CR-135357

TRW 31526.000

EXTENDED PERFORMANCE ELECTRIC PROPULSION POWER PROCESSOR DESIGN STUDY

FINAL REPORT

VOLUME I - EXECUTIVE SUMMARY

November 1977

by:

TRW Defense and Space Systems Group
Power Conversion Electronics Department

Prepared for:

National Aeronautics and Space Adminstration
NASA Lewis Research Center

Contract NAS 3-20403

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16. Abstract

Electric Propulsion Power Processor Technology has processed during the past decade to the point that is is considered ready for application. During this study, several power processor design concepts were evaluated and compared. Emphasis was placed on a 30cm ion thruster power processor with a beam supply power rating of 2.2kW to 10kW. Extensions in power processor performance were defined and were designed in sufficient detail to determine efficiency, component weight, part count, reliability and thermal control.

Preliminary electrical design, mechanical design and thermal analysis was performed on a 6kW power transformer for the beam supply.

Bi-Mod mechanical, structural and thermal control configurations were evaluated for the power processor and preliminary estimates of mechanical weight was determined.

A program development plan was formulated that outlines the work breakdown structure for the development, qualification and fabrication of the power processor flight hardware.

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FORWARD

The work described herein was performed in the Power Conversion Electronics Department of the Electrical System Laboratory within the Space Systems Division of TRW Defense and Space Systems Group. This department is managed by Mr. Bert J. McComb. The work was funded under contract NAS 3-20403 and monitored by Mr. Robert Frye of the NASA Lewis Research Center. The key technical contributors were:

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Chuck Louie	Project Engineer for Digital Interface Unit Microprocessor
Bernie Shupack	Project Engineer for Thermal Control of Power Processor and Power Magnetics
Bob Heile	Project Engineer for Reliability
A. D. Schoenfeld	Technical and Project Review
M. G. Monegan	Mechanical and Thermal Design Review

SUMMARY

The primary objective of this study was to provide a data base for a program plan for the development of the ion propulsion power processor for the Hälley's Comet Mission Spacecraft. This data base was to include:

- Conceptual design and tradeoffs for electric propulsion power processor with a power rating up to 10kW beam power.
- Identification of New Technology Requirements and potential savings and risks.
- Selection of a preferred Power Processor Configuration.
- Preliminary Electrical and Mechanical Design of the preferred configuration.
- Program plan for the electric propulsion power processor in support of Halley Comet Mission.

A preferred configuration for the power processor was selected as a result of detailed analysis of the data base. A complete electrical design was performed for a 6kW and 2.2kW beam supply power processor based on a revised power processor requirement specification and updated electrical design for product improvement in the area of part count reduction, weight reduction and efficiency improvement.

The following is a summary of the 6kW power processor design characteristics:

Electrical Component weight	21.3KG
Electrical Component losses	605W
Efficiency at nominal load	91.5%
Part count	2720
Mech. packaging/hardware wt.	21.0KG
Volume	.107 cu meter

The following is a summary of the 2.2kW power processor design characteristics:

Electrical Component weight	14.4KG
Electrical Component loss	333W
Efficiency at nominal load	89.2%
Part count	2587
Mech. pkg./hdwr weight	14.4KG
Volume	.073 cu meter

The designs were based on existing component technologies and therefore the technical risks were minimal and would not compromise the overall program schedule.

A detailed program plan schedule and cost estimate was completed for the following list of hardware:

- Engineering/qualification model
- Prototype models (quantity 4)
- Flight models (quanty 18)
- Associated manufacturing test support equipment

The overall costing based on 1977 dollars was 17.2M over a four year period in support of the Halley Comet Mission Launch in 1982. The major program risk was the timely funding of the different design, qualification and manufacturing phases to meet the schedule launch date.

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1. INTRODUCTION

Solar electric propulsion is being viewed as matured, developed technology that can be applied to new high energy missions in the 1980 time frame with the Shuttle/IUS as the launch vehicle.

The Halley Comet rendezvous mission requires a major decrease in the ion drive system specific mass currently projected for the 3kW, 30cm ion thruster as approximately 50kg/kW. This requirement necessitates a thrust system design which increases the output power to greater than 6kW.

Because of the increase in output power level, it is necessary to redesign the power processor. Contract NAS3-20403, "Extended Performance Electric Propulsion Power Processor Design Study," performed the necessary conceptual design and tradeoffs to identify the preferred power processor circuit configuration that meet the new requirements while at the same time reducing the specific mass KG/KW and improving the power processor efficiency and reliability.

This study program had three objectives. The first was to evaluate the power processor unit at higher beam supply power levels (from 2.2 to 10kW). The second was to evaluate revised requirements and alternate methods of implementation for the low power supplies of power processing unit; and the third was to develop a power processor program plan to support a Halley's Comet Mission. The outputs of the first two objectives are system approaches versus weight, efficiency, parts count, reliability, and component technology requirements.

The information obtained from this contracted effort was used in direct support of a Halley Comet rendezvous mission study completed in the summer of 1977 and other alternate electric propulsion missions being planned in the 1980 time period.

This report summarizes the results of a six month study to define the design, program plan and cost of the electric propulsion power processor for the Halley's Comet Mission Spacecraft.

The following sections summarize the results of the design tradeoff studies. After the selection and approval of the preferred configuration by NASA Lewis, a detailed electrical design, magnetic design and thermal control and conceptual mechanical packaging was performed.

A brief description of the program plan and work breakdown structure and associated schedules is presented.

An assessment of the technical risks is also presented.

2. DESIGN TRADEOFF STUDIES

The first task of the study program considered a spectrum of alternate power distribution systems, mechanization of the beam supply up to 10KW, mechanization of discharge supply, mechanization of the low voltage supplies and the method of controlling the power processors by means of central computer or localized microprocessor. The following sections present the results of the design tradeoff studies. Section 3.0 Baseline Design presents the results of the detail design of the selected power processor configuration.

2.1 Power Distribution System

Two separate power distribution systems were studied:

a) a single 200-400VDC solar array bus supplies all the power to the thrust subsystem and the mission module.

b) a 200-400VDC solar array bus supplies power to beam and discharge supplies for the thrust subsystem and a separate 28VDC solar array supplies power to the ion thruster low level outputs and the mission module.

Figures 2-1 and 2-2 present the basic block diagrams for these different power distribution systems. Table 2-I and 2-II summarizes the characteristics of the two different systems.

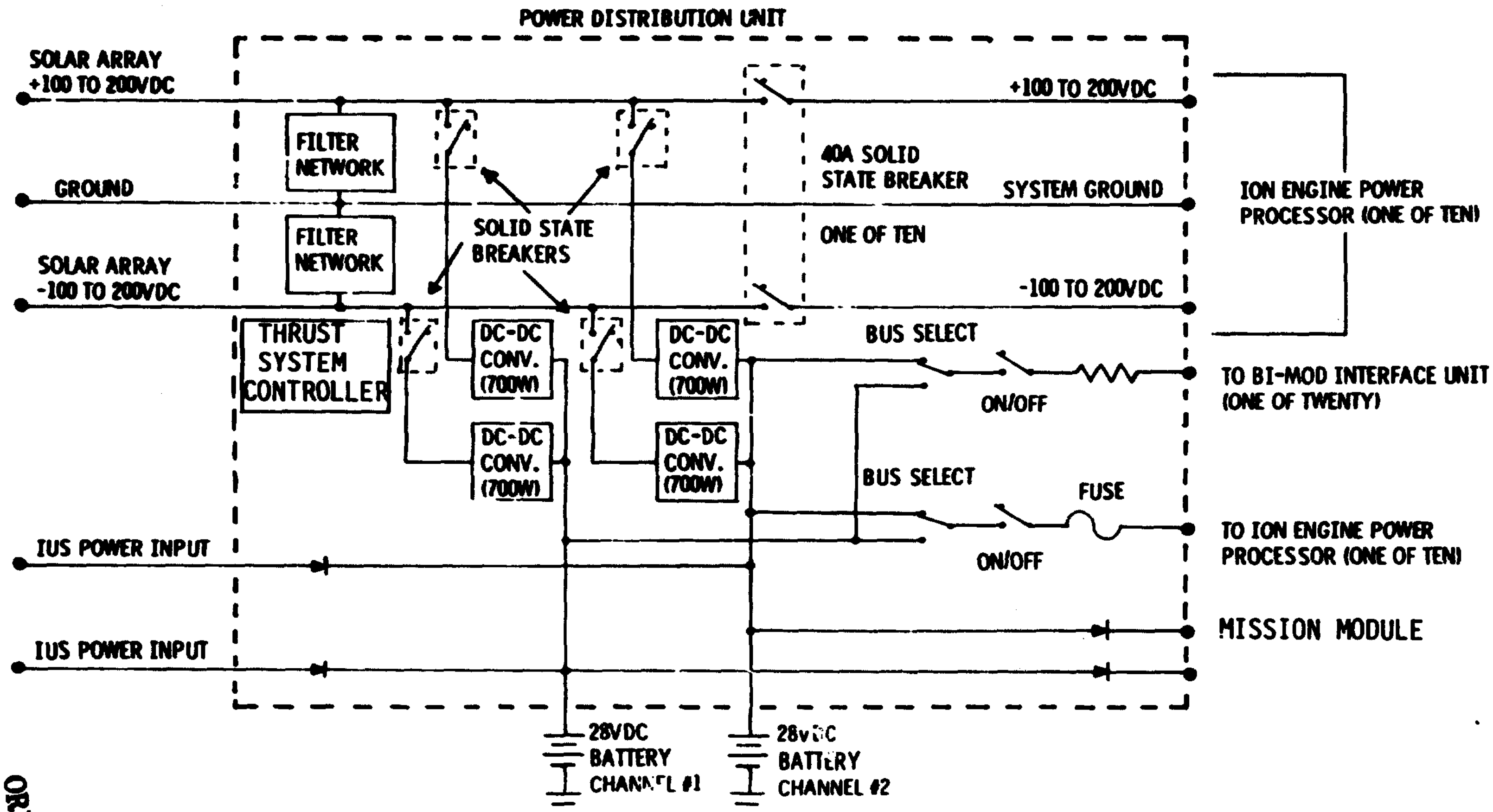

Figure 2-1. 200-400VDC Power Distribution System

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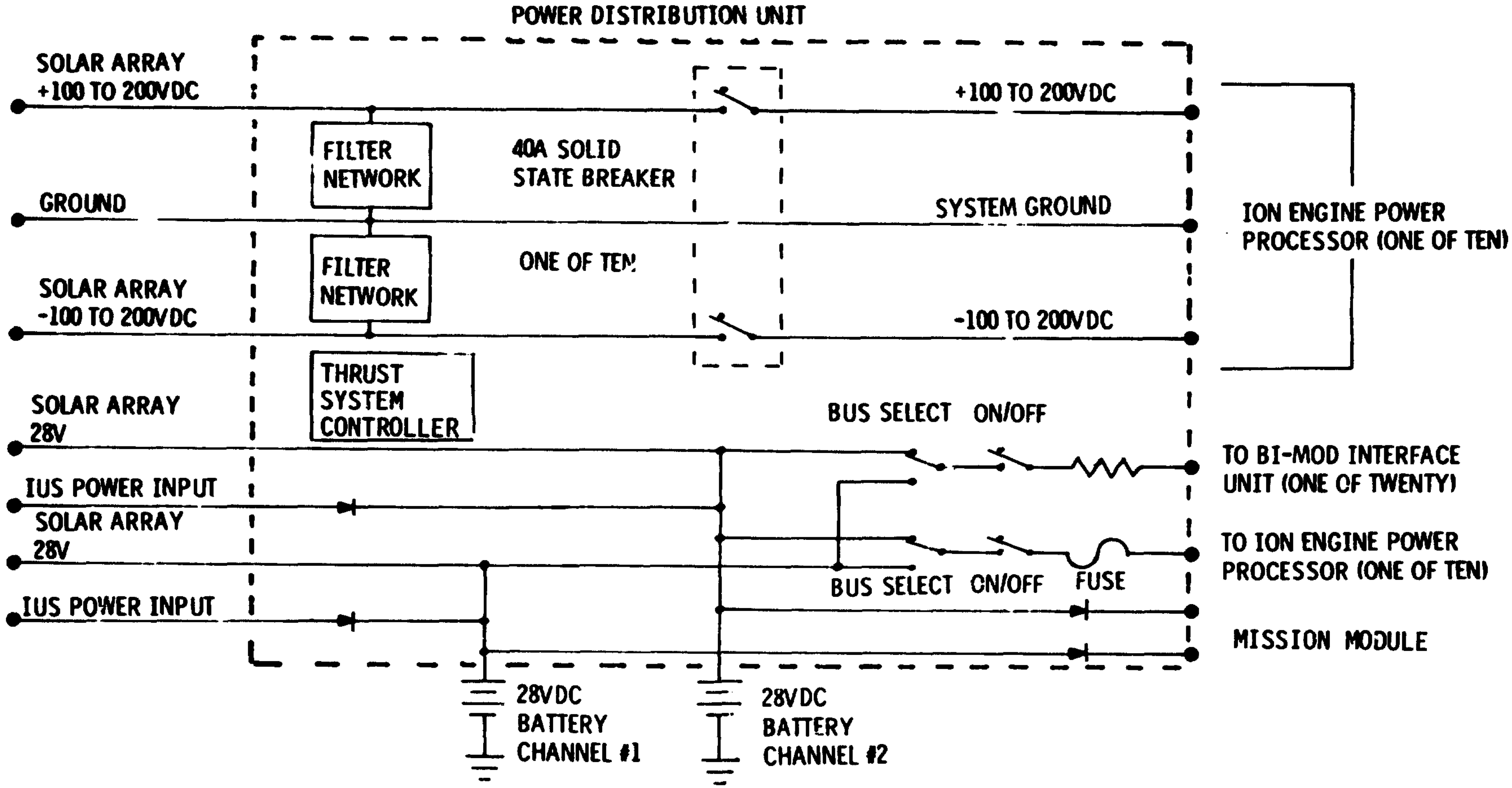


Figure 2-2. 200 to 400VDC and 28VDC Power Distribution System

Table 2-I. Summary of 200-400VDC Power Distribution System Characteristics

- Plus (+) and Minus (-) Solar Array Voltage Reduces:
  - a) Component stresses (Solid State Breaker)
  - b) Space Charge Interaction
- Filter Network Controls Bus Impedance for EMC
- Thrust System Controller Perfoms all Power Control & Management (Max Power Tracking, Bi-Mod Control, Failure Analysis, Attitude Control, Thrust & Gimbal Angle).
- Solid State Breaker for Loads on ±100 to 200VDC Distribution Bus.
- Low Voltage DC Power Distribution for EMC Control and Ease of Integration of All Low Power Equipment.
- Redundant +28VDC Buses for Low Power Distribution:
  - a) Interface with Mission Module
  - b) Interface with IUS
  - c) Interface with Bi-Mod
- Battery Supplies Transient Loads such as Startup and Fault Clearing.
- Plus (+) and Minus (-) DC-DC Converters Condition Power for 28VDC Bus (700W Rating to Carry Maximum Load if Required for Redundancy).
- On/Off Control, Bus Selection and Fault Clearing for 28VDC Loads.
- Compatible with IUS Power Bus.

Table 2-II. Summary of 200-400VDC and 28VDC Power Distribution System Characteristics

- Plus (+) and Minus (-) Solar Array Voltage Reduces:
  - a) Component Stresses (Solid State Breaker)
  - b) Space Charge Interaction
- Filter Network Controls Bus Impedance for EMC.
- Thrust System Controller Performs all Power Control & Management (Max Power Tracking Bi-Mod Control, Failure Analysis, Attitude Control, Thrust & Gimbal Angle).
- Solid State Breaker for Loads on ±100 to 200VDC Distribution Bus.
- Low Voltage DC Power Distribution for EMC Control and Ease of Integration of all Low Power Equipment
- Redundant +28VDC Buses for Low Power Distribution:
  - a) Interface with Mission Module
  - b) Interface with IUS
  - c) Interface with Bi-Mod
- Battery Supplies Transient Loads such as Startup and Fault Clearing.
- On/Off Control, Bus Selection and Fault Clearing for 28VDC Loads.
- Compatible with IUS Power Bus.
- Isolated 28VDC Solar Array to Supply Low Level Electronic Loads.

2.2 Beam Supply Tradeoff Analysis

In order to obtain beam power levels up to 10kW with existing high power thyristors, different power stage mechanization and modularization had to be designed and analyzed.

The power stage configuration selected for review included:

- Single full bridge 6KW power rating
- 2 Channel full bridge 10KW power rating
- 2 Channel half bridge 6KW power rating
- 3 Channel half bridge 10KW power rating
- 4 Channel half bridge 10KW power rating

Figure 2-3 presents the schematic of the thyristor full bridge operating at maximum frequency of 20kHz.

Figure 2-4 presents the schematic of the thyristor half bridge operating at maximum frequency of 20kHz.

Table 2-III summarizes the design results of different power and power stage configurations. The single full bridge (6KW rating) was the selected configuration due to its low component weight.

2.3 Discharge Supply Tradeoff Analysis

Due to the relatively lower power rating of the discharge supply (800W), new power conversion technology can be applied. The different configurations analyzed include the following:

- Thyristor 20kHz Half Bridge series resonant inverter
- Transistor 50kHz Full Bridge series resonant inverter

The half bridge configuration is similar to that shown in Figure 2-4.

Figure 2-5 presents the schematic of the transistorized 50kHz full bridge series resonant inverter.

Table 2-IV summarizes the design results of the two different configurations.

Due to the electrical component weight saving of about 1.1kG, the 50kHz full bridge transistorized series resonant inverter was selected as the preferred configuration.

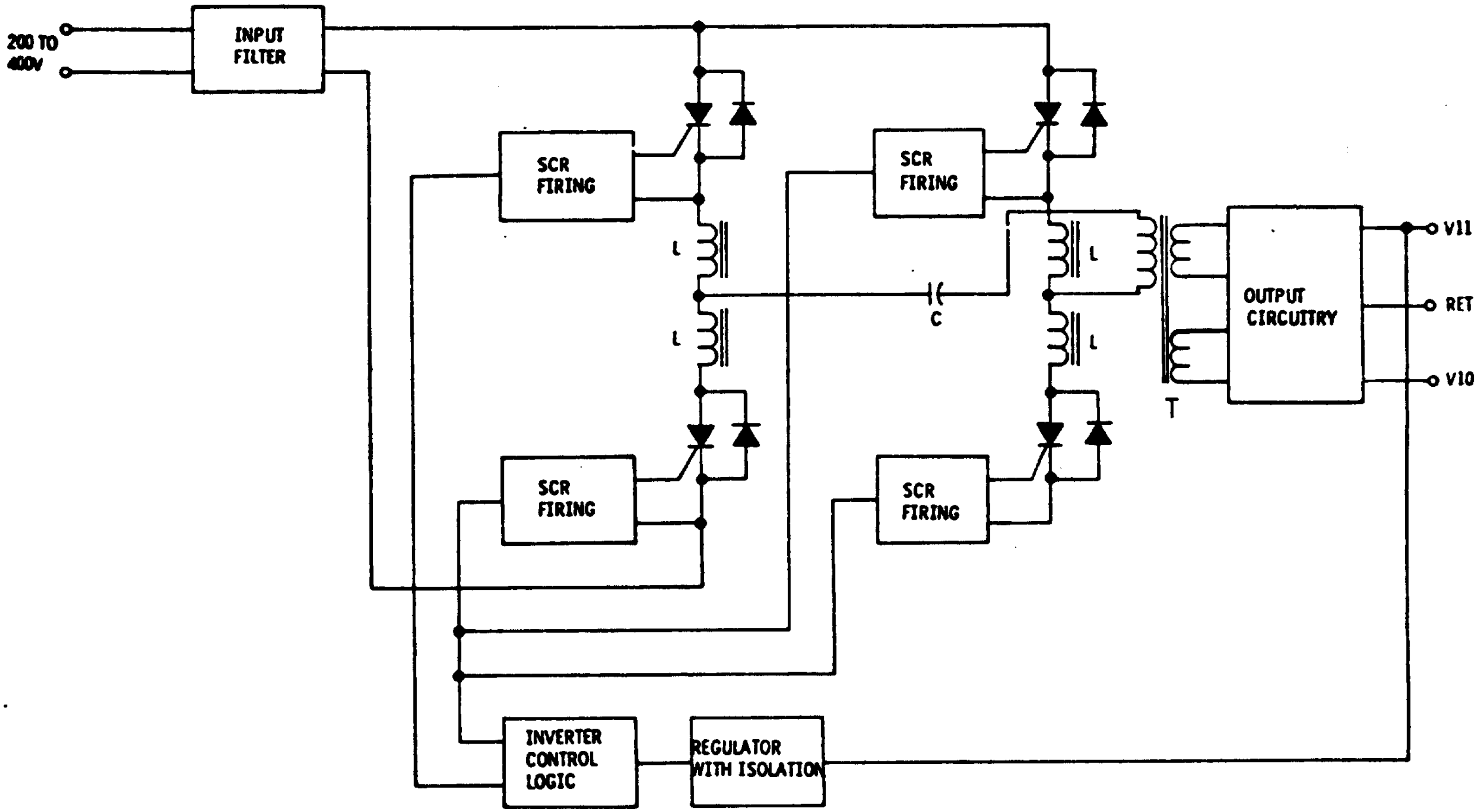


Figure 2-3. Schematic of the Thyristor Full Bridge Series Resonant Beam Inverter

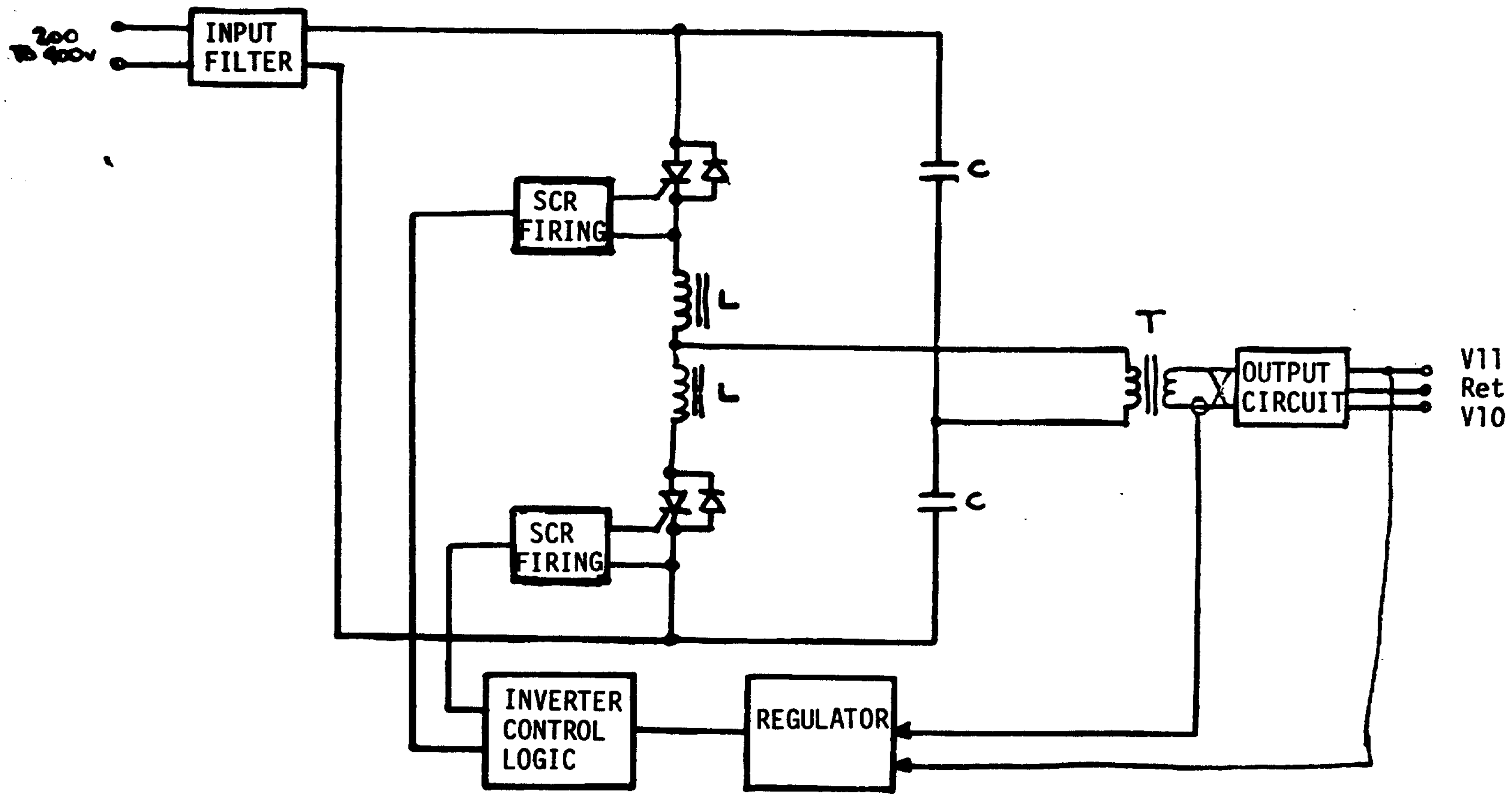


Figure 2-4. Schematic of the Thyristor Half Bridge Series Resonant Beam Inverter

Table 2-III Summary of Beam Supply Tradeoff Analysis

CONFIGURATION	MAXIMUM PWR RATING	COMPONENT WEIGHT (KG)	LOSS (WATTS)*	PART COUNT	POWER STAGE EFFIC. (%)
SINGLE FULL BRIDGE	6KW	9.4	440	521	93.6
2 CHANNEL FULL BRIDGE	10KW	16.0	743	910	93.5
2 CHANNEL HALF BRIDGE	6KW	11.4	478	740	93.1
3 CHANNEL HALF BRIDGE	10KW	18.1	770	1041	93.2
4 CHANNEL HALF BRIDGE	10KW	19.1	784	1352	93.2

*Losses include power stage and control losses

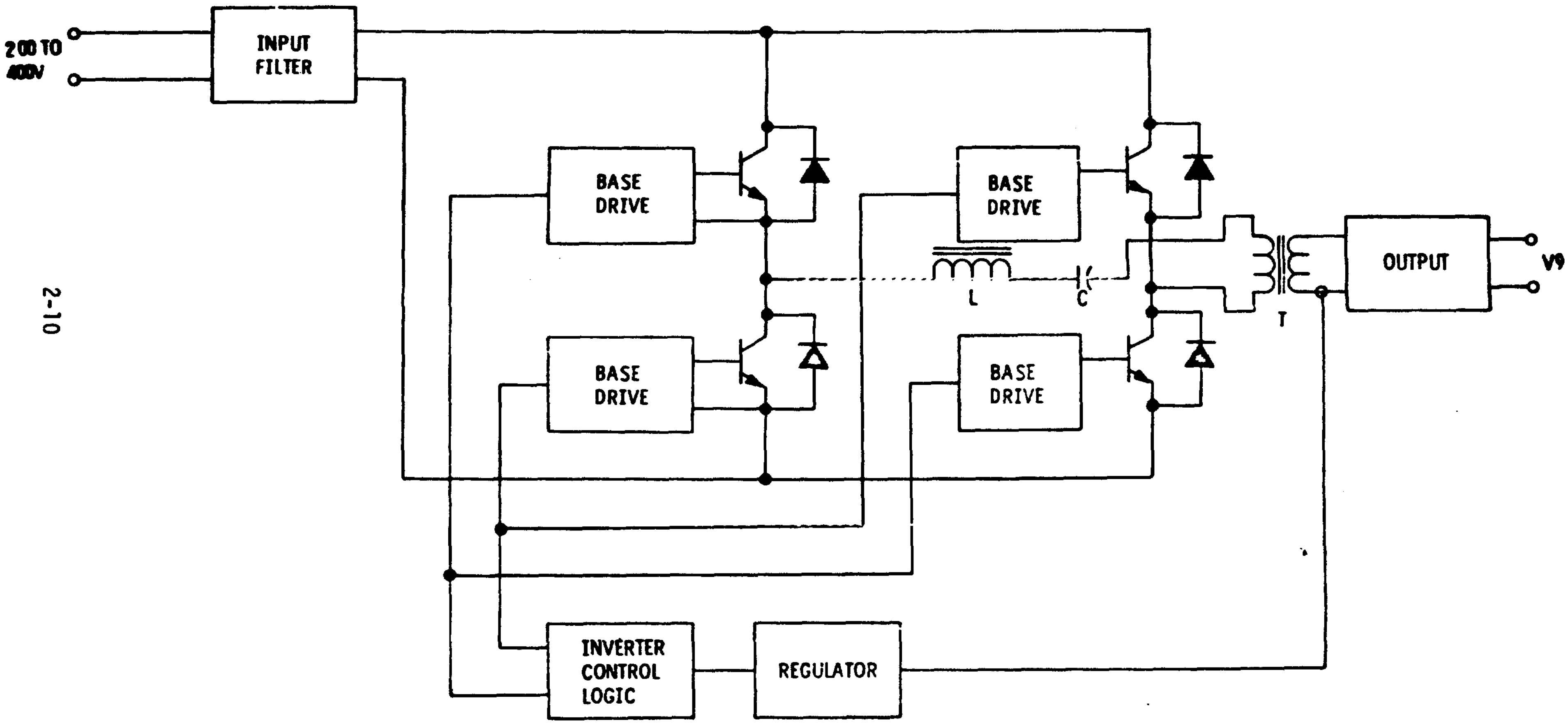


Figure 2-5. Schematic of Transistorized Bridge Series Resonant Discharge Inverter

Table 2-IV Summary of Discharge Supply Tradeoff Analysis

CONFIGURATION	MAXIMUM PWR RATING	COMPONENT WT. (KG)	LOSS AT 415W OUTPUT (W) *	PART COUNT	POWER STAGE EFFIC. (%)
THYRISTOR 20kHz HALF BRIDGE	815W	3.3	70.7	331	88.0
TRANSISTOR 50kHz FULL BRIDGE	815W	2.2	79.1	473	87.2

*Losses include power stage and control losses

2.4 Low Voltage Supplies Tradeoff Analysis

The low voltage supplies greatly affect the total power processor weight, losses and part count. Tradeoffs were performed on new power stage configurations, sharing of power functions between two thrusters in a Bi-Mod configuration and the application of latest integrated circuit techniques.

The power electronics mechanization to satisfy the revised power processor requirements include:

- Transistor Half Bridge 50kHz Series Resonant Inverter (Figure 2-6)
- Transistor Half Bridge 50kHz Series Resonant Inverter to Operate Two Ion Thrusters in a Bi-Mod Configuration (Figure 2-7)
- Buck/Boost DC/DC Converter for Each Separate Output Load (Figure 2-8)

Table 2-V summarizes the characteristics of the low voltage supply configurations.

The dedicated Buck/Boost DC/DC Converter is the preferred configuration mainly since it has the highest overall efficiency in comparison with the other proposed configurations.

2.5 Power Processor Configuration Tradeoff

Two separate power processor configurations were mechanized to satisfy the requirements of the two power distribution system identified in Section 2.1.

These configurations include:

a) a single 200-400VDC solar array bus to supply all power (Figure 2-9).

b) 200-400VDC bus supplies power to high power loads, such as beam and discharge and a 28VDC solar array bus supplies power for the low level supply (Figure 2-10).

Table 2-VI and VIII summarizes the characteristics for the two block diagrams, respectively.

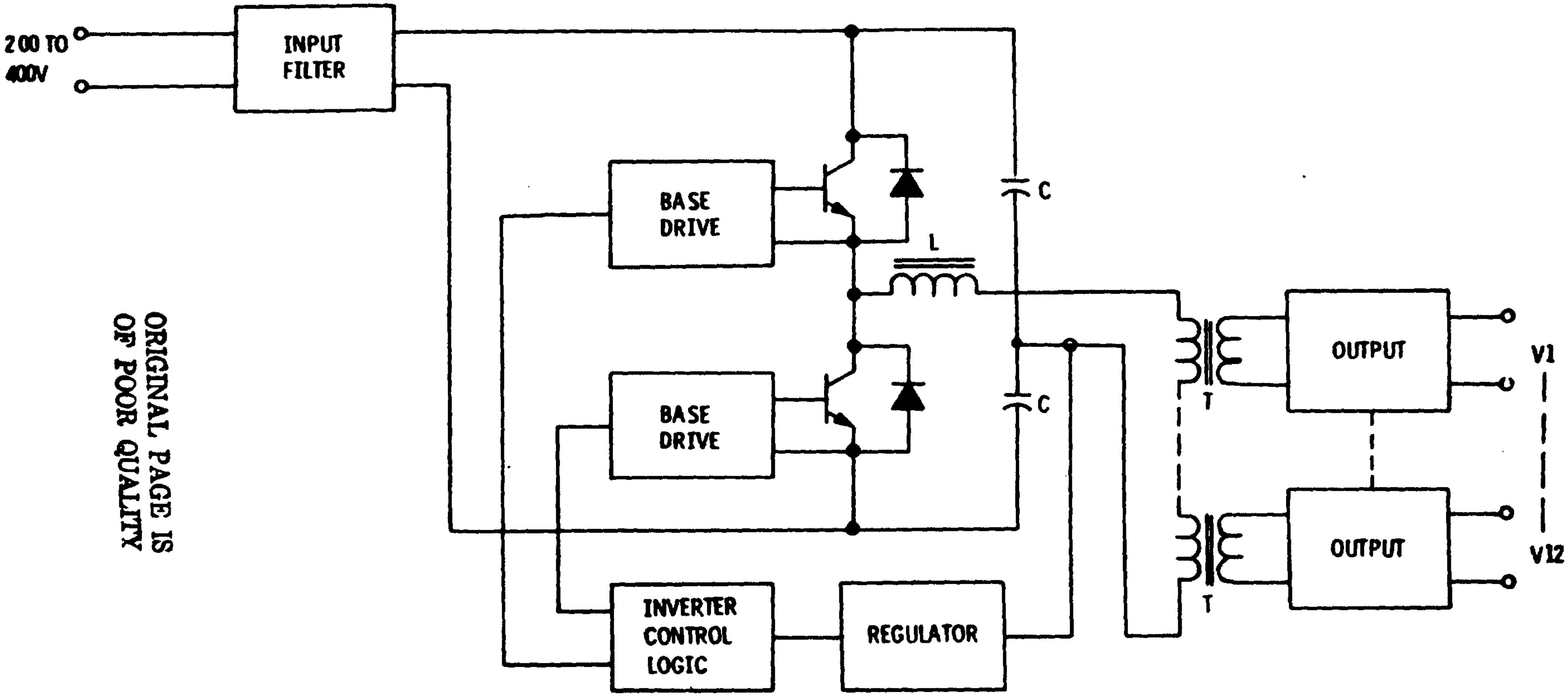


Figure 2-6. Schematic for Half Bridge 50kHz Series Resonant Inverter for the Low Voltage Supplies

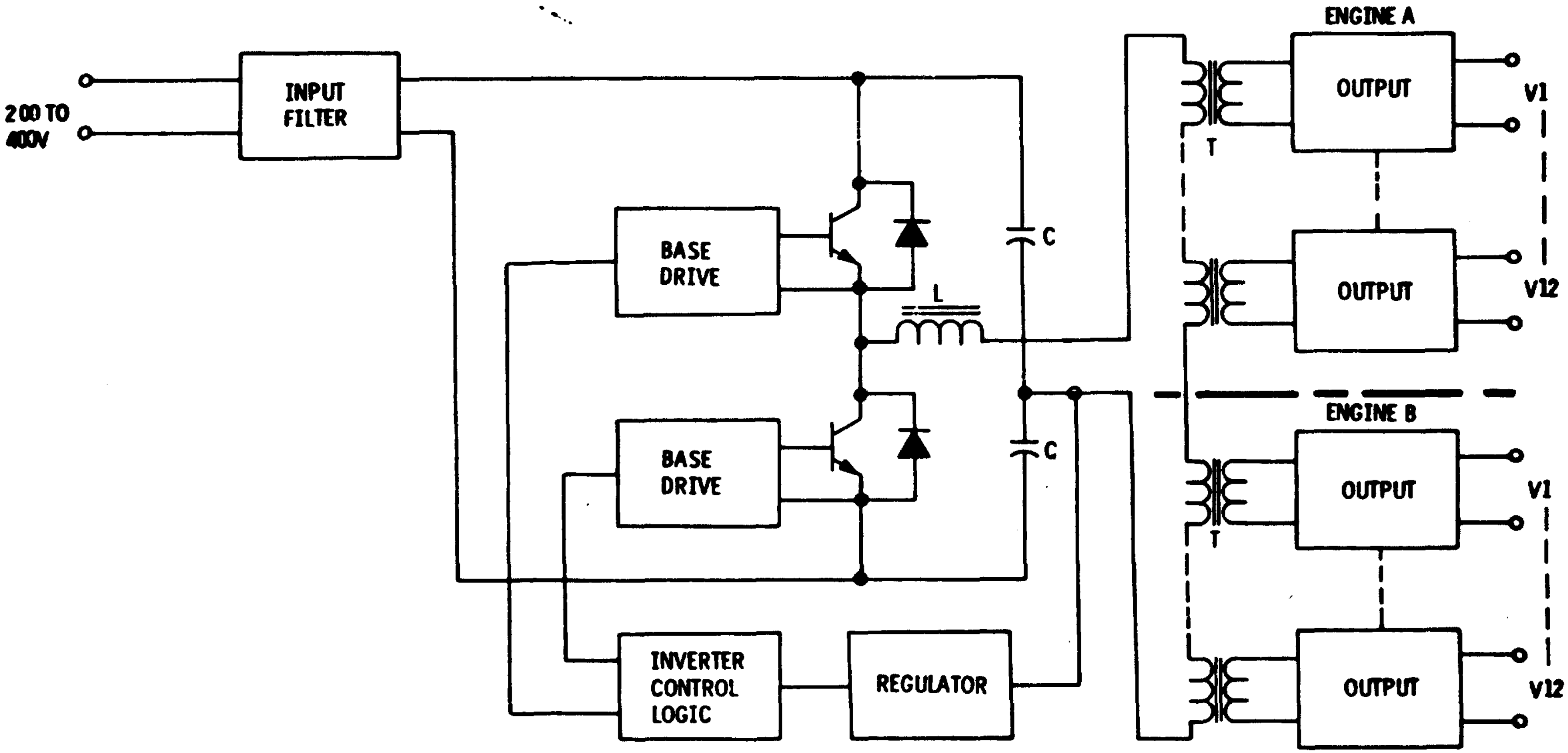


Figure 2-7. Schematic of Transistorized 50kHz Series Resonant Inverter Configurated to Supply Low Voltage Outputs for Two Thrusters in Bi-Mod Configuration

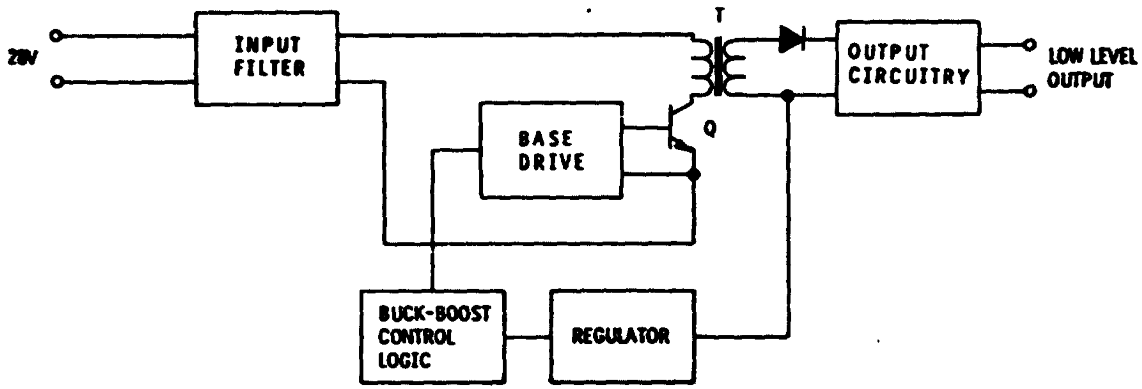


Figure 2-8. Schematic of Buck/Boost DC/DC Converter for Typical Low Voltage Supply

CONFIGURATION	MAXIMUM PWR RATING	COMPONENT WT. (KG)	LOSS AT 45W OUTPUT (W)*	PART COUNT	POWER STAGE EFFIC. (%)
Transistor Half Bridge Series Resonant Inverter	200W	2.7	65.8	1001	46.0
Transistor Half Bridge Series Resonant Inv. for Bi-Mod	250W	4.8	109.9(@90W)	1673 (2 Units)	48.9
Dedicated Buck/Boost DC-DC Converter	200W	2.6	25.6	1039	66.5

*Losses include power stage and control losses.

Table 2-V Summary Data for Low Voltage Supply Design Configurations

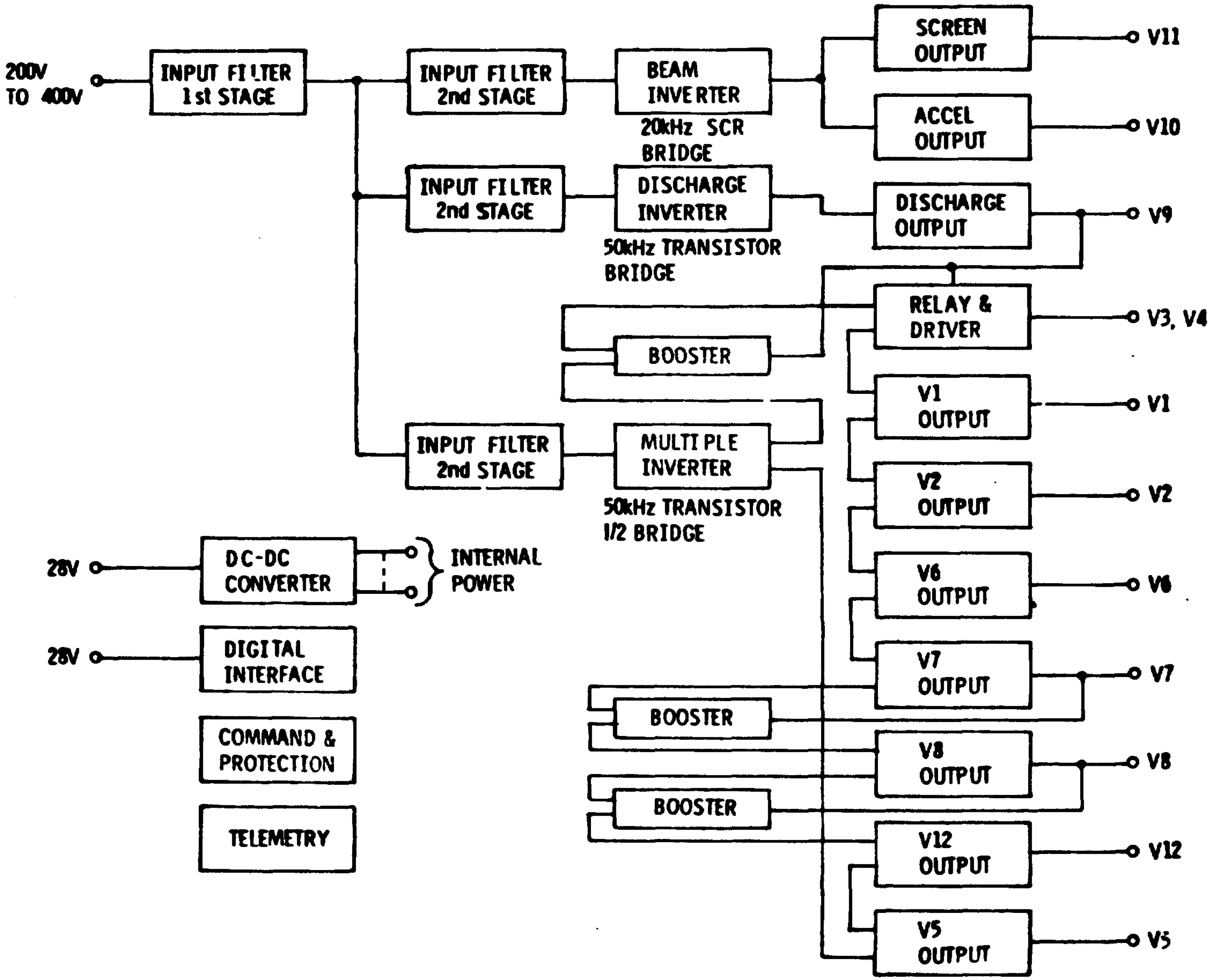


Figure 29. Power Processor Block Diagram

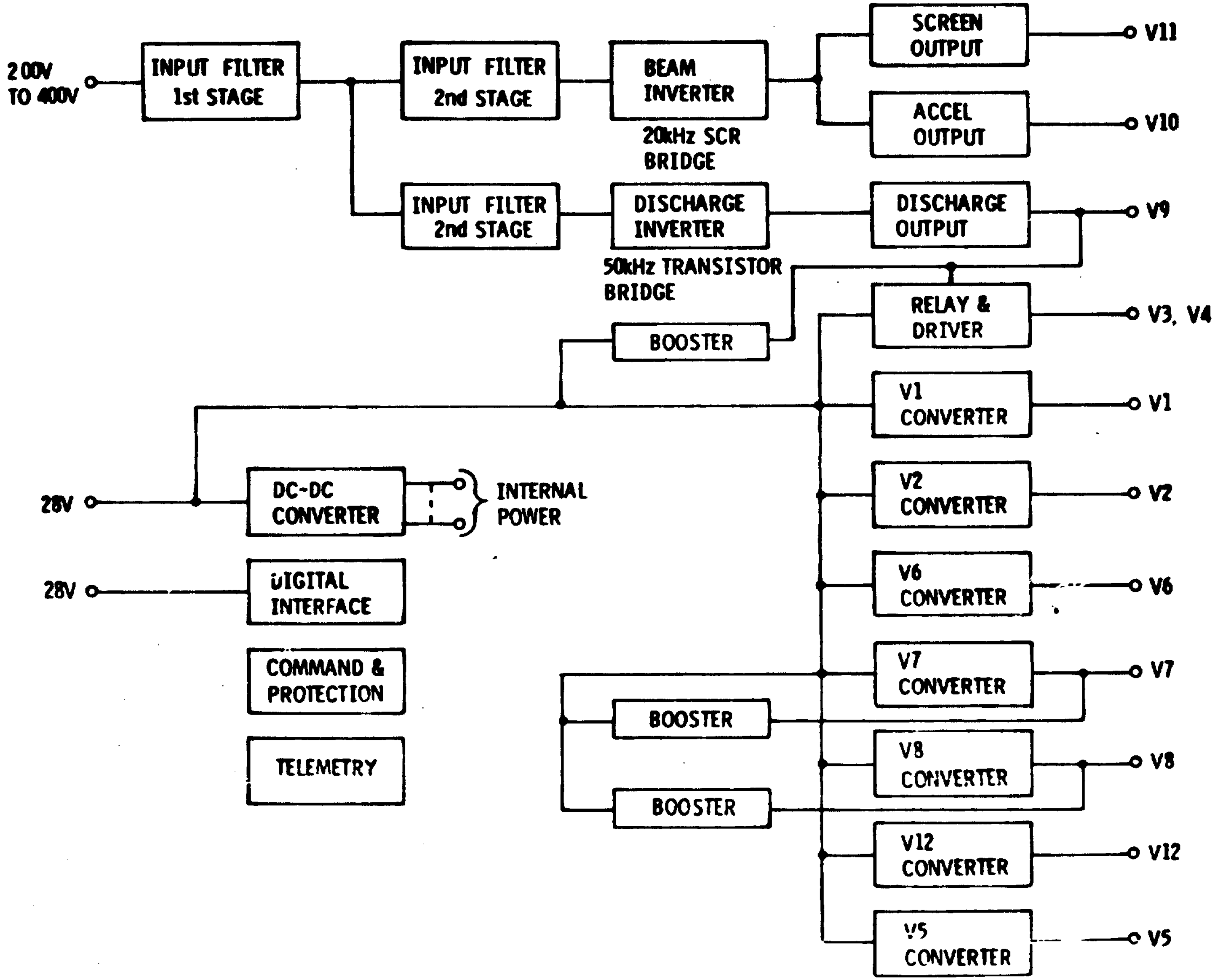


Figure 2-10. Power Processor Block Diagram (200 to 400V and 28V Solar Array)

Table 2-IV Power Processor Estimate - High Voltage System

		PART COUNT	WEIGHT (gms)	LOSSES (W)	EFFIC.
Beam Inverter (6000W)	Power Stage	81	8893.3	408.42	93.6%
	SCR Firing	152	165	23.6	
	Series Inverter Control	125	116.45	1.379	
	Regulator	92	120.75	2.121	
	Accelerator Regulator	71	107.5	4.021	
	Beam Total	521	9403.0	439.541	
Discharge Inverter (415W)	Power Stage	33	1639.35	60.64	87.3%
	Transistor Drive	218	288.6	16.0	
	Series Inverter Control	125	116.45	1.379	
	Regulator	97	131.8	1.082	
	Discharge Total	473	2176.2	79.101	
Multiple Inverter (45W) (Series Inverter)	Power Stage	10	207	15.50	46%
	Controls	319	362.3	10.202	
	Outputs - Power	146	1522.85	37.141	
	Regulators	526	592.9	2.975	
	Multiple Total	1001	2685.05	65.818	
Input Filter		45	4410	20.60	
	Sub Totals	2040	18674.25	605.06	91.4%
Telemetry		239	686.35	5.528	
Protection		235	186.3	3.00	
Command		52	181.6	2.57	
Interface Unit		91	454	.97	
28V Converter		122	611.8	16.46	
Output power ≅ 6460W	TOTALS	2779	20784.3	633.588	91.07%

Table 2-VII Power Processor Estimate - High & Low Voltage System

		PART COUNT	WEIGHT (gms)	LOSSES (W)	EFFIC.
Beam Inverter (6000W)	Power Stage	81	8893.3	408.42	93.6%
	SCR Firing	152	165	23.6	
	Series Inverter Control	125	116.45	1.379	
	Regulator	92	120.75	2.121	
	Accelerator Regulator	71	107.5	4.021	
	Beam Total	521	9403.0	439.541	
Discharge Inverter (415W)	Power Stage	33	1639.35	60.64	87.3%
	Transistor Drive	218	288.6	16.0	
	Series Inverter Control	125	116.45	1:379	
	Regulator	97	131.8	1.082	
	Discharge Total	473	2176.2	79.101	
Multiple Outputs (45W) (Buck-Boost)	Power Stage	336	1859.2	22.662	66.5%
	Controls	703	733.3	2.963	
	Multiple Total	1039	2592.5	25.625	
Input Filter		45	4385	20.6	
	Sub Totals	2078	18556.7	564.867	91.9 %
Telemetry		239	686.35	5.528	
Protection		235	186.3	3.00	
Command		52	181.6	2.57	
Interface Unit		91	454	.97	
28V Converter		122	611.8	16.46	
Output Power ≅ 6460W	TOTALS	2817	20676.75	593.395	91.6%

The two solar array bus (Figure 2-10) was the preferred configuration due to its lower weight and higher efficiency.

2.6 Power Processor Weight-Efficiency Optimization

The optimization of a power processor design is dependent on the design of the spacecraft, basically the solar array and the thermal control system used to reject the heat loss generated by the power processor.

In the solar electric mission, the solar array power capability varies constantly during its mission due to the variation of the distance between the Sun and the spacecraft and makes the optimization more difficult.

Figure 2-11 shows the characteristic optimization curves where the power processor weight is plotted as a function of its losses. The summation of the weight for the power processor, the weight for the solar array due to losses and the weight of the thermal control system to radiate the internal losses is also plotted as a function of the power processor losses. The optimization point is where the power processor weight is equal to 1/2 of the total weight.

For the Halley's Comet Mission, the following spacecraft characteristics were estimated:

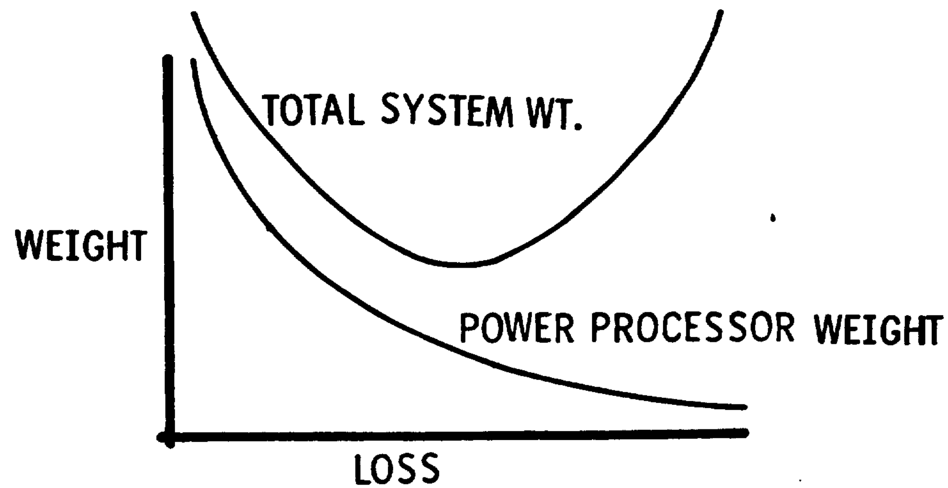
- Solar Array Density (Averaged overflight profile) $\frac{20KG}{KW}$
- Thermal Control System Density $\frac{28KG}{KW}$

The following is an estimate of the preferred power processor configuration design:

- Packaged Weight (2 times component weight) 40KG
- Power Processor Losses 593 Watts
- Solar Array Weight for Losses $\frac{20KG}{KW}$ x .593KW) = 11.8KG
- Thermal Control System Weight $\frac{28KG}{KW}$ x .593KW) = 16.6KG

The total power processor, solar array and thermal control system weight is 68.8KG and the ratio of power processor weight total is .587. This ratio is off the 1/2 point and shows that a different design could reduce the overall weight.

Figure 2-11. Power Processor Weight-Efficiency Optimization



The estimated optimum solution is:

Total weight	65KG
Power processor weight	32.5KG
Power processor losses	677W
Power processor efficiency	90.5%

A redesign of the magnetic components would easily provide these optimum characteristics.

This example shows the optimization procedure and is dependent on the solar array density and the thermal control system density.

3.0 BASELINE DESIGN

After the review and approval of the preferred configuration by the NASA Project Office, a more detailed electrical and mechanical design of the power processor was performed for a beam power rating of 2.2KW and 6KW. Both the electrical, mechanical and thermal interfaces were reviewed and incorporated into the preliminary design concept.

3.1 Power Distribution System

Figure 3-1 illustrates the power distribution system used to establish the necessary electrical interfaces for detailed electrical design of the power processor. Power from the high power solar array is supplied to the main power distribution unit at ±100 to ±200VDC. Electromagnetic interference filters control the reflected ac noise that can be returned from the spacecraft load to the large solar array surfaces.

Solid State dc breakers are used with each ion engine power processor to protect against any power line failure or failures in the power processor power electronics.

The unregulated solar array bus also goes through separate solid state breakers to two redundant dc-dc converters that generate 28VDC to supply the low voltage electronics of the ion engine power processor and to the spacecraft.

Figure 3-2 illustrates the schematic of the 28V dc-dc converter. It is a half bridge thyristor series resonant inverter operating at 20kHz. Table 3-I summarizes the component weight, losses and part count for the electrical design.

During launch, 28VDC power will be supplied directly from the shuttle interim upper stage (IUS) and provides necessary 28VDC power for the ion engine power processors and to the spacecraft.

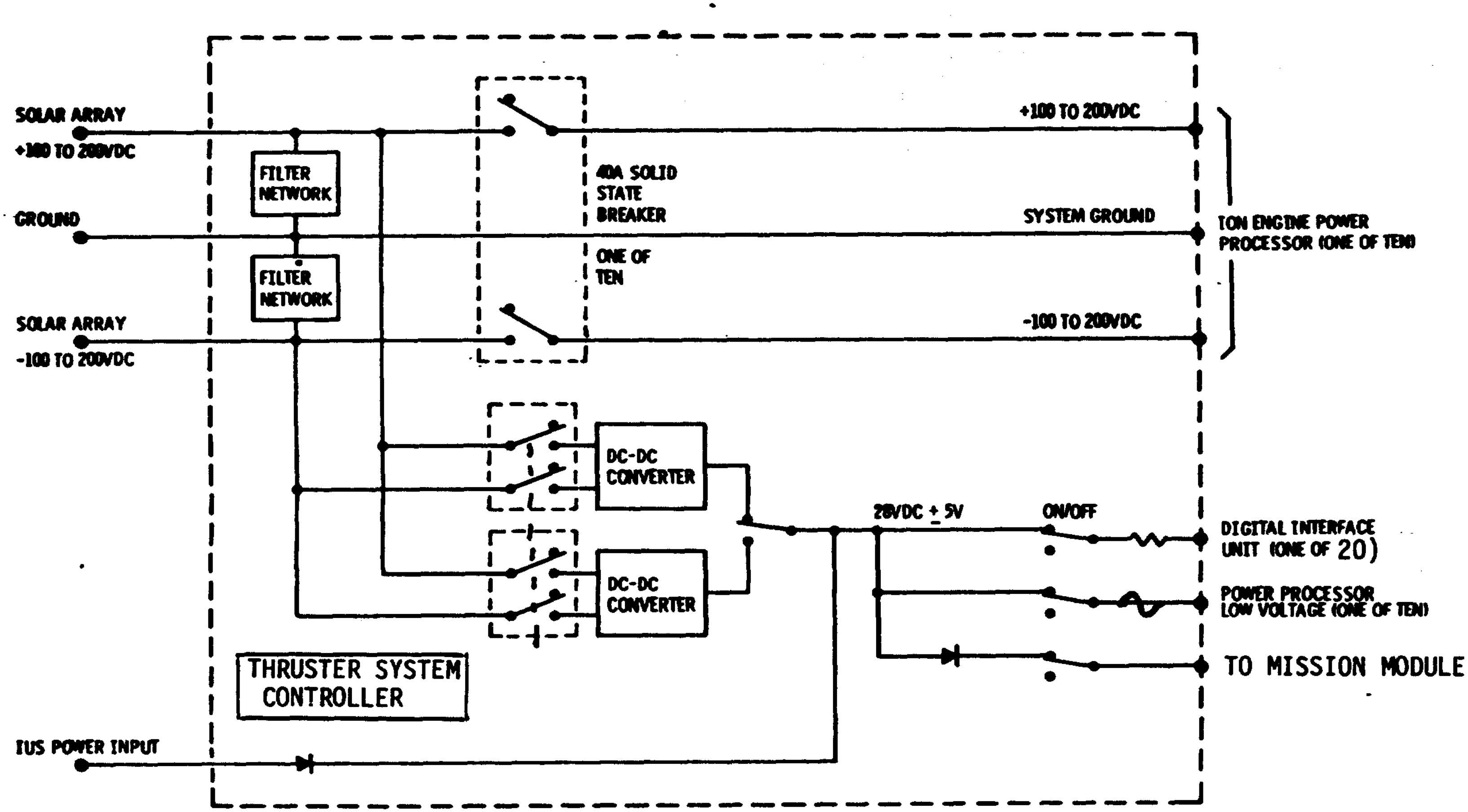


Figure 3-1. Power Distribution System Block Diagram

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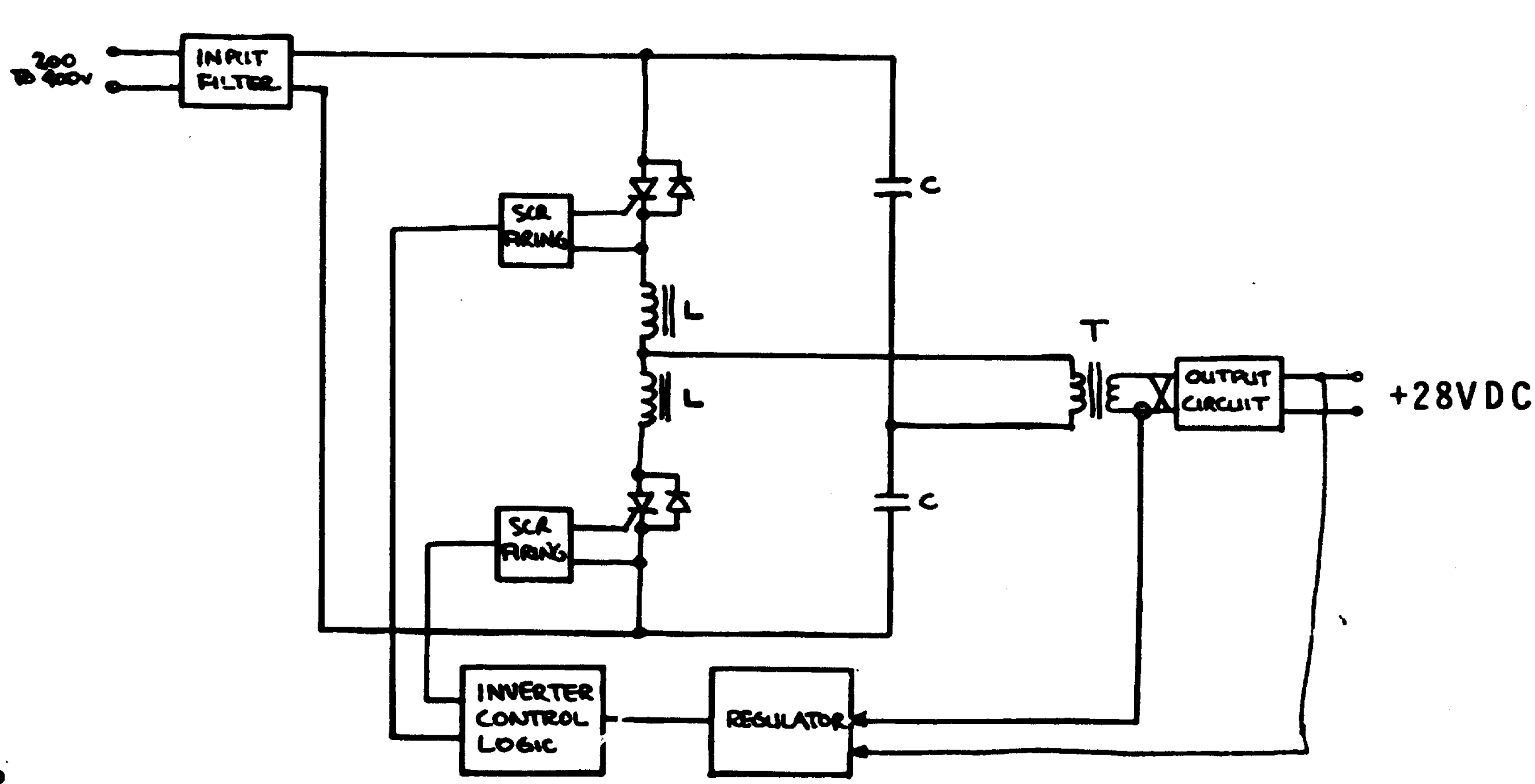


Figure 3-2. Schematic of DC-DC Converters Used to Generate 28VDC Power Bus

Table 3-I Summary of 28VDC Bus Converter (1.5KW Output Power Rating)

	COMP. WT. gms	LOSSES Watts	PART COUNT
Power Stage	6677.3	186.601	55
SCR Firing	90.83	13.331	78
Series Inverter Control	76.83	.980	140
Regulator	82.44	.325	72
Bias Supply	314.41	2.714	91
	7241.81 gm	203.951 W	436

88% EFFIC

A redundant microprocessor thrust system controller performs all power control and management, Bi-Mod control, thrust control and failure analysis.

The features of this system configuration are:

- ±100VDC to ±200VDC supplies the high power loads
- 28VDC power distribution for EMC control and ease of integration of all low power equipment
- Interfaces with Bi-Mod, Mission Module, and IUS
- Filter networks control high power bus impedance for EMC control
- Solid state breakers provide the necessary protection and fault clearing of ±100 to ±200VDC for the power system
- Thrust system controls the flow of power and the operation of the ion engines
- On/Off control and fault clearing for 28VDC loads.

3.2 Command System

The overall spacecraft command system must include the electric propulsion module and its power processor modules.

Figure 3-3 shows the basic block diagram for the command system and the inter-relationship of the spacecraft central computer, thrust system controller, located in the power distribution unit and electric propulsion Bi-Mod. The ring bus command line allows for open in the cabling and still allows total system operation.

With the use of microprocessors, most of the operational controls can be located at the Bi-Mod and we can limit the amount of data that must be transferred and processed by the thrust system controller and the spacecraft computer.

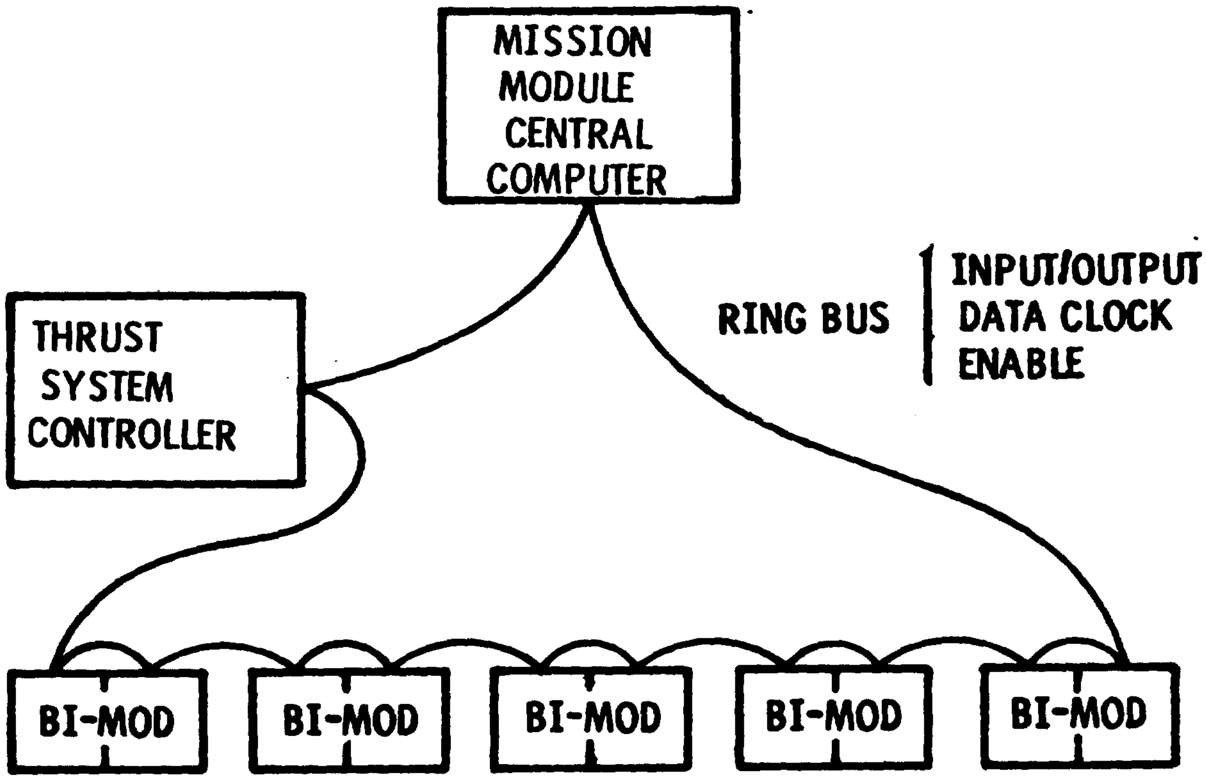


Figure 3-3. Command System Block Diagram

3.3 Bi-Mod Configuration

Figure 3-4 shows the block diagram for the electric propulsion Bi-Mod where two ion engines and two power processors form a complete mechanical subassembly. All of the electrical interfaces are illustrated in the diagram:

- Serial command data (high speed)
- 28VDC for microprocessor interface unit
- Low speed parallel command & data between the interface unit and the power processor for high noise immunity
- $\pm$100V to $\pm$200VDC solar array input to each power processor
- 28VDC for the low level power processor electronics
- Power processor output lines to the ion engine

Each power processor is dedicated to its own ion engine and there is no sharing of electric functions between the power processors.

The ion engines and power processors share only the mechanical structure and heat pipe/radiator assembly to affect a overall system weight saving.

Figure 3-5 shows the interfaces between the microprocessor digital interface unit and the two power processors. The input data to the microprocessor is high speed serial data. The outputs to the power processor are low speed parallel data lines which extro filtering can be added to provide high noise immunity for the power processor control electronics.

Table 3-I summarizes the features of this proposed digital control system.

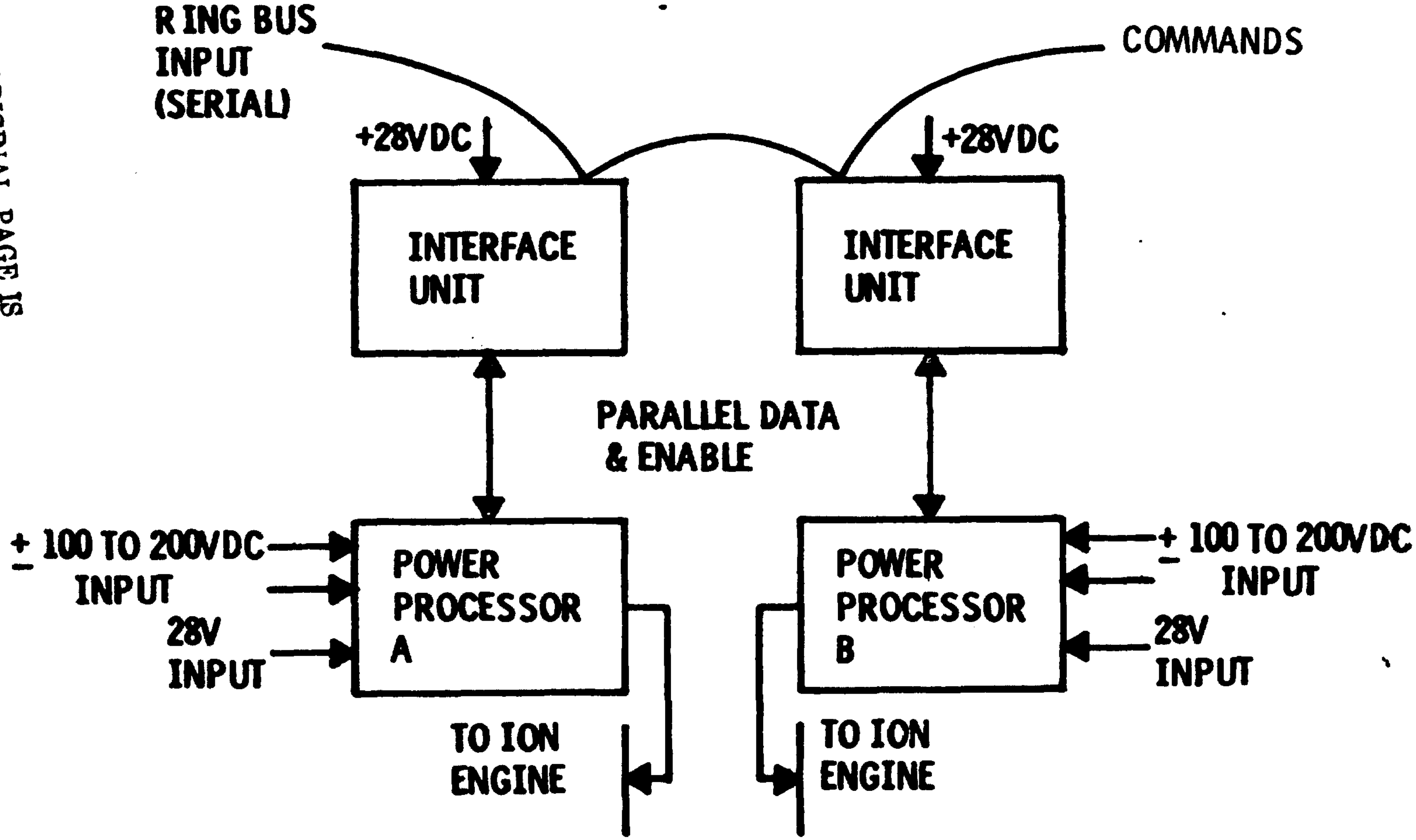


Figure 3-4. Bi-Mod Configuration Blodk Diagram

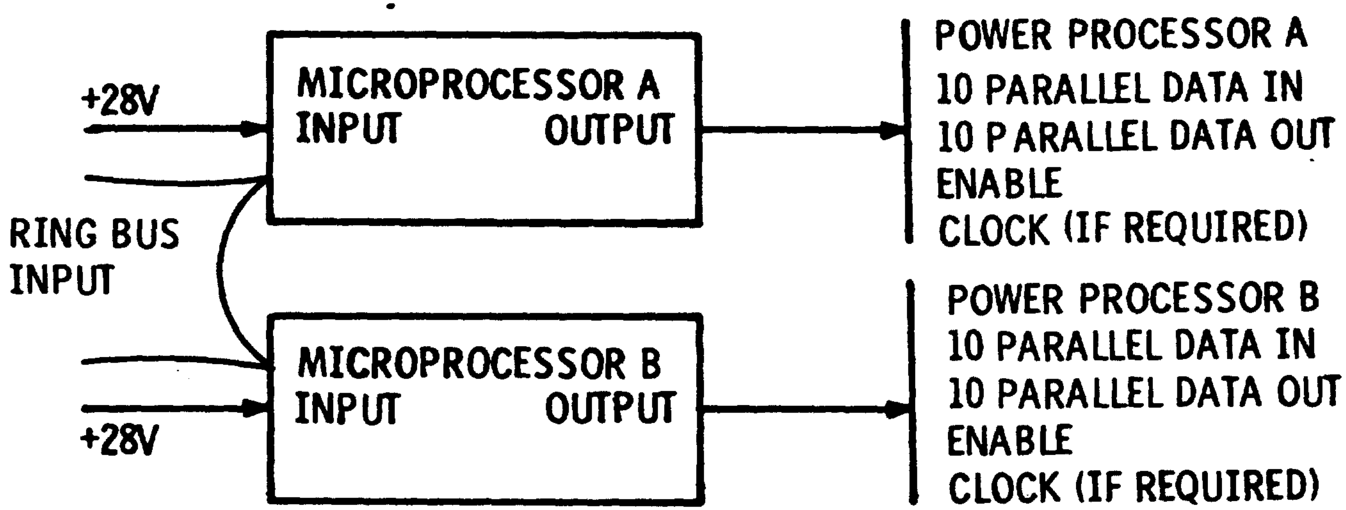


Figure 3-5. Bi-Mod Interface Unit Configuration

Table 3-I Features of Bi-Mod Interface Unit Configuration

- Separate Interface Unit (Microprocessor) for Each Ion Engine
- 28V Power can Turn On/Off Each Interface Unit
- All Output Lines Filtered
- 10 Parallel Outputs (3 for Address & 7 for Data)
- Optical Isolation for Input and Output
- High Speed Input Data/Low Speed Output Data

3.4 Power Processor Block Diagram

Figure 3-6 illustrates the basic block diagram for the Extended Performance Power Processor. The 200 to 400VDC bus supplies power through a common first stage input filter and separate 2nd stage input filters to the beam inverter and the discharge inverter, respectively.

28VDC supplies power to the low level outputs each with their own dedicated dc/dc converter that provides the necessary regulation, control and isolation for the different ion engine outputs.

A separated dc/dc converter supplies internal control logic power.

A microprocessor digital interface unit controls the total power processor through the command, protection and telemetry electronics:

- to startup an ion engine
- to throttle the ion engine thrust
- to change power processor set point to be compatible with ion engine thrust
- to recycle the outputs during ion engine arcs or overloads
- to provide an orderly shut-down of the ion engine.

The discharge supply V9 is used during startup to supply power to V3 and V4 outputs and reduce the power processor part count.

Separate boosters are used for the V9, V7 and V8 outputs to initiate a discharge in the mercury plasma.

Figure 3-7 presents the grounding system designed into the power processor electronics to eliminate high ground loop currents that could damage low level control electronics during ion engine overload or shorts.

Use of both optical coupling and transformer magnetic isolation is used to provide the necessary separation between:

Microprocessor Digital Interface Unit
PPU Signal Electronics
PPU Power Stage Electronics
Ion Engine

A separate ground return wire goes from each area to a single point ground located in the electric propulsion system interface module which connects the solar array and its drive system to the Bi-Mod mechanical assembly.

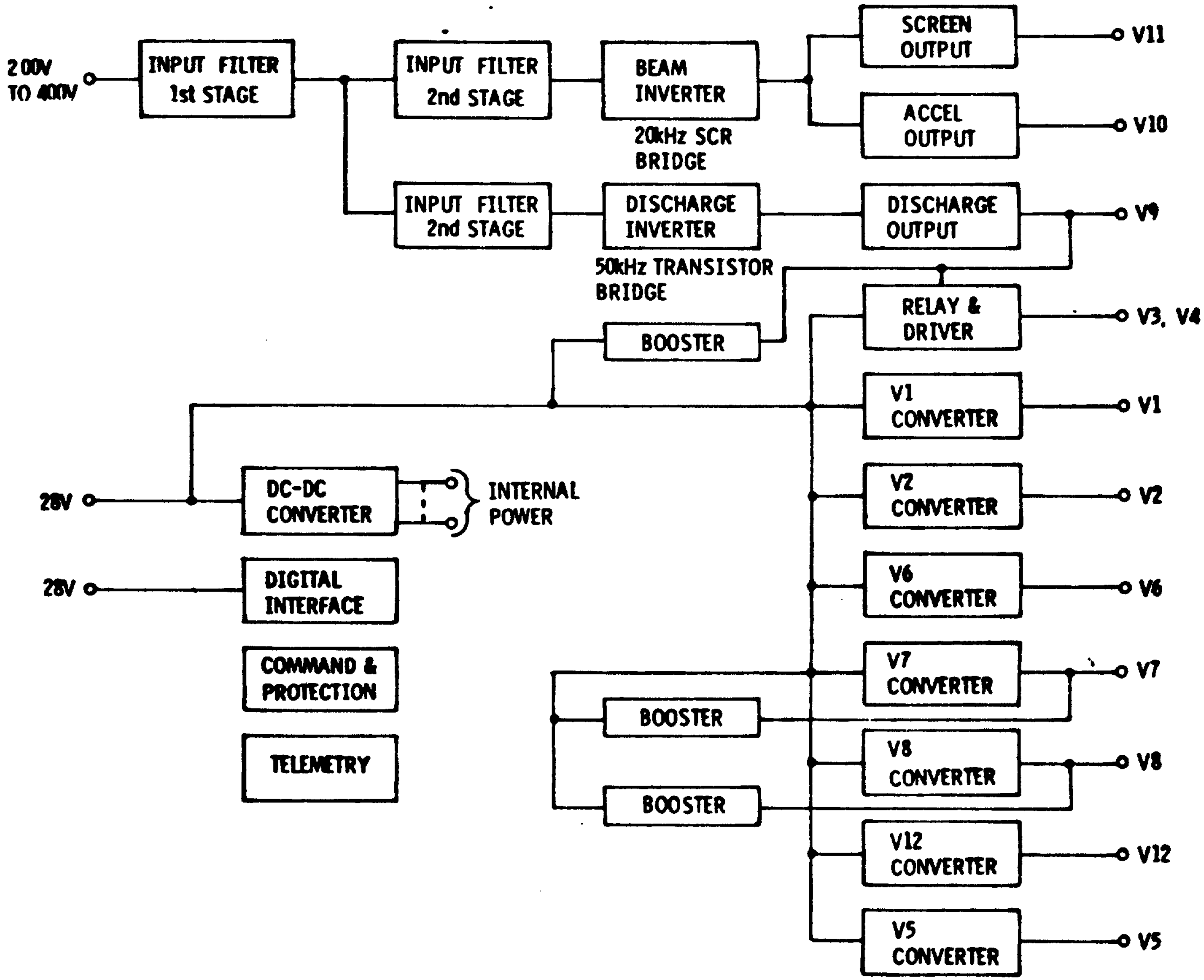


Figure 3-6. Electric Propulsion Power Processor Block Diagram

This basic grounding system has been used on three other electric propulsion power processor breadboard designs and the Transmitter Experiment Package without any operational problems. This ground isolation technique does have a slight weight and loss penalty.

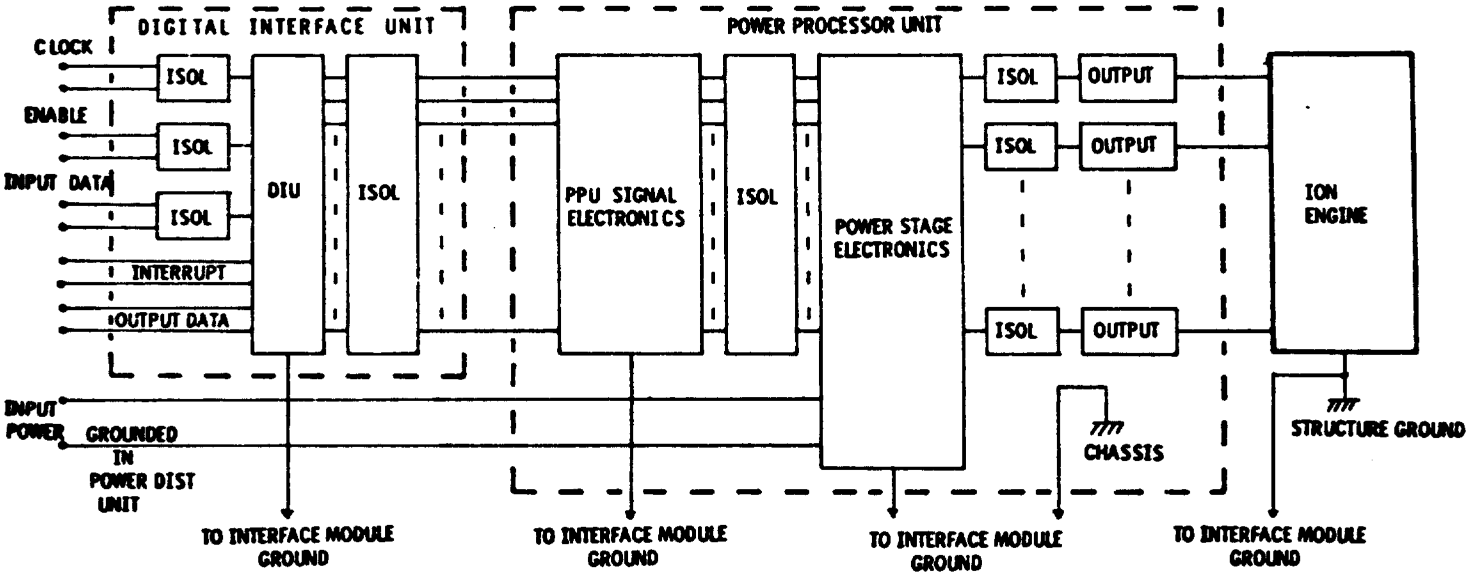


Figure 3-7. Power Processor Grounding System Block Diagram

3.5 Electrical Design

Two separate electrical designs were performed:

6KW Beam Supply for Halley Comet Mission
2.2KW Beam Supply for Alternate Electric Propulsion Mission

Figure 3-8 presents the schematic of the full bridge thyristor series resonant inverter for the 6KW beam supply.

Figure 3-9 presents the schematic of the half bridge thyristor series resonant inverter for the 2.2KW beam supply. These inverters were designed to operate at a maximum switching frequency of 20kHz.

Figure 3-10 presents the schematic of the 50kHz transistorized series resonant inverter for the discharge supply. This design is common to both the 6KW and the 2.2KW beam supplies since the beam current is the same but only the positive acceleration voltage is changed to increase the ion engine output thrust level.

Figure 3-11 shows a typical dc/dc converter using the transistorized series inductor power stage to provide the necessary output power control and isolation.

Table 3-II & 3-III summarize the 6KW and 2.2KW power processor component weight, losses, part count and overall efficiency respectively.

A detailed electrical design was performed on the power processor and included the following items:

- Detail schematic
- Parts list
- Magnetic components design
- Component weight
- Component loss

Component design, analysis and optimization was performed in the following areas as part of the detailed electrical design work to identify weight-loss reductions and to assess technology improvements:

- Power Thyristor
- Power Transistors
- Transformer - Beam
- Transformer - Discharge

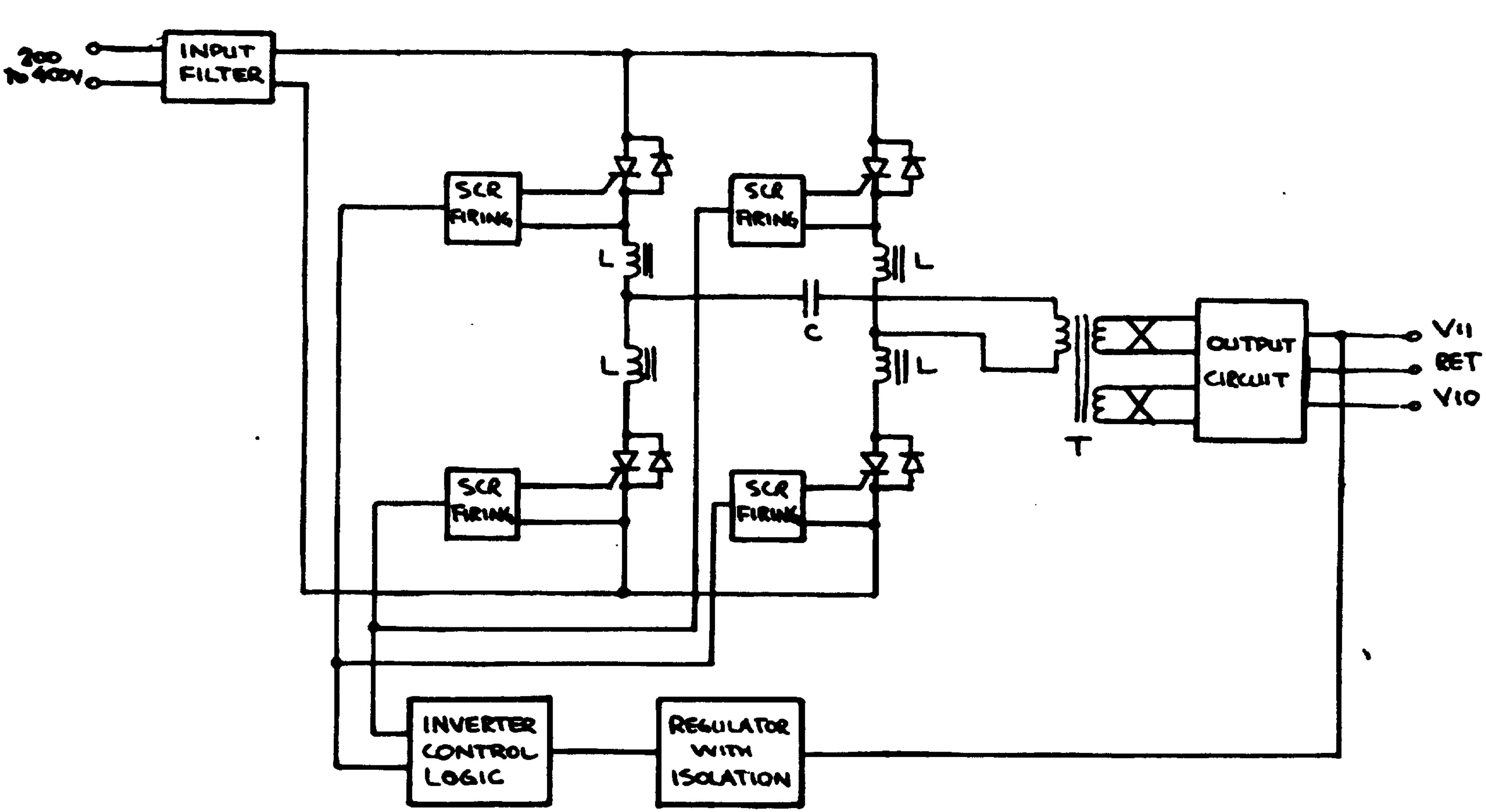


Figure 3-8. Schematic of 6KW Beam Full Bridge Series Resonant Inverter

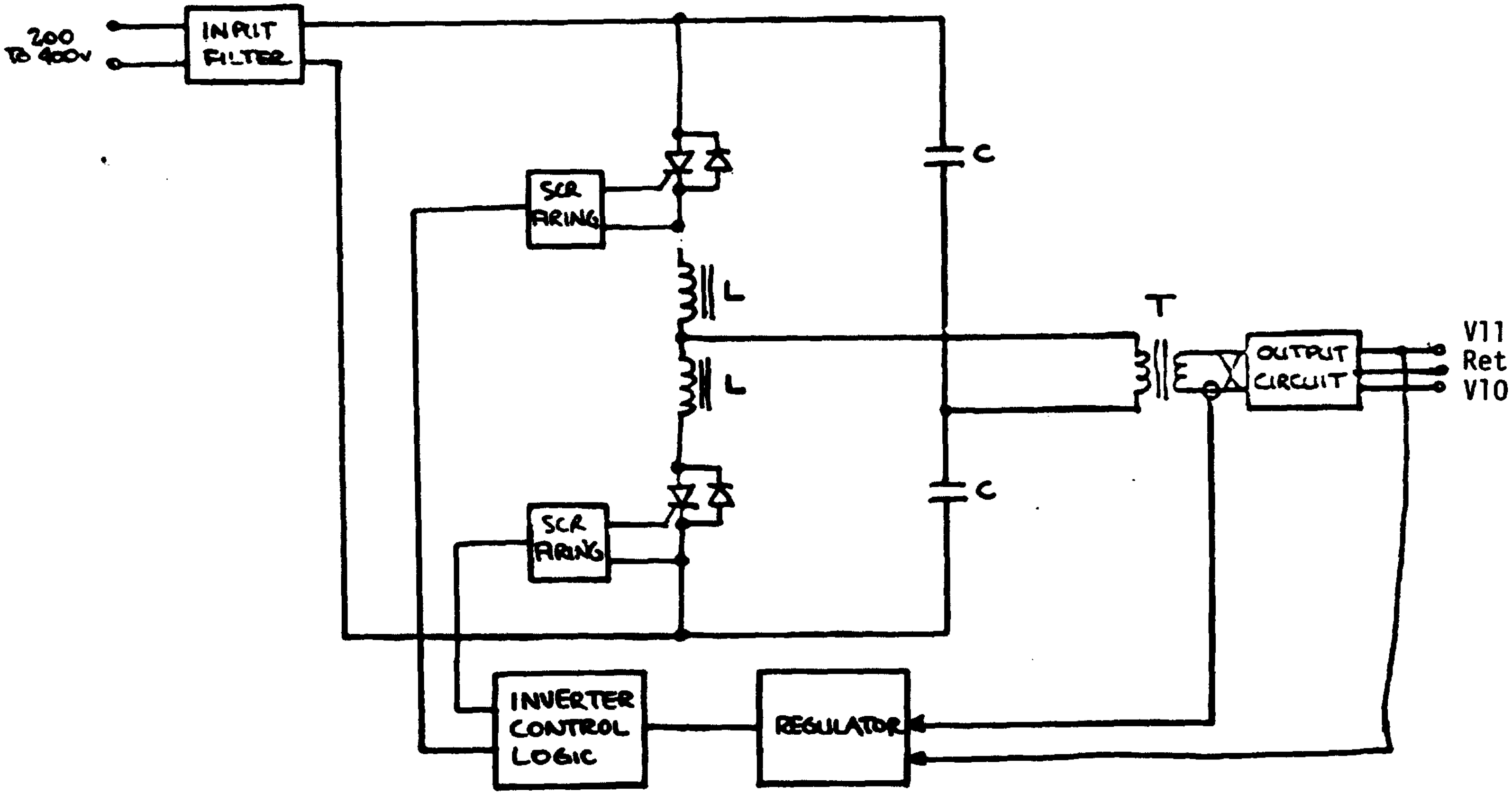


Figure 3.9. Schematic of 2.2KW Beam Half Bridge Series Resonant Inverter

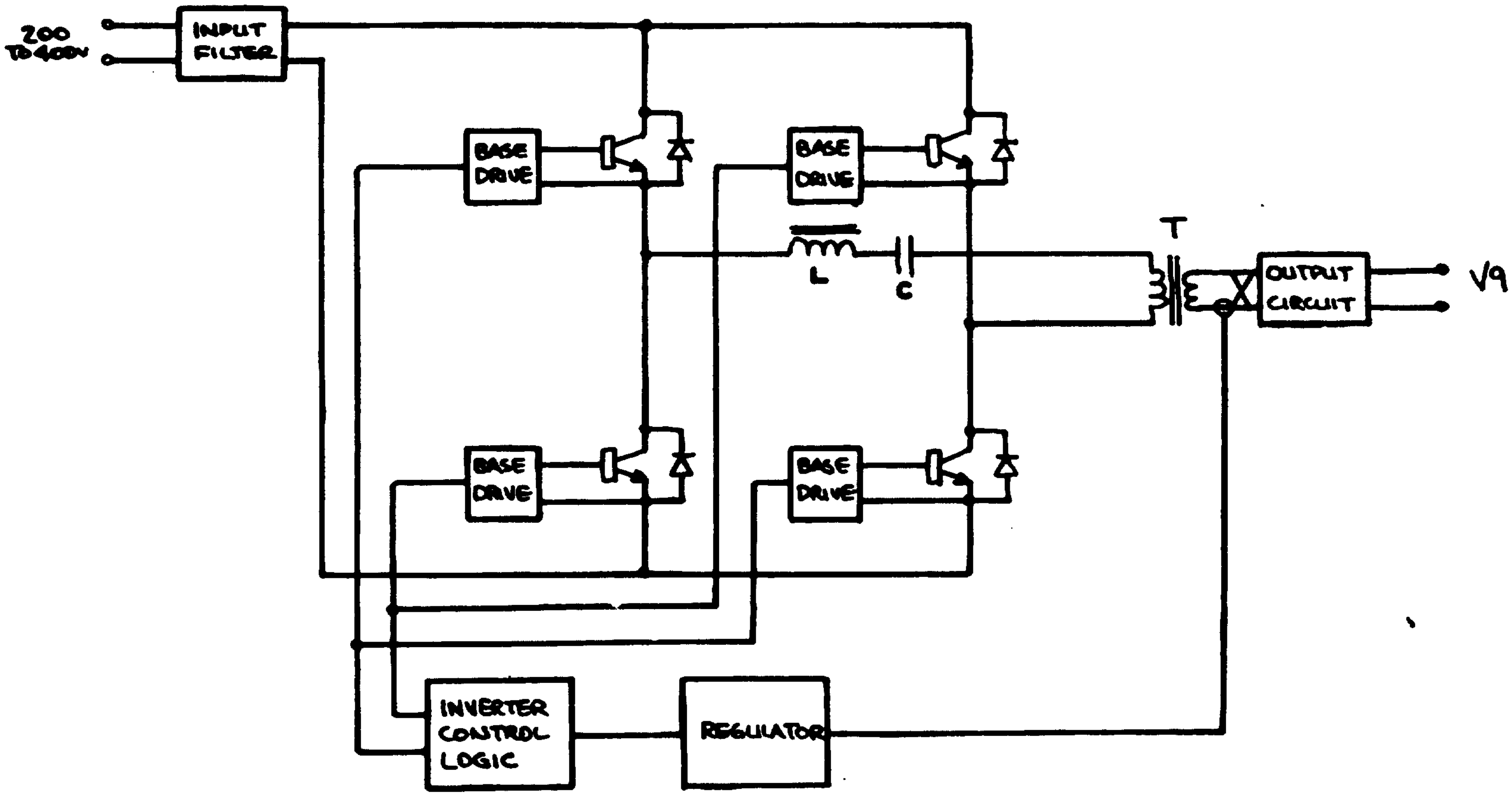


Figure 3-10. Schematic of 50kHz Discharge Series Resonant Inverter

- Series Resonant Inductor
- Input Filter Inductors
- Magnetic Materials and Process
- Capacitors
  a) input filter
  b) series resonant
  c) low voltage output filter
  d) high voltage output filter

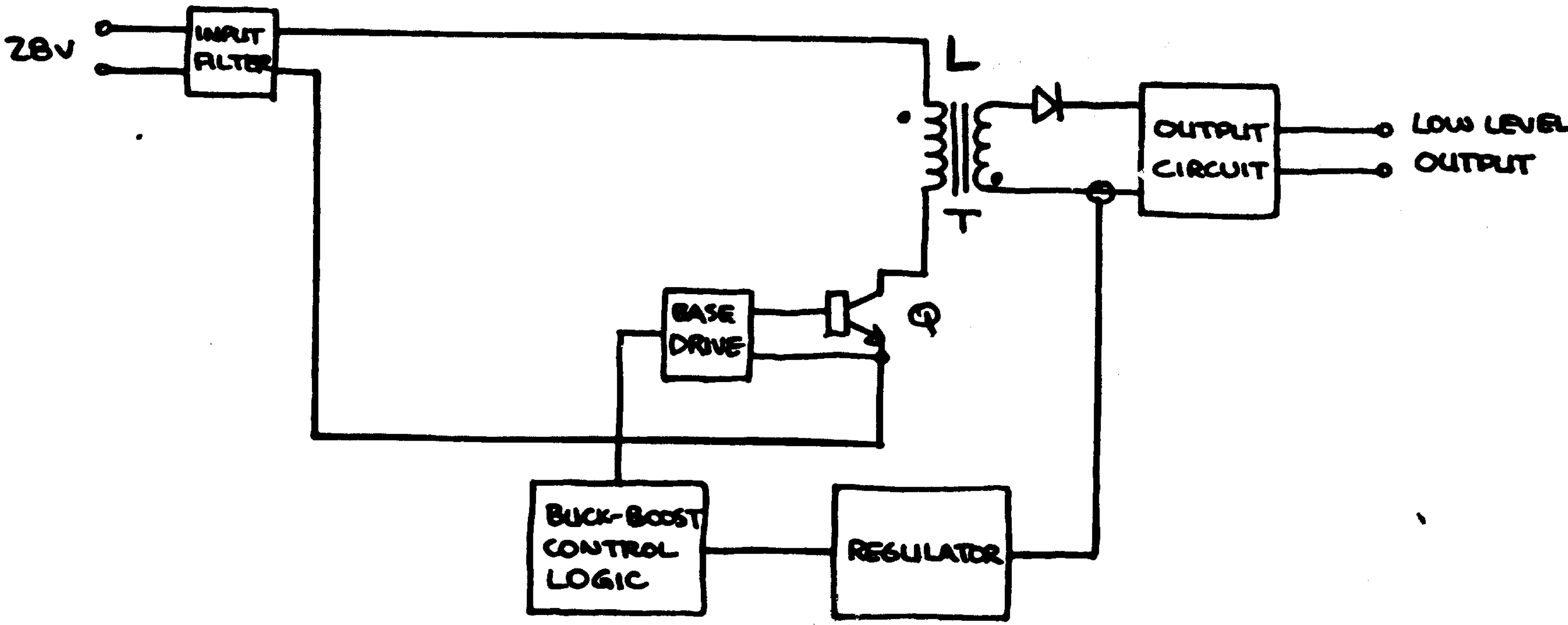


Figure 3-11. Schematic for DC-DC Converter Used on the Low Level Outputs

Table 3-II Summary of 6KW Power Processor Design Characteristics

	WEIGHT GMS	LOSSES (W)	PART COUNT	PWR. STAGE EFFIC. (%)
INPUT FILTER	4368.1	20.98	44	
Beam Inverter (6000W)	9852.03	439.255*	562	93.6
Discharge Inverter (500 W)	2055.68	96.73 *	481	86.6
Low Level Outputs (45W)	3026.12	27.76 *	953	64.7
TELEMETRY	688.93	4.05	168	
DIGITAL INTERFACE	147.1	.973	92	
COMMAND & PROTECTION	243.05	3.479	224	
AUXILIARY CONVERTER	599.36	9.066	106	
INTERFACE CONVERTER	309.36	2.864	90	
TOTALS	21289.73	605.157	2720	91.5%

*Losses include power stage and control losses

Table 3-III Summary of 2.2KW Power Processor Design Characteristics

	PART COUNT	WEIGHT GMS	LOSSES WATTS	EFFIC. %
INPUT FILTER	32	2147	8.24	
BEAM INVERTER (2200W)				
Power Stage	59	4803.2	161.92	93.1%
SCR Firing	74	87	13.1	
Series Inverter Control	140	76.83	.980	
Regulator	118	123.47	1.320	
Accelerator Regulator	50	89.78	2.104	
	441	5180.28	179.424	
DISCHARGE INVERTER (500W)				
Power Stage	28	1493.6	77.54	86.6%
Transistor Drive	167	243.17	16.99	
Series Inverter Control	130	71.03	.924	
Regulator	97	113.87	.493	
Booster	59	134.01	.783	
	481	2055.68	96.73	
LOW LEVEL OUTPUTS (45W)				
Power stage	330	2495.23	24.563	64.7%
Controls	623	530.89	3.197	
	953	3026.12	27.76	
TELEMETRY	168	688.93	4.05	
DIGITAL INTERFACE	92	147.1	.973	
COMMAND AND PROTECTION	224	243.05	3.479	
AUXILIARY CONVERTER	106	599.36	9.066	
INTERFACE CONVERTER	90	309.36	2.864	
	680	1987.8	20.432	
TOTALS	2587	14396.88	332.586	89.2%

3.6 Reliability Estimate

A preliminary reliability assessment was performed based on the detailed electrical schematics and parts list generated for the 6KW electric propulsion power processor shown in Figure 3-6 and for the Power Distribution Unit DC-DC Converter shown in Figure 3-2.

Figure 3-12 presents the electric propulsion power processor reliability block diagram. The component temperature was estimated at 70°C. The failure rate for each power processor function has been identified in order to show where reliability improvement can be made without large weight or power loss penalties.

The major failure rates were in the digital interface unit due to the high failure rate of the LSI parts used in the microprocessor. A three to one reduction in failure rate was obtained by lowering these component temperatures from 70°C to 55°C by thermal isolation from the power component in the power processor.

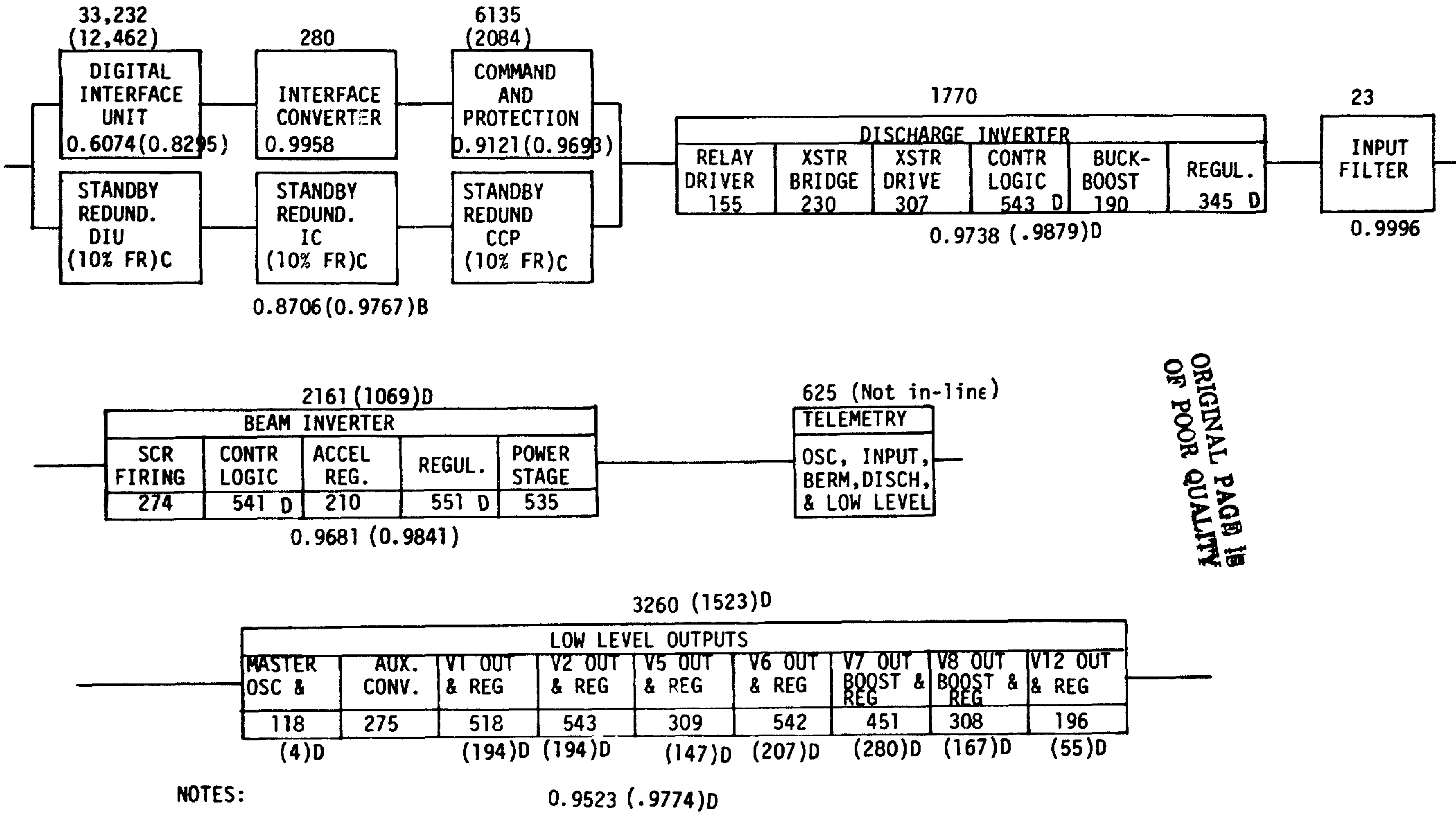
Further analysis of the other power processor functions identified two specific IC components that contribute to about 50% of the power processor reliability:

HA2-2700 Operational amplifier
LM139D Quad Comparitor

Additional component screening or selection of alternate IC components could further reduce the power processor failure rate.

Table 3-IV summarizes the present reliability prediction. Reliability improvement can be obtained by the following methods:

- Redundancy in digital interface unit and command protection electronics
- Redundancy in the low level electronics in the power processor
- Reduction of the control electronics temperature
- Component screening



NOTES:

A) Failure rates shown are per billion hours.
B) Failure rates in parenthesis assume slice is thermally isolated.
C) Standby unit is at 10% of operative failure rate while in standby mode.
D) Majority voting used for low power control electronics

Figure 3-12. 6KW Electric Propulsion Power Processing Unit Reliability Block Diagram

Table 3-IV PPU Reliability Assessment

	No Redundancy		Redundancy	Comment
Digital Interface Unit Interface Converter & Command and Protection	70°C Internal Ambient	0.5522	0.8706	Standby Redundant
	55°C Internal Ambient	0.8008	0.9767	Standby Redundant
Input Filter		0.9996	0.9996	No Redundancy
Beam Supply		0.9681	0.9841	Majority Voting Control Electronics
Discharge Supply		0.9738	0.9879	Majority Voting Control Electronics
Low Level Supplies		0.9523	0.9774	Majority Voting Control Electronics
Telemetry		Not in line	Not in line	
Total		0.7186	0.9277	

Notes: A) T = 15,000 hours

Figure 3-13 presents the Power Distribution Unit DC-DC Converter reliability block diagram in order to fully evaluate the total thrust system reliability. The basic reliability for 15,000 hours is 0.9905. With an additional unit in standby redundancy, the reliability is improved to 0.99997.

1537 (635)*

28V BUS CONVERTER				
POWER STAGE	SCR FIRING	CONTR LOGIC*	REGUL.*	BIAS SUPPLY
200	160	613	289	275

*Majority voting control electronics redundancy

Figure 3-13. Power Distribution Unit DC-DC Converter Reliability Block Diagram

3.7 Beam Power Transformer

Due to higher power rating of the Beam Supply, a detailed electrical and mechanical design was performed on the beam power transformer. A thermal analysis was performed to check the thermal control aspects of the design.

A detailed electrical design was performed on the 6KW beam transformer, based on the 2.2KW beam transformer that was designed, fabricated and tested on Contract NAS3-19730 Electrical Prototype Power Processor Unit.

Table 3-V summarizes the electrical design details for the 2.2KW, 6KW and 10KW beam power transformers. The core material used in the design was 1/2 mil supermalloy.

Figure 3-14 shows the mechanical design of the 6KW beam transformer.

Table 3-VI summarizes the weight losses for the 6KW beam power transformer. 40% of the total weight was in the tape core, 28% of the weight was in the coil and the remaining 32% of the weight is for the mechanical mounting and transformer thermal control. By the use of more core material and less winding coil weight, the loss in the windings is minimized in order to reduce thermal control aspects of the design.

Figure 3-15 shows the exploded view of the 6KW beam transformer. It is composed o₁ the following subassemblies:

- One piece mounting base
- Molded coils/core configuration
- End clamping plates

The low profile is used to reduce the thermal resistances to the baseplate and the cooling loop saddle.

The coil/core assembly is composed of two molded coils with the electrostatic shield extended outside of the coil by copper tabs. BeO spacers are placed between the coil and core to act as heat shunts to carry heat from the coil and core to outside mounting surfaces. These heat shunts reduce the winding hot spots.

The primary power leads use lead sinks to further remove winding heat to the mounting base.

Table 3-V Electrical Characteristics

OUTPUT POWER	2KW	6KW	10KW
CONFIG.	1/2 BR	FB	FB
# NUMBER REACTORS	2	4	4
CORE DXEXFXG	.75X.438X2.375X1.000 2 USED	1.000X1.000X3.500X1.5750	1.188X1.188X4.500X2.000
WT GMS	638G	1650g	2860G
LOSS	10W	30W	52W
PRIMARY TURNS	16t (2L, 1 COIL)	12+12 1 (2 COILS)	16+16 t
WIRE	5X3X21X33	5X3X35X33	5X3X35X33
CURRENT	33 Arms	45 Arms	75 Arms
WEIGHT	208 gms	525 gms	740 gms
DCR	6.3mΩ	5.85mΩ	8.2mΩ
LOSS	6.9W	11.9W	46.1W
SECONDARY TURNS	204t	408t	950t
WIRE	32/33	32/33	32/33
CURRENT	2.7 Arms	2.7 Arms	2.7 Arms
WEIGHT	350 gms	610 gms	1500 gms
DCR	.91Ω	1.59Ω	4.1Ω
LOSS	6.6W	11.6W	29.9W

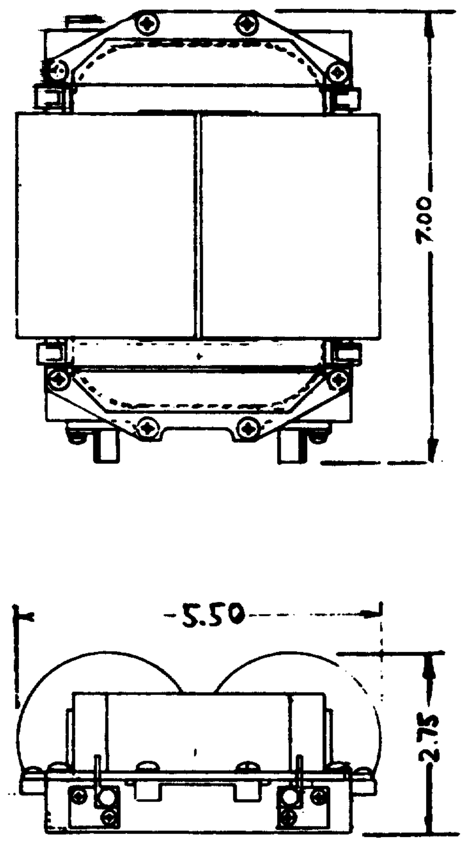


Figure 3-14 Outline Drawing of 6KW Beam Transformer

Table 3-VI Loss-Weight Estimate

	LOSS	WT	%
CORE	30	1650	40%
COILS	27	1165	28%
ESS	3		
BeO		270	
FRAME		300	
TERMS & BeO		100	32%
POTTING		500	
SCREWS & HARDWARE		40	
AUXILIARY TRANSFORMER		100	
	60W	.4125 grams	

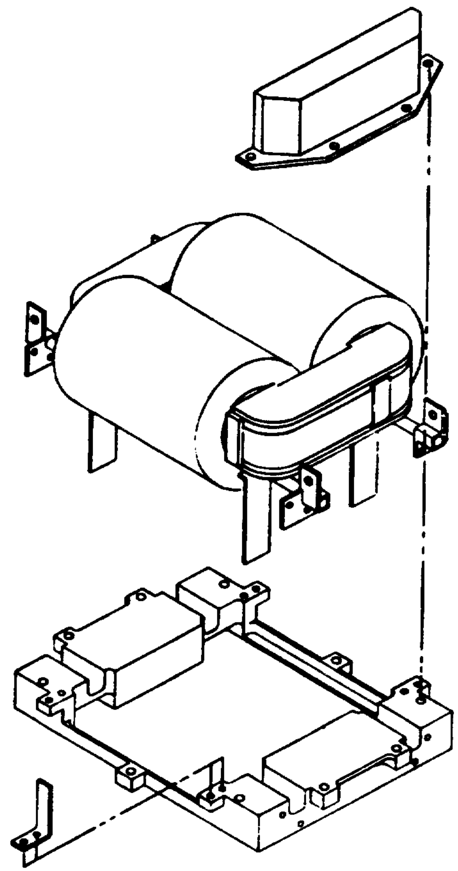


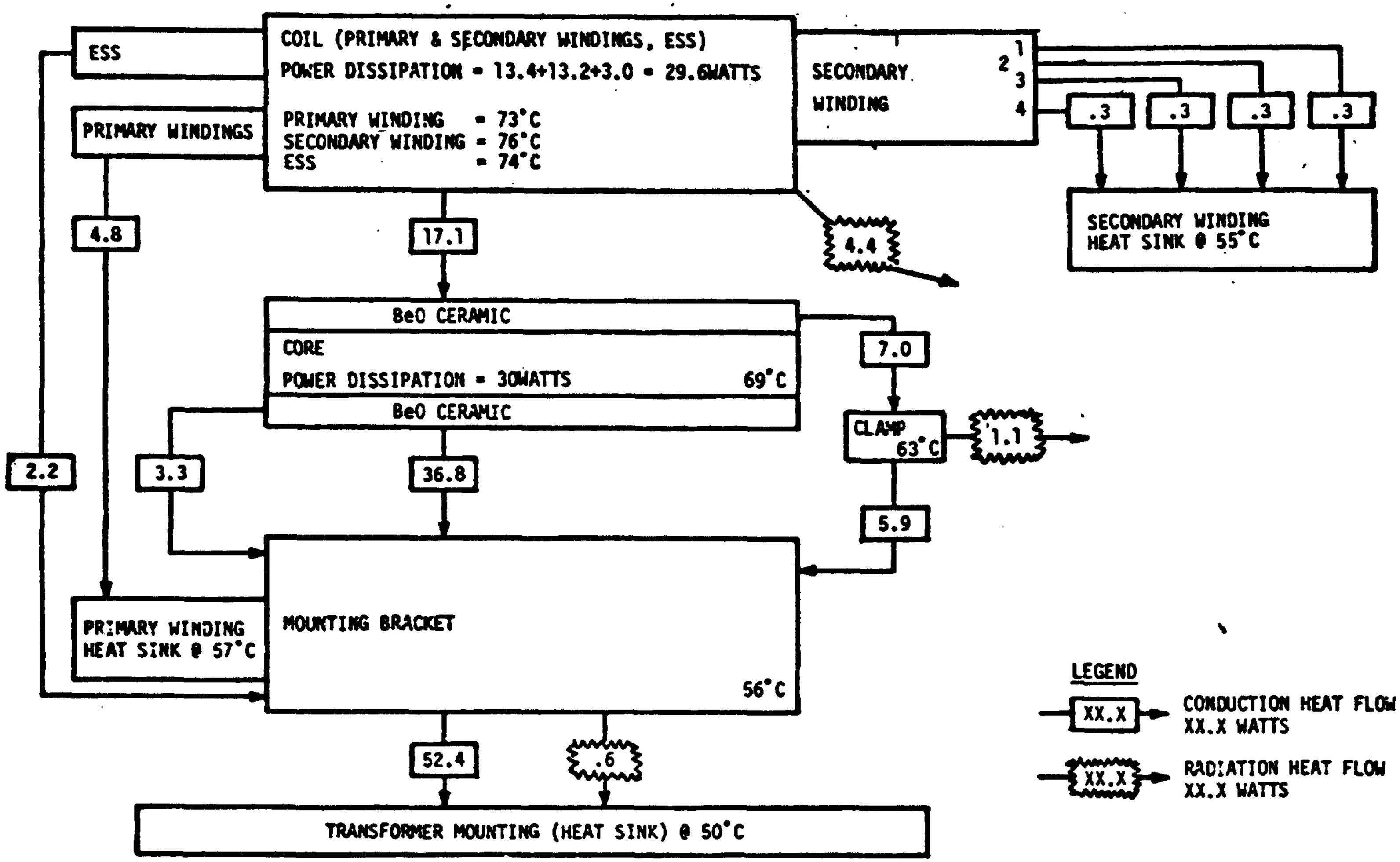
Figure 3-15 6KW Beam Transformer - Exploded View

A detailed thermal analysis was performed on the 6KW beam power transformer. The computer analysis was based on the thermal model generated for the 2.2KW beam power transformer, developed under Contract NAS3-19730.

Figure 3-16 contains the results of the thermal analysis. Power loss is identified for the coil and core where the heat flow from the transformer is present to show the effectiveness of the thermal control technique. The temperatures for each transformer part is also presented based on a transformer heat sink of 50°C.

The maximum hot temperature was 76°C in the secondary transformer winding. This temperature is below the maximum design hot spot limit of 85°C.

Due to the results of this thermal analysis, a transformer redesign was made that would reduce transformer weight and have a hot spot temperature of 85°C. The present limitation of 85°C is based on the polyurethane potting material used as the impregnation for the winding coils.



3-16 6KW Beam Transformer Thermal Analysis Results

3.8 Conceptual Mechanical Design

The structural and thermal interfaces were reviewed in order to be compatible with Bi-Mod power processor configuration. The power processor electrical design was also analyzed to determine the optimum modularization.

Figure 3-17 presents the mechanical packaging concept for a side-by-side power processor configuration. Figure 3-17 shows the interface module structure which is connected to the platform/evaporator heat saddle with its radiator panels. The two separate power processors are connected to the base of the evaporator saddle.

The power processor is divided up into three separate modules that can be individually tested. The modules are divided up into the following functions:

- o Input filter, interface unit & low voltage outputs
- o Beam supply & high voltage outputs
- o Discharge supply & high voltage outputs

The cabling harness is recessed into the side of the power processor and is accessible through a cover plate.

The top of the evaporator saddle is available for other electronic hardware necessary for the interface module operation.

Table 3-VII highlights the packaging concept featured for the power processor. This packaging concept is applicable to both the 6KW & 2.2KW beam supply designs.

Figure 3-18 presents an estimate of the 6KW power processor physical dimensions and volume, and is compatible with the proposed size of the platform/evaporator saddle.

Figure 3-19 illustrates the size of a typical 6KW beam module, location of large heat producing components and cutout for the interconnecting connectors and cable harness. With this location of the cable harness, the module can be easily removed for maintenance and testing.

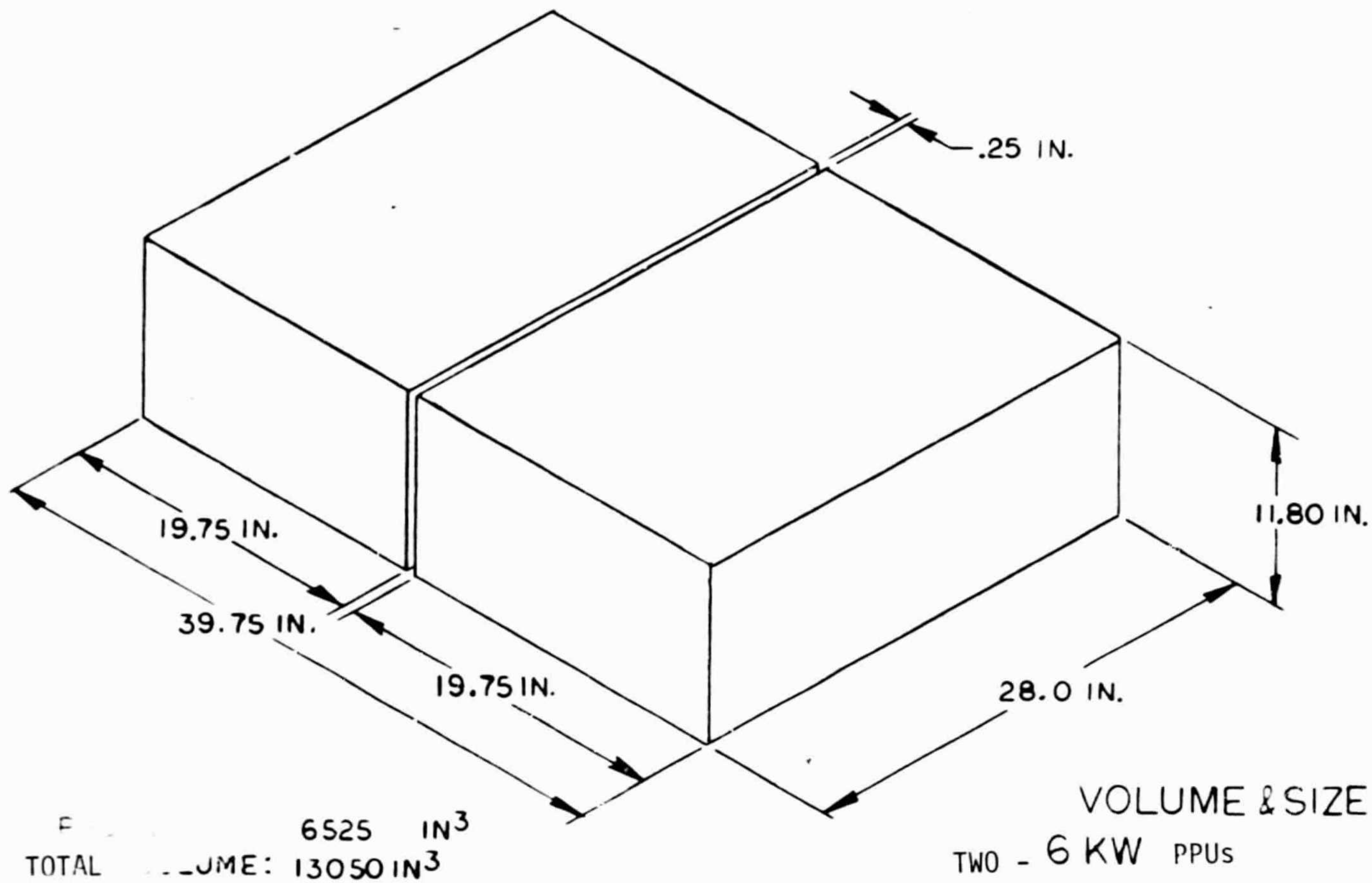


Figure 3-17 Size and Volume Estimate for two 6KW Beam Supply Power Processors

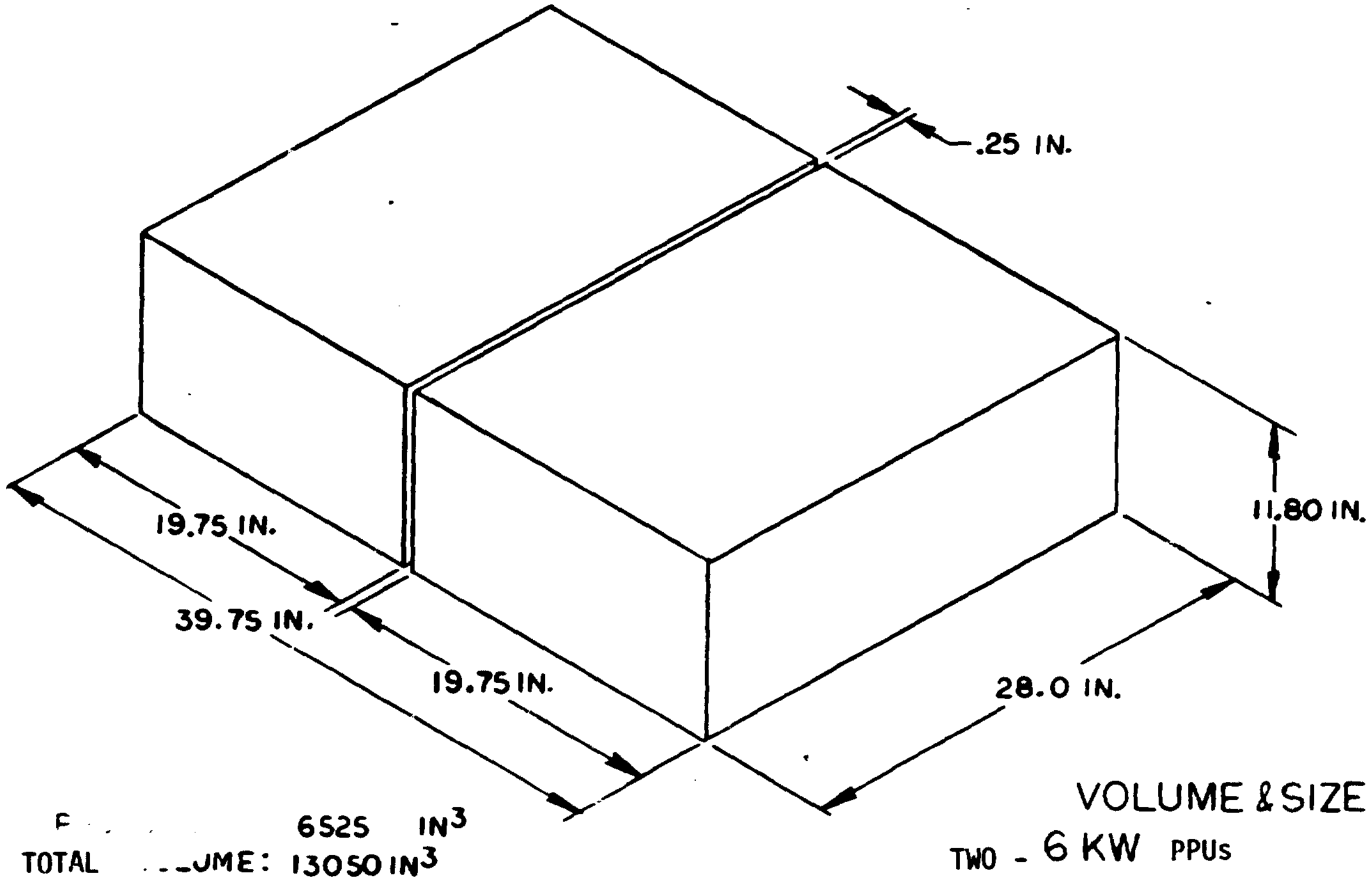


Figure 3-17 Size and Volume Estimate for two 6KW Beam Supply Power Processors

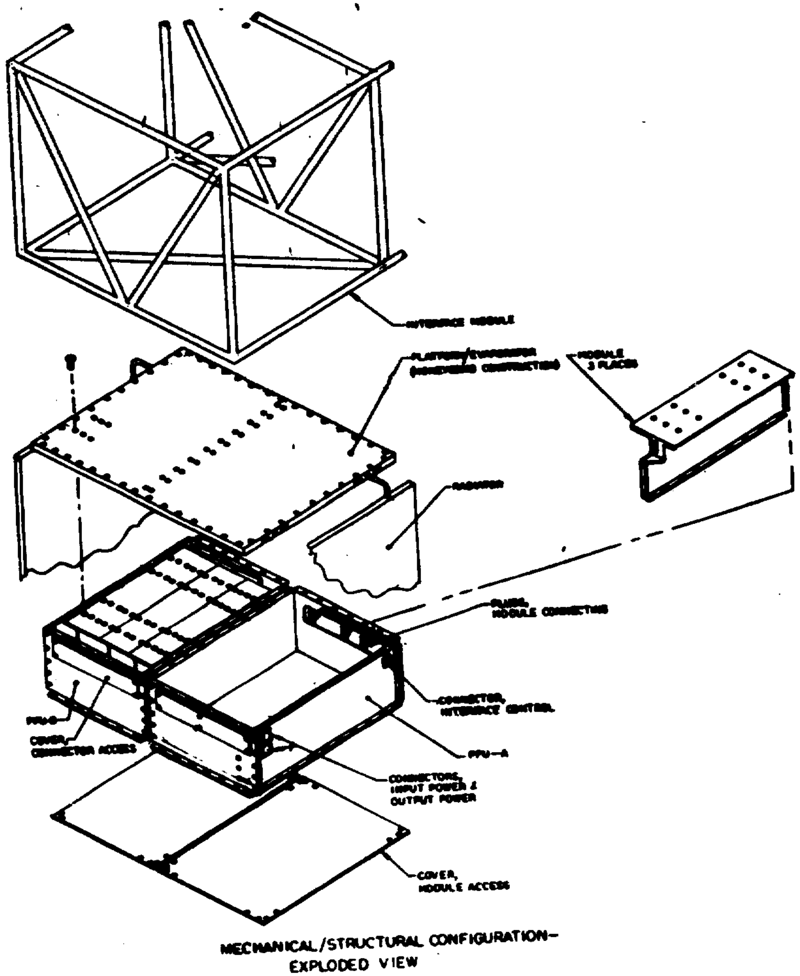


Figure 3-18 Power Processor Conceptual Mechanical Configuration

Table 3-VII Features of Bi-Mod Power Processor Conceptual Mechanical Configuration

- Power processor circuit packaged in three individually removeable modules.
- PPU enclosure consists of two (2) side walls, two (2) end walls and a top cover.
- Modules are screw fastened to the side panels, top cover, and finally to the platform/evaporator.
- Wire harness is internal to and captive to the PPU enclosure.
- Module connecting plugs are accessible thru covered ports in the side panels.
- External connectors (input/output and interface control) are located on the end panel facing the heat pipe radiators.

Based upon the proposed packaging concepts, Tables 3-VIII and 3-IX present the mechanical hardware weight estimates for both the 6KW and 2.2KW power processors respectively.

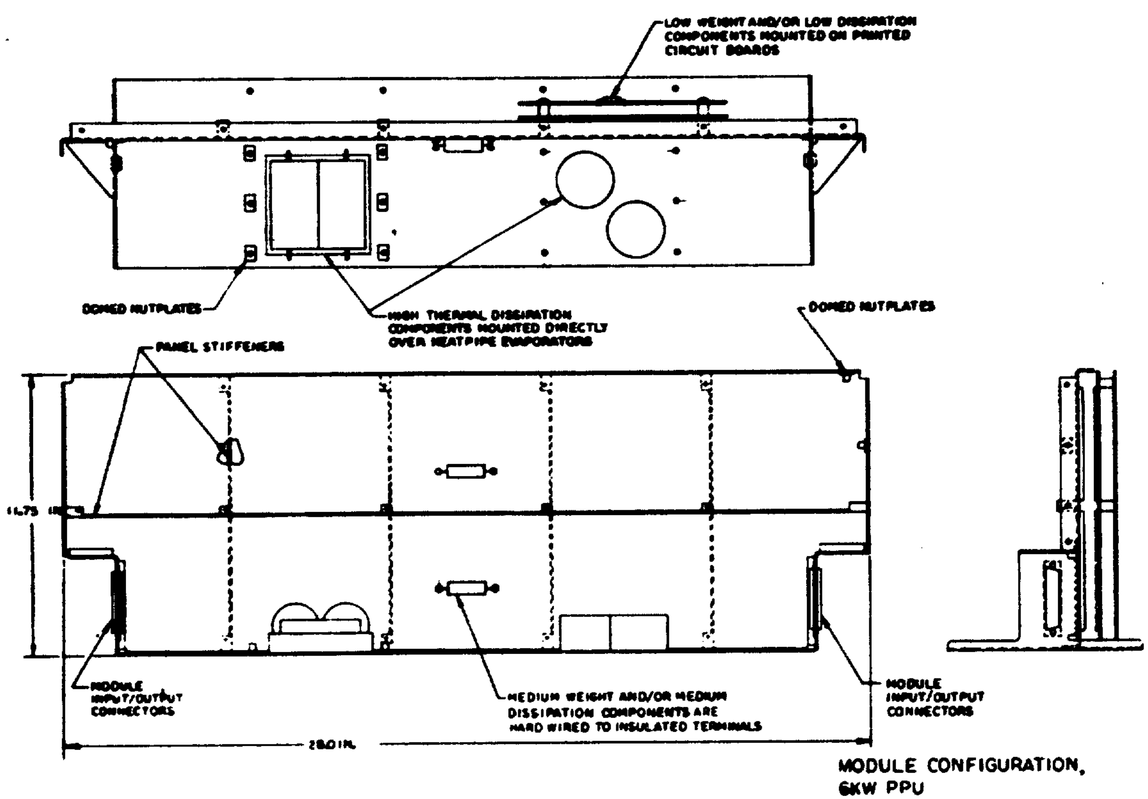


Figure 3-19. Proposed Moudle Subassembly

Table 3-VIII Mechanical Weight Estimate - 6KW Beam Power Processor

	LBS	GMS
Panel, Side	1.17	531.2
Panel, Side	1.17	531.2
Panel, End	1.76	799.04
Panel, End	1.76	799.04
Cover, Top	3.30	1498.2
Printed Ckt. Bds.	7.40	3359.6
Board Frames	3.00	1362.0
Modules	12.49	5670.4
Screws	3.39	1539.06
Nutplates	.75	340.5
Spacers	1.82	826.2
Wiring	4.00	1816.0
Connectors	1.40	635.6
Conformal Coat	1.11	503.9
Bonding & Potting	.75	340.5
Misc. Brackets & Insulators	1.00	454.0
	46.27	21006.4

Table 3-IX Mechanical Weight Estimate - 2.2KW Beam Power Processor

	LBS	GMS
Panel, Side	.80	363.9
Panel, Side	.80	363.9
Panel, End	1.20	547.34
Panel, End	1.20	547.34
Cover, Top	2.26	1026.27
Printed Ckt. Bds.	5.07	2301.33
Board Frames	2.05	932.97
Modules	8.55	3884.22
Screws	2.32	1054.26
Nutplates	.51	233.24
Spacers	1.25	565.95
Wiring	2.74	1243.96
Connectors	.96	435.39
Conformal Coat	.76	345.17
Bonding & Potting	.51	233.24
Misc. Brackets & Insulators	.68	311.
Total	31.7	14389.4

4.0 PROGRAM PLAN

The program plan for the Electric Propulsion Power Processor was developed in support of the Halley's Comet Mission. The program plan addressed the following items:

- Program Schedule
- Major Milestones
- Hardware List
- Test Support Equipment
- Power Processor Program Funding

4.1 Work Breakdown Structure and Schedule

A work breakdown structure was generated for the following Electric Propulsion Power Processor phases:

- Engineering/Qualification Model
- Test Support Equipment
- Prototype Models
- Flight Units

A detailed schedule was prepared for each phase and coordinated with the NASA Lewis Project Manager.

The basic equipment list was determined in support of the Electric Propulsion Power Processor program:

- Engineering/Qualification Model
- Prototype Models (Quantity 4)
- Flight Models (Quantity 18)
- Module Testers (2 Sets)
- Power Processor Unit Test Sets (Quantity 3)

Figure 4-1 presents the work breakdown structure and the schedule for each subtask. The following major milestones were identified from the overall schedule:

- Engineering/Qualification Model Design Complete October '78
- Engineering/Qualification Model Test Complete July '79
- First Set of Test Support Equipment Complete November '78
- Test Support Equipment Complete May '79

POWER PROCESSOR PROGRAM SCHEDULE FY 78 TO 80

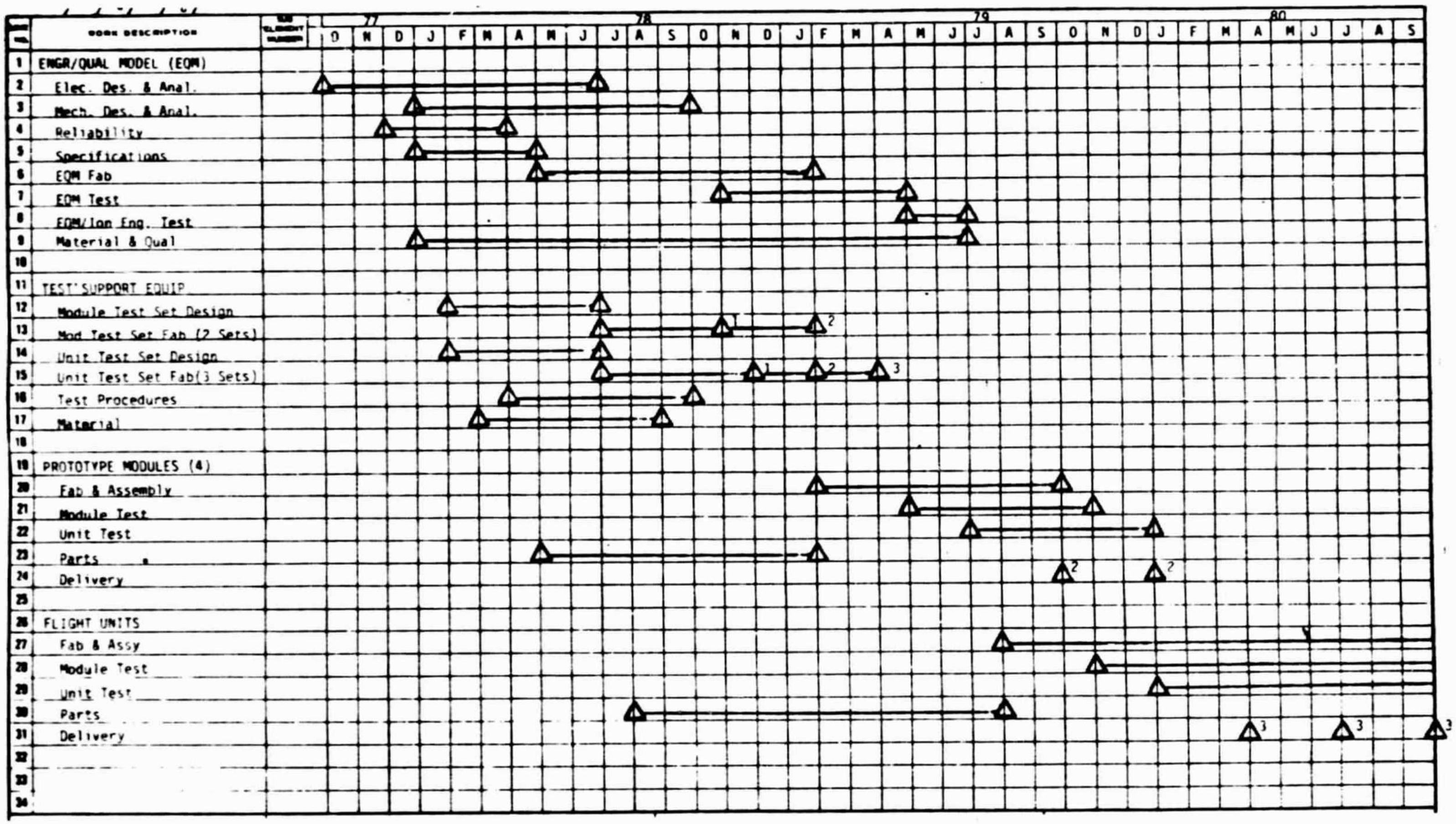


Figure 4-1 Power Processor Program Schedule

POWER PROCESSOR PROGRAM SCHEDULE FY 81

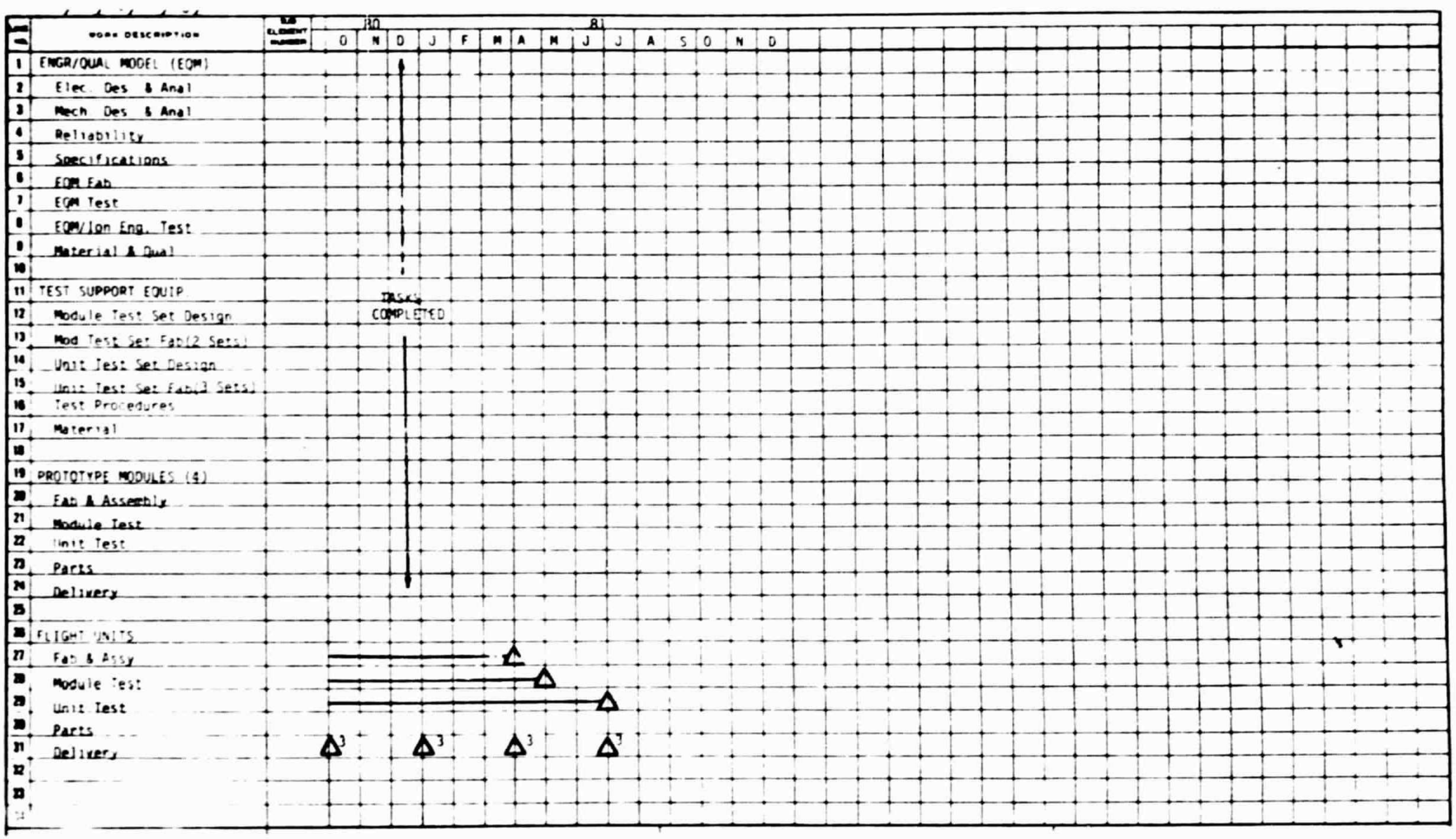


Figure 4-1 Power Processor Program Schedule

POWER PROCESSOR PROGRAM SCHEDULE FY 81

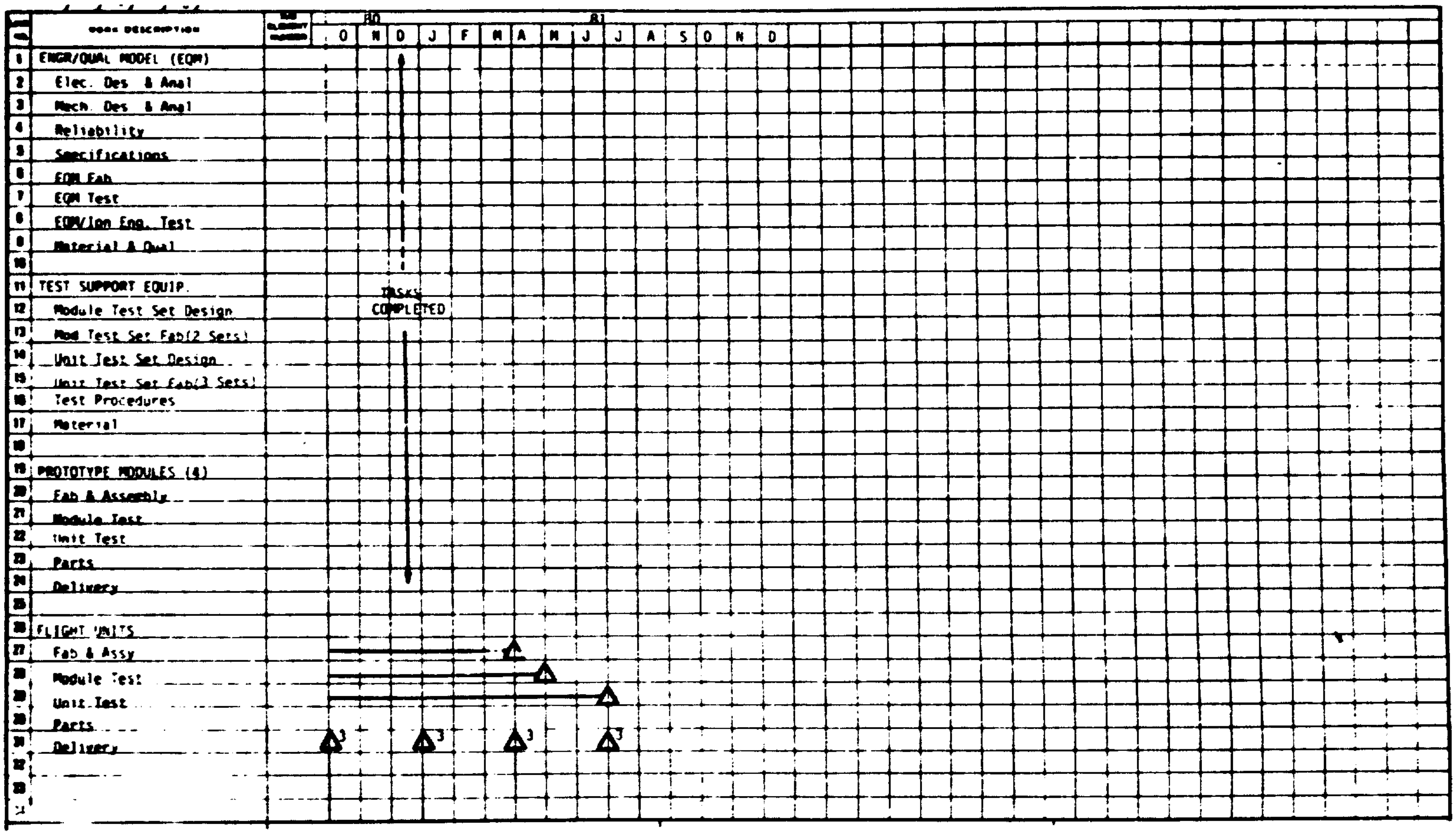


Figure 4-1 Power Processor Program Schedule

- Prototype Models (4) Delivery — January '80
- Order Flight Components — August '78
- First Flight Unit Delivery — April '80
- Flight Models Complete — July '81

The flight model delivery schedule is limited by the number of Power Processor Unit test sets and is not limited to manufacturing facilities at TRW Systems. No new test or manufacturing facilities are required in support of the Electric Propulsion Power Processor program.

4.2 Program Funding

A detailed manpower estimate was prepared based on the work breakdown structure and proposed schedule, presented in Section 4.1.

The electrical design was based on the 6KW beam supply and a total electrical part count of 3600.

The program was costed based on 1977 dollars and was based on the equipment list presented in Section 4.1 for the engineering qualification model, prototype models, flight models and the manufacturing test support equipment.

Table 4-I is a summary of the costing for each phase as a function of the Fiscal year so that timely funding would be allocated for the program.

Table 4-I Electric Propulsion Power Processor Program Funding Requirements

($ IN 000's)

TASK	FISCAL YEAR				TOTAL
	78	79	80	81	
ENG. QUAL. MODEL	$3,610	$ 868	--	--	$ 4,478
PROTOTYPE UNITS	173	2,387	141	--	2,701
FLIGHT UNITS	448	2,239	5,222	733	8,642
TEST EQUIPMENT	993	344	21	21	1,379
	$5,224	$5,837	$5,384	$754	$17,199

Costs based on 1977 dollars

5.0 RISK ASSESSMENT

The design technical risks have been minimized due to the past development of the series resonant inverter circuit and the demonstrated operational reliability of three power processor breadboards:

- Thermal Vacuum Breadboard Contract NAS3-14383.
- New Technology Breadboard Power Processor Contract NAS3-18924.
- Electrical Prototype Power Processor Unit Contract NAS3-19730.

Present redesign activities further address component and circuit design techniques that can further reduce component weight, reduce losses and reduce overall component part count. By reducing part count, the unit production costs will also be reduced.

Risks can be identified in two basic areas; critical technologies and potential problems.

5.1 Critical Technologies

The electric propulsion technology is extending the state-of-the-art for high power processing technologies for space flight applications. For low weight, high efficiency and high reliability power processing equipment, new power semiconductors and power magnetics technology application must be used.

The following critical technologies have been identified:

- High speed low loss power thyristors for the beam series resonant inverter
- High speed low loss power transistors for the discharge series resonant inverter
- High voltage high power beam transformer and power magnetics.

In order to maintain the low weight estimates for the power processor, it is necessary that component manufactures continue to further improve and develop manufacturing lines that can produce the required high reliability power semiconductors.

Magnetic components are a major weight element for the power processor. Design techniques need to be improved in order to reduce magnetic component weight and provide the necessary thermal control for high reliability operation.

5.2 Potential Problem Areas

In order to obtain a flight power processor design that is ready for the future electric propulsion missions, it is necessary that a realistic schedule be adopted with timely funding of the different design, development, qualification and manufacturing phases.

Additional high power components development and qualification must be funded in support of the basic power processor schedule in order that timely high reliable component delivery will meet the power processor manufacturing schedule.

6.0 CONCLUSIONS

This study program has demonstrated that the electric propulsion power processor technology is capable of performing the planned electric propulsion mission applications. The program plan also demonstrates the capability of meeting the critical launch dates proposed for the Halley's Comet Mission.

In the event that the Halley Comet Program is not funded, alternate technology readiness programs can be initiated. This program includes the following:

a) Engineering/Qualification Model

b) Product Improvement Tasks

- 6KW Beam Supply
- 50kHz Discharge Supply
- Low Level Supply
- Microprocessor Digital Interface Unit
- Component Improvement
    1) Beam power transformer
    2) Transformer potting material
- Structural Thermal Mockup

The relative funding of each program is quite different with the product improvement cost being a lower cost compared to an Engineering/Qualification Model.

The product improvement tasks ensures that the future Engineering/Qualification could be designed, fabricated and tested with minimum technical problems and would meet the contracted schedule and funding allotment.

The sequential funding of the two programs would be a cost effective approach where there is no immediate launch date that must be met.