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A MECHANICAL, THERMAL AND ELECTRICAL PACKAGING DESIGN FOR A PROTOTYPE POWER MANAGEMENT AND CONTROL SYSTEM FOR THE 30 cm MERCURY ION THRUSTER

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SUMMARY

A prototype Electric Power Management and Thruster Control System for a 30 cm ion thruster has been built and is ready to support a first mission application. The system meets all of the requirements necessary to operate a thruster in a fully automatic mode. Power input to the system can vary over a full two to one dynamic range (200 to 400 V) for the solar array or other power source. The Power Management and Control system is designed to protect the thruster, the flight system and itself from arcs and is fully compatible with standard spacecraft electronics. The system is designed to be easily integrated into flight systems which can operate over a thermal environment ranging from 0.3 to 5 AU. The complete Power Management and Control system measures 45.7 cm (18 in.) x 15.2 cm (6 in.) x 114.8 cm (45.2 in.) and weighs 36.2 kg (79.7 lb). At full power the overall efficiency of the system is estimated to be 87.4 percent. Three systems are currently being built and a full schedule of environmental and electrical testing is planned.

INTRODUCTION

The National Aeronautics and Space Administration is now preparing to embark on its first solar electrically propelled mission. Descriptions of proposed flight systems for such a mission can be found in references 1 and 2. These flight systems would employ between six and ten 30 cm mercury ion thrusters for prime propulsion. An Electric Power Management and Thruster Control system is required for each ion thruster to convert the raw solar array power into the power and control functions necessary to the operation of the ion thruster.

The basic electrical design for such a system was presented by Biess, Inouye, Shoenfeld, and Shank at the AIAA Eleventh Electrical Propulsion Conference. Since that time an Electrical Prototype Power Processing Unit (EP/PPU) has been built for the Lewis Research Center by the TRW Systems Group. A complete description of this unit is

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being presented by Biess and Frye at the AIAA/DGLR Thirteenth International Electric Propulsion Conference (ref. 3).

Flight weight and flight configured custom electrical components in combination with flight type commercial parts were used to build the EP/PPU. The EP/PPU is configured using a modular approach similar to that given by Maloy and Sharp at the Eleventh Electrical Propulsion Conference (ref. 4). Because the EP/PPU was an electrical prototype and accessibility to the electrical circuits was of prime importance, a final package configuration was not attempted at that time.

When the EP/PPU design effort was well along, a packaging effort was undertaken at the LeRC. The resulting prototype Power Management and Control (PMAC) system is constructed from electrical components identical to those of the EP/PPU. The topography of the PMAC modules is also similar to the EP/PPU.

However, the prototype PMAC was designed with the elimination of weight at the system level (BIMOD) as an ultimate goal. It is the result of extensive thermal and structural design and analysis. It is designed to withstand any conceivable launch vehicle vibration environment and to be operated in a vacuum at expected flight system temperatures. Units are being built which will undergo vibration, thermal vacuum, 30 cm mercury ion thruster electrical integration and life testing.

This paper describes the PMAC system thermal, mechanical, and electrical packaging design considerations, the final PMAC system design configuration and the PMAC system electrical, thermal and mechanical interfaces. This interface information should be useful to systems designers for planning future electrically propelled flight systems and to the mission analyst for feasibility and mission implementation studies.

DESIGN REQUIREMENTS AND APPROACH

General Systems Design

Modular approaches to packaging power processors for ion thrusters were first proposed about 10 years ago for use with 15 cm ion thrusters. Since that time the concept of modular packaging has not changed even though the form of the package has varied extensively. The modular approach was originally chosen for several reasons. Modules subdivide the overall PMAC package into manageable and workable portions thus facilitating easier and more economical manufacture. Electrical noise isolation can be achieved by separation of sensitive control functions from noisy high power or high voltage functions. Modules can be given individual electrical acceptance tests before final assembly. Because of their simplicity relative to an entire PMAC system, modules have the potential for relatively inexpensive mass manufacture. Modules can also be readily replaced and repaired as single units. Since the modules in all the power processors are identical, the total stock of exchange PMAC units or modules can also be smaller. Lastly, modules lend themselves readily to individual thermal and mechanical analysis.

The first step in the design of a modular power processor is to divide the electrical circuitry into logical unitized blocks with minimal electrical interconnections. The electrical schematics for these blocks are then used to prepare a preliminary component layout. Both thermal and structural computer analysis are used to improve the layout within the given electrical limitations and a commitment to the final design is made.

MECHANICAL DESIGN

The mechanical design criteria for the PMAC system are that it be as light in weight as possible and yet accommodate the rigors of the launch environment and the vacuum operational thermal requirements. A programmatic weight goal of 25 kg (55 lb) was established for the PMAC system (see the System Description and Results section for discrepancies between present weight and programmatic goals).

Mechanical Design Requirements

The structural design requirements for either the single or dual PMAC configurations are twofold:

(1) The structural integrity of the system should be maintained for any currently conceivable launch environments.

(2) All major resonant frequencies of the PMAC package should be greater than 200 Hz in order to preclude coupling of PMAC package resonances with those of the spacecraft (ref. 5).

Mechanical Design Approach

It was decided that the best way to achieve the overall weight goal was to design the PMAC package to be as compact as possible within the overall dimensional limitations of the then contemplated thrust system configurations. The minimum allowable thruster spacing for a thrust system is 61.0 cm (24.0 in.) in order to allow adequate clearances when gimbaling the thrusters. Thus, the maximum width of the overall PMAC package could be 61.0 cm (24.0 in.) without influencing thruster spacing. Since it was found that the electrical components for each module could be conveniently grouped on 45.7 cm (18.0 in.) long modules, this dimension was chosen for the width of the PMAC package. The height of the modules was determined by the desire for a 12.7 cm (5.0 in.) high Printed Wiring Board (PWB) and the availability of 15.2 cm (6.0 in.) maximum thickness aluminum plate from which the modules were to be machined. There was no overall length requirement for the PMAC.

Mechanical Design Results

The modular approach for the design of the PMAC package results in a rectangular box type configuration (fig. 1). This figure shows that each module is attached to an outer frame which in turn supports the entire PMAC package at four hand points near the corners of the box. The package is then made completely rigid by the attachment of the 1 mm (0.040 in.) thick magnesium cover plates to each module and the heat pipe evaporator saddles to the remaining side of the entire rectangular package.

The PMAC package is designed to be mounted either singly (refs. 6 to 8) against a set of heat pipes (fig. 1) or with two PMAC packages back to back (refs. 7 and 8) against a common set of heat pipes (figs. 2 and 3). For each of these cases the machined aluminum cross beam modules are bolted directly to the heat pipe saddle assemblies and these become the structural backbones of the PMAC package. The heavier electrical components with greater thermal dissipation are then mounted to the baseplates of the individual modules as close to the heat pipe saddles as possible (fig. 2).

Launch vehicle acceleration loads on heavy electronics components are conducted along the cross beams to 1 mm (0.040 in.) thick magnesium sheet metal PMAC side members. The acceleration loads are then transmitted to four columns near the corners of the PMAC box (figs. 1 and 2). For the dual PMAC box BIMOD configuration (fig. 4), these side columns also transmit the launch vehicle acceleration loads of the thruster and heat pipe radiators via the BIMOD truss to a central supporting truss.

The dual PMAC BIMOD package readily meets the structural design requirements. A PMAC package mounted singly would need additional structural reinforcement at the side members and at the heat pipe saddles in order to meet these requirements. Complete structural and dynamic analyses were done on only the dual PMAC BIMOD configuration.

Dynamically the PMAC package was assumed to act as a series of short deep beams. The baseplate connecting these beams was also analyzed to determine the individual heavier electronics component vibration modes (a finite element analysis using NASTRAN was employed). Individual panels of the shear webs were checked dynamically as isolated systems. The results of these analyses were that all baseplate and individual panel modes of vibration are above 200 Hz and are decoupled from the short deep beam resonances which are generally greater than 400 Hz.

The dual assembled PMAC (BIMOD) configuration was analyzed for a 72 g acceleration ultimate load. This load was derived from reference 9 and should be adequate for any conceivable launch vehicle.

THERMAL DESIGN

General Thermal Design

The PMAC package consists of roughly 4000 electronic parts. The thermal dissipation of these parts ranges from zero or a few milliwatts to 32 watts for the large thruster screen supply transformer.

The heat dissipation from each PMAC system was expected to be about 317 watts for a nominal ion engine full power condition. Because of the relatively large number of electronic parts and circuits, the actual operating parameters for each part was not determined. Most of the components dissipating heat were assumed to be at their maximum rated condition. This assumption yielded a total PMAC heat dissipation of 380 watts. The PMAC system thermal analysis has been performed for this 380 watts of heat dissipation and therefore should accommodate all starting and running conditions.

Component Junction Temperature

The reliability of electronic components is generally inversely proportional to the temperature as an exponential. (Failure rate = $A \exp(-Q/KT)$) (Arrhenius equation where Q is the device power and T is the absolute temperature.) For a constant component derating factor, the failure rate can be doubled for only a 10° C rise in the component junction temperature (ref. 10).

Many electronic components operating at rated conditions have a 25° to 30° C temperature drop between the component junction and its base. Choosing a maximum operating junction temperature of 100° C the electronic components must be positioned so that their base is at a maximum temperature of 70° to 75° C. A 50° C heat pipe temperature was selected in that it was felt that this was the highest temperature for which the component junction temperature could be kept at 100° C or less. Higher heat pipe temperatures mean smaller heat pipe radiators which in turn gives lower heat pipe system weight.

Heat Pipe System Design

For many missions it is necessary that the PMAC system non-operating heat losses be minimized. An all variable conductance heat pipe system is inoperative (turned off) for a non-operating PMAC system condition. Heat transfer is then only by conduction along the pipe wall connecting the heat pipe evaporator to the heat pipe radiator. The heat pipes chosen for this design are fabricated of stainless steel tubing thus heat conducted along the tube wall should be about 1 watt per tube. A parametric study of an all variable conductance heat pipe thermal control system, an all direct radiating system, and combination of the two was made by Maloy and Sharp (ref. 4). In that study, an all variable conductance heat pipe thermal control system (ref. 11) produced the lightest weight system that also minimized the heat loss during non-operating conditions.

Single PMAC System Design

For a single PMAC system configuration (fig. 1) four heat pipes would be required for thermal control, with two of these being redundant. High heat dissipating components are mounted to the module base plate directly over or near the heat pipe evaporator saddles. (Fig. 5 is a photograph of the high power high voltage beam supply module.) All other components except those on printed wiring boards are distributed on the remaining portion of the base-plate and on the module crossbeam web. The crossbeams are machined from a single piece of aluminum in order to minimize thermal resistance between the base plate and web. A thin layer of RTV 566 (a low outgassing silicon adhesive) was used to enhance thermal conduction by filling in voids between the large electronics components and the baseplate and between the heat pipe evaporator saddle and the baseplate.

The PMAC package has 45 printed wiring boards that are cooled by either radiation or conduction. Because of the small temperature difference between the required 70° C component base temperature and the 50° C heat pipe temperature, all components dissipating more than 15 mW are cooled primarily by conduction. The components are cemented to copper foils (not a part of the electrical circuit) on the printed wiring boards which are in turn riveted to aluminum frames that are bolted directly to the cross beam module baseplates. Aluminum spacers that are used to hold the printed wiring boards in position are also utilized to conduct heat to the cross beam webs.

Dual PMAC System Design

A back to back PMAC arrangement (BIMOD configuration, figs. 3 and 4) is preferred because only three heat pipes are then required per PMAC system. For the BIMOD configuration, six heat pipes are required in two groups of three (fig. 2) with one heat pipe in each group being redundant. The thermal design is otherwise identical to that for a single PMAC system configuration.

Thermal Design Results

The BIMOD configuration (fig. 4) has two single sided radiator fins, with the ion thrusters and supporting truss structure between the fins. This configuration has a narrow profile and the radiator fins can readily be fastened to the support structure. For a spacecraft configuration in which the radiator fins could extend horizontally from the PMAC package (no bend in the heat pipes), both sides of each fin could be utilized resulting in smaller more efficient radiators. Radiator support structures would be required and the radiator length would need to be limited by the overall width limitation of the launch vehicle.

A thermal analysis of the modular PMAC package presented here was made using the Systems Improved Numerical Differencing Analyzer (SINDA) program (ref. 12). The results of this analysis and a description of the nodal model are presented in appendix A.

ELECTRICAL DESIGN

General Electrical Design

The primary electrical requirement of the PMAC system is to efficiently convert electric power from a solar array into voltage and currents required by the ion thruster. Secondary requirements are: (1) to protect the solar array or other power source against electrical malfunction (electrical collapse of a solar array by drawing too much power from the array) by limiting transients, and (2) to protect the PMAC system and the thruster against arcs.

Electrical Circuit Description

A functional block diagram for the Series Resonant SCR PMAC circuitry is shown in figure 6. The design of these electrical circuits was developed for the LeRC by TRW Systems Group under contract NAS3-19730 (ref. 3). As shown in the block diagram, the PMAC system receives power from a 28±5 V dc source and a center tapped (ground reference) ±100 to ±200 V dc solar array source. The power from the 28 V dc source is processed to generate the necessary voltage for the command, telemetery and protection circuits. The power from the ±100 to ±200 V dc power source is processed by three separate series resonant inverters to provide power for the 12 output supplies shown in figure 6. The 440 watt multiple inverter is a transistor type series resonant inverter that supplies current regulated power to nine of the 12 supplies. The remaining 840 watt discharge inverter and the 2480 watt beam inverter and accelerator supplies are Silicon Controlled Rectifier (SCR) type series resonant inverters. A detailed description of the electrical function and the electrical test program for the PMAC system can be found in appendix B.

Electrical Packaging Design

A modular approach was taken to the overall packaging of the PMAC system. Thus the high voltage high power functions are separated from the more noise sensitive low power, control and telemetry functions in order to minimize signal interaction between circuits. The physical arrangement of the modules is shown in figure 7. Here, the sensitive circuitry of the A2 Digital Interface Unit is at one end of the PMAC package and separated from the high voltage (1100 V) high power (2480 W), A3 Screen and Accelerator Supply by the A1 Input Filter module. Throughout the rest of the PMAC package, the more sensitive regulator and telemetry circuits are separated from the power circuits by the webs of the aluminum cross-beams or special aluminum shields.

Modules can also be individually manufactured, assembled, and electronically checked out and tuned prior to final PMAC system electrical checkout. This simplifies trouble-shooting to using a detailed testing procedure at both the printed wiring board level and the module level (appendix B).

Special consideration must be given to the mounting of electronic components and circuits where high voltage is present such as in the Screen and Accelerator Supply (A3 Module) and smaller high voltage supplies (A6 Module). Electronics components for these circuits were designed to have an air or vacuum gap stress of less than 20 volts/mil. Where necessary, whole circuits were mounted on metal circuit boards (fig. 8) which were insulated from the module structure by dielectric materials (BeO ceramic and G11 fiberglas). The dielectric stresses of these materials were designed to be less than 50 volts/mil through the materials and 9 volts/mil or less along the surfaces of the dielectric materials.

Electrical Testing

The PMAC system includes over 4000 electronics parts. The majority of these parts are mounted on the 50 printed wiring boards that are assembled into the seven electronics modules that comprise the PMAC package. Figure 9 is a photograph of the assembled PMAC package with all exterior structure removed. A logical electronics check-out procedure was established to check each subassembly. First, each of the 50 PWBs were checked out electrically in ambient air. Where feasible, these boards were then tested in an air oven at 75° C to simulate thermal conditions of operating in a vacuum. When it was not possible to test a board in the oven due to the complexity of the electrical test setup, the board was first baked at 100° C for 2 hours before electrical checkout. The checked PWB's were then assembled into modules and the modules electrically checked out in ambient air. The entire PMAC package was then assembled and electrically operated with fully checked PWBs and fully checked modules.

SYSTEM DESCRIPTION AND RESULTS

Physical Size and Weight

When properly positioned, the seven modules fit into a space 114.8 cm (45.2 in.) x 45.7 cm (18.0 in.) x 15.2 cm (6.0 in.) deep (fig. 9). When the exterior structure (fig. 10), thermal control system (fig. 11) and electrical harnessing are added, the exterior dimensions for a single PMAC become 117.3 cm (46.2 in.) x 48.3 cm (19.0 in.) x 21.8 cm (8.6 in.) deep. For the back to back dual PMAC package BIMOD configuration, the overall dimensions are 117.3 cm (46.2 in.) x 50.8 cm (20.0 in.) x 42.2 cm (16.6 in.) deep.

The overall weight of a single assembled PMAC package excluding the thermal control system is 36.2 kg (79.7 lb). A breakdown of the PMAC package mass distribution is given in table I.

The programmatic weight goal of 25 kg (55 lb) was not met for the design of this unit. An examination of table I shows that the electronics components for this design weighed 17.16 kg (37.84 lb). Experience has shown that overall package weights of twice the electronics components weight (34.32 kg (75.68 lb)) are achievable. This design is within 5 percent of that more realistic weight goal.

In order to achieve the original weight goal it will be necessary to eliminate electronic components weight. This can be done by using more advanced circuit technology such as microprocessors and large scale integrated circuitry. The original weight goal can then be achieved by employing this type of packaging technology.

Assembly/Disassembly Sequence

The PMAC package is assembled by first loosely bolting the modules to the heat pipe evaporator saddles which are accurately positioned on a fixture plate. The sides and lids of the PMAC package are then loosely bolted to the modules to check alinement of all bolt holes. Next, each module is removed one at a time and then reinstalled with RTV 566 silicon rubber compound between the module baseplate and the heat pipe saddle. All attachment bolts for that module are then fully torqued.

Any given module can be removed from an assembled PMAC package by first removing the module lid and the lids of the adjacent modules. Next, all module to saddle and all module to PMAC package side bolts are removed. The module is then loosened from the saddles and removed for repair. (Good adhesion between the saddle and the module is not necessary for adequate thermal conduction when using RTV 566.)

Operating Temperature Projections

The operating temperature projections for the entire PMAC system are given in appendix A of this report. A thermal-vacuum test is planned to check thermal program predictions.

Electrical Results

The circuits for the prototype PMAC system are identical to those of the Electrical Prototype/Power Processing Unit EP/PPU (ref. 3). Therefore, the electrical test results for the prototype PMAC and the EP/PPU should be identical. Electrical tests are planned in the near future.

CONCLUDING REMARKS

The detailed design for a light weight sophisticated 3.0 kW prototype Power Management and Control System has now been completed. The unit will meet all of the functional requirements necessary to power a 30 cm ion thruster on Earth orbital or interplanetary missions. Power Processing Units are being built which will undergo vibration and thermal vacuum testing, Electro-Magnetic Interference (EMI) testing, 30 cm ion thruster electrical integration, multithruster system interaction testing and life testing. The design is economically reproducible on a large scale and as such is ready for flight system integration and subsequent space flight.

APPENDIX A

THERMAL MODEL TEMPERATURE PREDICTIONS

Thermal Design Description

The modular PMAC package consists of roughly 4000 electronic components. When assembled it measured 114.8 cm (45.2 in.) long by 45.7 cm (18.0 in.) wide by 15.2 cm (6.0 in.) high. Because of the relatively large number of electronic components, a thermal analytic model was assembled to predict area temperatures rather than individual component temperatures. A review of the heat generating components indicated that if the base temperature of the electronic components were limited to about 75° C the component junction temperatures would be 100° C or less.

The PMAC package is cooled by a heat pipe-radiator system. Figure A1 shows the arrangement of the PMAC package and location of the two heat pipe evaporator saddles of the heat pipe system. Any electronic components generating 3 watts or more of heat are located over or near the heat pipes which operate at 50° C. All of the printed wiring boards (PWBs) are riveted to aluminum frames which are bolted to the module base and are also attached to the model web by standoffs. The standoffs were made large enough to be used as conductive heat transfer paths to the web. All PWB mounted components generating 15 mW or more of heat were placed adjacent to the PWB frame and were cemented to the copper foil (not a part of the electrical circuit) of the printed wiring board which was rivited to the frame.

Thermal Model Description

Based upon the design configuration, a lumped mass thermal nodal network model consisting of 1282 diffusion and six boundary nodes was constructed which used a total of 3515 linear and radiative connections. The program used to solve the network was the Systems Improved Numerical Differencing Analyzer, or SINDA, which is a thermal network analyzer program described in reference 12. Once the necessary model information was obtained, it was coded in SINDA format and the steady state temperature distribution of the PMAC was calculated.

A computer printout of this temperature distribution is shown in figure A2. Each temperature represents a node in the model. The rectangular areas formed by asterisks represents the plan view of discrete areas of the PMAC package shown in figure A1. The temperatures outside the rectangular areas represent the PWB frame temperatures. For clarity, the nodes representing the stand offs have been removed.

Thermal Model Results

The thermal model indicates that some areas in modules six, four, and two may have temperatures between 75° and 80° C. The electronic components in these areas were identified. From the junction to base temperature drop per unit power specification and the expected power input, it was determined that these components should have a junction temperature of less than 100° C. It should be noted that the total heat input for the model was about 380 watts whereas the expected heat load should be about 317 watts. In the thermal analysis the maximum heat dissipation was used for most of the integrated circuit components located on the PWBs when in reality only part of the component may be used. Therefore, it is expected that the PWBs will operate at temperatures less than shown.

Module 3 has two inductors each dissipating seven watts of heat (fig. 5). These could not be located directly over the heat pipe evaporator. They are located on the baseplate between the right hand heat pipe (figs. A1 and A2) and the right side wall. The heat pipe saddle in this area is made 3.8 cm (1.5 in.) wider and extends under the inductors. Without this extention the inductor base temperature would be near 90° C.

A thermal-vacuum test of the PMAC will be performed with thermistors located at hot areas indicated by the computer analysis. This test will enable the thermal model to be calibrated, and adjustments to the model will be made, where necessary, to insure more accurate predictions.

APPENDIX B

ELECTRICAL PACKAGING REQUIREMENTS AND APPROACH

Electrical Circuit Design

The design of the electrical circuits for the Power Management and Control (PMAC) system was developed by TRW Systems Group under Contract NAS3-19730 (ref. 3). Figure 6 is a block diagram of the electrical circuits for the PMAC system. The PMAC system receives power from a 28±5 V dc source and a center tapped (ground reference) ±100 to ±200 V dc solar array source. The power from the 28 volt source is processed by an energy pump type converter and generates +15, -15, and +5 voltages for the command, telemetry, protection control diode, reference voltage, and 2 kHz ramp generator circuits.

The power from the ±100 to ±200 V dc power source is processed by three separate series resonant inverters to provide power for the 12 output supplies shown in figure 6. The 440 watt multiple inverter is a transistor type series resonant inverter. The 840 watt discharge inverter and the 2480 watt beam inverter are SCR type series resonant inverters.

Modular Approach

The 12 power supplies required for the thruster and the low voltage command, telemetry, and protection circuits are packaged into seven modules. Figure B1 shows a block diagram of the modules and indicates the grouping of the various power supplies.

Module A1 contains the circuitry for the power interface between the two power sources and the PMAC system circuitry. Module A2 contains the digital to analog and analog to digital circuitry for the interface between a spacecraft type computer and the PMAC power circuits.

Module A3 contains the SCR series resonant inverter, regulators, controls, and analog telemetry outputs for the screen (+1100 V dc) and accelerator supplies (-500 V dc). Module A4 contains the SCR series resonant inverter, regulators, controls, and analog telemetry outputs for the discharge supply (50 V at 14 amp).

The physical divisions for modules A5, A6, and A7 are different than for modules A3 and A4. For A3 and A4 modules, the primary and secondary power for the supplies are contained in the same module. For modules A5, A6, and A7 the primary power developed by the inverter is located in module A5 and the secondary powers for the various supplies are located in modules A6 and A7. Module A6 contains the output power for supplies V3, V4, V8, and V12. These four supplies have their outputs referenced to screen potential (+1100 V dc). The regulation, controls, and telemetry circuits are magnetically isolated from the screen potential. Module A7 contains the output power circuits, regulation, controls, and telemetry circuits for supplies V1, V2, V5, V6, and V7. These five supplies have their outputs referenced to ground.

Figure B2 shows the component layout for module A3 and figure B3 shows the component layout for module A6. In both figures the plan view of the modules is shown in the top portion of the figure. In this view the component boards are shown along the bottom edge of the plan view. In the bottom portion of the figures the web portions of the modules are shown. The cross-hatched areas in both figures show the components that are referenced to screen potential (+1100 V dc). These components have been mounted to boards which are isolated from ground with beryllium oxide insulators (fig. 8).

Physical Arrangement

The physical arrangement of grouping of 12 output power supplies into seven modules was chosen to minimize signal interaction between circuits. Since all of the outputs of V3, V4, V8, and V12 supplies are referenced to screen potential they must be electrically compatible. Thus these supplies were physically located in the same module. The control and regulation circuits for these supplies are also located in the same module. However, these control and protection circuits are physically separated from the output power circuits to minimize the radiation interaction between circuits.

PMAC System Considerations

Although the intent of the modular approach is to minimize conductive and radiation interaction by physical separation, the modules are electrically dependent upon a common source of power (A1 module) and commands and telemetry (A2 module). To minimize the interaction among power circuits, command circuits, and telemetry circuits, the grounds for these circuits are isolated from each other. In addition, to separate grounds, decoupling capacitors are connected across the +15 and -15 voltage sources on each individual board within the individual modules. All of the isolated grounds inside the PMAC package are terminated at a single point outside the package. This type of grounding system prevents electrical transients of circuits from interacting with each other.

In the A2 module, which is the interface between computer and power circuits in the FM/PPU, the clocking and reset lines will have physical separation on the printed wiring boards (PWBs) to minimize the affects of current and voltage surges on the logic functions performed in this module.

TEST PHILOSOPHY

Printed Wiring Board Testing

Each of the 50 printed wiring boards (PWBs) were checked out electrically before the boards were installed into a module. Of the 50 boards, 35 of them were also operated electrically in an air oven at an elevated temperature of 75° C. (75° C is the operating temperature predicted by the thermal analysis.) The other 12 boards needed very complicated testing equipment to operate them at elevated temperature. These 12 boards (for A2 module) were placed in an oven at 100° C for 2 hours and then tested at room temperature.

Module Testing

The modular approach, in addition to the physical isolation, allowed the assembly and testing of the PMAC package to be accomplished at module level. Each module can be individually electrically tested prior to combining the seven modules into a PMAC package. After an electrical checkout at room temperature each module could then be operated at an elevated temperature of 60° C in an air oven.

PMAC System Testing

After final assembly and air testing of the PMAC package, 85 thermistors will be located in those areas where the thermal analysis has predicted temperature close to 75° C on PWBs and areas where high power dissipation components are located on the baseplate and web of the modules. The PMAC package will then be subjected to a thermal vacuum test with an average baseplate temperature of 50° C. After completing thermal vacuum test the PMAC package will be integrated with an ion thruster. During the first phase of the thruster integration the PMAC package will be in air. During the second phase the PMAC package will be operated in a vacuum.

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TABLE I. - PMAC PACKAGE MASS DISTRIBUTION

Module \ Item	Cross beam-structure with hardware, kg (lb)	Back cover plates, kg (lb)	High voltage shield, kg (lb)	Printed wiring boards with frames, kg (lb)	Printed wiring board mounting hardware, kg (lb)	Component mounting plates and frames, kg (lb)	Component mounting plate insulators, kg (lb)	Module mounting hardware, kg (lb)	Module electrical terminals, kg (lb)	Module electrical components, kg (lb)	Module wiring harness, kg (lb)	Voltage regulator brackets, kg (lb)	Component mounting hardware, kg (lb)	Conformal coating, kg (lb)	Intermodule harness and connectors, kg (lb)	Miscellaneous, kg (lb)	Totals, kg (lb)
A1 Input filter	0.54 (1.19)	0.08 (0.18)		0.05 (0.10)		0.40 (0.88)		0.07 (0.16)	0.12 (0.26)	3.72 (8.21)	0.43 (0.94)	0.00 (0.01)	0.24 (0.52)		0.17 (0.38)	0.07 (0.15)	5.89 (12.98)
A2 Digital interface unit	0.49 (1.07)	0.10 (0.23)	0.18 (0.39)	1.35 (2.98)	0.27 (0.60)			0.03 (0.07)		0.53 (1.16)	0.19 (0.42)		0.02 0.04	0.10 (0.24)	0.08 (0.18)	0.05 (0.12)	3.40 (7.50)
A3 Screen and accelerator supplies	0.64 (1.42)	0.26 (0.57)	0.17 (0.38)	0.65 (1.43)	0.09 (0.20)	0.14 (0.31)		0.04 (0.08)	0.10 (0.21)	5.44 (11.99)	0.32 (0.71)	0.06 (0.15)	0.35 (0.78)	0.04 (0.08)	0.25 (0.56)	0.10 (0.21)	8.65 (19.08)
A4 Discharge supply	0.59 (1.29)	0.11 (0.25)		0.41 (0.91)	0.09 (0.20)	0.09 (0.20)	0.01 (0.02)	0.04 (0.08)	0.05 (0.12)	3.36 (7.40)	0.71 (1.57)	0.12 (0.26)	0.30 (0.65)	0.04 (0.08)	0.11 (0.23)	0.08 (0.18)	6.09 (13.44)
A5 Multiple inverter power stage	0.47 (1.04)	0.11 (0.24)		0.43 (0.95)	0.08 (0.17)	0.07 (0.16)	0.01 (0.03)	0.03 (0.07)	0.16 (0.35)	0.77 (1.70)	0.08 (0.18)	0.03 (0.07)	0.09 (0.20)	0.03 (0.07)	0.11 (0.24)	0.05 (0.12)	2.54 (5.59)
A6 High voltage supplies	0.54 (1.19)	0.23 (0.50)		0.64 (1.41)	0.13 (0.29)	0.06 (0.13)	0.03 (0.06)	0.04 (0.08)	0.12 (0.26)	1.34 (2.96)	0.12 (0.26)	0.04 (0.30)	0.07 (0.16)	0.05 (0.10)	0.13 (0.29)	0.09 (0.19)	3.71 (8.18)
A7 Low voltage supplies	0.66 (1.46)	0.25 (0.55)		1.06 (2.34)	0.19 (0.41)			0.04 (0.09)	0.15 (0.34)	2.00 (4.42)	0.10 (0.23)	0.05 (0.10)	0.14 (0.31)	0.07 (0.16)	0.11 (0.24)	0.12 (0.26)	4.95 (10.91)
Subtotals	3.93 (8.66)	1.14 (2.52)	0.35 (0.77)	4.59 (10.12)	0.85 (1.87)	0.76 (1.68)	0.05 (0.11)	0.29 (0.63)	0.70 (1.54)	17.16 (37.84)	1.95 (4.31)	0.40 (0.89)	1.21 (2.66)	0.33 (0.73)	0.96 (2.12)	0.56 (1.23)	35.23 (77.68)
PMAC side members																	0.94 (2.08)
Total																	36.18 (79.76)

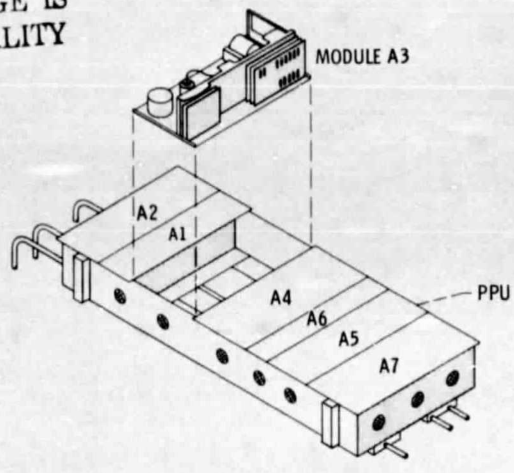

Figure 1. - Basic packaging concept.

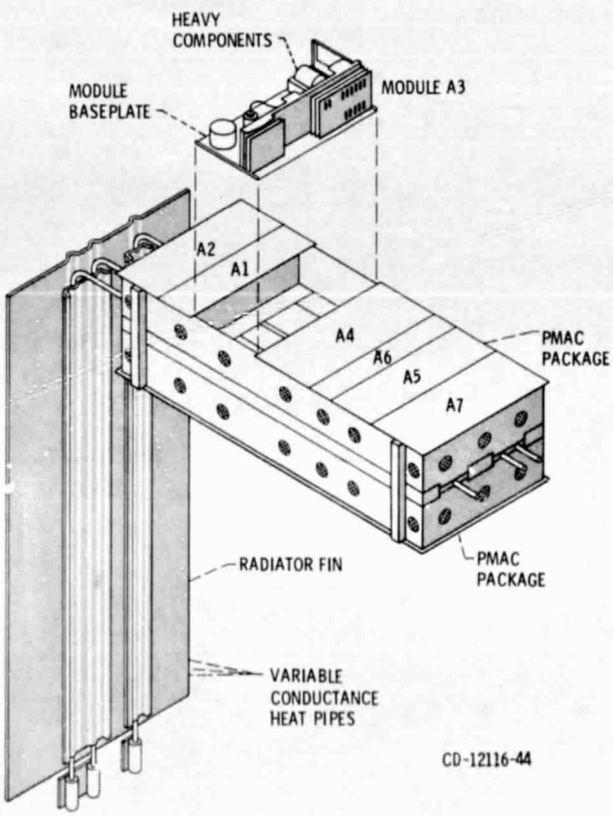

Figure 2. - Thermal control system.

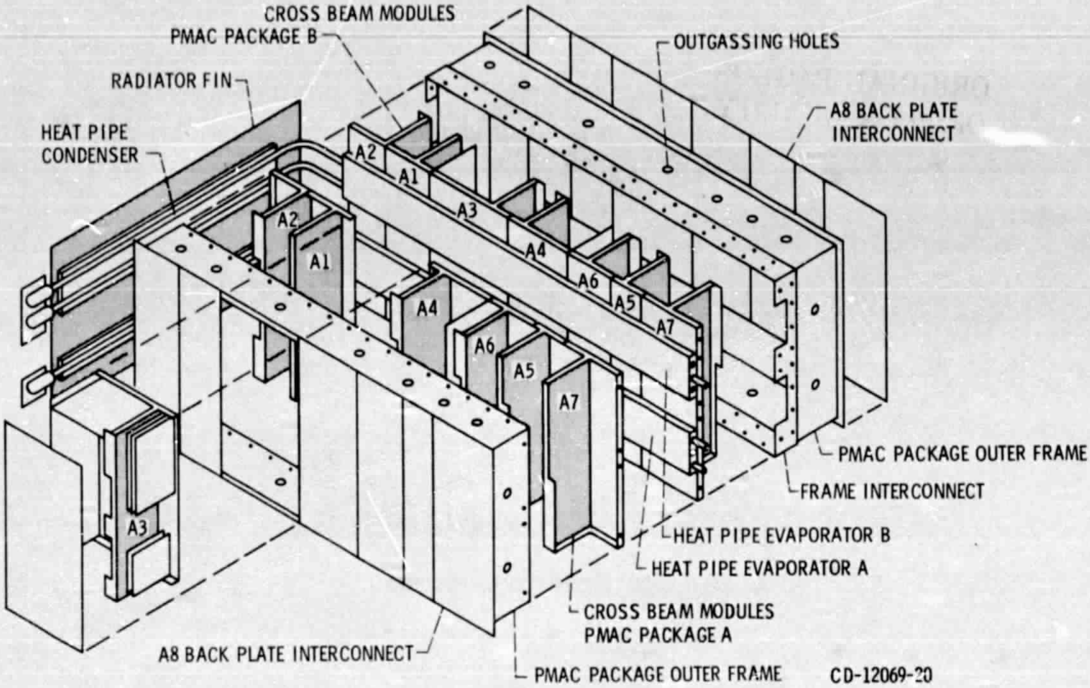

Figure 3. - BIMOD assembly.

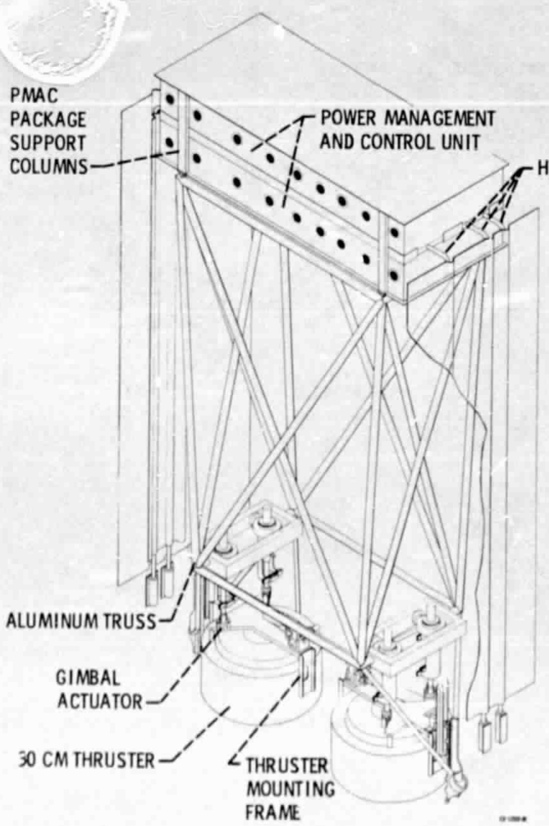

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Figure 4. - Isometric view of BIMOD.

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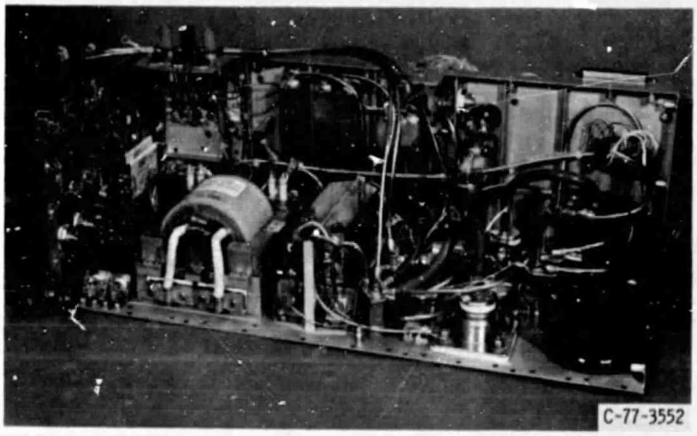

Figure 5. - A3 module, screen accelerator supplies, high power high voltage side.

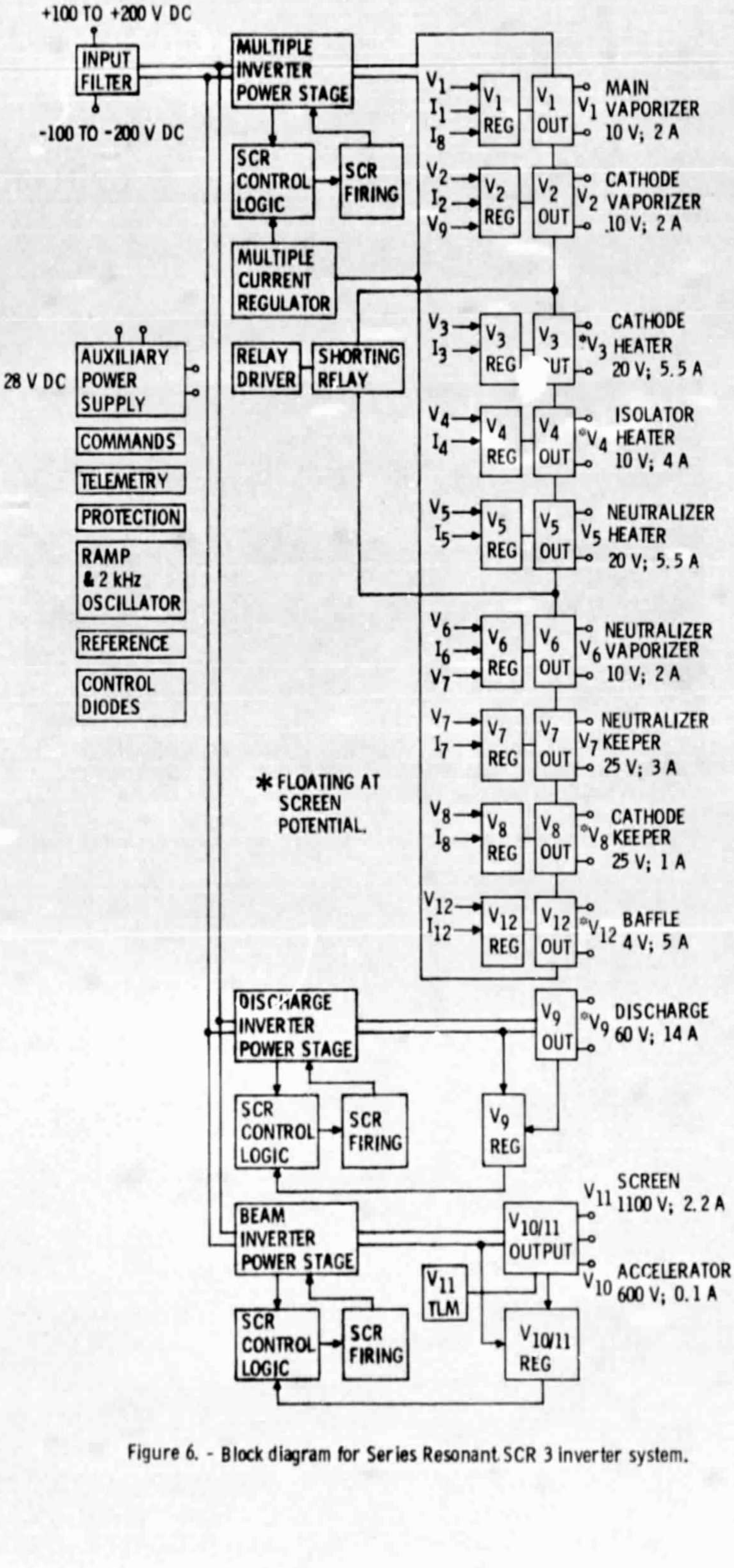

Figure 6. - Block diagram for Series Resonant SCR 3 inverter system.

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A2	DIGITAL INTERFACE UNIT
A1	INPUT FILTER
A3	SCREEN AND ACCELERATOR SUPPLIES
A4	DISCHARGE SUPPLY
A5	HIGH VOLTAGE SUPPLIES
A6	MULTIPLE INVERTER POWER STAGE
A7	LOW VOLTAGE SUPPLIES

Figure 7. - PMAC system functions by module.

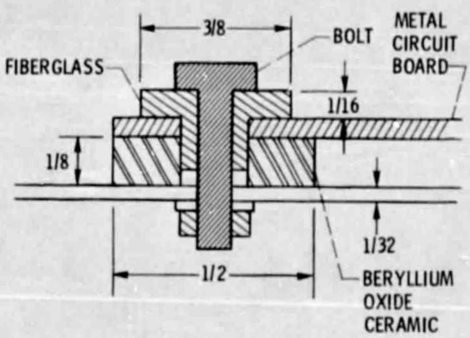

Figure 8. - Typical electrically insulated standoff cross section.

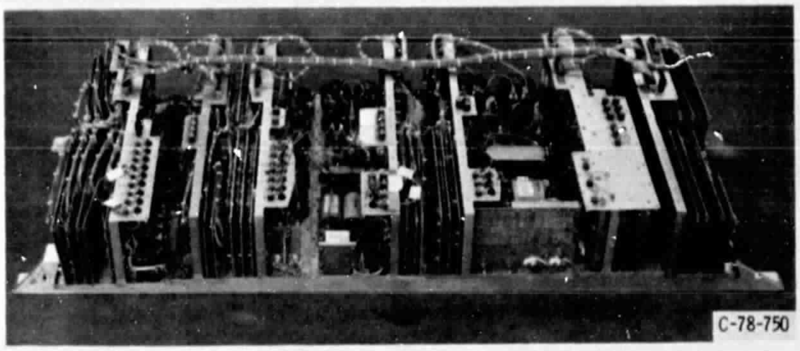

Figure 9. - PMAC assembly with exterior structure removed.

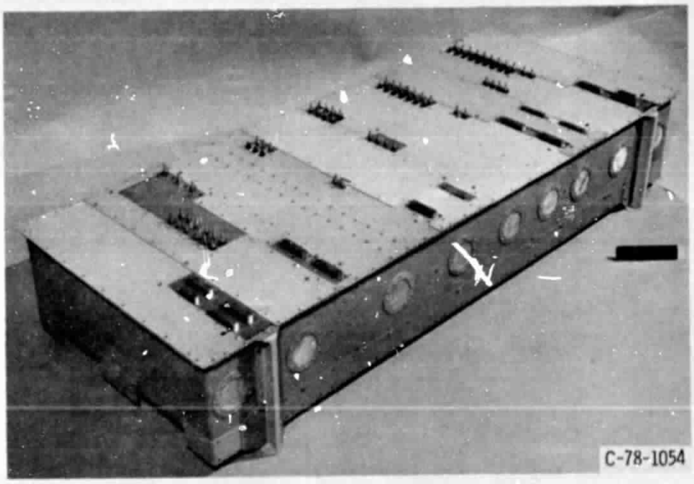

Figure 10. - PMAC package exterior structure.

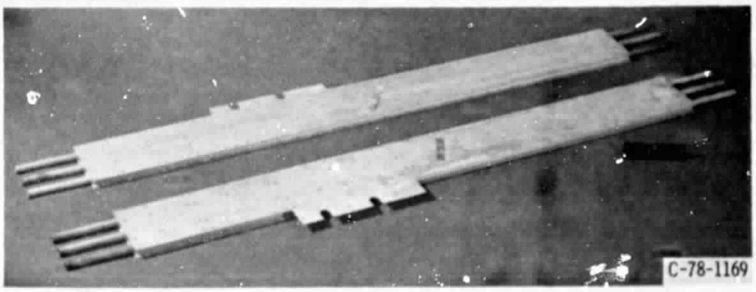

Figure 11. - PMAC package thermal control system.

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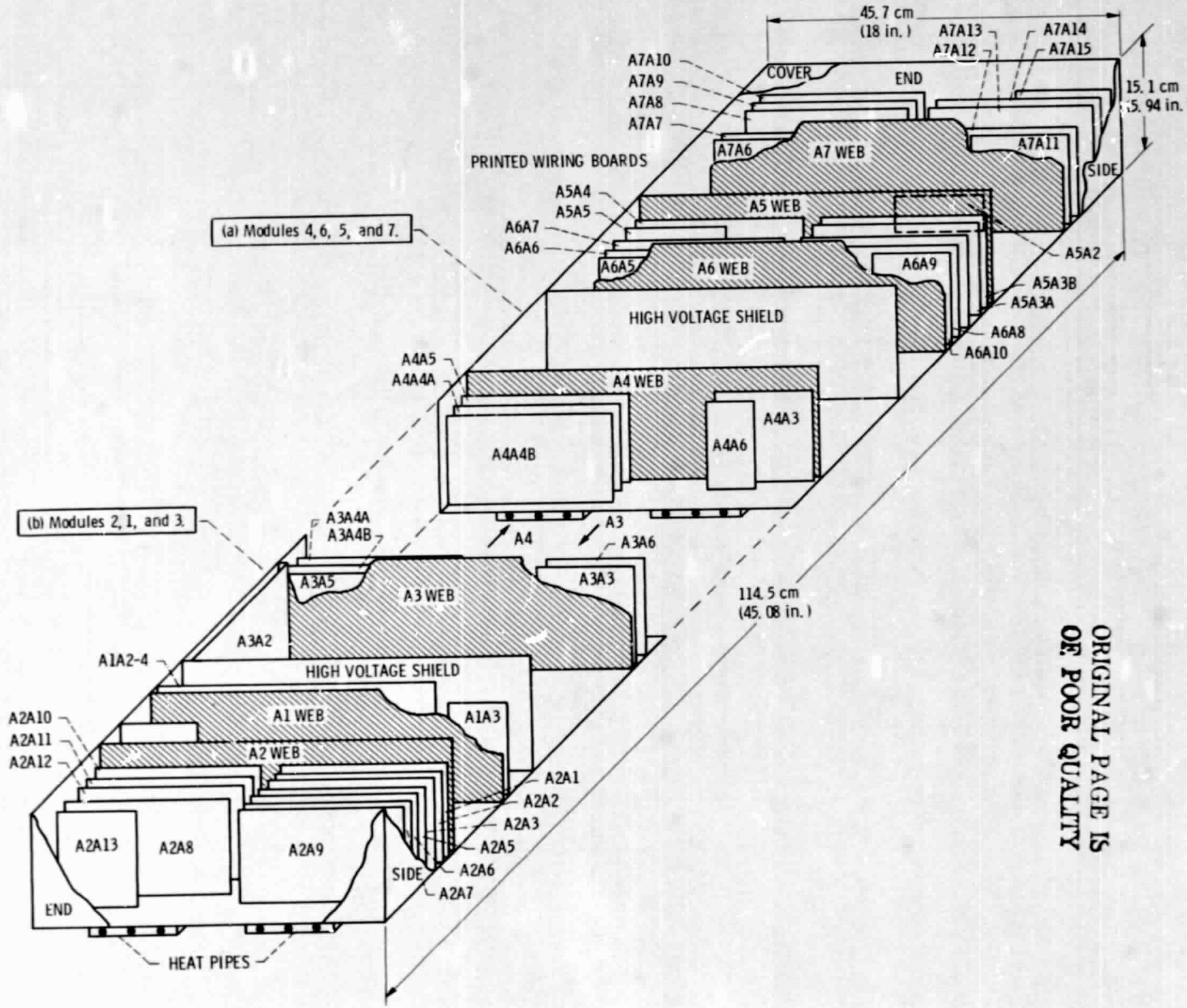

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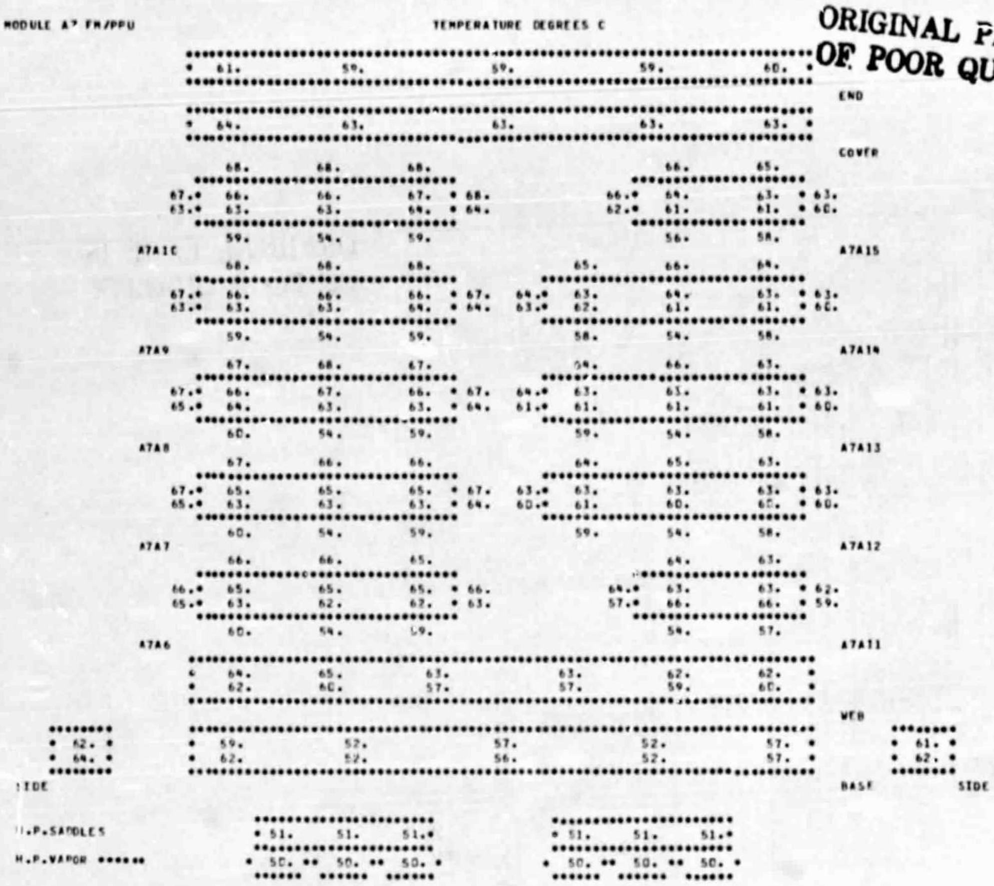
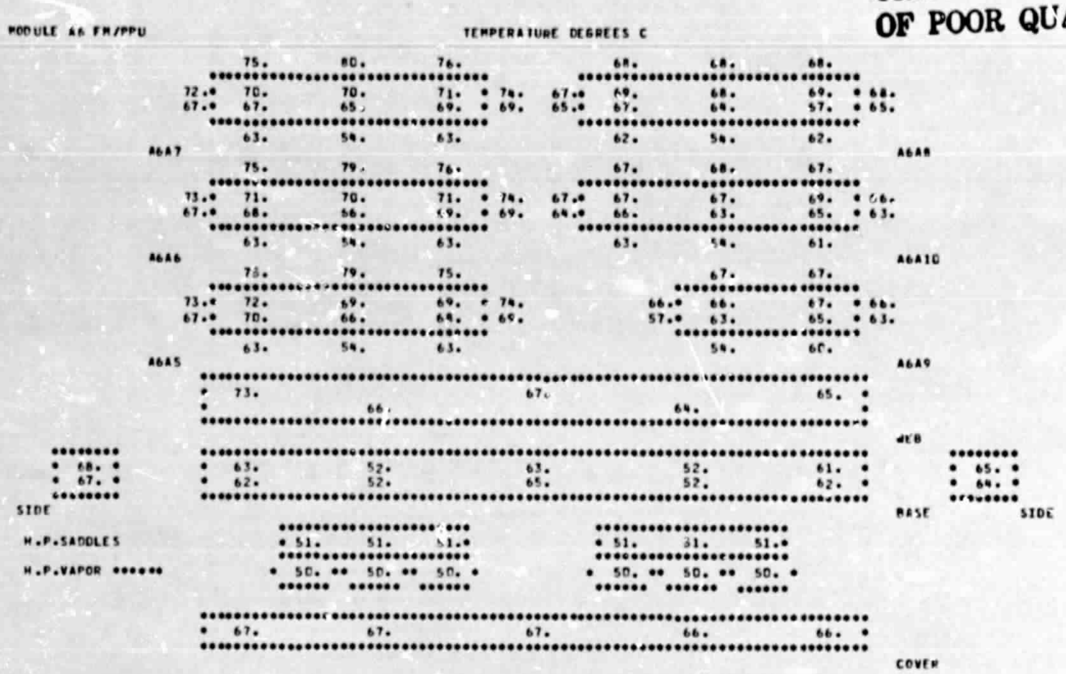
Figure A1. - PMAC Package Assembly.



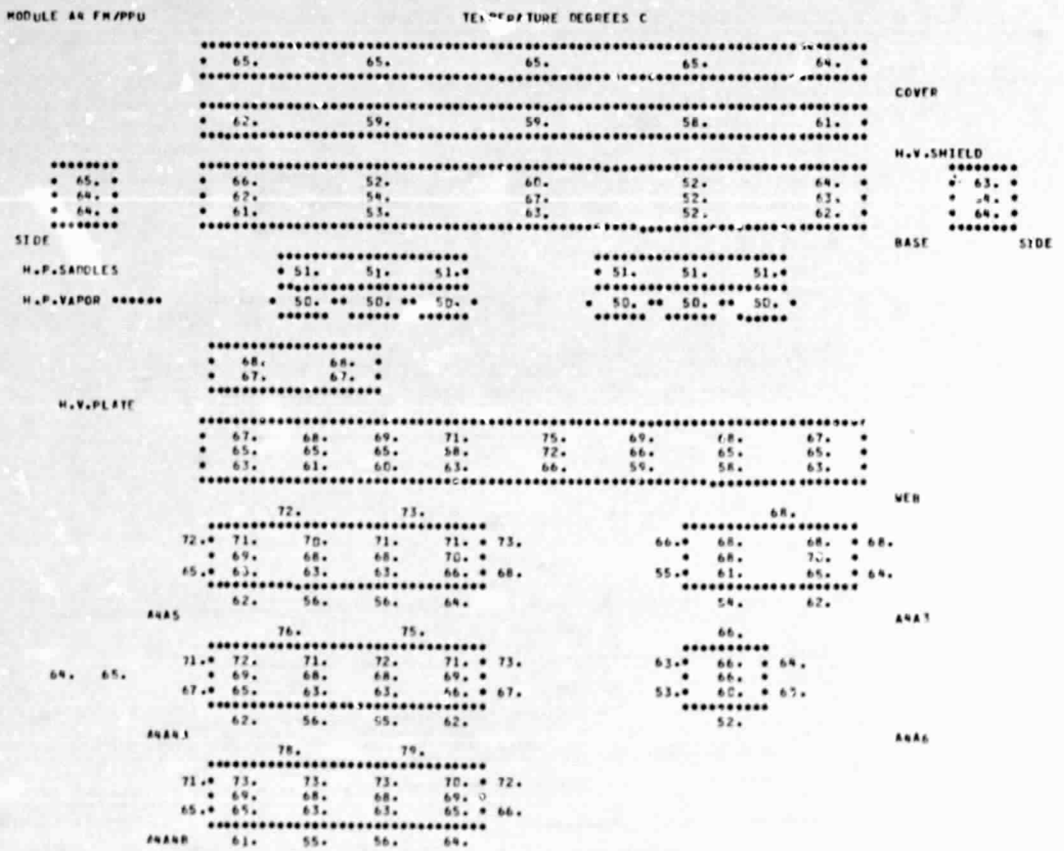
(a) MODULE 7.

(b) MODULE 5.

Figure A2. - PMAC package temperature distribution.

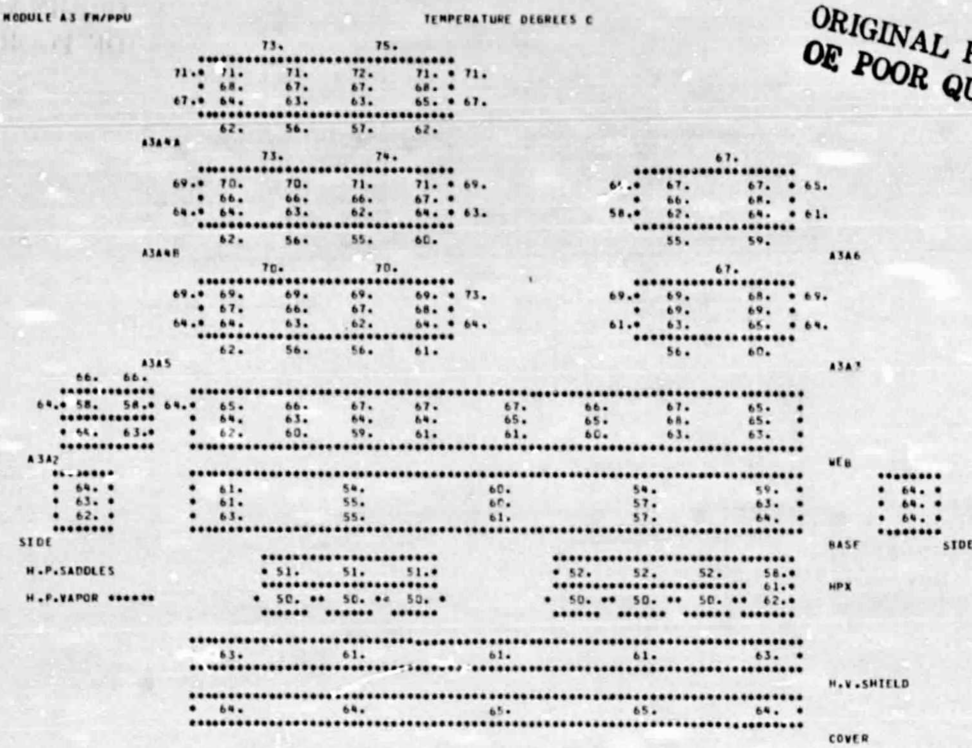


(c) MODULE 6.



(d) MODULE 4.

Figure A2. - Continued.

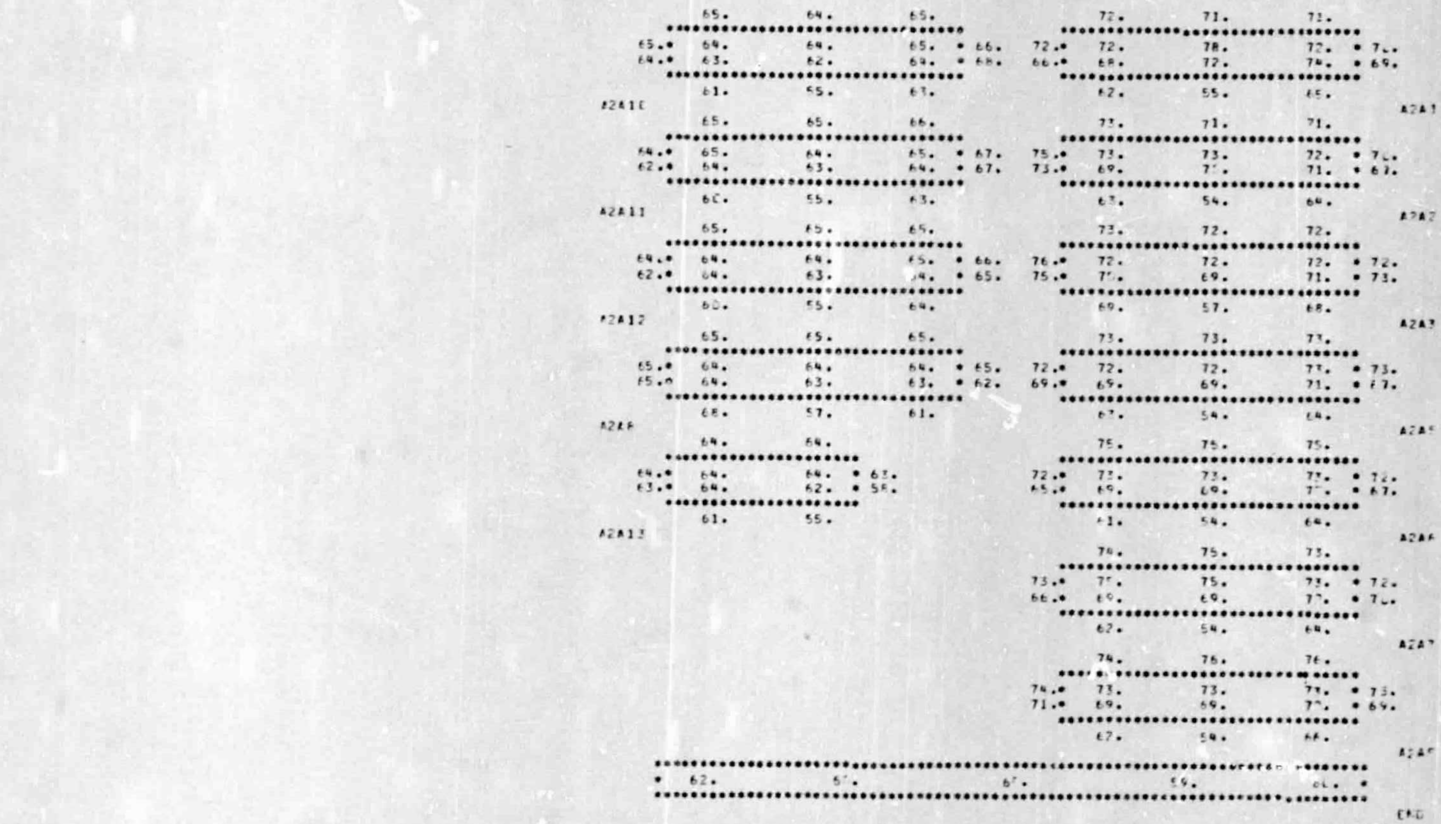


(e) MODULE 3.

(f) MODULE 1.

(g) MODULE 2.

Figure A2. - Continued.



(g) MODULE 2 (CONCLUDED).

Figure A2. - Concluded.

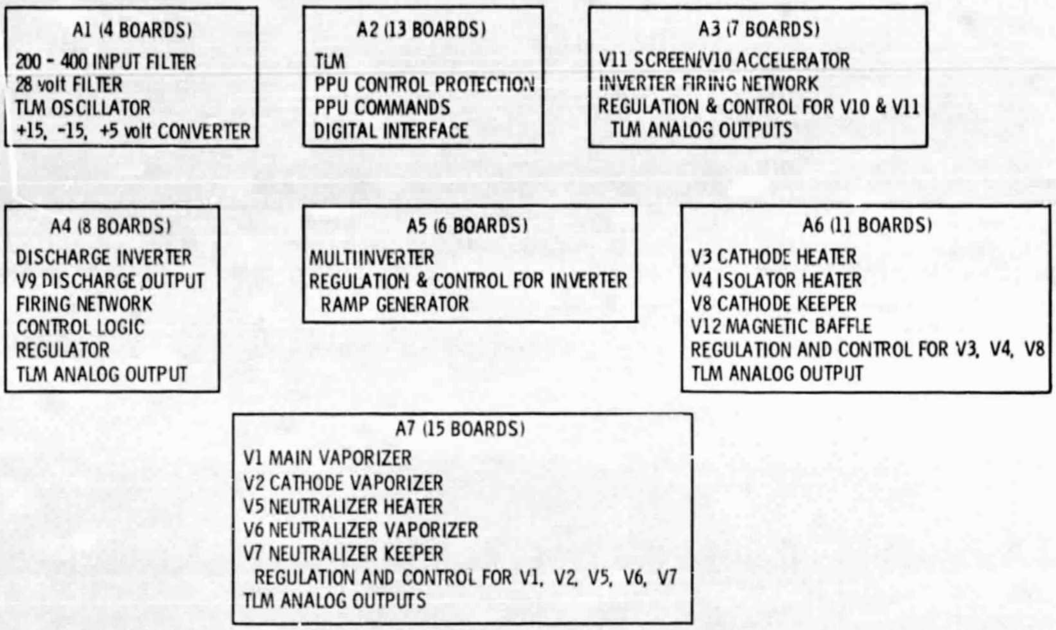


Figure B1. - Block diagram of seven modules.

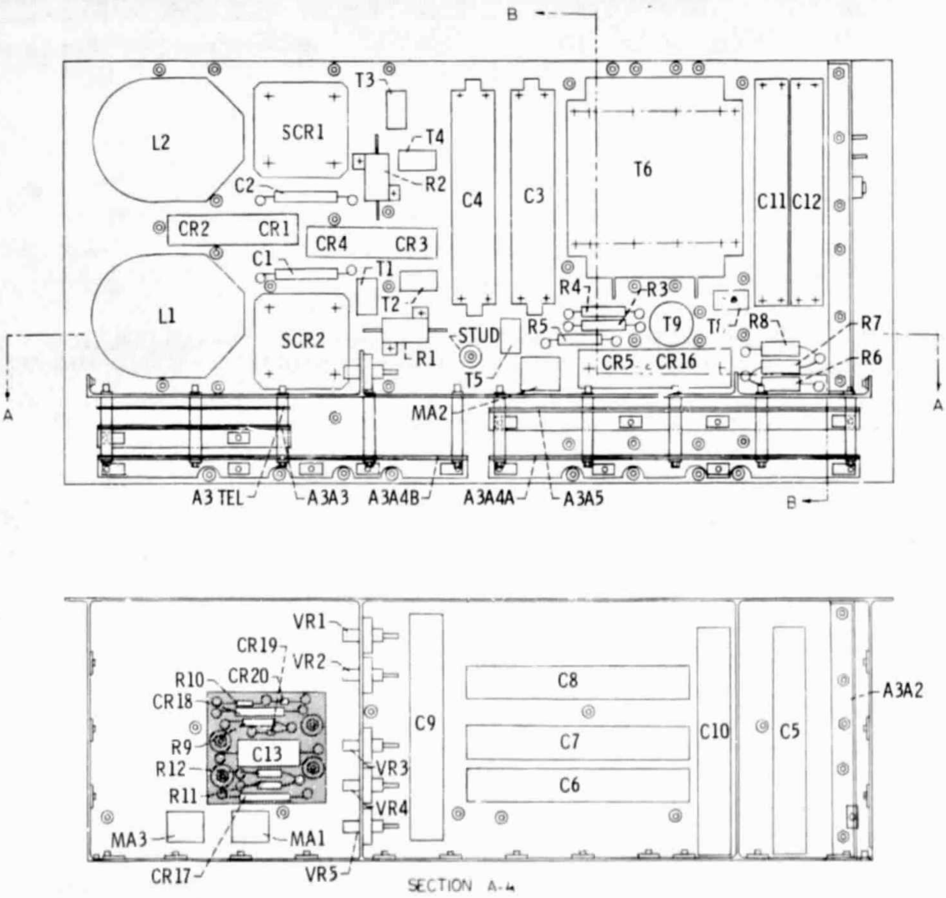
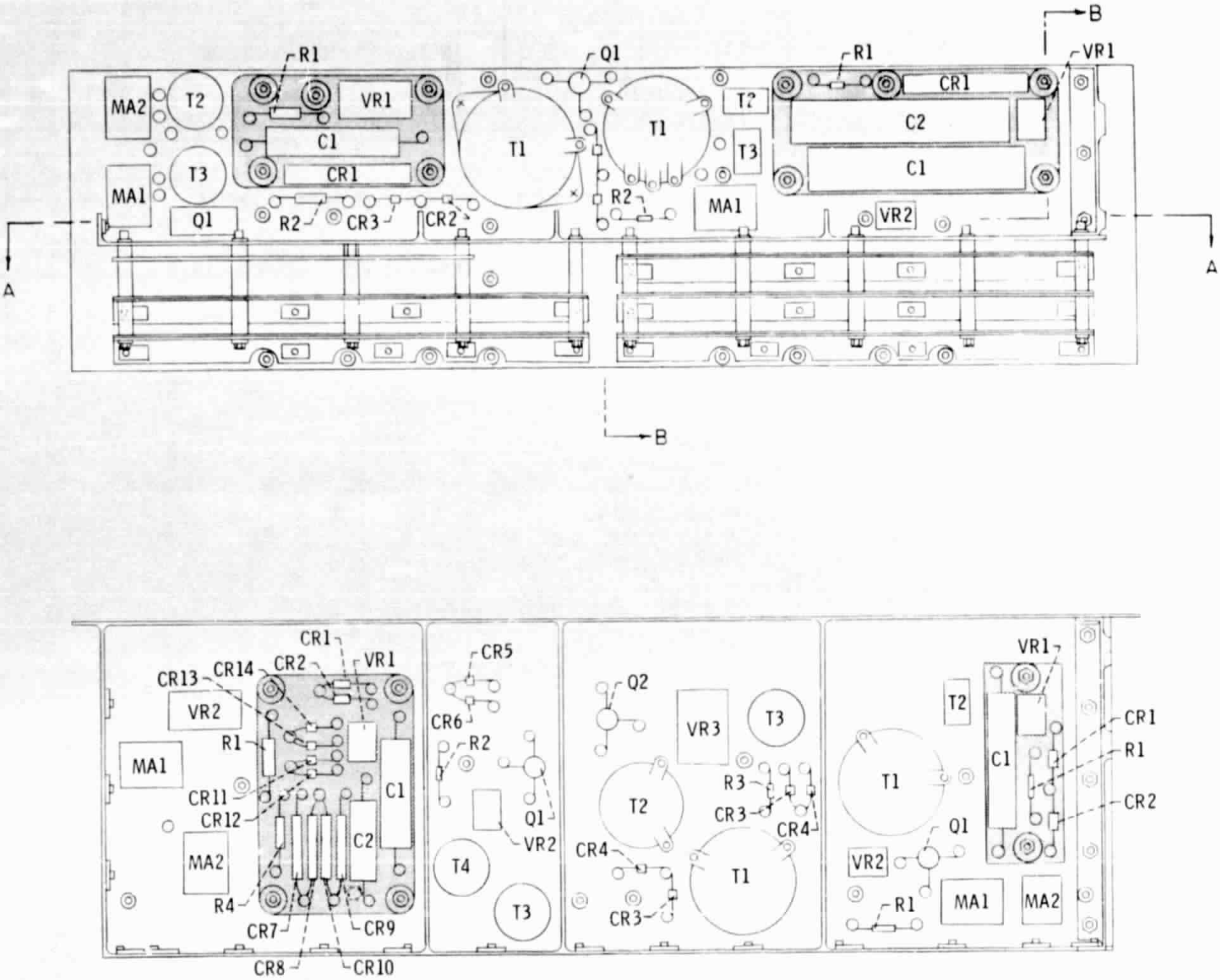


Figure B2- Component Layout of Submodule A3, Screen/Accelerator Supply



SECTION A-A

Figure B3. - Component Layout of Submodule A6, Consisting of Cathode Heater (V3), Isolator Heater (V4), Cathode Keeper (V8), and Magnetic Baffle (V12). (Shaded Areas indicated Component Boards Referenced to Screen Potential, +1100 VDC).