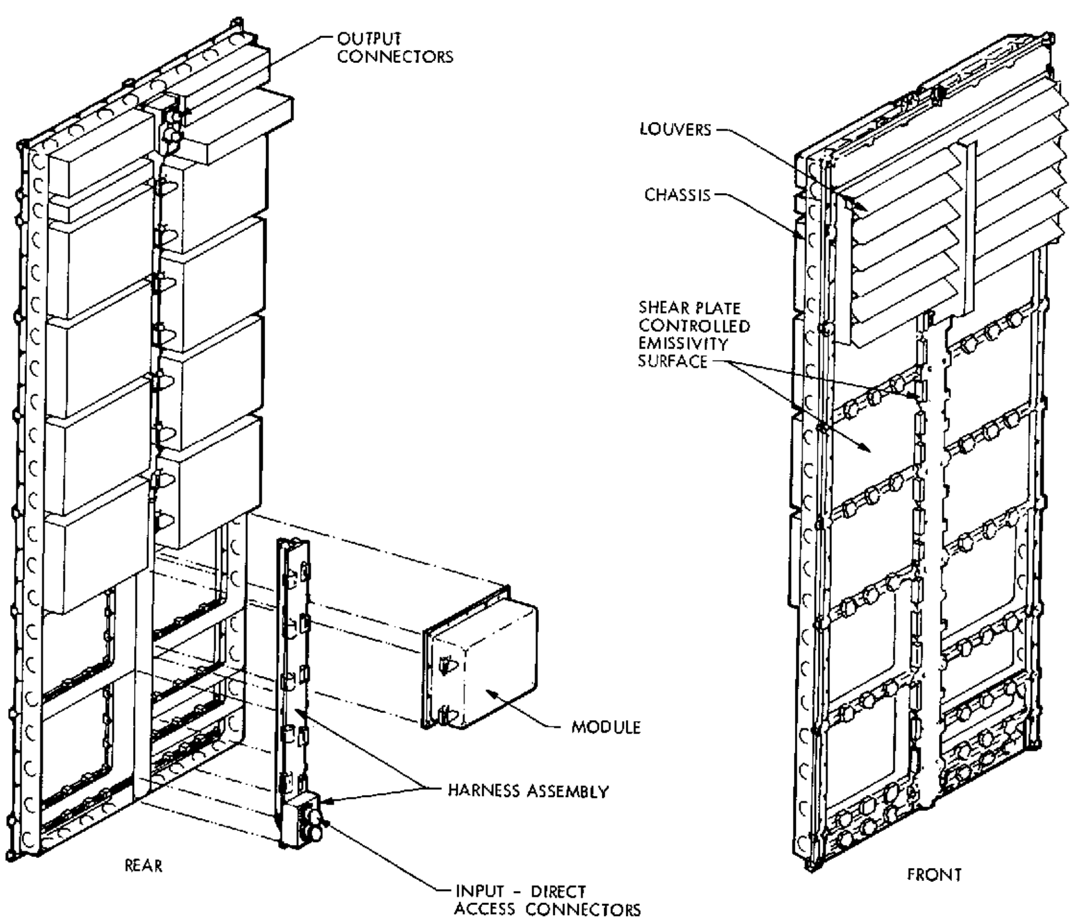


Fig. 27. SEP power conditioner assembly using eggcrate construction

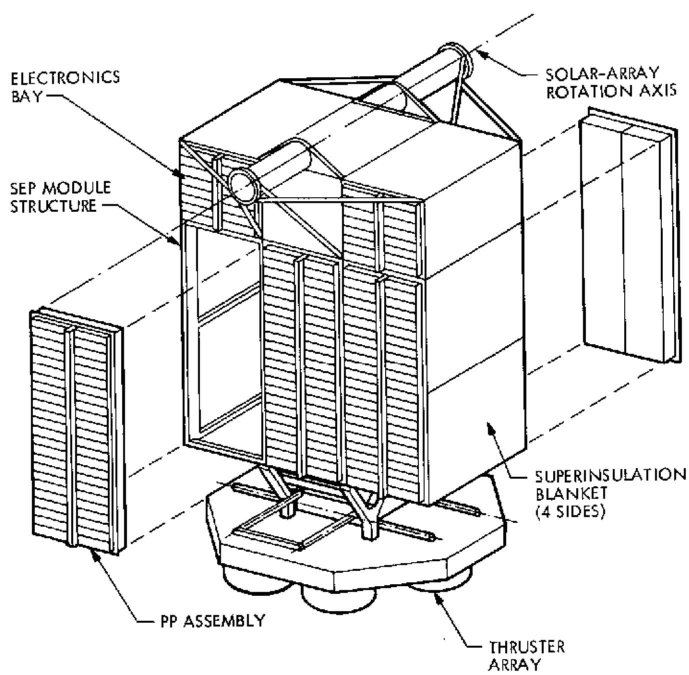


Fig. 28. PC and support electronics compartment

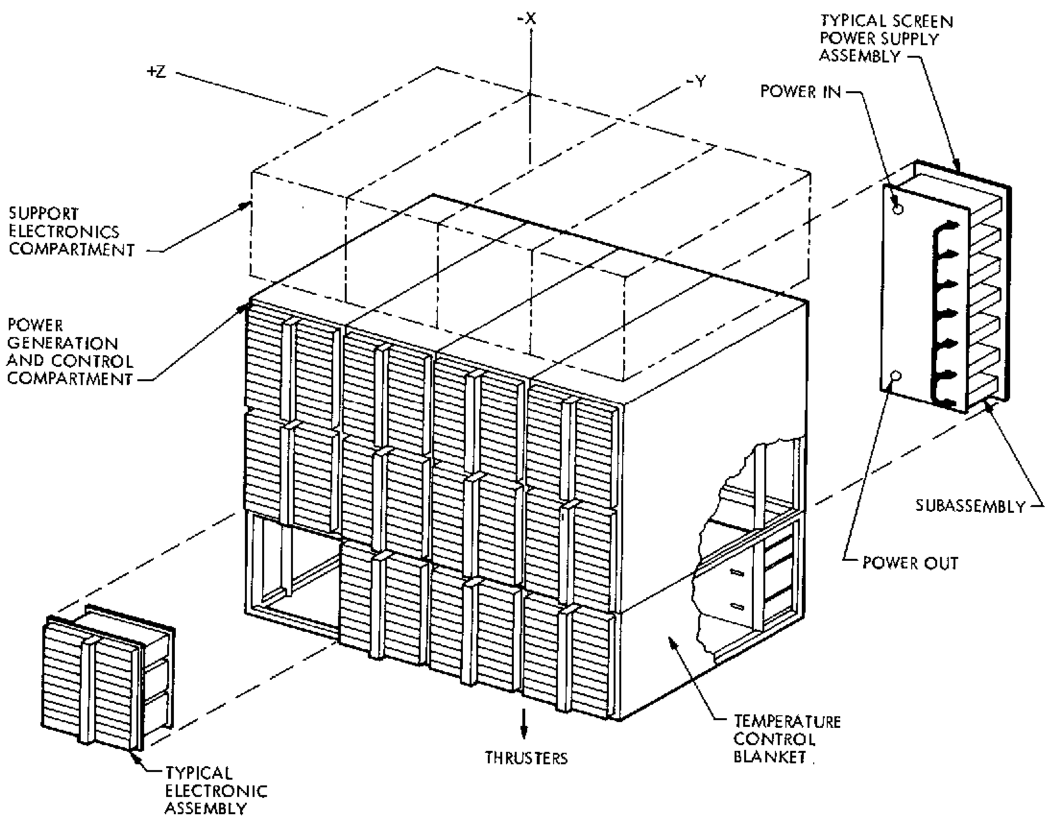


Fig. 29. Thrust subsystem SEP module electronics compartment

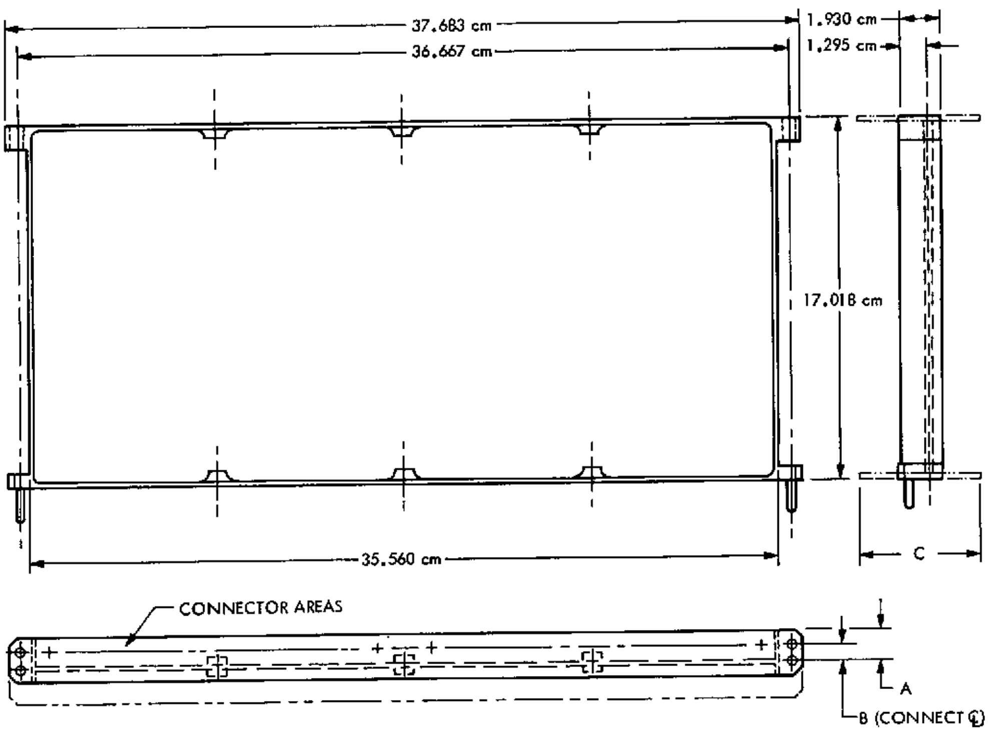


Fig. 30. SEP subchassis envelope

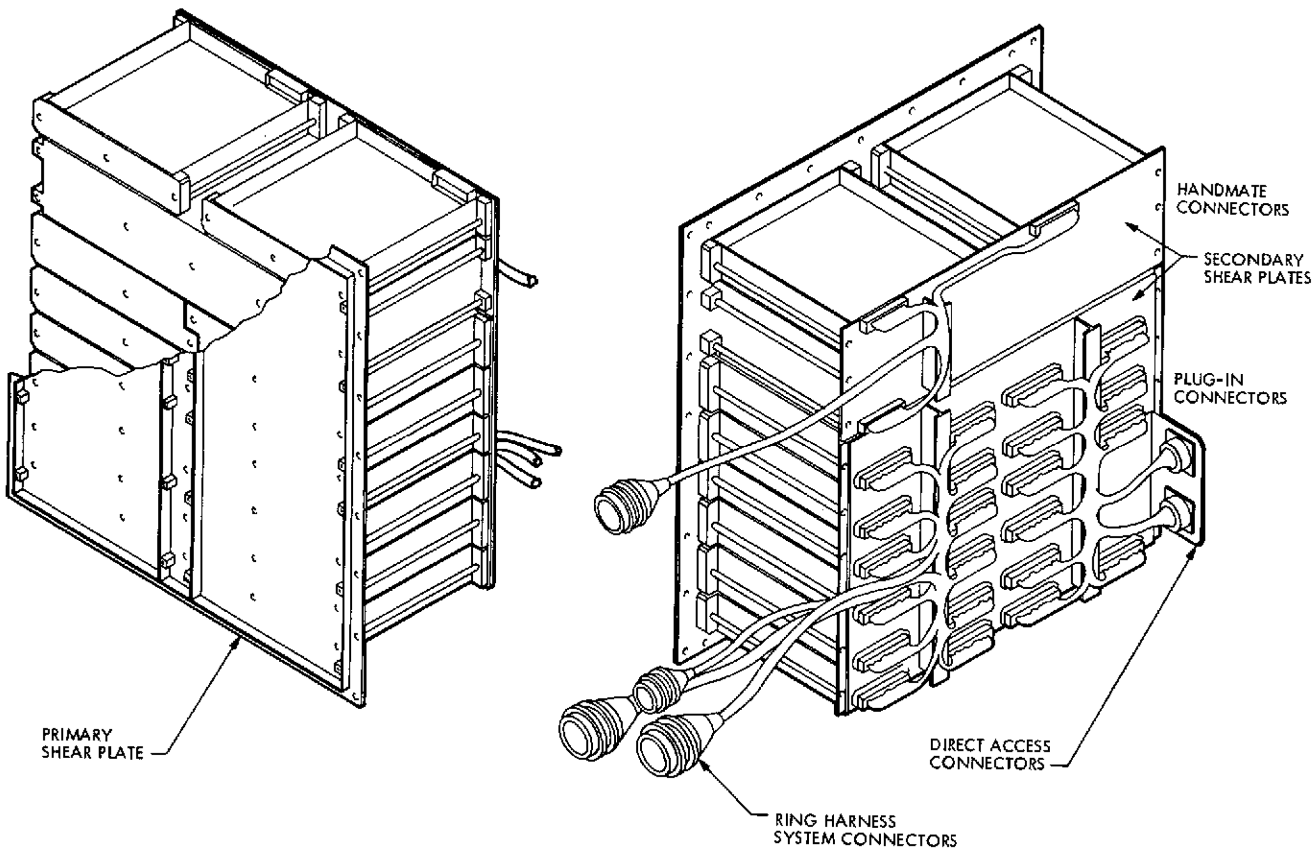


Fig. 31. Typical dual shear plate electronic assembly

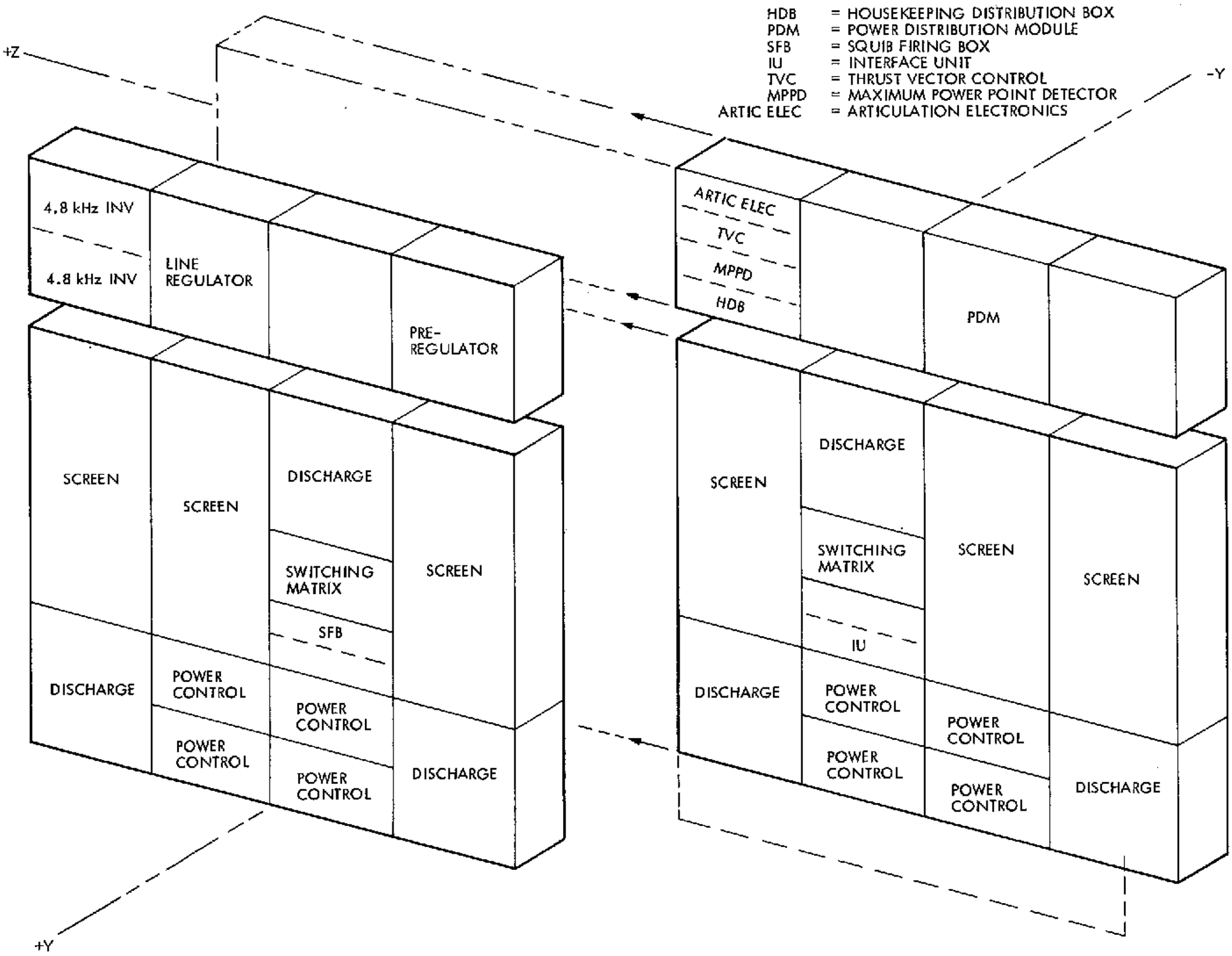


Fig. 32. Thrust subsystem SEP module electronics packaging arrangement

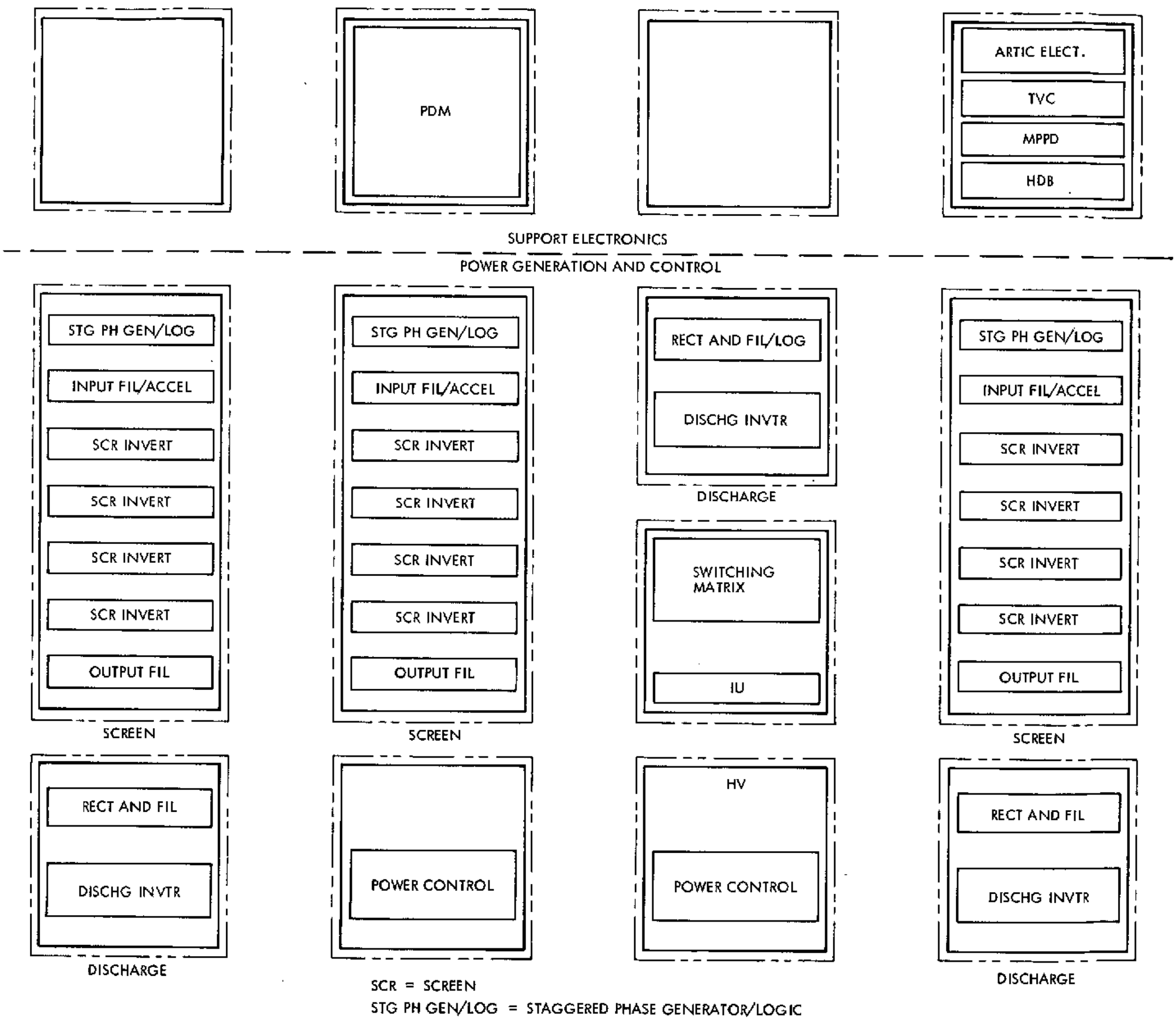


Fig. 33. Thrust subsystem SEP module electronics packaging arrangement, -Y side

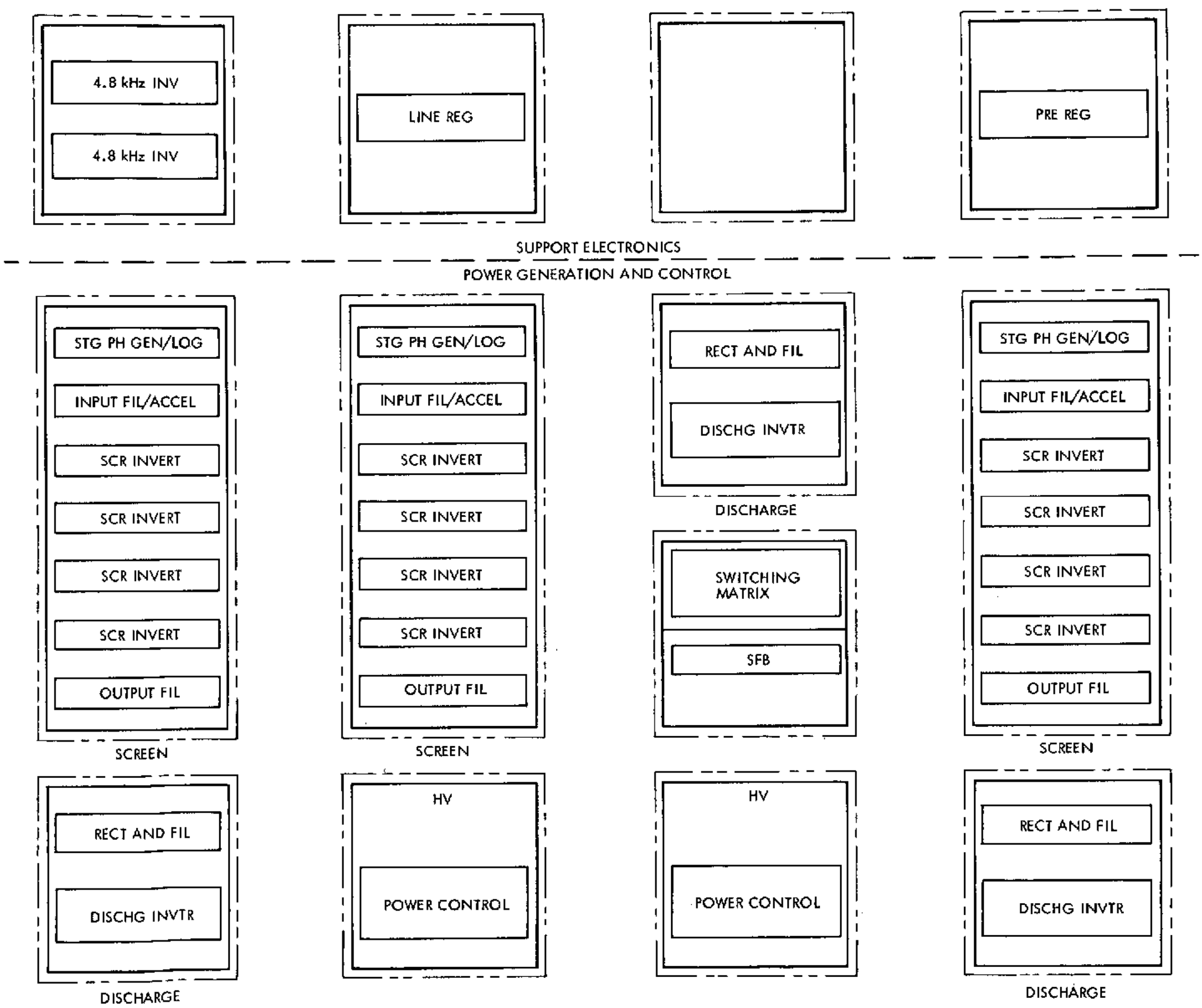


Fig. 34. Thrust subsystem SEP module electronics packaging arrangement, +Y side



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