IN-44
195121
164P

NASA Contractor Report CR-191136

Power Conditioning System Modelling for Nuclear Electric Propulsion

Kenneth J. Metcalf
Rockwell International
Rocketdyne Division
Canoga Park, California

November 1993

PREPARED FOR
LEWIS RESEARCH CENTER
UNDER CONTRACT NAS3-25808

NASA

National Aeronautics and
Space Administration

Foreword

Systems engineering efforts initiated by NASA's Lewis Research Center (LeRC) in FY92 under RTOP 593-72, for Nuclear Electric Propulsion (NEP), have enabled the development of detailed mathematical (computer) models to predict NEP subsystem performance and mass. The computer models are intended to help provide greater depth to NEP subsystem (and system) modeling, required for more accurately verifying performance projections and assessing the impact of specific technology developments.

The following **subsystem** models have been developed:

1) liquid-metal-cooled pin-type, and
2) gas-cooled NERVA (Nuclear Engine for Rocket Vehicle Applications) -derived **for reactor/shield;**
3) Potassium-Rankine, and
4) Brayton **for power conversion;**
5) **heat rejection general model** (includes direct Brayton, pumped loop Brayton, and shear flow condenser (Potassium-Rankine);
6) **power management and distribution (PMAD) general model;** and
7) ion electric engine, and
8) magnetoplasmadynamic thruster for the **electric propulsion subsystem.**

These subsystem models for NEP were authored by the Oak Ridge National Laboratory (ORNL) for the reactor (NASA CR-191133), by the Rocketdyne Division of Rockwell International for Potassium Rankine (NASA CR-191134) and Brayton (NASA CR-191135) power conversion, heat rejection (NASA CR-191132), and power management and distribution (NASA CR-191136), and by Sverdrup Technology for the thrusters (NASA CR-191137).

At the time of this writing, these eight VAX/FORTRAN source and executable codes are resident on one of LeRC's Scientific VAX computers.

CONTENTS

FIGURES

TABLES

1.0 Summary

NASA LeRC is currently developing a Fortran based model of a complete nuclear electric propulsion (NEP) vehicle that would be used for piloted and cargo missions to the Moon or Mars. The proposed vehicle design will use either a Brayton or K-Rankine power conversion cycle to drive a turbine coupled with a rotary alternator. Two thruster types are also being studied, ion and MPD. In support of this NEP model, Rocketdyne has developed power conversion, heat rejection, and power management and distribution (PMAD) subroutines. These subroutines will be incorporated into the NEP vehicle model and be driven by a master module to be written by NASA LeRC. The purpose of this report is to document the end-to-end PMAD model subroutine and the component model subroutines called by it.

The PMAD system subroutine is designed to provide parametric outputs based on externally defined characteristics such as the alternator operating voltage and frequency, the thruster type, the system power level, and the electronics coldplate temperature. These parametrics will then be used by the master NEP module to determine the NEP vehicle mass and efficiency, and to conduct system level trades. It is intended that the models developed during this study be used only for conceptual design studies requiring "ballpark" PMAD mass estimates. To determine specific PMAD design choices such as component topologies, and accurate transmission and distribution voltages and frequencies requires specific power system requirements and far more detailed analyses.

The end-to-end PMAD model described in this report is based on the direct use of the alternator voltage and frequency for transmitting power to either ion or magnetoplasmadynamic (MPD) thrusters. This low frequency transmission approach was compared with dc and high frequency ac designs, and selected on the basis of mass, efficiency, and qualitative assessments of reliability and development costs. The low frequency architecture has the lowest mass, highest efficiency, and on the basis of complexity it is judged to have the highest reliability and lowest development costs. While its power quality is not as good as that provided by a high frequency system, it was considered adequate for both ion and MPD engine applications. The low frequency architecture will be used as the reference in future NEP PMAD studies.

The PMAD model development is based on the fact that power conditioning components have common stages and that their interconnection and control determines the function and operation of the component. The component models permit passive or active thermal management and estimate component heat sink, coldplate, and radiator masses (the hardware that connects the coldplate to the radiator is not included). The transmission line model is based on a litz wire configuration and it uses first order electrical and thermal principles to calculate attributes such as line mass, diameter, and temperature. It is recommended that other transmission line models be developed when funding permits so that alternate transmission line configurations can be evaluated.

The model documentation includes a block diagram of the component and shows the logic employed during the model development. Valid input ranges are also defined and suitable component applications discussed. The end-to-end PMAD model documentation shows the basic PMAD architecture form and explains how certain inputs are used to define a particular architecture configuration.

2.0 Introduction

The PMAD models presented in this report were developed to allow a previously selected PMAD architecture to be evaluated within the context of an overall NEP power system. This architecture is based on the use of ac power transmission at a designated alternator voltage and frequency, and it was selected at the conclusion of the Task Order 14 studies (Ref. II-1, II-2). These studies evaluated methods of supplying power from a 3-phase rotary alternator to either ion or MPD thrusters. The primary discriminators were mass and efficiency, but complexity, development costs, and reliability were also considered. Initially, dc and ac transmission approaches were evaluated. Subsequent analyses addressed single- and 3-phase ac, and low and high frequency transmission. The Task Order 14 results determined the types of PMAD models and their form; therefore, an overview of these results is presented below. If the user is not interested in this background information and simply wishes to run the PMAD models, they should read the following paragraph carefully and then skip to Section 3.0 which contains the PMAD model documentation. The model documentation has a description of the system or component the model is based on, suggestions on how to properly apply the models, a flow chart depicting the model operating logic, and a table defining valid input ranges. This documentation is followed by a section that discusses the conclusions reached during this study and the recommendations for future work.

The PMAD model subroutines are encoded in Fortran 77 and located on the accompanying computer disk. Generally, a four step process is used to run a PMAD case; (1) the user creates an input file with the desired PMAD input data, (2) "MAIN" is typed to run the case, (3) the selected input file name is provided, and (4) the generated output data is examined. It is probably best to create a new input file by editing an existing input file. This can be accomplished with any ASCII editor and an input file, "PMAD.IN", is available for this purpose. The user may want to view the input file "PMAD.IN" and note its form. The data is arranged in blocks. The first block defines the PMAD architecture and system operating values; subsequent blocks define specific component data. If the user does not supply a value, a default value will be used. The model input names and their defaults are defined in the individual model documentation sections. The Fortran code listings in Appendixes A through H also list the input value defaults. After creating an input file, the user types "MAIN" to start a run. "MAIN.EXE" is an executable file that requests an input file and then directs the ensuing calculation steps. This file is temporary; the NEP system driver to be written by NASA LeRC will replace it. After an input file name is provided, the computer runs the case. The output data is printed to a file having the same filename as the input file, but the extension "OUT". For example, the input file "PMAD.IN" generates the output file "PMAD.OUT".

2.1 DC versus AC Power Transmission

Two basic power transmission methods, dc and ac, were evaluated for the NEP vehicle on the basis of mass, efficiency, reliability, and development costs. Figure 1 compares the basic operating steps employed in these two approaches. The dc approach would utilize a rectifier immediately following the alternator to convert the alternator's ac output into dc. A dc transmission line would then carry this power to the power processing units (PPUs) located next to the thrusters. Within the PPUs, a chopper converts the dc into high frequency ac

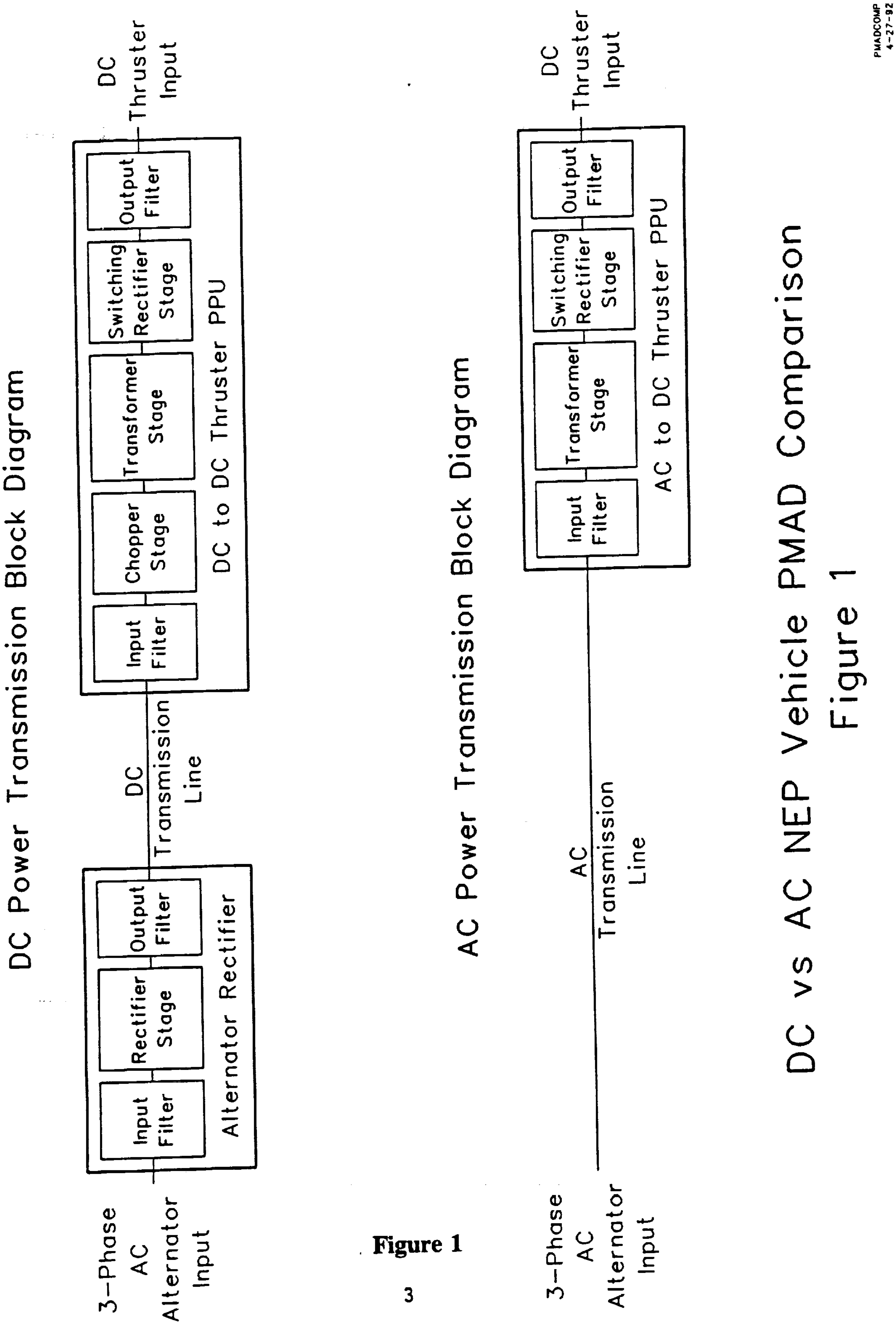

DC Power Transmission Block Diagram
3-Phase AC Alternator Input
Input Filter
Rectifier Stage
Output Filter
Alternator Rectifier
DC Transmission Line
Input Filter
Chopper Stage
Transformer Stage
Switching Rectifier Stage
Output Filter
DC to DC Thruster PPU
DC Thruster Input
AC Power Transmission Block Diagram
3-Phase AC Alternator Input
AC Transmission Line
Input Filter
Transformer Stage
Switching Rectifier Stage
Output Filter
AC to DC Thruster PPU
DC Thruster Input
DC vs AC NEP Vehicle PMAD Comparison
Figure 1
PMADCOMP
4-27-92

Figure 1

so that a subsequent transformer can step this high transmission line voltage down to a level suitable for the thrusters. The lower voltage ac is then converted into dc for the thrusters.

It is possible to design a simpler transmission system based on the alternator 3-phase ac output. If a high voltage alternator design is used, power can be efficiently conducted from the alternator to the PPUs using an ac transmission line. Within the PPUs, a transformer steps the high voltage ac down and a rectifier converts it into dc for the thrusters.

Comparing the two approaches, it is apparent that the dc system is much more complex. This leads to mass, efficiency, and reliability penalties. Key PMAD parameters are compared in Table 1 for the two approaches. Although the dc system is notably heavier, the mass difference would be even larger except for the fact that the chopper in the dc to dc PPU operates at a high frequency. This reduces the subsequent PPU transformer and filter masses, and improves the quality of the power provided to the thruster. However, there are disadvantages associated with the use of complex dc to dc converters instead of transformers. The added conversion steps substantially lower the end-to-end PMAD efficiency. This means a larger power source is needed to offset the losses. The dc system development and hardware costs are also probably higher, and the added conversion steps will tend to reduce system reliability. In fact because of the megawatt power levels, the chopper stage in the dc to dc PPU would probably be a high risk development item.

Table 1
DC vs AC Comparison for Ion and MPD Thrusters

Parameter	Low Frequency Transmission (Alternator Frequency)		DC Power Transmission	
	Ion	MPD	Ion	MPD
Mass	48,350 kg 1.68 kg/kWe	50,450 kg 1.75 kg/kWe	64,080 kg 2.32 kg/kWe	65,170 kg 2.36 kg/kWe
Efficiency	95.0%	95.1%	88.9%	89.0%
Power Quality	Good	Good	Excellent	Excellent
Complexity	Low	Low	High	High

(1) PMAD values based on 3 channels providing a total of 30 MWe, 150 meter main transmission line length, 8000 Volt transmission voltage, and 100° C electronics coldplate temperature.

The chopper stage switches dc power at a high rate to generate an alternating voltage and current. High frequency ac is generated to reduce the mass of the subsequent transformer. Switch synchronization is critical in a chopper, but it can be quite difficult in a high power, high voltage chopper because numerous switches must be paralleled or connected in series to handle the high current and/or voltage levels. If an individual switch fails to operate properly, it can result in an internal short and cause the switch at fault to fail. To reduce the chances of this occurring, special circuits force the switches to load share, and snubbers are used to protect against voltage spikes. While they can be very effective, they add to the mass of the chopper. Due to these problems, there are programs currently in progress to develop higher power and voltage switching devices that are rugged and have improved switching characteristics. The development of these devices is crucial to the fabrication of a dc to dc converter rated for megawatt power levels.

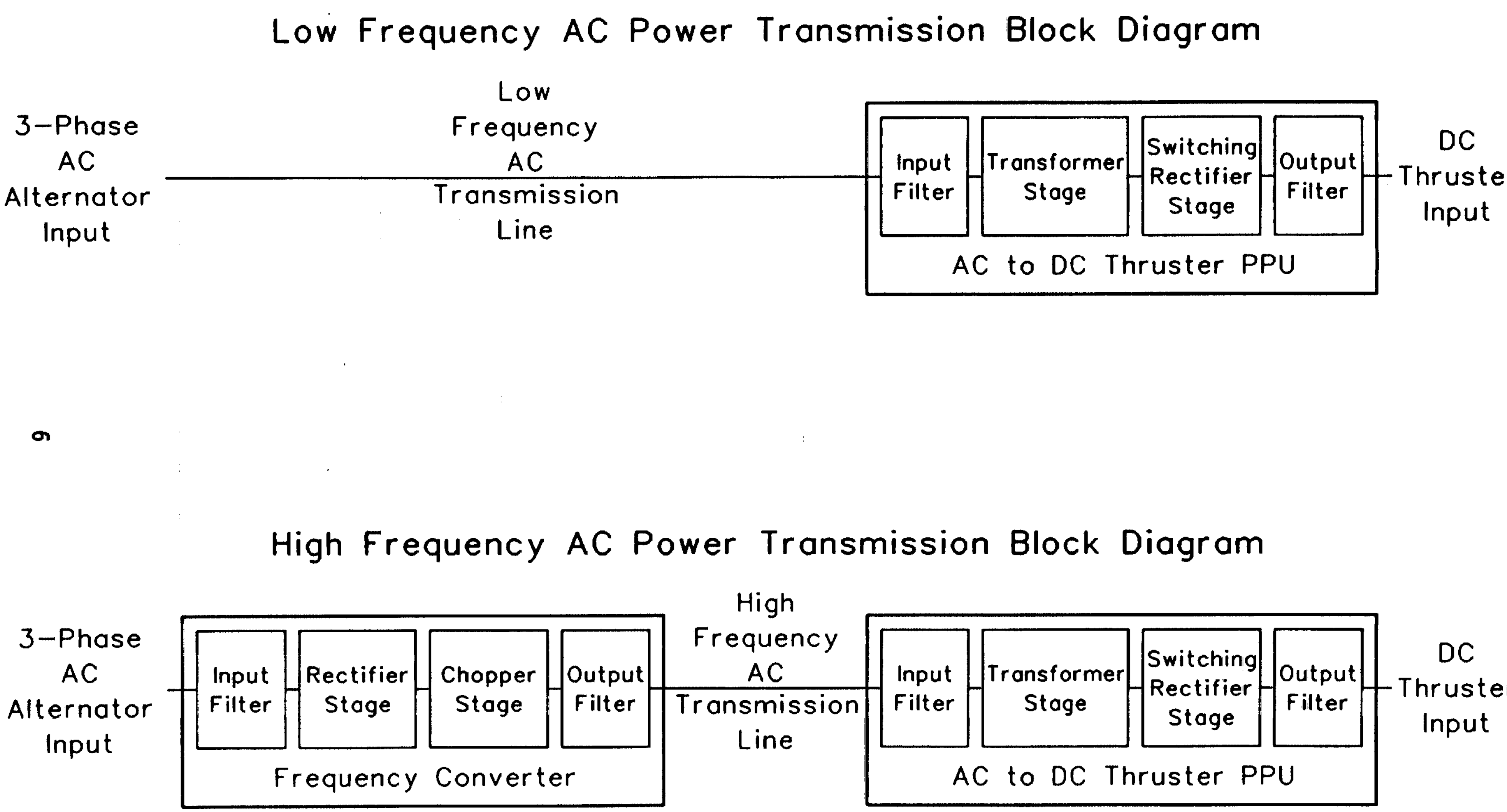
Although it is not shown in Figure 1, another dc power transmission component that will require extensive development is a dc switchgear unit. The remote bus isolators (RBIs) in the dc switchgear unit must use a mechanical and/or semiconductor switch capable of interrupting the maximum calculated bus voltage. Depending on the design, these switches will draw an arc or encounter high electromagnetic forces during opening that will generate high stresses and concentrated heating. This forces the dc RBI construction to be heavier. A comparable ac RBI switch can open during the zero current crossing. This dramatically reduces the stresses encountered and consequently its mass. At the present time, a major design issue is the development of a suitable dc RBI for the Space Station Freedom (SSF) electrical power system. The power levels on SSF are on the order of tens of kilowatts; the power levels on the proposed NEP vehicle are on the order of megawatts. Based on this comparison, a dc RBI rated for megawatt power levels would be a feasibility issue.

Based on the results of Task Order 14, briefly summarized above, ac transmission was selected over dc. It appears to have several advantages, lower development costs, higher projected component reliabilities, simplified fault protection, and a higher overall PMAD system efficiency. For a dc system to be competitive, it would need to offer substantial mass savings. This is not the case. Results to date indicate a dc system would actually be heavier.

2.2 Low Frequency versus High Frequency Power Transmission

After selecting ac power transmission, further studies were conducted to determine the best ac transmission approach. Basically two methods are available, a low frequency approach that bases the transmission voltage and frequency on the alternator output, and a high frequency approach that utilizes a frequency converter following the alternator to generate a selected high frequency output. Diagrams for the two approaches, displaying the required components and internal conversion steps, are shown in Figure 2.

The low frequency system, because it uses the alternator voltage and frequency directly, is less complex. The 3-phase ac alternator output is good for high power delivery. A 3-phase power system delivers a steadier power flow, whereas a single-phase system exhibits a pulsating power effect. 3-phase systems also have a higher power transfer capability which promotes the design of an efficient, light weight transmission line. Finally, because the transmission frequency is relatively low, line inductance and skin effect losses are less of a problem. However, low frequency distribution is not optimum for transformer and filter design and it causes the transformers and dc output filters located in the PPUs to be relatively heavy. Consequently, high frequency distribution was evaluated.



Low vs High Frequency NEP Vehicle PMAD Comparison
Figure 2

LVSHPMAD
4-27-92

The high frequency approach utilizes a frequency converter following the alternator to convert the alternator's low frequency output into high frequency ac. It can be designed to provide a single- or 3-phase output, and a wide range of frequencies. Hence, the number of phases and transmission frequency can be selected to yield the optimum PMAD system design. This allows significant mass savings in the PPUs due to the reduced transformer and filter mass, and because high frequency power is easier to filter it improves the quality of the power fed to the thrusters. However, a high frequency PMAD system has certain drawbacks. The addition of the frequency converter increases system mass, and reduces the end-to-end efficiency and reliability. Also at megawatt power levels, the chopper stage in the frequency converter would probably be a high risk development item for the same reasons previously presented in the discussion regarding the dc to dc PPU.

Three power distribution techniques using low and high frequency, and single- and 3-phase distribution are compared in Table 2. Based on this evaluation, the low frequency approach was selected. It has the lowest mass, highest efficiency, and on the basis of complexity it was judged to have the highest reliability and lowest development costs. While its power quality is not as good as a high frequency system, it was considered adequate for both ion and MPD engine applications. The low frequency architecture was designated the reference configuration and component models based on it were developed to support the creation of a Fortran based model of a PMAD system. This PMAD subroutine will be included in a Fortran program being developed by NASA LeRC for the purpose of conducting system level trade studies on a complete NEP vehicle.

Table 2
Low vs High Frequency Comparison for Ion and MPD Thrusters

Parameter	Low Frequency (Alternator Frequency)		Single-Phase High Frequency		3-Phase High Frequency	
	Ion	MPD	Ion	MPD	Ion	MPD
Mass	48,350 kg 1.68 kg/kWe	50,450 kg 1.75 kg/kWe	68,020 kg 2.36 kg/kWe	69,170 kg 2.40 kg/kWe	67,880 kg 2.36 kg/kWe	68,470 kg 2.38 kg/kWe
Efficiency	95.0%	95.1%	88.4%	88.6%	88.5%	88.6%
Power Quality	Poorest	Poorest	Much Better	Much Better	Best	Best
Complexity	Lowest	Lowest	Much More Complex	Much More Complex	Most Complex	Most Complex

(1) PMAD values based on 3 channels providing a total of 30 MWe, 150 meter main transmission line length, 8000 Vrms transmission voltage, and 100° C electronics coldplate temperature.

3.0 End-to-End Power Management and Distribution Model

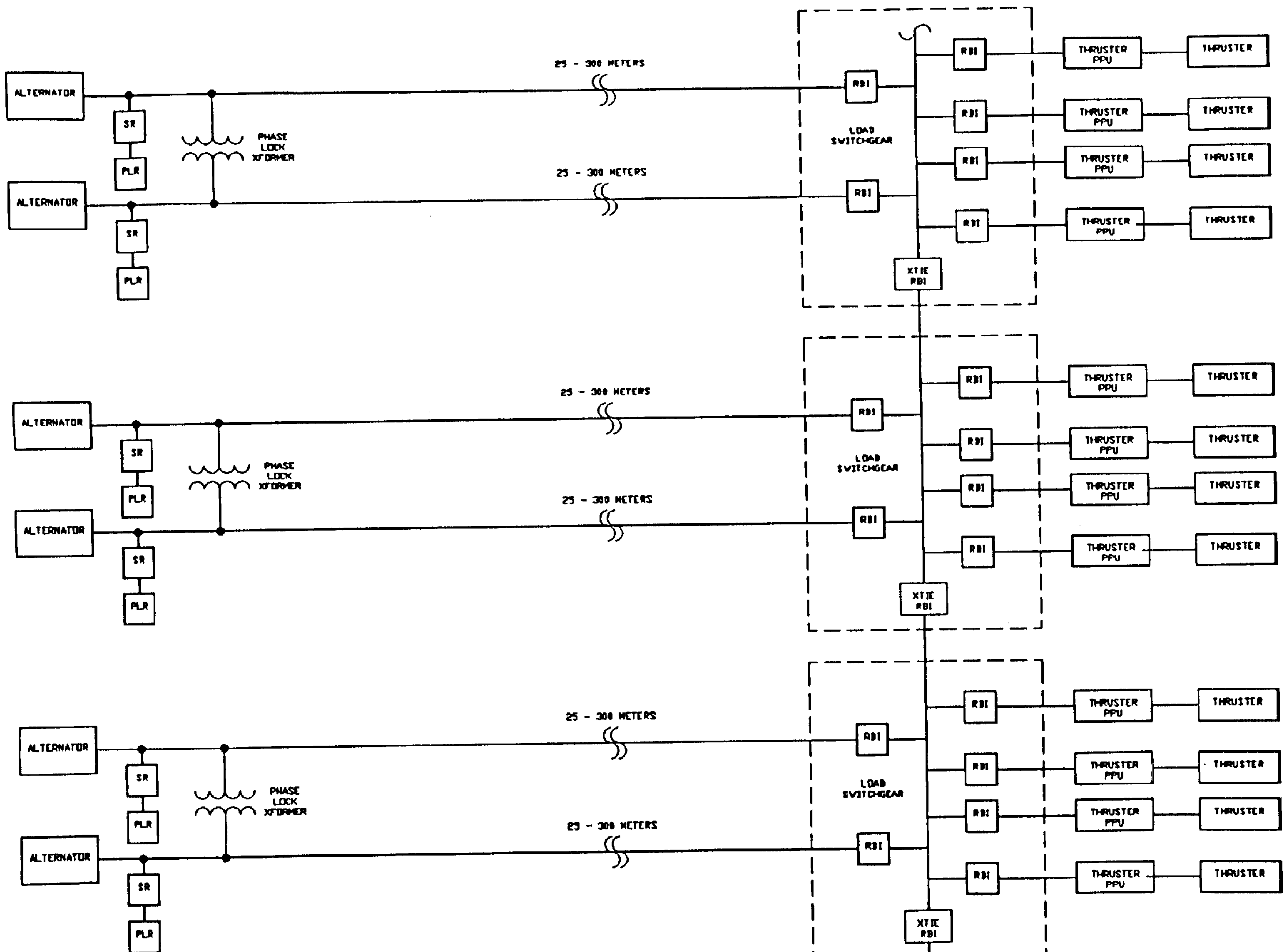
The end-to-end power management and distribution (PMAD) model is based on an alternator power input that determines the transmission voltage and frequency. This approach was selected because supporting studies showed it was the lightest weight and most efficient. It is also the most simple, which should reduce development costs and enhance reliability. A block diagram of this architecture, entitled "Low Frequency PMAD Architecture" is shown in Figure 3. This particular figure shows three parallel channels and counter rotating alternators, but the user can define other configurations. The alternator provides 3-phase ac power, and depending on its design, a wide range of voltages (1000 to 10,000 Vrms) and frequencies (60 Hz to 5 kHz) can be specified.

The alternator operating frequency is generally obtained from the power conversion module; however, one should be aware of fundamental alternator operating limits. The permissible alternator frequency range is largely determined by the alternator type. A two-pole, toothless alternator is a lightweight machine, but its two pole design results in a lower frequency output. Conversely, the homopolar induction alternator can operate at high frequencies, but it is heavier and often less efficient. The operating frequency of multiple pole, permanent magnet and wound rotor machines lies between these two. Furthermore, for a specific alternator type the operating frequency is inversely proportional to the power level. This occurs because the rotor in a high power alternator is larger in diameter and it is subject to higher stresses at a given rotational speed. While the allowable operating voltage is more variable, it too is subject to limits. Large alternators can provide high voltages; however, because the insulation occupies considerable space, it probably would not be practical to design a high voltage, low power alternator.

Following the alternator is a speed regulator. It controls the alternator-turbine speed by matching the power demand with the power supply, and shunts excess power to a parasitic load radiator. The phase lock transformer is only required if counter rotating alternators are specified. Its function is to force the alternators to operate in synchronism. A change in the rotational speed of one alternator is opposed by an equal change in the other alternator, thus cancelling the moments applied to the vehicle. The switchgear unit energizes the individual power processing units (PPUs), interrupts fault currents, and isolates failed components. The PPUs convert the ac power supplied by the alternators into dc for the thrusters. They also regulate the voltage output to control the thruster operation and startup. Each of these components is interconnected by transmission lines. The power conditioning components rely on heat pipe based radiators for cooling; the transmission lines radiate directly to space.

Application Notes: The low frequency PMAD architecture model is designed to provide overall PMAD system mass and efficiency information. It is capable of modelling the effects of different alternator and thruster types; and it can accept powers ranging from 10 kWe to 100 MWe, transmission voltages ranging from 1000 to 10,000 Vrms, and alternator frequencies ranging from 60 Hz to 5 kHz. Coldplate temperatures ranging from 60 to 200° C can also be input to allow preliminary assessments of high temperature electronics devices. Because the component efficiencies are automatically adjusted to correspond to the coldplate temperature, the impact of these devices on the complete power

LOW FREQUENCY PMAD ARCHITECTURE



LEGEND

PLR - PARASITIC LOAD RESISTOR
PPU - POWER PROCESSING UNIT
RBI - REMOTE BUS ISOLATOR
SR - SPEED REGULATOR
XFORMER - TRANSFORMER
XTIE RBI - CROSS TIE REMOTE BUS ISOLATOR

Figure 3

system can be evaluated (See Appendix A for a discussion on the efficiency-temperature algorithm development). Finally, solar and earth insolation information that can be obtained from the heat rejection module can be used to evaluate the thermal impact of different solar distances on the PMAD system.

Model Specifics: The flow chart shown in Figure 4 shows the logic employed during the development of the PMAD model. The overall mass, area, and efficiency information listed in the right hand column represents an estimate of the users needs. Additional information can be obtained from a Fortran common block data statement containing detailed component design details. The basic model operations are shown in the middle column, and the system inputs are listed in the boxes on the left. Default values are provided for these inputs, but the user can use a data input file to change these values as long as they stay within the specified model limits.

The PMAD model is suitable for a specific range of input parameters. Using input parameters outside of these ranges could result in inaccurate mass estimates or errors, and it is not recommended. Table 3 lists appropriate input ranges and recommended values for selected cases. These values are suggested if the PMAD model is being run outside of the NEP power system model. Parameters normally obtained from external modules are addressed by the notes.

The parameters listed in Table 3 are used to define the PMAD system architecture. The notes and comments associated with these values specify limits and identify information sources, but they do not explain how these values are used to define the overall PMAD architecture. Hence, a brief explanation is offered. It is expected that the user will know the total power required for the mission, and that they will generally define a PMAD architecture that contains multiple channels. The power level input by the user defines the total power provided to the PPUs to operate all the thrusters, and not the power per channel. The "Required PMAD Channels" (RPC) defines the number of channels actually needed to supply full power to the load. The "Available PMAD Channels" (APC) value is used to determine how many spare channels exist. For example, suppose a 10 MWe system is under study, and RPC is set equal to 2, and APC to 3. The resulting PMAD architecture would have 3 channels each sized to handle 5 MWe; consequently, only 2 channels are required to deliver full power to the load and the third channel is in effect a spare. Within a channel, single or counter rotating alternators can also be defined. If a counter rotating alternator is selected, a phase lock transformer is automatically incorporated into the architecture.

The variables and constants utilized in the NEP PMAD model are listed in Table 4 in alphabetical order. A complete listing of the PMAD model subroutine, the PMAD driver, the common block statement, and the print output Fortran source codes are presented in Appendix A. These subroutines are called "PMAD.FOR", "MAIN.FOR", "COMMON.FOR", and "PRINTO.FOR", respectively. The code "MAIN.FOR" is a temporary driver. It is assumed that the master module code to be written by NASA LeRC will largely replace it, and also incorporate the elements of "PRINTO.FOR" desired for print output. The subroutine "COMMON.FOR" is simply a large common block containing detailed component input and output design information. Selected information can be obtained by modifying the print output subroutine. All four files are located on the accompanying computer disk, along with the executable file "MAIN.EXE". A sample PMAD input file entitled "PMAD.IN" is also located on the disk to show the user how alternate design configurations can be generated.

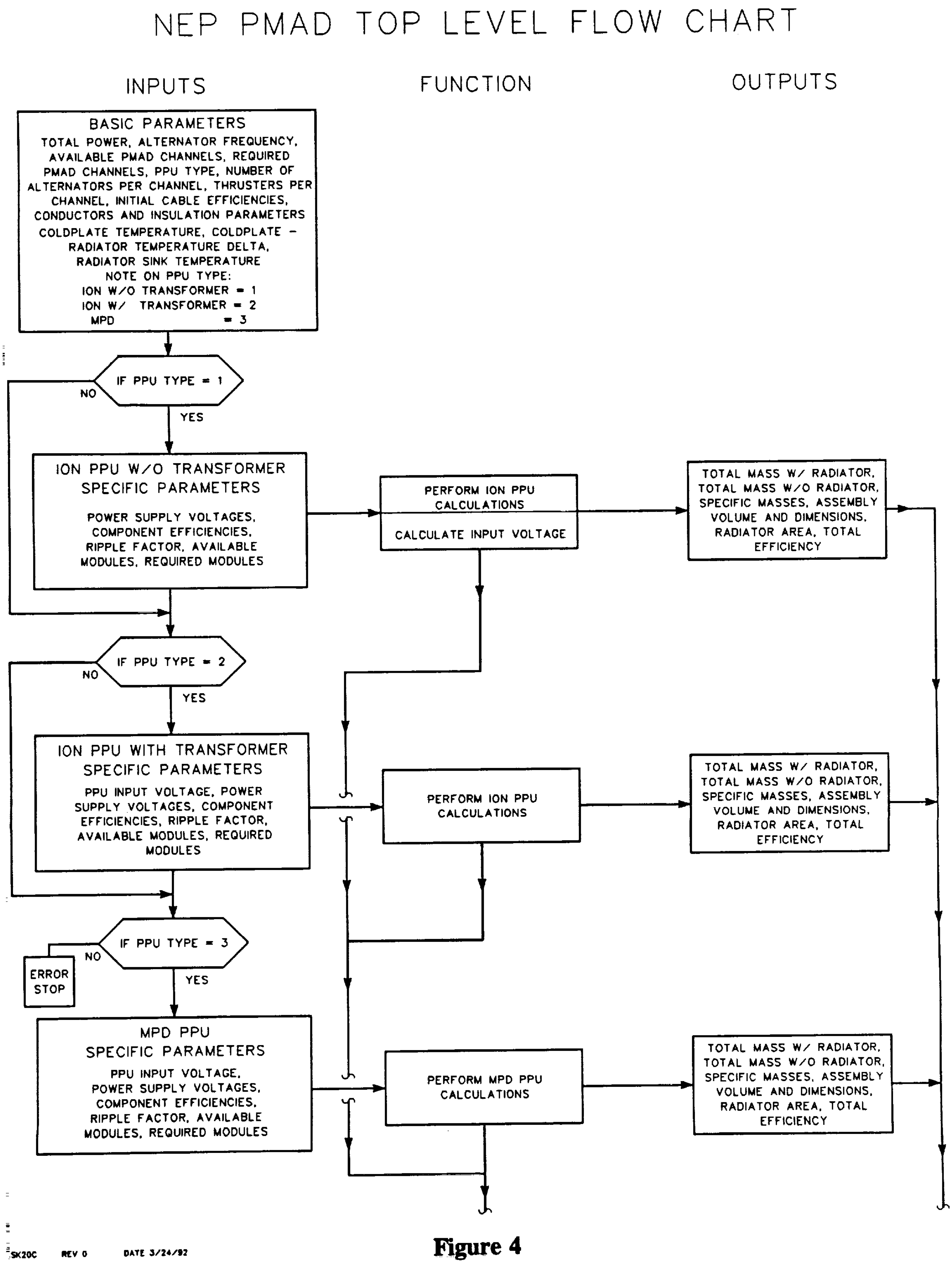

NEP PMAD TOP LEVEL FLOW CHART
INPUTS
FUNCTION
OUTPUTS
BASIC PARAMETERS
TOTAL POWER, ALTERNATOR FREQUENCY, AVAILABLE PMAD CHANNELS, REQUIRED PMAD CHANNELS, PPU TYPE, NUMBER OF ALTERNATORS PER CHANNEL, THRUSTERS PER CHANNEL, INITIAL CABLE EFFICIENCIES, CONDUCTORS AND INSULATION PARAMETERS
COLDPLATE TEMPERATURE, COLDPLATE – RADIATOR TEMPERATURE DELTA, RADIATOR SINK TEMPERATURE
NOTE ON PPU TYPE:
ION W/O TRANSFORMER = 1
ION W/ TRANSFORMER = 2
MPD = 3
IF PPU TYPE = 1
NO
YES
ION PPU W/O TRANSFORMER SPECIFIC PARAMETERS
POWER SUPPLY VOLTAGES, COMPONENT EFFICIENCIES, RIPPLE FACTOR, AVAILABLE MODULES, REQUIRED MODULES
PERFORM ION PPU CALCULATIONS
CALCULATE INPUT VOLTAGE
TOTAL MASS W/ RADIATOR, TOTAL MASS W/O RADIATOR, SPECIFIC MASSES, ASSEMBLY VOLUME AND DIMENSIONS, RADIATOR AREA, TOTAL EFFICIENCY
IF PPU TYPE = 2
NO
YES
ION PPU WITH TRANSFORMER SPECIFIC PARAMETERS
PPU INPUT VOLTAGE, POWER SUPPLY VOLTAGES, COMPONENT EFFICIENCIES, RIPPLE FACTOR, AVAILABLE MODULES, REQUIRED MODULES
PERFORM ION PPU CALCULATIONS
TOTAL MASS W/ RADIATOR, TOTAL MASS W/O RADIATOR, SPECIFIC MASSES, ASSEMBLY VOLUME AND DIMENSIONS, RADIATOR AREA, TOTAL EFFICIENCY
IF PPU TYPE = 3
NO
ERROR STOP
YES
MPD PPU SPECIFIC PARAMETERS
PPU INPUT VOLTAGE, POWER SUPPLY VOLTAGES, COMPONENT EFFICIENCIES, RIPPLE FACTOR, AVAILABLE MODULES, REQUIRED MODULES
PERFORM MPD PPU CALCULATIONS
TOTAL MASS W/ RADIATOR, TOTAL MASS W/O RADIATOR, SPECIFIC MASSES, ASSEMBLY VOLUME AND DIMENSIONS, RADIATOR AREA, TOTAL EFFICIENCY
SK20C REV 0 DATE 3/24/92

Figure 4

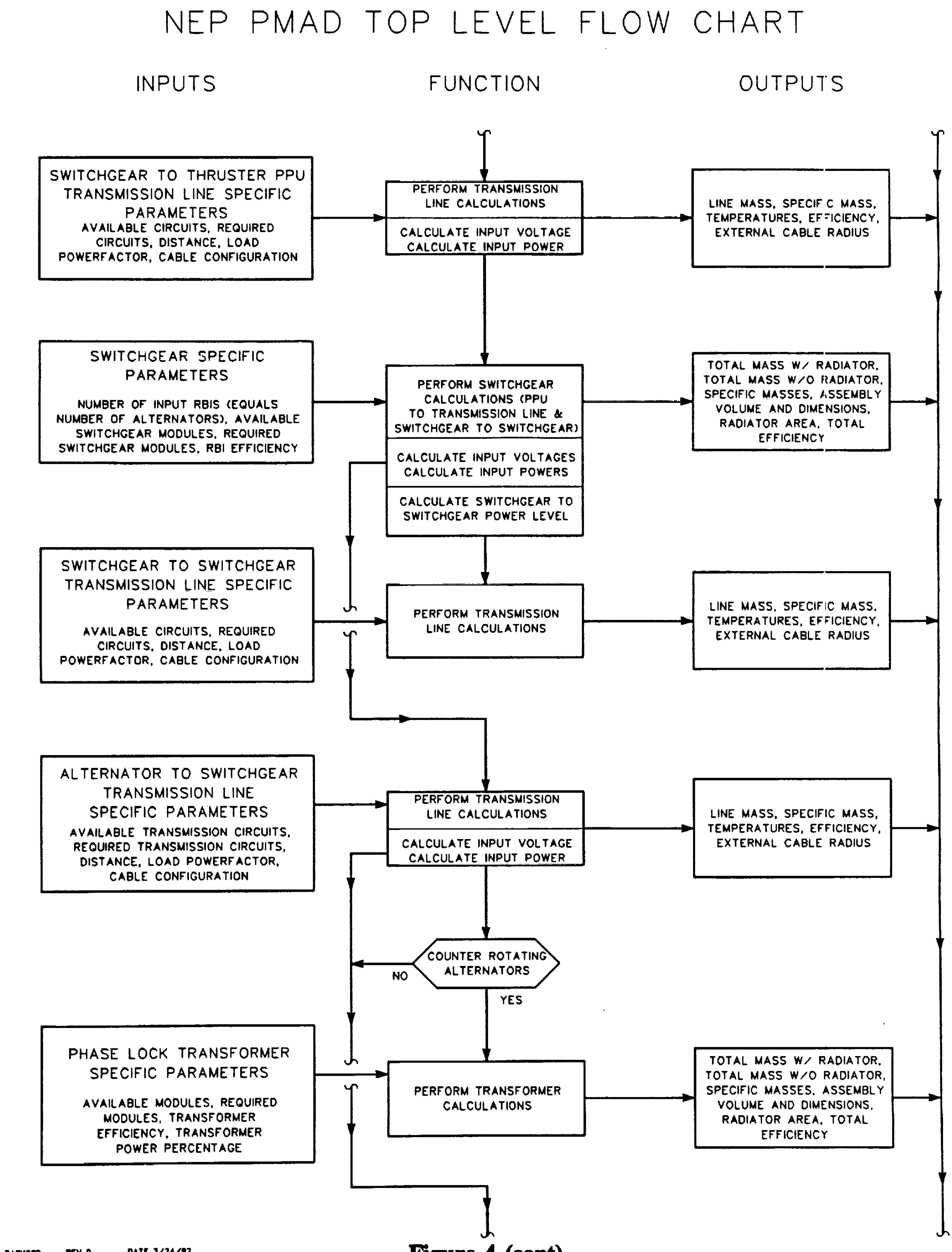


Figure 4 (cont)

NEP PMAD TOP LEVEL FLOW CHART

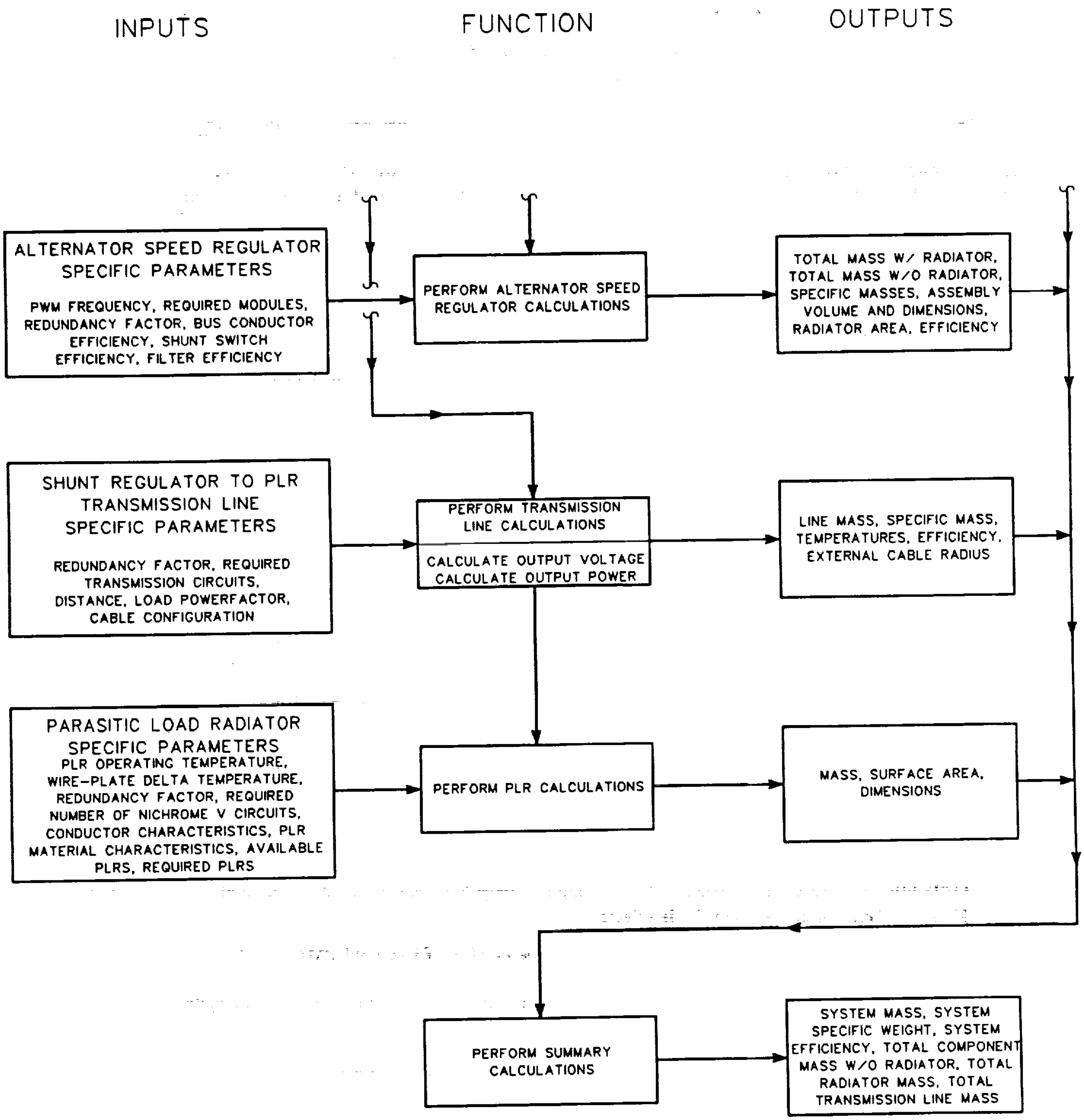


Figure 4 (cont)

Table 3
End-to-End NEP PMAD System Model
Input Parameter Ranges

Input Parameter	Recommended Input Range
Total PMAD System Power Level (Measured at the Thruster PPU Input)	100 kWe to 100 MWe (Limited to 10 MWe/Channel)
Thruster PPU Input Voltage Level (See Note 1)	1500 to 10,000 Vrms
Available PMAD Channels	Equal to or Greater than Required Channels
Required PMAD Channels (See Note 2)	No Limit
Number of Alternators per Channel (See Note 2)	No Limit
Number of Thrusters per Channel (See Note 2)	No Limit
Counter Rotating Alternators	Yes=1, No=0
Power Processing Unit Type	Ion PPU w/o Transformer = 1 Ion PPU with Transformer = 2 MPD PPU = 3
Alternator Operating Frequency (See Note 3)	60 Hz to 5 kHz 0.8 kHz is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 4 247.67 K Calculated for LEO

1. A PPU input voltage level is only specified when the Ion PPU with Transformer, Option #2; or the MPD PPU, Option #3, is selected. The PPU input voltage level is calculated by the model when the Ion PPU w/o Transformer, Option #1, is selected.

2. The PMAD model does not have a limit regarding the number of Required PMAD Channels (RPC), the Number of Alternators per Channel (NAC), and the Number of Thruster per Channel (NTC); however, there are of course practical limits on these values. The user is responsible for selecting appropriate values.

3. The Alternator Operating Frequency (AOF) is normally obtained from the Power Conversion module (CR-191134 or CR-191135). If the PMAD module is run separately, a value must be input by the user.

4. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 4
End-to-End NEP PMAD System Model
Variable Definitions

AOF	Alternator Operating Frequency (kHz)
APC	Available PMAD Channels
CPT	Electronics Coldplate Temperature (°C)
CRTD	Electronics Coldplate to Radiator Temperature Delta (°C)
EEPE	End-to-End PMAD System Efficiency (%)
IDPPU	Variable to Select Power Processing Unit Type
KRA	Variable to Select Counter Rotating Alternators
NAC	Number of Alternators per PMAD Channel
NTC	Number of Thrusters per PMAD Channel
PMADPO	PMAD System Power Output (kWe)
PPUVI	Power Processing Unit Input Voltage (Vrms)
RPC	Required PMAD Channels
RST	Electronics Radiator Sink Temperature (K)
TERA	Total Electronics Radiator Area (m^2)
TERM	Total Electronics Radiator Mass (kg)
TPCM	Total Power Conditioning Component Mass (kg)
TPM	Total PMAD System Mass (kg)
TPSM	Total PMAD System Specific Mass (kg/kWe)
TTLM	Total Transmission Line Mass (kg)

3.1 Ion Power Processing Unit w/o Beam Power Supply Transformer

Two ion power processing unit (PPU) models are available. They utilize similar topologies, but the individual power supply designs differ. Because the first type, designated option #1, does not contain a beam power supply transformer, the user can not specify the PPU input voltage level. Instead, the PPU input voltage is calculated by the model from the user defined beam voltage level. This design feature affects the operation of the PPU, and largely determines its suitable applications. These items are discussed further in the subsequent application notes.

A block diagram of the option #1 ion PPU design is shown in Figure 5. Note that there are four distinct power supplies, beam, discharge, accelerator, and neutralizer. Each of these supplies can be controlled independently to facilitate engine startup and provide flexibility when responding to off-normal conditions. Because the operating voltage of the discharge, accelerator, and neutralizer power supplies is much lower than the beam power supply voltage, a step down transformer is incorporated into the design of each of these supplies. All four power supplies contain a switching rectifier, and an output dc filter. The switching rectifier converts the ac power supplied by the alternator into dc for the engine, and employs pulse-width-modulation (PWM) switching to precisely regulate the output voltage of each power supply. The dc filter stage reduces the ripple content to a level acceptable for the engine. The model is completed with the addition of control and monitoring hardware, identified in the figure as the main engine controller, and an enclosure assumed to be largely constructed from carbon-carbon. It is assumed that the enclosure mounting plate is firmly bonded to the assembly coldplate to facilitate heat transfer. This improves component thermal management, but makes it more difficult to replace. The assumption is that maintenance will be very limited if not precluded on a nuclear electric propulsion vehicle once a mission has begun.

Application Notes: It was previously mentioned that the beam power supply in the option #1 PPU does not have a transformer stage. Eliminating this transformer greatly reduces PPU mass, but there are two drawbacks. Because the PPU input voltage is determined by the beam supply output voltage, and this voltage is relatively low (1800 Vdc), the mass of all upstream transmission lines will be increased. Consequently, this PPU configuration is really only practical if the transmission distance is fairly short, probably less than a 150 meters. For distances greater than this, the option #2 PPU appears to be a better choice.

The other drawback associated with this design is it is not possible to provide the isolation between the PMAD system and the thrusters that a transformer would afford. Electromagnetic interference (EMI) will be generated by the thrusters and the PWM switching. This may cause the PMAD system to have a fairly high level of EMI, and diminish power system grounding effectiveness. While detailed analysis is required to determine the implications associated with this approach, it should be reasonable to design the power system to withstand this level of EMI. Furthermore, the components connected to the PMAD system, the alternators and thrusters, can tolerate high levels of EMI if they are suitably designed for this environment.

LOW FREQUENCY ION THRUSTER PPU TOPOLOGY (W/O BEAM POWER SUPPLY TRANSFORMER)

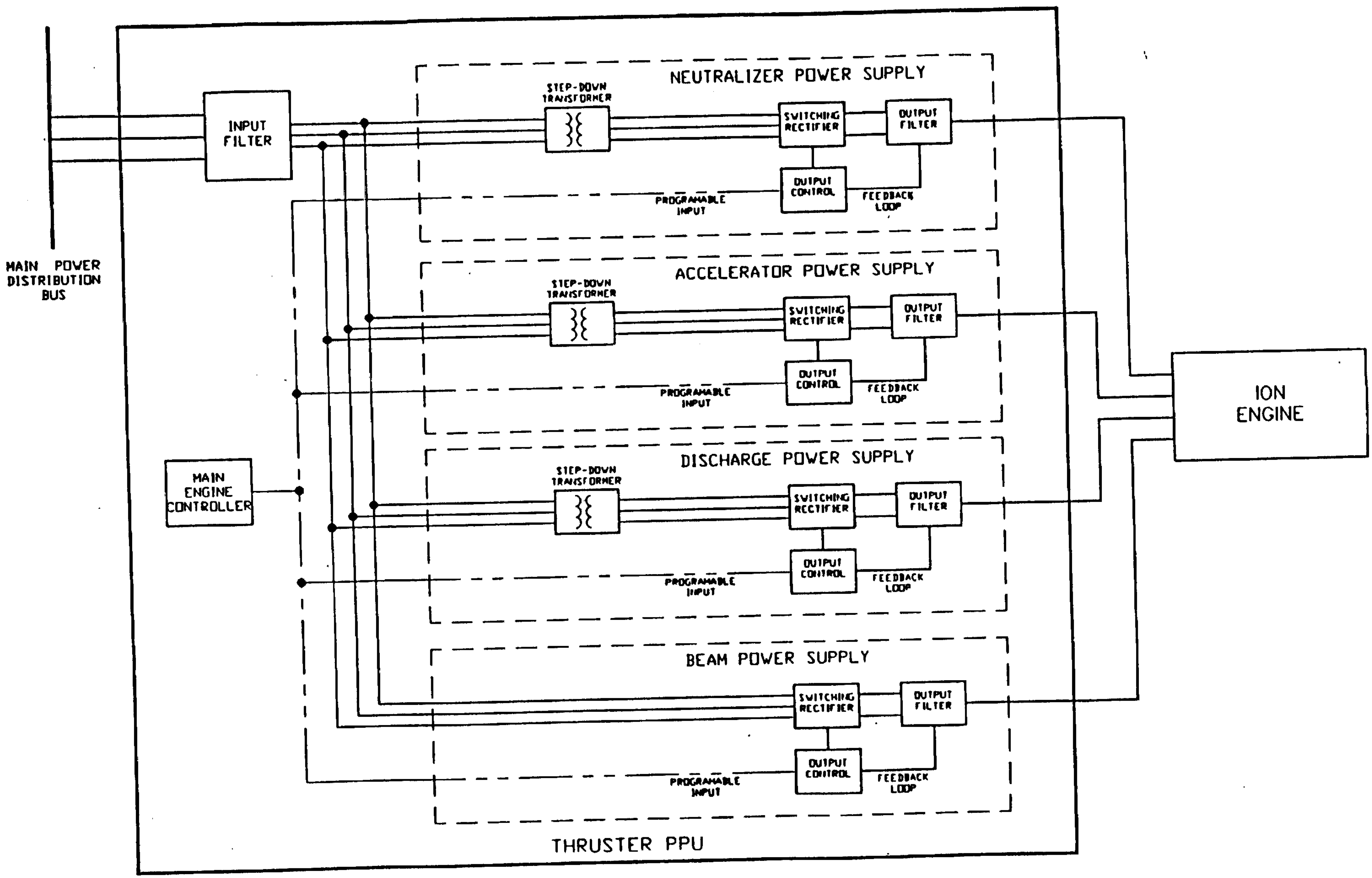


Figure 5

Model Specifics: The flow chart shown in Figure 6 depicts the logic employed during the development of the option #1 PPU model. It should be noted that the outputs listed in the right column represent a best estimate of the users needs. A limited number of parameters are printed, but many more are available. These outputs can be accessed by modifying the print routine so that it prints additional data contained in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

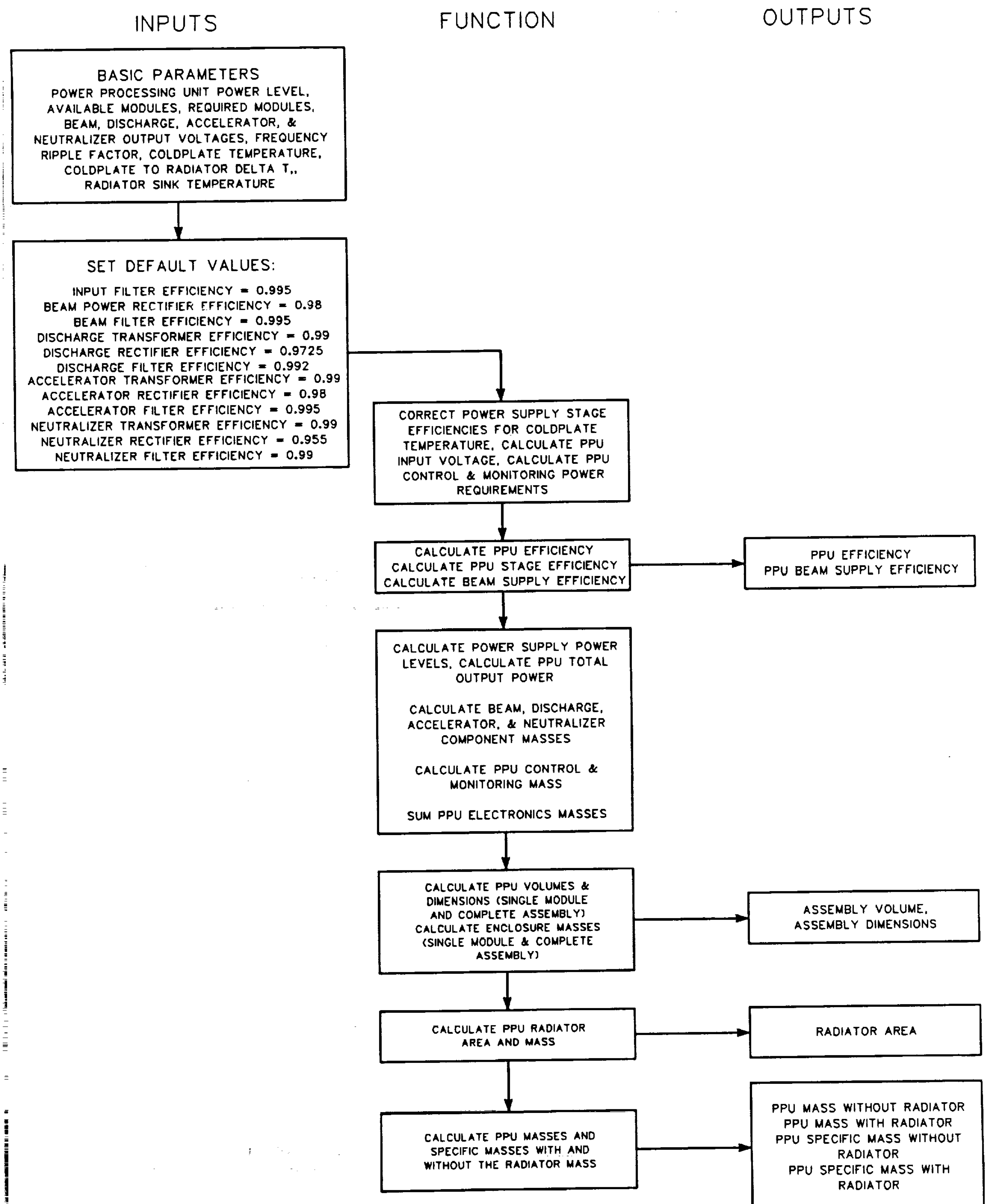
The model is designed to cover a specific range of input parameters. Using input parameters outside of these ranges could result in inaccurate mass estimates and it is not recommended. Table 5 lists the appropriate input ranges and values recommended to yield the best results for the primary input parameters. Certain parameters are normally obtained from external modules. The notes identify the modules that are the sources of this data.

Many of the input values, particularly the component efficiencies, are relatively fixed, and they should only be changed if the user is quite familiar with the model operation and power conditioning component designs in general. Although component efficiencies change with temperature, normally downward as temperature rises, it is not necessary to manually adjust these values. The models contain algorithms that will automatically adjust the component efficiencies based on the selected coldplate temperature. These temperature adjusted efficiencies are then used by the component mass estimation algorithms. The only reason to manually change these values would be to conduct mass-efficiency tradeoffs. In general, the efficiency of a component can be increased by enlarging its internal conductors and other power elements. While this reduces radiator and power source mass, it increases the mass of the component itself.

The default efficiency values utilized by the model were carefully selected to yield mass and total component efficiency estimates consistent with the proposed applications and the specified time period. These individual element efficiency values are referred to as secondary input parameters, and acceptable ranges and default values are listed for them in Table 6. Because the discharge and neutralizer power supply voltages are quite low, less than 120 Vdc, it will be necessary for the user to adjust the efficiencies of the rectifier and filter stages if he changes the default voltage levels. The present rectifier and filter default efficiency values are for discharge and neutralizer power supply voltages of 30 Vdc and 20 Vdc, respectively. This adjustment would be necessary to maintain representative efficiencies and obtain realistic mass estimates. Suitable efficiencies for voltages ranging from 20 to 120 Vdc are shown in Tables 7 and 8.

The variables and constants utilized in the option #1 PPU model are listed in Table 9 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix B. This subroutine is located on the accompanying computer disk and it has the file name "IONPU1.FOR".

ION THRUSTER PPU OPTION #1 FLOW CHART



TASK20L REV 0 DATE 4/9/92

Figure 6

Table 5
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Primary Input Parameter Ranges

Power Processing Unit Primary Input Parameter	Recommended Input Range
PPU Input Power Level	100 kWe to 10 MWe
PPU Input Voltage Level	See Note 1
Beam Power Supply Output Voltage Level	120 to 10,000 Vdc
Discharge Power Supply Output Voltage Level	20 to 200 Vdc
Accelerator Power Supply Output Voltage Level	120 to 10,000 Vdc
Neutralizer Power Supply Output Voltage Level	20 to 200 Vdc
Ripple Factor Percentage	0.5 to 8%
PPU Available Modules	Equal to or Greater than Required Modules
PPU Required Modules	No Limit
Alternator Operating Frequency (See Note 2)	60 Hz to 5 kHz 0.8 kHz is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 3 247.67 K Calculated for LEO

1. The input voltage level is calculated from the beam supply output voltage level. It will be approximately 0.72 times the output voltage level.

2. The alternator operating frequency (AOF) will normally be obtained from the power conversion module (CR-191134 or CR-191135). If the PMAD module is run separately, AOF must be input.

3. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 6
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Secondary Input Parameter Ranges

Power Processing Unit Secondary Input Parameter	Recommended Input Range
Input AC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Beam Power Supply Rectifier Efficiency	Normal Range: 97.0 to 99.0% 98.0% is Recommended
Beam Power Supply Output DC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Discharge Power Supply Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Discharge Power Supply Rectifier Efficiency (See Note 1)	Normal Range: 95.5 to 98.0% 97.25% Recommended for 30 Vdc
Discharge Power Supply Output DC Filter Efficiency (See Note 2)	Range: 99.0 to 99.5% 99.2% Recommended for 30 Vdc
Accelerator Power Supply Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Accelerator Power Supply Rectifier Efficiency	Normal Range: 97.0 to 99.0% 98.0% is Recommended
Accelerator Power Supply Output DC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Neutralizer Power Supply Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Neutralizer Power Supply Rectifier Efficiency (See Note 1)	Normal Range: 95.5 to 98.0% 95.5% Recommended for 20 Vdc
Neutralizer Power Supply Output DC Filter Efficiency (See Note 2)	Range: 99.0 to 99.5% 99.0% Recommended for 20 Vdc

1. Refer to Table 7 for corrected rectifier efficiencies when the voltage output is less than 120 Vdc.
2. Refer to Table 8 for corrected dc filter efficiencies when the voltage output is less than 120 Vdc.

Table 7
Efficiency Corrections for Discharge and Neutralizer Power Supply Rectifier Mass Estimates

Input Voltage (Vdc)	Switching Rectifier Input Efficiency (percent)
120	98.00
110	98.00
100	97.98
90	97.96
80	97.94
70	97.86
60	97.80
50	97.68
40	97.50
30	97.25
20	95.50

Table 8
Efficiency Corrections for Discharge and Neutralizer Power Supply Filter Mass Estimates

Input Voltage (Vdc)	Output Filter Input Efficiency (percent)
120	99.50
110	99.50
100	99.49
90	99.48
80	99.47
70	99.45
60	99.42
50	99.38
40	99.31
30	99.20
20	99.00

Table 9
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Variable Definitions

ACCM	Accelerator Power Supply Conductor and Connector Mass (kg)
AFE	Accelerator Power Supply Filter Efficiency (%)
AFET	Accelerator Power Supply Filter Efficiency at the Coldplate Temperature (%)
AFM	Accelerator Power Supply Filter Mass (kg)
AOF	Alternator Operating Frequency (kHz)
AOP	Accelerator Supply Output Power Level (kWe)
AOV	Accelerator Supply Output Voltage (Vdc)
ARE	Accelerator Power Supply Rectifier Efficiency (%)
ARET	Accelerator Power Supply Rectifier Efficiency at the Coldplate Temperature (%)
ARM	Accelerator Power Supply Rectifier Mass (kg)
ATE	Accelerator Power Supply Transformer Efficiency (%)
ATET	Accelerator Power Supply Transformer Efficiency at the Coldplate Temperature (%)
ATM	Accelerator Power Supply Transformer Mass (kg)
BCCM	Beam Power Supply Conductor and Connector Mass (kg)
BFE	Beam Power Supply Filter Efficiency (%)
BFET	Beam Power Supply Filter Efficiency at the Coldplate Temperature (%)
BFM	Beam Power Supply Filter Mass (kg)
BOP	Beam Supply Output Power Level (kWe)
BOV	Beam Supply Output Voltage (Vdc)

Table 9 (cont)
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Variable Definitions

BRE	Beam Power Supply Rectifier Efficiency (%)
BRET	Beam Power Supply Rectifier Efficiency at the Coldplate Temperature (%)
BRM	Beam Power Supply Rectifier Mass (kg)
CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power Demand (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
DCCM	Discharge Power Supply Conductor and Connector Mass (kg)
DFE	Discharge Power Supply Filter Efficiency (%)
DFET	Discharge Power Supply Filter Efficiency at the Coldplate Temperature (%)
DFM	Discharge Power Supply Filter Mass (kg)
DOP	Discharge Supply Output Power Level (kWe)
DOV	Discharge Supply Output Voltage (Vdc)
DRE	Discharge Power Supply Rectifier Efficiency (%)
DRET	Discharge Power Supply Rectifier Efficiency at the Cold-plate Temperature (%)

Table 9 (cont)
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Variable Definitions

DRM	Discharge Power Supply Rectifier Mass (kg)
DTE	Discharge Power Supply Transformer Efficiency (%)
DTET	Discharge Power Supply Transformer Efficiency at the Coldplate Temperature (%)
DTM	Discharge Power Supply Transformer Mass (kg)
IFE	Power Processing Unit Input Filter Efficiency (%)
IFET	Power Processing Unit Input Filter Efficiency at the Cold-plate Temperature (%)
IFM	Power Processing Unit Input Filter Mass (kg)
NCCM	Neutralizer Power Supply Conductor and Connector Mass (kg)
NFE	Neutralizer Power Supply Filter Efficiency (%)
NFET	Neutralizer Power Supply Filter Efficiency at the Coldplate Temperature (%)
NFM	Neutralizer Power Supply Filter Mass (kg)
NOP	Neutralizer Supply Output Power Level (kWe)
NOV	Neutralizer Supply Output Voltage (Vdc)
NRE	Neutralizer Power Supply Rectifier Efficiency (%)
NRET	Neutralizer Power Supply Rectifier Efficiency at the Cold-plate Temperature (%)
NRM	Neutralizer Power Supply Rectifier Mass (kg)
NTE	Neutralizer Power Supply Transformer Efficiency (%)
NTET	Neutralizer Power Supply Transformer Efficiency at the Coldplate Temperature (%)
NTM	Neutralizer Power Supply Transformer Mass (kg)

Table 9 (cont)
Ion Thruster PPU Option #1 Model
(w/o Beam Power Supply Transformer)
Variable Definitions

PPAM	Power Processing Unit Available Modules
PPBE	Power Processing Unit Beam Supply Efficiency Measure (%)
PPE	Power Processing Unit Efficiency (%)
PPEM	Power Processing Unit Electronics Mass (kg)
PPIP	Power Processing Unit Input Power Level (kWe)
PPIV	Power Processing Unit Input Voltage Level (Vrms)
PPM	Power Processing Unit Mass w/o Radiator (kg)
PPMR	Power Processing Unit Mass with Radiator (kg)
PPOP	Power Processing Unit Output Power Level (kWe)
PPRM	Power Processing Unit Required Modules
PPSE	Power Processing Unit Stage Efficiency (%)
PPSM	Power Processing Unit Specific Mass w/o Radiator (kg/kWe)
PPSMR	Power Processing Unit Specific Mass with Radiator (kg/kWe)
RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RF	Ripple Factor (%)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)

3.2 Ion Power Processing Unit with Beam Power Supply Transformer

The option #2 ion power processing unit (PPU) topology is similar to the option #1 PPU configuration; however, the design of the power supplies, especially the beam power supply, differs. Because the option #2 design contains a beam power supply transformer to allow higher transmission voltages, the user is free to specify a wide range of PPU input voltages. This allows the option #2 PPU to be used in a wider range of applications and in certain cases it should improve the overall operation of the PMAD system.

A block diagram of the option #2 ion PPU design is shown in Figure 7. There are four separate power supplies, beam, discharge, accelerator, and neutralizer; each independently controllable to facilitate engine startup and improve flexibility. The beam and accelerator power supplies each use a single transformer to step down the high transmission line voltage to a level suitable for the engine. However, the discharge and neutralizer power supplies require two transformers because their output voltage is extremely low. The voltage ratio of power supply input over output is too large for a single transformer. The difference in the number of primary and secondary turns would be so high that the magnetic coupling between turns would be very poor, and the resulting flux leakage would cause a single transformer to be inefficient. Using two series connected transformers to sequentially step down the voltage is better. The turns ratio for each is cut in half; therefore, good coupling between the primary and secondary coils can be achieved. The voltage transformation efficiency is thus higher and the overall electrical performance is much better.

Each of the four power supplies also contains a switching rectifier, and an output dc filter. The rectifier converts the ac power supplied by the alternator into dc for the engine. It also utilizes pulse-width-modulation (PWM) switching to accurately regulate the output voltage of each power supply. The dc filter stage reduces the ripple content to a level acceptable for the engine. The model is completed with the addition of control and monitoring hardware, identified in the figure as the main engine controller, an enclosure assumed to be largely constructed from carbon-carbon, and a carbon-carbon heat pipe radiator. It is assumed that the enclosure mounting plate is bonded to the assembly coldplate to facilitate heat transfer. This improves component thermal management, but makes it more difficult to replace. The assumption is that maintenance will be very limited if not precluded on a nuclear electric propulsion vehicle once a mission has begun.

Application Notes: The option #2 ion PPU with the transformer in the beam power supply has greater versatility and better operating characteristics, but its mass is considerably larger. Because the user can specify a wide range of PPU input voltages, they can utilize lighter weight transmission lines and optimize the PMAD system based upon voltage. Consequently, this PPU configuration can be used with virtually any transmission line length. In fact, for distances greater than 150 meters, it is probably the only practical approach. The option #1 PPU only appears superior if mass is an overriding concern and the transmission distance is quite short.

This PPU design also enhances the isolation between the PMAD system and the thrusters. The electromagnetic interference (EMI) introduced into the PMAD system by the thrusters and the PWM switching will be greatly reduced. This design also improves grounding flexibility, because the transformer allows the designer to establish two separate ground planes. This should improve ground-

LOW FREQUENCY ION THRUSTER PPU TOPOLOGY (WITH BEAM POWER SUPPLY TRANSFORMER)

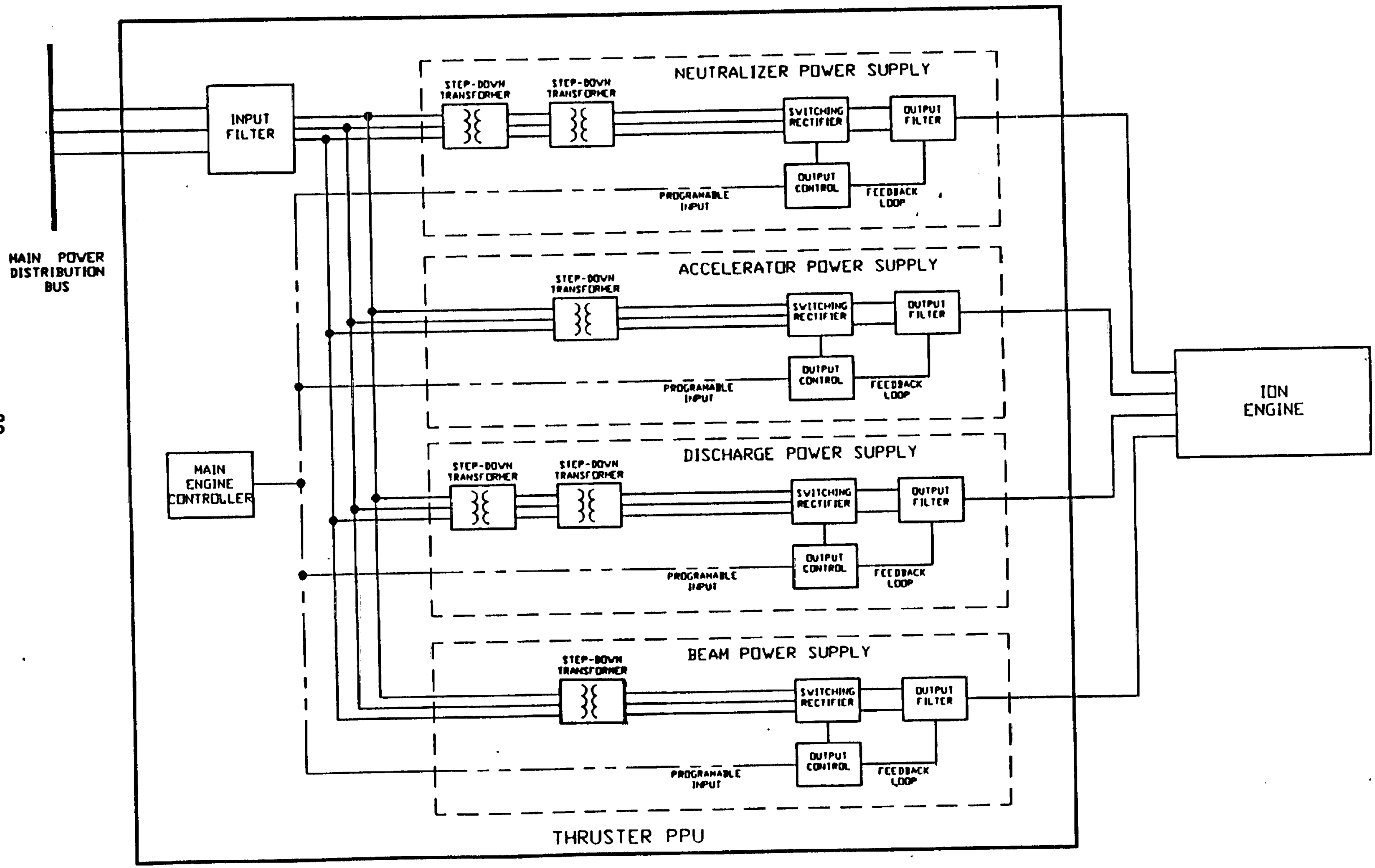


Figure 7

ing effectiveness, since the ground currents generated by the thruster and PWM switching will not circulate through out the rest of the PMAD system. This may ultimately simplify the thruster and PMAD system designs; however, it is necessary to conduct detailed system analyses to determine the operating qualities of this approach.

Model Specifics: The flow chart shown in Figure 8 presents the logic that was followed during the development of the option #2 PPU model. The outputs listed in the right column represent a best estimate of the users needs and many more parameters are available. These parameters can be accessed by modifying the print routine so that it prints the desired additional data contained in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

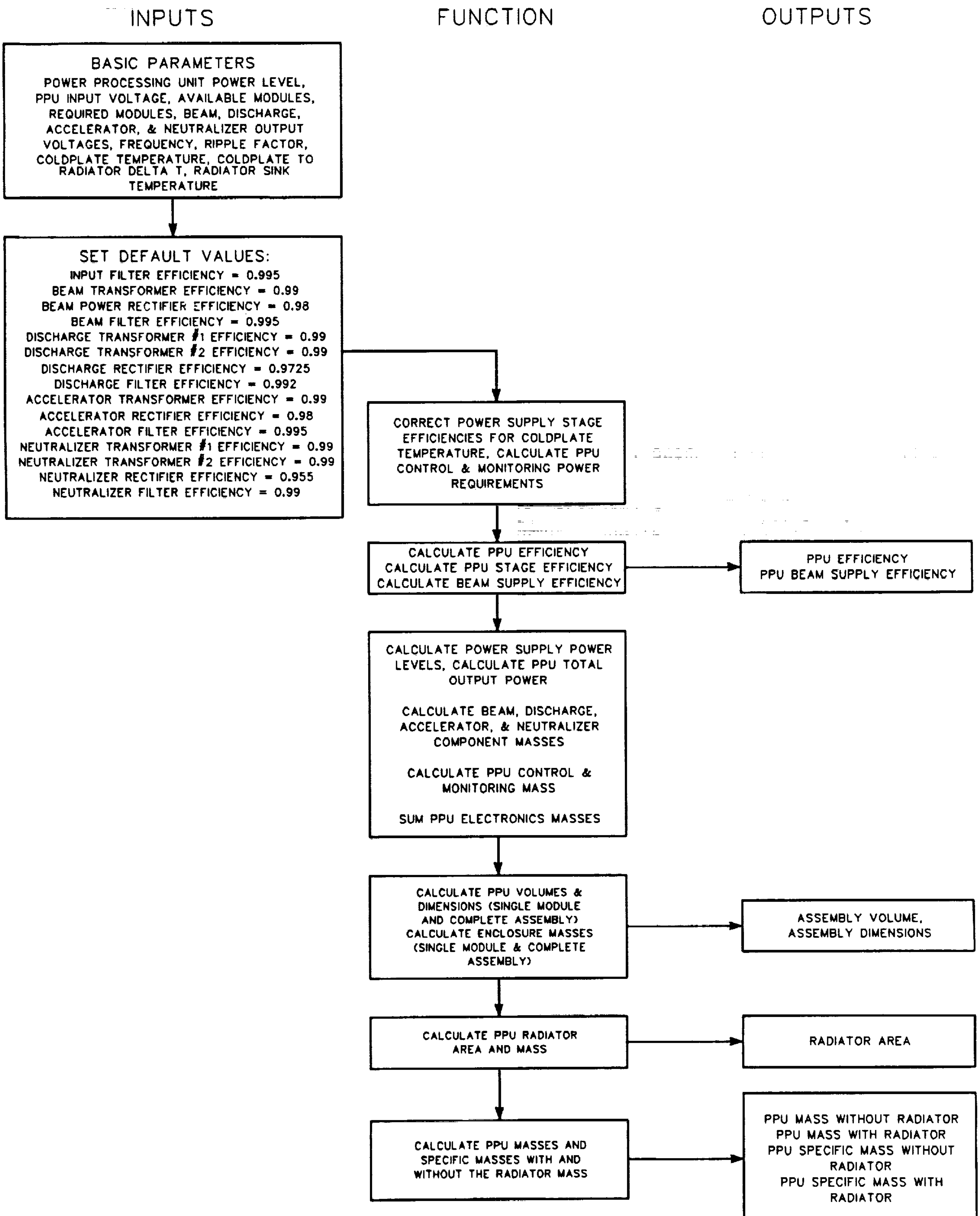
The model is designed to cover a specific range of input parameters. Using input parameters outside of these ranges could result in inaccurate mass estimates and it is discouraged. Table 10 lists the input ranges and values that were determined to yield the best results for the primary input parameters. The notes that accompany certain input parameters identify the modules that will normally provide these values.

In general, the default efficiency values should not be changed unless the user is quite familiar with the model operation and power conditioning component designs in general. Although component efficiencies generally decline with temperature, it is not necessary to manually adjust these values. The models utilize algorithms to automatically adjust the efficiency values for the selected coldplate temperature. The component algorithms then use these temperature adjusted efficiencies to estimate mass. The only reason to manually change these values would be to conduct mass-efficiency tradeoffs. The efficiency of a component can generally be increased by enlarging its internal conductors and other power elements. This reduces radiator and power source mass, but it increases the mass of the component itself.

The recommended efficiency values were selected to yield mass and total component efficiency estimates consistent with the proposed applications and the specified time period. These device efficiency values are referred to as secondary input parameters, and acceptable ranges and default values are listed for them in Table 11. Because the discharge and neutralizer power supply output voltages are quite low, less than 120 Vdc, the user will need to adjust the rectifier and filter efficiency inputs if a different output voltage level is specified. The present rectifier and filter default efficiency values are for discharge and neutralizer power supply voltages of 30 Vdc and 20 Vdc, respectively. These adjustments are necessary to maintain proper component efficiencies and obtain realistic mass estimates. Appropriate efficiencies for voltages ranging from 20 to 120 Vdc are shown in Tables 12 and 13.

The variables and constants utilized in the option #2 PPU model are listed in Table 14 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix C. This subroutine has the file name "IONPU2.FOR", and it is located on the accompanying computer disk.

ION THRUSTER PPU OPTION #2 FLOW CHART



TASK20M REV 0 DATE 4/9/92

Figure 8

Table 10
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Primary Input Parameter Ranges

Power Processing Unit Primary Input Parameter	Recommended Input Range
PPU Input Power Level	100 kWe to 10 MWe
PPU Input Voltage Level	200 to 10,000 Vrms
Beam Power Supply Output Voltage Level	120 to 10,000 Vdc
Discharge Power Supply Output Voltage Level	20 to 200 Vdc
Accelerator Power Supply Output Voltage Level	120 to 10,000 Vdc
Neutralizer Power Supply Output Voltage Level	20 to 200 Vdc
Ripple Factor Percentage	0.5 to 8%
PPU Available Modules	Equal to or Greater than Required Modules
PPU Required Modules	No Limit
Alternator Operating Frequency (See Note 1)	60 Hz to 5 kHz 0.8 kHz is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 2 247.67 K Calculated for LEO

1. The alternator operating frequency (AOF) will normally be obtained from the power conversion module (CR-191134 or CR-191135). If the PMAD module is run separately, AOF must be input.

2. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 11
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Secondary Input Parameter Ranges

Power Processing Unit Secondary Input Parameter	Recommended Input Range
Input AC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Beam Power Supply Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Beam Power Supply Rectifier Efficiency	Normal Range: 97.0 to 99.0% 98.0% is Recommended
Beam Power Supply Output DC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Discharge Power Supply Transformer #1 Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Discharge Power Supply Transformer #2 Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Discharge Power Supply Rectifier Efficiency (See Note 1)	Normal Range: 95.5 to 98.0% 97.25% Recommended for 30 Vdc
Discharge Power Supply Output DC Filter Efficiency (See Note 2)	Range: 99.0 to 99.5% 99.2% Recommended for 30 Vdc
Accelerator Power Supply Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Accelerator Power Supply Rectifier Efficiency	Normal Range: 97.0 to 99.0% 98.0% is Recommended
Accelerator Power Supply Output DC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended

1. Refer to Table 12 for corrected rectifier efficiencies when the voltage output is less than 120 Vdc.
2. Refer to Table 13 for corrected dc filter efficiencies when the voltage output is less than 120 Vdc.

Table 11 (cont)
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Secondary Input Parameter Ranges

Power Processing Unit Secondary Input Parameter	Recommended Input Range
Neutralizer Power Supply Transformer #1 Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Neutralizer Power Supply Transformer #2 Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Neutralizer Power Supply Rectifier Efficiency (See Note 1)	Normal Range: 95.5 to 98.0% 95.5% Recommended for 20 Vdc
Neutralizer Power Supply Output DC Filter Efficiency (See Note 2)	Range: 99.0 to 99.5% 99.0% Recommended for 20 Vdc

1. Refer to Table 12 for corrected rectifier efficiencies when the voltage output is less than 120 Vdc.
2. Refer to Table 13 for corrected dc filter efficiencies when the voltage output is less than 120 Vdc.

Table 12
Efficiency Corrections for Discharge and Neutralizer Power Supply Rectifier Mass Estimates

Input Voltage (Vdc)	Switching Rectifier Input Efficiency (percent)
120	98.00
110	98.00
100	97.98
90	97.96
80	97.94
70	97.86
60	97.80
50	97.68
40	97.50
30	97.25
20	95.50

Table 13
Efficiency Corrections for Discharge and Neutralizer Power Supply Filter Mass Estimates

Input Voltage (Vdc)	Output Filter Input Efficiency (percent)
120	99.50
110	99.50
100	99.49
90	99.48
80	99.47
70	99.45
60	99.42
50	99.38
40	99.31
30	99.20
20	99.00

Table 14
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Variable Definitions

ACCM	Accelerator Power Supply Conductor and Connector Mass (kg)
AFE	Accelerator Power Supply Filter Efficiency (%)
AFET	Accelerator Power Supply Filter Efficiency at the Coldplate Temperature (%)
AFM	Accelerator Power Supply Filter Mass (kg)
AOF	Alternator Operating Frequency (kHz)
AOP	Accelerator Supply Output Power Level (kWe)
AOV	Accelerator Supply Output Voltage (Vdc)
ARE	Accelerator Power Supply Rectifier Efficiency (%)
ARET	Accelerator Power Supply Rectifier Efficiency at the Cold-plate Temperature (%)
ARM	Accelerator Power Supply Rectifier Mass (kg)
ATE	Accelerator Power Supply Transformer Efficiency (%)
ATET	Accelerator Power Supply Transformer Efficiency at the Coldplate Temperature (%)
ATM	Accelerator Power Supply Transformer Mass (kg)
BCCM	Beam Power Supply Conductor and Connector Mass (kg)
BFE	Beam Power Supply Filter Efficiency (%)
BFET	Beam Power Supply Filter Efficiency at the Coldplate Temperature (%)
BFM	Beam Power Supply Filter Mass (kg)
BOP	Beam Supply Output Power Level (kWe)
BOV	Beam Supply Output Voltage (Vdc)

Table 14 (cont)
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Variable Definitions

BRE	Beam Power Supply Rectifier Efficiency (%)
BRET	Beam Power Supply Rectifier Efficiency at the Coldplate Temperature (%)
BRM	Beam Power Supply Rectifier Mass (kg)
BTE	Beam Power Supply Transformer Efficiency (%)
BTET	Beam Power Supply Transformer Efficiency at the Cold-plate Temperature (%)
BTM	Beam Power Supply Transformer Mass (kg)
CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power Demand (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
DCCM	Discharge Power Supply Conductor and Connector Mass (kg)
DFE	Discharge Power Supply Filter Efficiency (%)
DFET	Discharge Power Supply Filter Efficiency at the Coldplate Temperature (%)
DFM	Discharge Power Supply Filter Mass (kg)
DIV	Intermediate Discharge Supply Output Voltage (Vdc)

Table 14 (cont)
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Variable Definitions

DOP	Discharge Supply Output Power Level (kWe)
DOV	Discharge Supply Output Voltage (Vdc)
DRE	Discharge Power Supply Rectifier Efficiency (%)
DRET	Discharge Power Supply Rectifier Efficiency at the Coldplate Temperature (%)
DRM	Discharge Power Supply Rectifier Mass (kg)
DT1E	Discharge Power Supply Transformer #1 Efficiency (%)
DT1ET	Discharge Power Supply Transformer #1 Efficiency at the Coldplate Temperature (%)
DT2E	Discharge Power Supply Transformer #2 Efficiency (%)
DT2ET	Discharge Power Supply Transformer #2 Efficiency at the Coldplate Temperature (%)
DT1M	Discharge Power Supply Transformer #1 Mass (kg)
DT2M	Discharge Power Supply Transformer #2 Mass (kg)
IFE	Power Processing Unit Input Filter Efficiency (%)
IFET	Power Processing Unit Input Filter Efficiency at the Coldplate Temperature (%)
IFM	Power Processing Unit Input Filter Mass (kg)
NCCM	Neutralizer Power Supply Conductor and Connector Mass (kg)
NFE	Neutralizer Power Supply Filter Efficiency (%)
NFET	Neutralizer Power Supply Filter Efficiency at the Coldplate Temperature (%)
NFM	Neutralizer Power Supply Filter Mass (kg)
NIV	Intermediate Neutralizer Supply Output Voltage (Vdc)

Table 14 (cont)
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Variable Definitions

NOP	Neutralizer Supply Output Power Level (kWe)
NOV	Neutralizer Supply Output Voltage (Vdc)
NRE	Neutralizer Power Supply Rectifier Efficiency (%)
NRET	Neutralizer Power Supply Rectifier Efficiency at the Coldplate Temperature (%)
NRM	Neutralizer Power Supply Rectifier Mass (kg)
NT1E	Neutralizer Power Supply Transformer #1 Efficiency (%)
NT1ET	Neutralizer Power Supply Transformer #1 Efficiency at the Coldplate Temperature (%)
NT2E	Neutralizer Power Supply Transformer #2 Efficiency (%)
NT2ET	Neutralizer Power Supply Transformer #2 Efficiency at the Coldplate Temperature (%)
NT1M	Neutralizer Power Supply Transformer #1 Mass (kg)
NT2M	Neutralizer Power Supply Transformer #2 Mass (kg)
PPAM	Power Processing Unit Available Modules
PPBE	Power Processing Unit Beam Supply Efficiency Measure (%)
PPE	Power Processing Unit Efficiency (%)
PPEM	Power Processing Unit Electronics Mass (kg)
PPIP	Power Processing Unit Input Power Level (kWe)
PPIV	Power Processing Unit Input Voltage Level (Vrms)
PPM	Power Processing Unit Mass w/o Radiator (kg)
PPMR	Power Processing Unit Mass with Radiator (kg)
PPOP	Power Processing Unit Output Power Level (kWe)

Table 14 (cont)
Ion Thruster PPU Option #2 Model
(with Beam Power Supply Transformer)
Variable Definitions

PPRM	Power Processing Unit Required Modules
PPSE	Power Processing Unit Stage Efficiency (%)
PPSM	Power Processing Unit Specific Mass w/o Radiator (kg/kWe)
PPSMR	Power Processing Unit Specific Mass with Radiator (kg/kWe)
RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RF	Ripple Factor (%)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)

3.3 MPD Power Processing Unit

The MPD power processing unit (PPU) topology differs considerably from the ion PPU configurations in that it has one main power supply, not four separate supplies. Because the MPD thruster operates at a relatively low voltage, 300 Vdc, the MPD PPU has an integral transformer. This allows the user to specify a wide range of PPU input voltages and results in greater isolation between the PMAD system and the MPD thruster. The features of this design are discussed in detail in the following paragraphs.

A block diagram of the MPD PPU design is shown in Figure 9. Its single power supply has four stages, an input filter, a step down transformer, a switching rectifier, and an output filter. The input filter limits the EMI introduced into the PMAD system by the thruster and rectifier, while the output filter reduces the ripple content in the power feed to the MPD thruster. The transformer steps down the transmission line voltage, which is normally well above 1000 Vrms, to a level suitable for the engine. The MPD engine input voltage is high enough that a single transformer should be adequate in most cases. However, if a homopolar induction alternator operating at frequencies above 2 kHz is used in conjunction with a transmission line voltage that exceeds 7000 Vrms, it may be necessary to use two series connected step down transformers. This case is considered unusual, but a MPD PPU model addressing these conditions can be quickly generated if analysis indicates it is a viable alternative. The reason two series connected transformers would be required is the voltage ratio at this frequency is too large for a single transformer. The difference in the number of primary and secondary turns would be so high that the magnetic coupling between turns would be very poor and a phenomenon known as ringing might occur. Ringing is caused when the leakage inductance and turn-to-turn capacitance transfer energy back and forth and generate circulating currents. These circulating currents increase the I^2R losses. It is primarily a function of the turns' ratio and frequency. Poor turn-to-turn coupling causes high flux leakage which leads to poor transformer efficiency. Two series connected transformers that sequentially step down the voltage are better. The turns ratio for each is cut in half; therefore, the coupling between the primary and secondary coils is improved and the likelihood of ringing is greatly reduced. The end result is a more efficient voltage transformation.

The remaining stage in the MPD PPU is a switching rectifier. It converts the ac input power into dc for the engine, and uses pulse-width-modulation (PWM) switching to regulate the PPU output voltage. Voltage control is necessary to control engine startup and operation. Control and monitoring hardware, identified in the figure as the main engine controller, and an enclosure assumed to be largely constructed from carbon-carbon complete the model. The enclosure mounting plate was assumed to be firmly bonded to the assembly coldplate to enhance heat transfer. This improves component thermal management, but makes it more difficult to replace. PMAD maintenance was considered impractical on a nuclear electric propulsion vehicle once a mission has begun.

<u>Application Notes:</u> The MPD PPU design includes a transformer; consequently, the model can accept a wide range of input voltages. The MPD input voltage, approximately 300 Vdc, is much too low for practical power transmission from the alternator to the thruster. The mass of the transmission lines would be

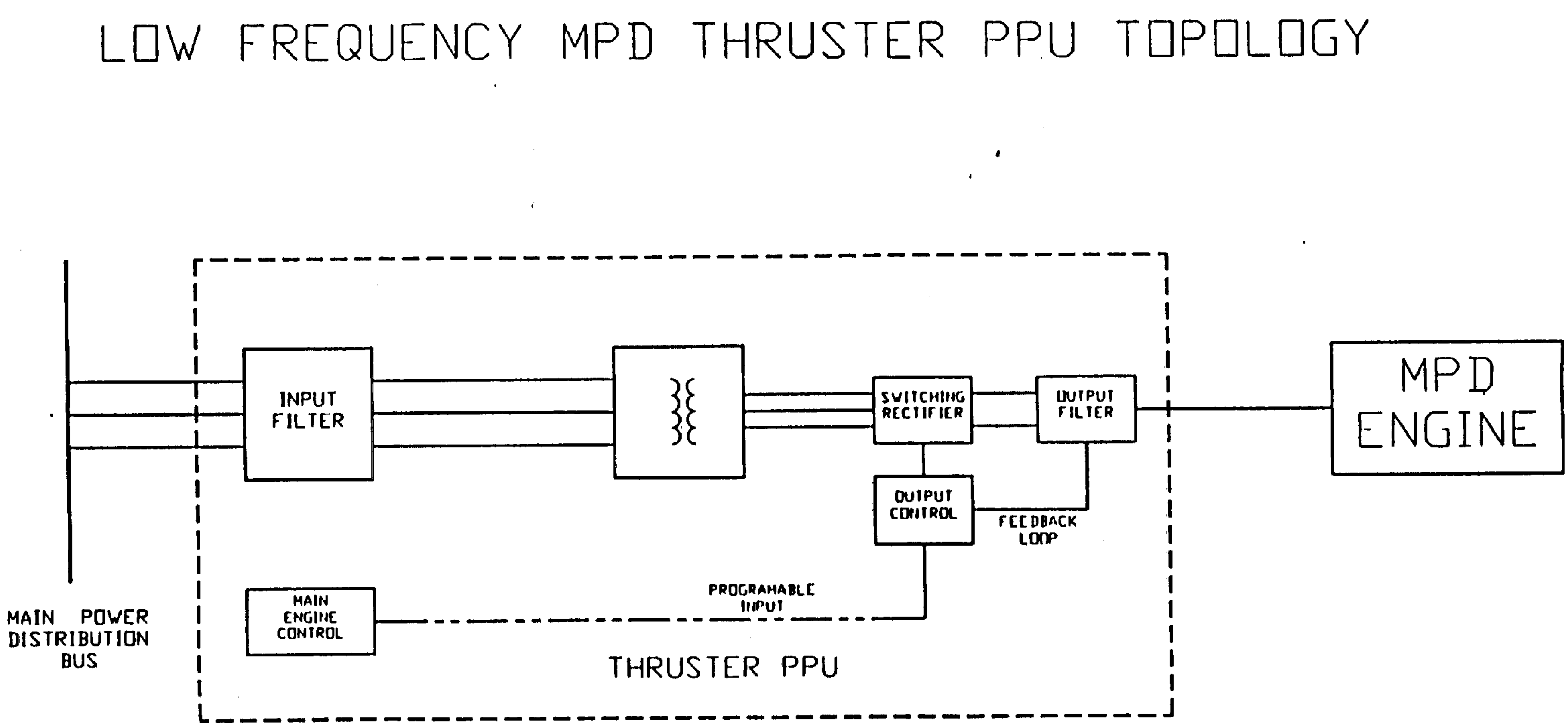

LOW FREQUENCY MPD THRUSTER PPU TOPOLOGY
MAIN POWER DISTRIBUTION BUS
INPUT FILTER
SWITCHING RECTIFIER
OUTPUT FILTER
OUTPUT CONTROL
FEEDBACK LOOP
PROGRAMABLE INPUT
MAIN ENGINE CONTROL
THRUSTER PPU
MPD ENGINE

Figure 9

prohibitive. However, a transformer allows the user to select the PPU input voltage that optimizes PMAD system mass for transmission line lengths ranging from 25 to 300 meters.

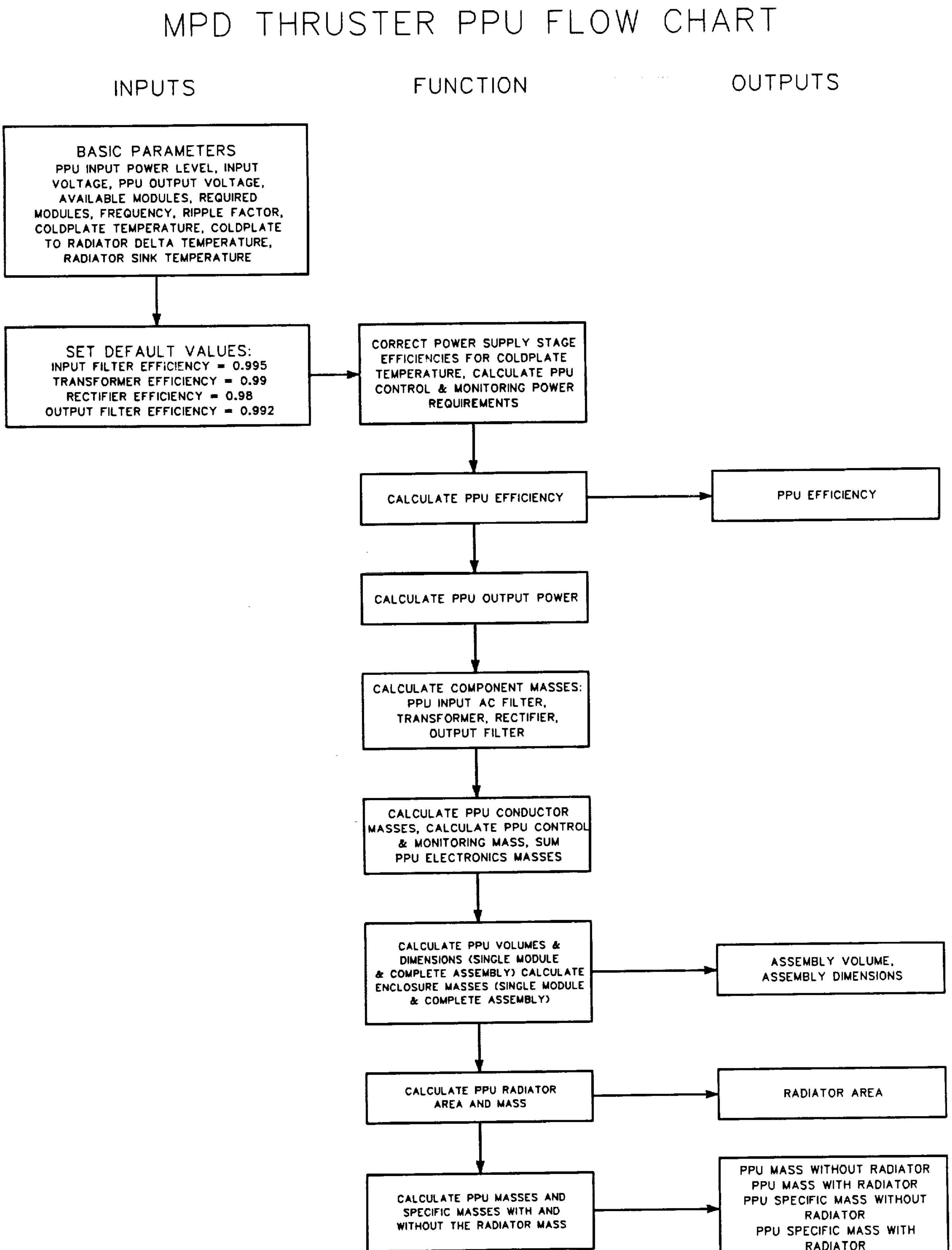
The transformer in the PPU provides isolation between the PMAD system and the thrusters. It reduces the electromagnetic interference (EMI) generated by the thrusters and PWM switching. System grounding is also improved, because separate grounds can be established for the PMAD system and the engine. Consequently, ground currents generated by the thruster and PWM switching elements will not interfere with the operation of the rest of the PMAD system.

Model Specifics: The logic employed during the development of the MPD PPU model is depicted by the flow chart shown in Figure 10. The outputs in the right hand column represent a best estimate of the users needs and more parameters are available. These outputs can be accessed by modifying the print routine so that it prints additional data contained in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

The model is designed to cover a specific range of input parameters. Using input parameters outside of these ranges may result in inaccurate mass estimates and it is not recommended. Table 15 lists the input ranges and values that were determined to yield the best results for the primary input parameters. In certain instances, operating information will be obtained from other modules. The notes associated with some of the input parameters identify the modules that are the sources of this information.

The listed component efficiencies are relatively fixed and they should only be changed if the user is quite familiar with the model operation and power conditioning component designs in general. Although component efficiencies generally decline with temperature, it is not necessary to manually adjust these values. The models utilize algorithms to automatically adjust the efficiency values for the selected coldplate temperature. The component algorithms then use these temperature adjusted efficiencies to estimate mass. The only reason to manually change these values would be to conduct mass-efficiency tradeoffs. Component efficiency can be increased if larger internal conductors and power elements are utilized. This reduces radiator and power source mass, but it increases the mass of the component itself. The default values utilized by the model were selected to yield mass and efficiency estimates consistent with the proposed applications and the specified time period. These component efficiency values are referred to as secondary input parameters, and acceptable ranges and default values are listed for them in Table 16.

The variables and constants utilized in the MPD PPU model are listed in Table 17 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix D. This subroutine is located on the accompanying computer disk under the file name "MPDPPU.FOR".



TASK201 REV 0 DATE 4/3/92

Figure 10

Table 15
MPD Thruster PPU Model
Primary Input Parameter Ranges

Power Processing Unit **Primary Input Parameter**	**Recommended** **Input Range**
PPU Input Power Level	100 kWe to 10 MWe
PPU Input Voltage Level	200 to 10,000 Vrms
PPU Output Voltage Level	120 to 10,000 Vdc
Ripple Factor Percentage	0.5 to 8%
PPU Available Modules	Equal to or Greater than Required Modules
PPU Required Modules	No Limit
Alternator Operating Frequency (See Note 1)	60 Hz to 5 kHz 0.8 kHz is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 2 247.67 K Calculated for LEO

1. The alternator operating frequency (AOF) will normally be obtained from the power conversion module (CR-191134 or CR-191135). If the PMAD module is run separately, AOF must be input.

2. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 16
MPD Thruster PPU Model
Secondary Input Parameter Ranges

Power Processing Unit Secondary Input Parameter	Recommended Input Range
Input AC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended
Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Rectifier Efficiency	Normal Range: 97.0 to 99.0% 98.0% is Recommended
Output DC Filter Efficiency	Range: 99.0 to 99.9% 99.5% is Recommended

Table 17
MPD Thruster PPU Model
Variable Definitions

AOF	Alternator Operating Frequency (kHz)
CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CCM	Conductor and Connector Mass (kg)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power Demand (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
IFE	Input Filter Efficiency (%)
IFET	Input Filter Efficiency at the Coldplate Temperature (%)
IFM	Input Filter Mass (kg)
OFE	Output Filter Efficiency (%)
OFET	Output Filter Efficiency at the Coldplate Temperature (%)
OFM	Output Filter Mass (kg)
PPAM	Power Processing Unit Available Modules
PPE	Power Processing Unit Efficiency (%)
PPEM	Power Processing Unit Electronics Mass (kg)
PPIP	Power Processing Unit Input Power Level (kWe)
PPIV	Power Processing Unit Input Voltage Level (Vrms)

Table 17 (cont)
MPD Thruster PPU Model
Variable Definitions

PPM	Power Processing Unit Mass w/o Radiator (kg)
PPMR	Power Processing Unit Mass with Radiator (kg)
PPOP	Power Processing Unit Output Power Level (kWe)
PPOV	Power Processing Unit Output Voltage Level (Vrms)
PPRM	Power Processing Unit Required Modules
PPSE	Power Processing Unit Stage Efficiency (%)
PPSM	Power Processing Unit Specific Mass w/o Radiator (kg/kWe)
PPSMR	Power Processing Unit Specific Mass with Radiator (kg/kWe)
RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RE	Rectifier Efficiency (%)
RET	Rectifier Efficiency at the Coldplate Temperature (%)
RF	Ripple Factor (%)
RM	Rectifier Mass (kg)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)
TE	Transformer Efficiency (%)
TET	Transformer Efficiency at the Coldplate Temperature (%)
TM	Transformer Mass (kg)

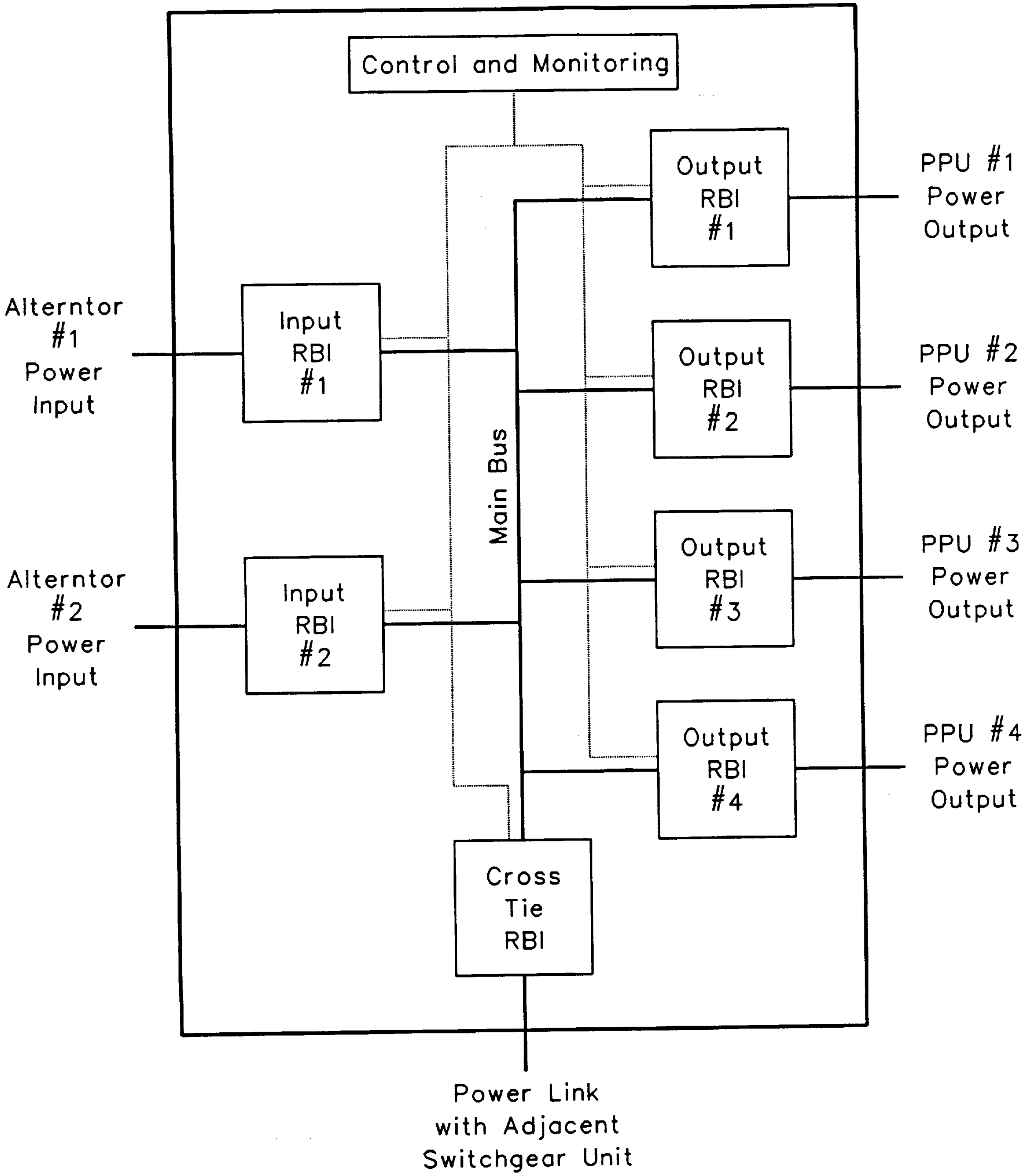
3.4 AC Switchgear Unit

The ac switchgear unit employs remote bus isolators (RBIs) to turn power feeds on and off and provide circuit protection. RBIs are high power switching and circuit protection devices that are equipped with sensors to provide voltage and current information. Because RBIs are the primary means of circuit protection, they contain rugged switch modules that are specifically designed to interrupt high fault currents. Fault interruption is normally performed during the zero current crossing point. During each half cycle of an ac waveform the current becomes zero. Opening the switch at this point greatly reduces electromagnetic and thermal stress, since it is a function of the current level. This is the main advantage of the ac RBI over its dc counterpart and it allows them to be utilized at much higher power levels.

An ac RBI switch module can employ one of two designs, a hybrid arrangement consisting of a fast acting mechanical relay paralleled with a back-to-back pair of semiconductor switches, or just a back-to-back pair of semiconductor switches. A solitary mechanical relay is not fast enough to open during the zero current crossing; consequently, this configuration is not practical. The hybrid arrangement has certain advantages because the relay and semiconductor switch can function together to improve the operating characteristics of the RBI switch. The relay carries the bulk of the current during normal operation because its conduction losses are low. This results in a high efficiency RBI. The main need for the semiconductor switch is during opening and closing periods. It closes immediately before relay closing to quell relay chatter transients, and opens after the relay to suppress opening transients. The design that only uses a semiconductor switch exhibits very good opening and closing characteristics, but the conduction resistance of a semiconductor is higher than a relay contact. This would cause the RBI losses to be significantly higher and necessitate larger heat sinks and associated thermal management hardware.

The ac RBI algorithm utilized by the switchgear unit model is based on a hybrid switch configuration. This design was considered to provide the best combination of mass, efficiency, and switching characteristics. Near term RBIs would probably use a vacuum switch in parallel with back-to-back silicon controlled rectifiers (SCRs) or MOS controlled thyristors (MCTs). However, because the specified time frame is 2005 to 2020, a more advanced device, the optical switch was assumed to be available. Optical switches consist of a silicon wafer that is turned on and off by means of a laser. They are currently being developed for Space Defense Initiative applications. Results to date indicate they will be very lightweight, but capable of interrupting tens of megawatts.

A block diagram of the switchgear unit is shown in Figure 11. The number of thrusters determines the number of output RBIs, while the number of input RBIs is equivalent to the number of alternator power feeds. A cross tie RBI, that is normally open, is available to conduct power from one switchgear unit to the next if alternator, thruster, or PPU failures occur. A central bus distributes the input RBI power to the output RBIs. This bus is sized to handle the maximum current level and withstand the worst case electromagnetic stresses resulting from a direct short. The switchgear model is completed by incor-



AC Switchgear Unit Block Diagram
Figure 11

ACSWGR
4-27-92

porating algorithms for the control and monitoring hardware, and an enclosure assumed to be largely constructed from carbon-carbon. The enclosure mounting plate was assumed to be bonded to the assembly coldplate to facilitate heat transfer. This makes it difficult to remove the switchgear unit; however, it was assumed that PMAD maintenance would not be performed during the mission.

Application Notes: The switchgear unit model is designed to be used over the full power and voltage range in any application requiring power switching and fault protection. In the case of the currently envisioned PMAD architecture, it would simulate a switchgear unit that is located near the thruster PPUs. This switchgear unit would be utilized to selectively power individual PPUs, interrupt thruster or PPU based faults, and isolate these components if they are defective.

Model Specifics: The flow chart in Figure 12 shows the logic employed in the ac switchgear unit model. The outputs in the right hand column represent a best estimate of the users needs and more parameters are available. These values can be accessed by modifying the print routine so that it prints other data elements contained in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

The model is designed to cover a wide range of input parameters; however, using parameters outside of these ranges may result in inaccurate mass estimates and it is not recommended. Table 18 lists the acceptable input ranges and certain recommended values. Some input parameters will normally be obtained from other modules. The notes associated with these parameters identify the modules that provide these inputs.

The default RBI efficiency contained in Table 18 is relatively fixed and it should only be changed if the user is quite familiar with the model operation and power conditioning component designs in general. Although component efficiencies typically decline with temperature, it is not necessary to manually adjust this value. An algorithm automatically adjusts this efficiency based on the selected coldplate temperature. The RBI algorithms use this temperature adjusted efficiency to estimate mass. The only reason to manually change this value would be to conduct a mass-efficiency tradeoff. RBI efficiency can be increased by using larger conductors and switch modules. This would reduce the mass of the switchgear radiator and the power source feeding it, but the mass of the RBI itself would increase. The default value produces mass and efficiency estimates consistent with the proposed application and the specified time period.

The variables and constants utilized in the ac switchgear model are listed in Table 19 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix E. This subroutine is located on the accompanying computer disk under the file name "ACSWGR.FOR".

AC SWITCHGEAR (SWGR) FLOW CHART

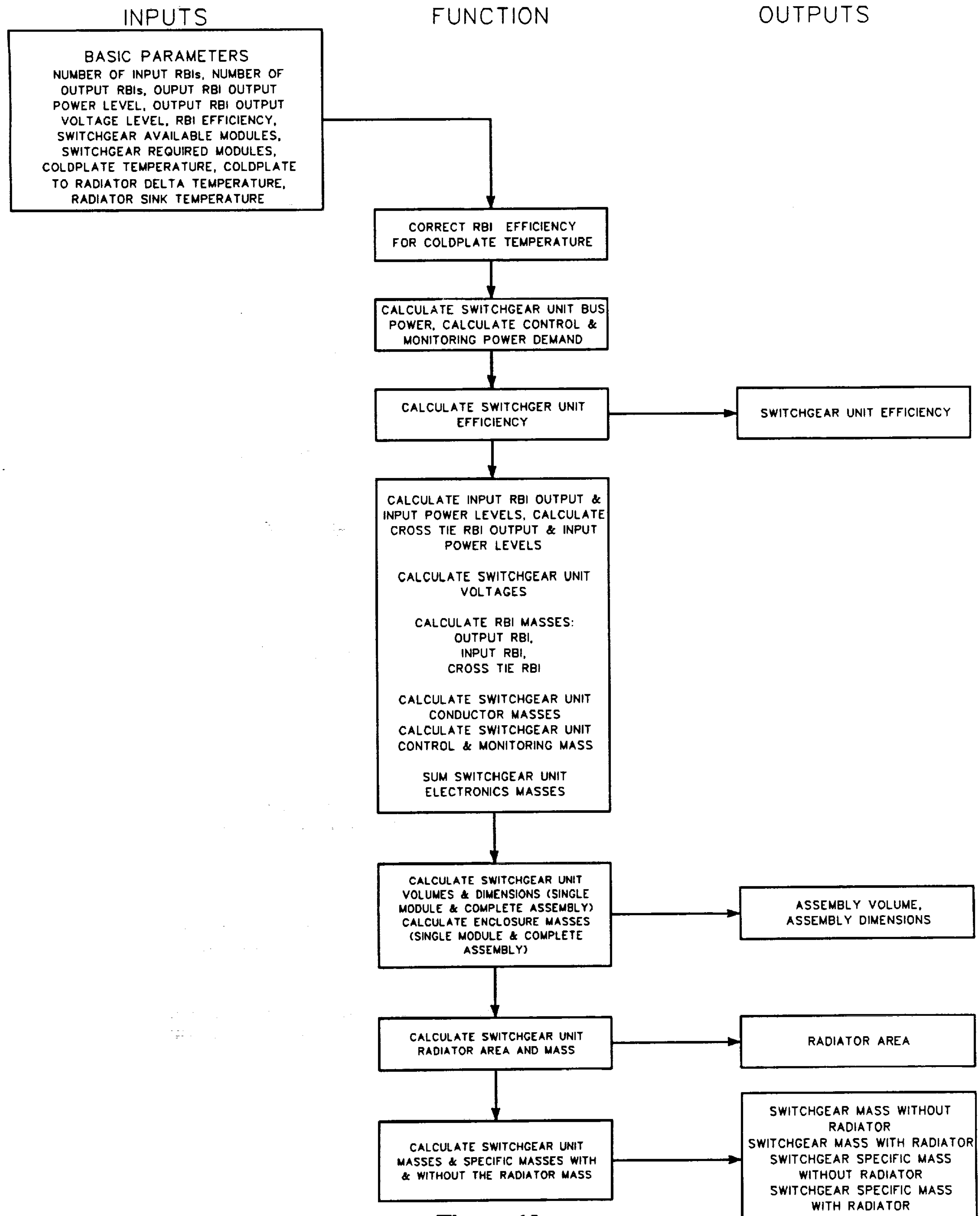


Figure 12

TASK20K REV 0 DATE 4/9/92

Table 18
AC Switchgear Unit Model
Input Parameter Ranges

AC RBI Switchgear Unit Input Parameter	Recommended Input Range
Number of Input RBI Units (See Note 1)	No Limit
Number of Output RBI Units (See Note 2)	No Limit
RBI Unit Output Power Level	10 kWe to 10 MWe
RBI Unit Output Voltage Level	100 to 10,000 Vrms
RBI Efficiency	Range: 99.8 to 99.9% 99.85% is Recommended
Available Switchgear Modules	Equal to or Greater than Required Modules
Required Switchgear Modules	No Limit
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 3 247.67 K Calculated for LEO

1. The number of input RBIs equals the number of alternators and it will normally be obtained from the master PMAD module. However, if this Switchgear model is run separately the number of input RBIs must be provided by the user.

2. The number of output RBIs equals the number of PPUs and it will normally be obtained from the master PMAD module. However, if this Switchgear model is run separately the number of output RBIs must be provided by the user.

3. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 19
AC Switchgear Model Variable Definitions

CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CCM	Conductor and Connector Mass (kg)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
IRBM	Mass of One Input RBI (kg)
IRBIP	Input RBI Input Power Level (kWe) It is assumed that all input RBIs will have the same rating; consequently, a single power level is calculated.
IRBIV	Input RBI Input Voltage Level (Vrms) It is assumed that all input RBIs will operate at the same voltage; consequently, a single voltage level is calculated.
IRBOP	Input RBI Output Power Level (kWe) It is assumed that all input RBIs will have the same rating; consequently, a single power level is calculated.
IRBOV	Input RBI Output Voltage Level (Vrms) It is assumed that all input RBIs will operate at the same voltage; consequently, a single voltage level is calculated.
NIRB	Number of Input RBIs
NORB	Number of Output RBIs

Table 19 (cont)
AC Switchgear Model Variable Definitions

ORBM	Mass of One Output RBI (kg)
ORBOP	Output RBI Output Power Level (kWe) It is assumed that all output RBIs will have the same rating; consequently, a single power level is specified.
ORBOV	Output RBI Output Voltage Level (Vrms) It is assumed that all output RBIs will operate at the same voltage; consequently, a single voltage level is specified.
RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RBE	RBI Unit Efficiency at 100° C (%)
RBET	RBI Unit Efficiency at Coldplate Temperature (%)
RBSE	Combined RBI and Bus Section Efficiency (%)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)
SWAM	Switchgear Available Modules
SWBP	Switchgear Bus Power Level (kWe)
SWBV	Switchgear Bus Voltage Level (Vrms)
SWE	Switchgear Unit Efficiency (%)
SWEM	Switchgear Unit Electronics Mass (kg)

Table 19 (cont)
AC Switchgear Model Variable Definitions

SWM	Switchgear Unit Mass w/o Radiator (kg)
SWMR	Switchgear Unit Mass with Radiator (kg)
SWRM	Switchgear Required Modules
SWSM	Switchgear Unit Specific Mass w/o Radiator (kg/kWe)
SWSMR	Switchgear Unit Specific Mass with Radiator (kg/kWe)
XRBM	Mass of Cross Tie RBI (kg)
XRBIP	Cross Tie RBI Input Power Level (kWe)
XRBIV	Cross Tie RBI Input Voltage Level (Vrms)
XRBOP	Cross Tie RBI Output Power Level (kWe)
XRBOV	Cross Tie RBI Output Voltage Level (Vrms)

3.5 Phase Lock Transformer

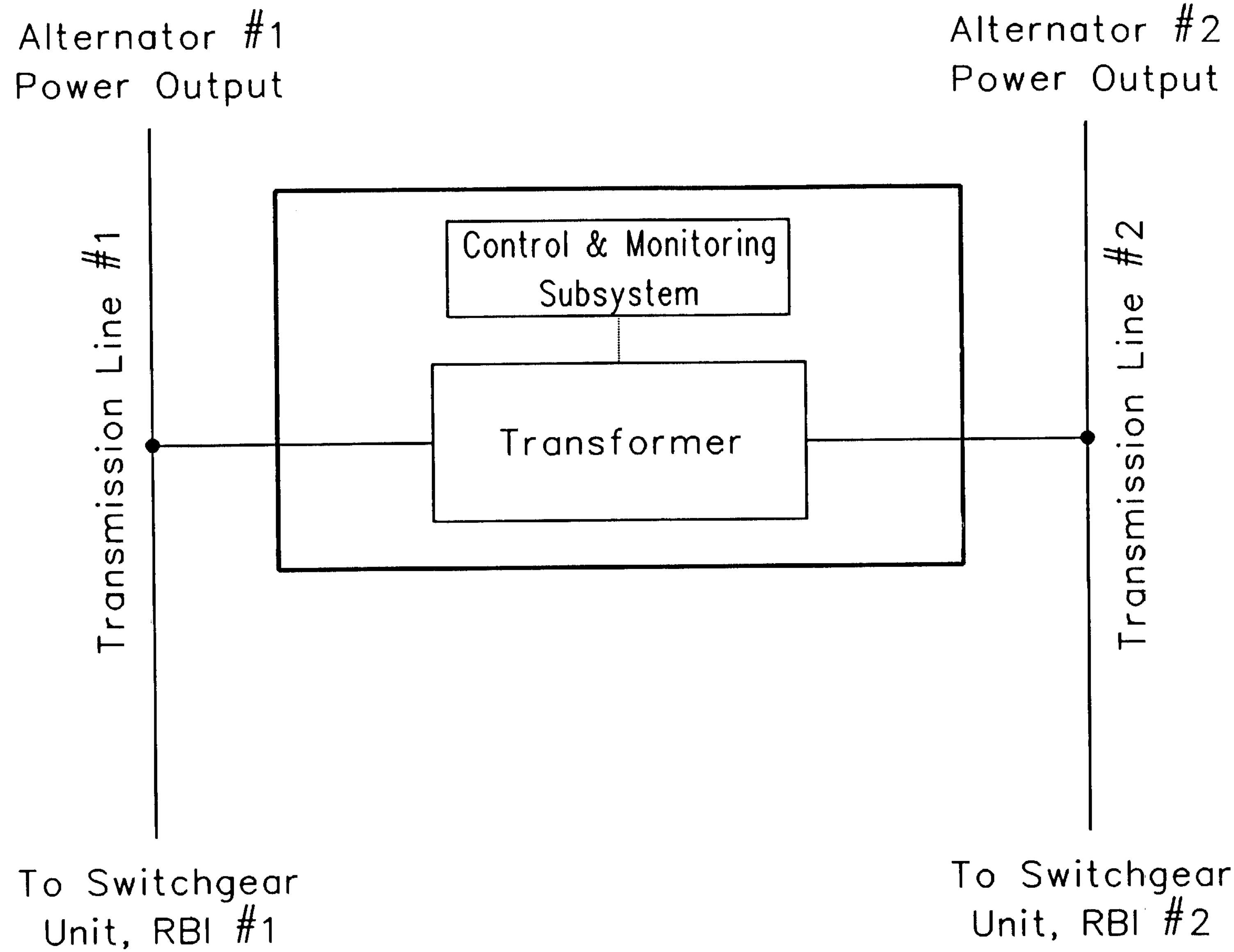
The phase lock transformer consists of a transformer module that is sized to transfer power back and forth between counter rotating alternators. A 3-phase transformer with a 1 to 1 voltage ratio is used. Its purpose is to ensure that the alternators share the common load equally and that a change in the rotational speed of one alternator is canceled by an equal change in the rotational speed of its alternator mate. This ensures that the NEP vehicle will not experience a torque moment due to unequal or unbalanced changes in alternator speed; the moments imparted by the two alternators will be fully canceled. If the alternator acceleration rates are modest and carefully controlled, a relatively small power transfer should be adequate. Consequently the phase lock transformer power rating is relatively low and it is fairly small in size.

A block diagram of the phase lock transformer is shown in Figure 13. It is a simple component, consisting only of a transformer and its associated monitoring hardware. Because a transformer is a passive component, there are not any control functions. Monitoring is required, however, to sense alternator operating imbalances and to ensure the transformer is not overloaded or overheating due to a hardware failure. In addition to the transformer stage mass algorithm, the phase lock transformer model contains algorithms that calculate the monitoring element and enclosure features. The enclosure is assumed to be largely constructed from carbon-carbon, with a mounting plate that is bonded to the assembly coldplate to facilitate heat transfer. This design makes it difficult to remove the phase lock transformer module, but it was assumed that PMAD maintenance would not be performed during the mission. If the phase lock transformer fails, it may be necessary to shut down the alternators connected to it. It would depend on the turbine speed control precision and the operating situation at that point in time. If it is an emergency situation, it may be crucial to continue operating.

Application Notes: The phase lock transformer model is relatively simple and it is designed to be used over the full transfer power, frequency, and voltage range in any case utilizing counter rotating alternators. If a power channel is fed by a single alternator, the phase lock transformer model is not used.

Model Specifics: The logic employed during the development of the phase lock transformer model is depicted in the flow chart shown in Figure 14. The outputs in the right hand column represent a best estimate of the users needs and additional parameters are available. These outputs can be accessed by modifying the print routine and instructing it to print other items in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

The model is designed to cover a wide range of input parameters; however, using parameters outside of these ranges may result in inaccurate mass estimates and it is not recommended. Table 20 lists the acceptable input ranges and certain recommended values. Input parameters that are normally obtained from other modules are identified by the accompanying notes.



Phase Lock Transformer Block Diagram
Figure 13

PHLKXFMR
4-27-92

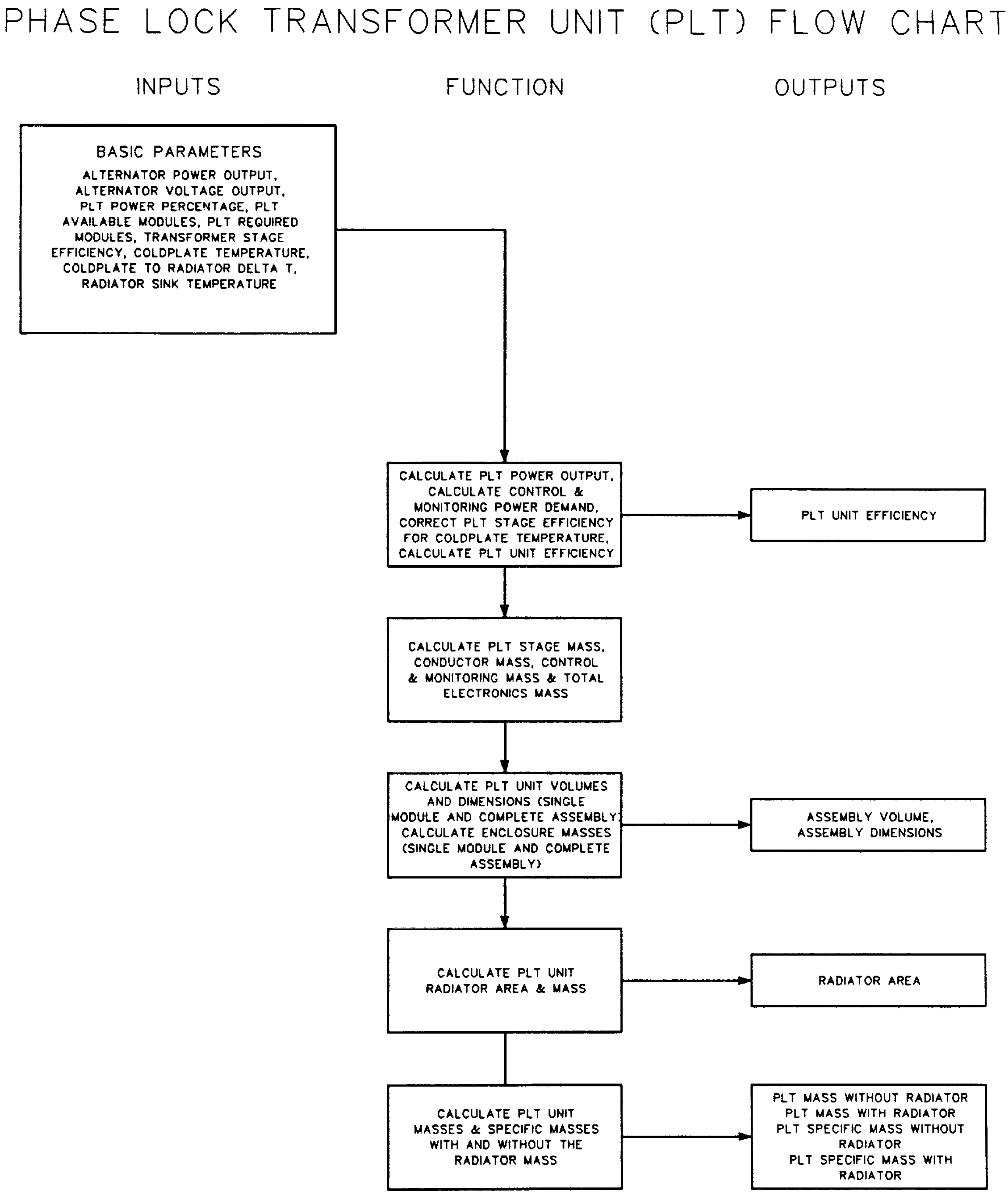

PHASE LOCK TRANSFORMER UNIT (PLT) FLOW CHART
INPUTS
FUNCTION
OUTPUTS
BASIC PARAMETERS
ALTERNATOR POWER OUTPUT, ALTERNATOR VOLTAGE OUTPUT, PLT POWER PERCENTAGE, PLT AVAILABLE MODULES, PLT REQUIRED MODULES, TRANSFORMER STAGE EFFICIENCY, COLDPLATE TEMPERATURE, COLDPLATE TO RADIATOR DELTA T, RADIATOR SINK TEMPERATURE
CALCULATE PLT POWER OUTPUT, CALCULATE CONTROL & MONITORING POWER DEMAND, CORRECT PLT STAGE EFFICIENCY FOR COLDPLATE TEMPERATURE, CALCULATE PLT UNIT EFFICIENCY
PLT UNIT EFFICIENCY
CALCULATE PLT STAGE MASS, CONDUCTOR MASS, CONTROL & MONITORING MASS & TOTAL ELECTRONICS MASS
CALCULATE PLT UNIT VOLUMES AND DIMENSIONS (SINGLE MODULE AND COMPLETE ASSEMBLY) CALCULATE ENCLOSURE MASSES (SINGLE MODULE AND COMPLETE ASSEMBLY)
ASSEMBLY VOLUME, ASSEMBLY DIMENSIONS
CALCULATE PLT UNIT RADIATOR AREA & MASS
RADIATOR AREA
CALCULATE PLT UNIT MASSES & SPECIFIC MASSES WITH AND WITHOUT THE RADIATOR MASS
PLT MASS WITHOUT RADIATOR
PLT MASS WITH RADIATOR
PLT SPECIFIC MASS WITHOUT RADIATOR
PLT SPECIFIC MASS WITH RADIATOR

Figure 14

Table 20
Phase Lock Transformer Unit Model
Input Parameter Ranges

Transformer Unit Input Parameter	Recommended Input Range
Alternator Output Power Level	100 kWe to 10 MWe
Alternator Output Voltage Level	200 to 10,000 Vrms
Phase Lock Transformer Power Percentage (%)	0.5 to 10% 2% is Recommended
Available Phase-Lock Transformer Modules	Equal to or Greater than Required Modules
Required Phase-Lock Transformer Modules	No Limit
Transformer Frequency	60 Hz to 5 kHz
Transformer Efficiency	Range: 97.5 to 99.5% 99% is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 1 247.67 K Calculated for LEO

1. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

The default transformer efficiency listed in Table 20 is relatively fixed and it should only be changed if the user is quite familiar with the model operation and power conditioning component designs in general. As the transformer operating temperature rises, transformer core losses decline but winding losses increase. The overall change in efficiency occurring with temperature is automatically calculated by an algorithm and it is not necessary to manually adjust this value. The transformer algorithms use this temperature adjusted efficiency to estimate mass. The only reason one would manually change the transformer efficiency would be to conduct a mass-efficiency tradeoff. Transformer efficiency can be increased by using a larger core and winding conductors. This would reduce the mass of the phase lock transformer radiator, but the mass of the transformer itself would increase. The phase lock transformer model will reflect these changes in mass if one changes the input efficiency. The default transformer efficiency was selected to produce mass and efficiency estimates consistent with the proposed application and the specified time period.

The variables and constants utilized in the phase lock transformer model are listed in Table 21 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix F. This subroutine is located on the accompanying computer disk under the file name "TRNFMR.FOR".

Table 21
Phase Lock Transformer Unit Model
Variable Definitions

AOF	Alternator Operating Frequency (kHz)
APO	Alternator Power Output (kWe)
AVO	Alternator Voltage Output (Vrms)
CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CCM	Conductor and Connector Mass (kg)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
PTAM	Phase Lock Transformer Available Modules
PTE	Phase Lock Transformer Efficiency (%)
PTEM	Phase Lock Transformer Electronics Mass (kg)
PTM	Phase Lock Transformer Mass w/o Radiator (kg)
PTMR	Phase Lock Transformer Mass with Radiator (kg)
PTPO	Phase Lock Transformer Power Output (kWe)
PTPP	Phase Lock Transformer Power Percentage (%)

Table 21 (cont)
Phase Lock Transformer Unit Model
Variable Definitions

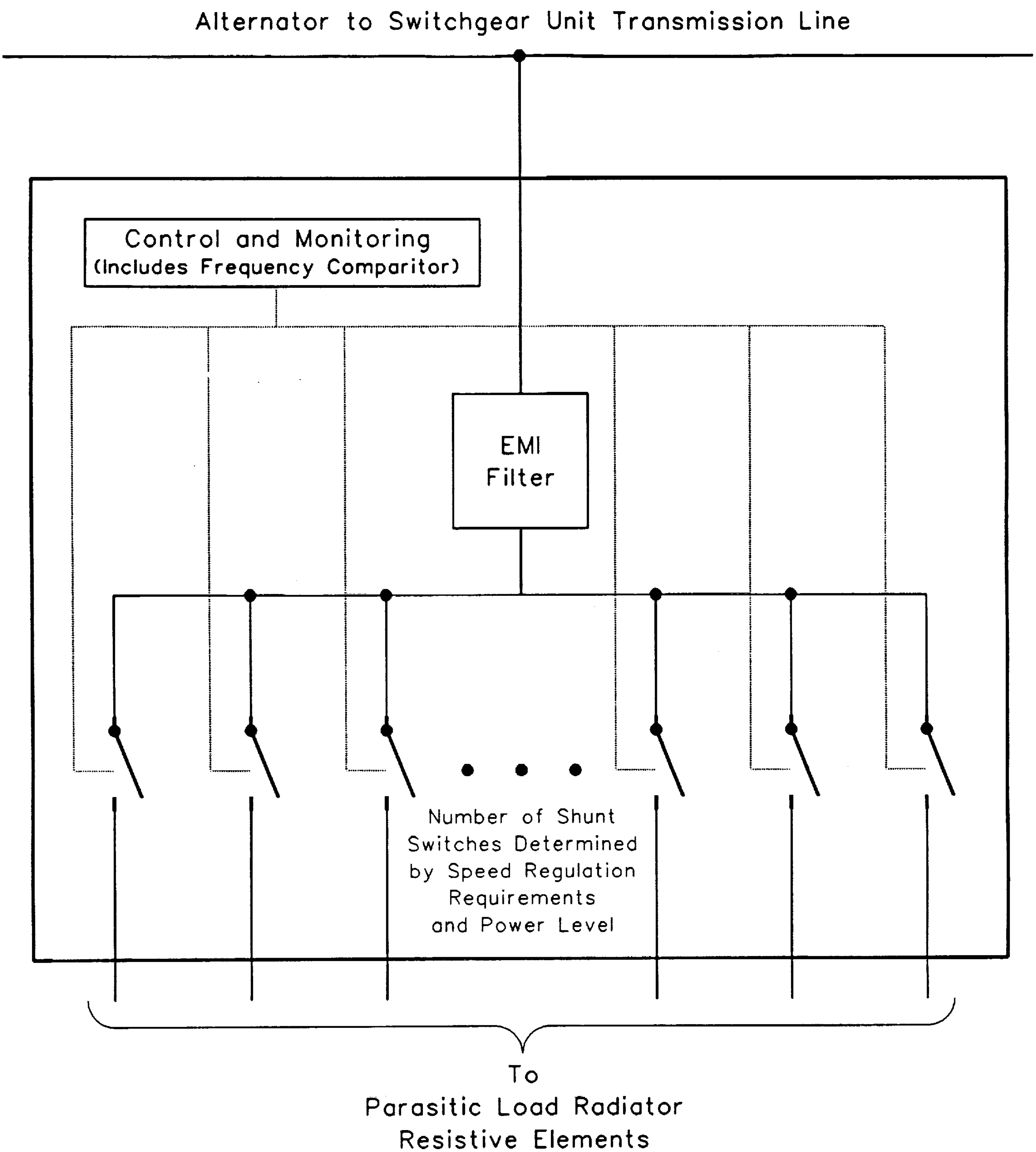
PTRM	Phase Lock Transformer Required Modules
PTSM	Phase Lock Transformer Specific Mass w/o Radiator (kg/kWe)
PTSMR	Phase Lock Transformer Specific Mass with Radiator (kg/kWe)
RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)
TSE	Transformer Stage Efficiency at 100° C (%)
TSET	Transformer Stage Efficiency at Coldplate Temperature (%)
TSM	Transformer Stage Mass (kg)

3.6 Speed Regulator

The speed regulator controls the alternator and turbine speed by adjusting the connected load. The load is increased to slow the alternator and reduced to increase speed. The objective is to maintain the total connected load, thrusters and parasitic load, at a fairly constant level. Because the speed regulator may be forced to shunt all alternator power at times, it is necessary to size it for this case. For example, prior to engine startup it may be necessary for the parasitic load to dissipate all alternator power to allow the power source to stabilize. Power is then gradually shifted from the parasitic load to the engines as they are brought on line and ramped up. When the engines are operating at full power very little power is dissipated in the parasitic load, only the power required to maintain a safe alternator operating margin. If a major fault or component failure should occur, the speed regulator would be required to immediately shunt full power until the alternator is shut down or the fault is cleared. This is necessary because the opening of an input RBI to isolate a fault would completely remove the normally connected engine load.

A block diagram of the speed regulator is shown in Figure 15. The speed regulator contains numerous discreet shunt elements that are individually activated to control the amount of power being dissipated in the parasitic load. The shunt switches are controlled by a frequency comparitor. Since frequency is directly related to speed, it is used to provide an accurate measurement of alternator speed. The measured speed signal and a reference signal are fed into a comparitor that generates a speed error signal. This error signal is utilized by the switch gate control logic to control the number of shunt elements that are activated. The switches are capable of rapid switching speeds, which enables the speed regulator to respond to load changes in milliseconds. Coarse speed regulation is provided by turning on and off individual shunt elements, thereby shunting power in steps. To achieve fine speed regulation, the final shunt element can be pulse width modulated (PWM). This yields stable speed control, and allows the shunted power to be precisely controlled. The speed regulator model is completed by incorporating algorithms for the control and monitoring hardware, and an enclosure assumed to be largely constructed from carbon-carbon. It was assumed that the enclosure mounting plate would be bonded to the assembly coldplate to facilitate heat transfer. This makes it difficult to remove the speed regulator, and probably necessitates an alternator shut down if the speed regulator fails. However, the speed regulator can be designed for high reliability by incorporating additional shunt elements into the design and specifying redundant control elements.

Several switch options are available for the speed regulator shunt elements. Near term shunt elements would probably use back-to-back metal-oxide-semiconductor field-effect-transistors (MOSFETs) for lower voltage applications, and back-to-back silicon controlled rectifiers (SCRs) or MOS controlled thyristors (MCTs) for high power, high voltage applications. However, because the specified time frame is 2005 to 2020, there should be time to develop more advanced devices. Silicon Carbide (SiC) appears particularly promising in this application for two reasons. SiC exhibits high resistance to radiation and it can operate at high temperatures. The speed regulator must be located immediately



Speed Regulator Block Diagram
Figure 15

SPDREG
4-27-92

after the alternator to function most effectively. Since this is also near the reactor, the radiation levels will be high. In addition, the thermal environment will make high temperature switches particularly desirable. Finally, because the speed regulator is not in the main power conduction path, see Figure 15, its efficiency is less of a concern. It is expected that SiC switches will not be as efficient as present day silicon devices.

Application Notes: The speed regulator model is designed to be used over the full power and voltage range in any application requiring alternator speed regulation. In the currently envisioned NEP PMAD architecture, it would be located immediately after the alternator and shunt power to the parasitic load to regulate alternator speed. If a permanent magnet based alternator is specified, the speed regulator would also regulate the alternator voltage because it is directly proportional to speed.

Model Specifics: The flow chart in Figure 16 shows the logic employed during the development of the speed regulator model. The outputs in the right hand column represent a best estimate of the users needs and additional parameters are available. These values can be accessed by modifying the print routine so that it prints additional data elements contained in the Fortran common block. The basic model operations are shown in the middle column, and the inputs are listed in the boxes on the left. Default values are provided for each of these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

The model is designed to cover a wide range of input parameters; however, using parameters outside of these ranges may result in inaccurate mass estimates and it is discouraged. Table 22 lists the acceptable input ranges and certain recommended values. The notes associated with some parameters identify modules that will normally provide the values for these input parameters.

The default bus, filter, and shunt switch efficiencies listed in Table 22 are relatively fixed and they should only be changed if the user is quite familiar with the model operation and power conditioning component designs in general. Although component efficiencies typically decline with temperature, it is not necessary to manually adjust this value. An algorithm automatically adjusts these efficiencies for different coldplate temperatures. The component mass estimation algorithms then use these temperature adjusted efficiencies. The only reason to manually change these values would be to conduct mass-efficiency tradeoffs. Conductor efficiency can be increased by increasing the conductor size, shunt switch efficiency by choosing higher rated switching elements, and filter efficiency by using larger inductors and capacitors. Increasing the speed regulator efficiency would reduce the mass of its radiator, but the mass of the speed regulator itself would increase. The default bus, filter, and shunt switch efficiencies were chosen to produce mass and efficiency estimates consistent with the proposed application and the specified time period.

The variables and constants utilized in the speed regulator model are listed in Table 23 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix F. This subroutine is located on the accompanying computer disk under the file name "SPDREG.FOR".

ALTERNATOR SPEED REGULATOR (ASR) FLOW CHART

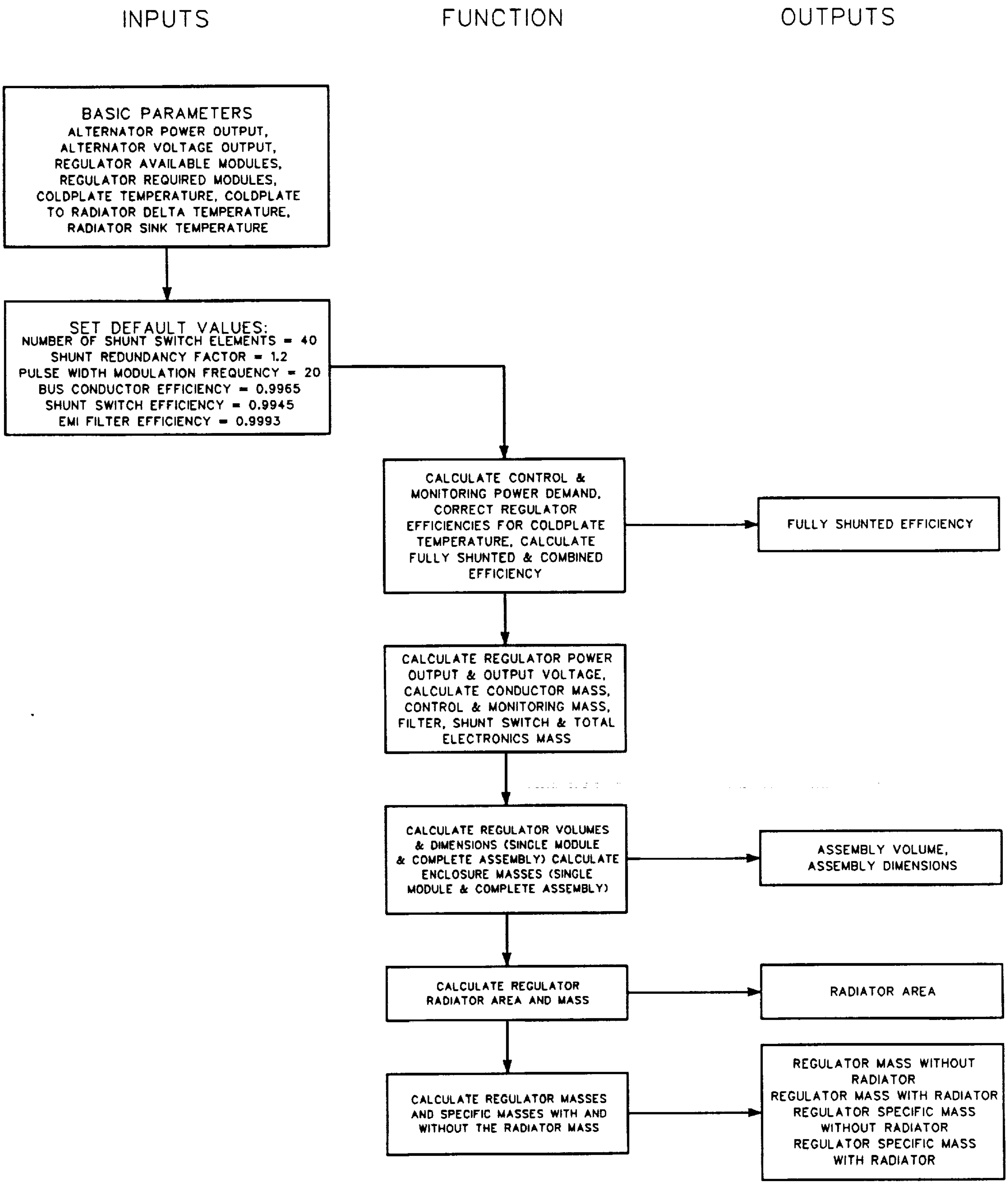


Figure 16

Table 22
Alternator Speed Regulator Model
Input Parameter Ranges

Speed Regulator <u>**Input Parameter**</u>	**Recommended** <u>**Input Range**</u>
Alternator Output Power Level	100 kWe to 10 MWe
Alternator Output Voltage Level	200 to 10,000 Vrms
Available Speed Regulator Modules	Equal to or Greater than Required Modules
Required Speed Regulator Modules	No Limit
Number of Shunt Switch Elements	20 to 100 40 is Suggested
Shunt Redundancy Factor	100 to 150% 120% is Recommended
Pulse-Width-Modulation Frequency	15 to 40 kHz 20 kHz is Recommended
Bus Conductor Efficiency	Range: 99.55 to 99.75% 99.65% is Recommended
Shunt Switch Efficiency	Range: 99.25 to 99.65% 99.45% is Recommended
EMI Filter Efficiency	Range: 99.90 to 99.95% 99.93% is Recommended
Coldplate Temperature	60 to 200° C 100° C Suggested as Initial Value
Coldplate to Radiator Temperature Delta	0 to 20° C 16.67° C is Recommended
Radiator Sink Temperature	See Note 1 247.67 K Calculated for LEO

1. The radiator sink temperature (RST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the RST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 23
Alternator Speed Regulator Model
Variable Definitions

APO	Alternator Power Output (kWe)
AVO	Alternator Voltage Output (Vrms)
BCE	Bus Conductor Efficiency at 100° C (%)
BCET	Bus Conductor Efficiency at Coldplate Temperature (%)
BCM	Bus Conductor Mass (kg)
BFSE	Combined Bus, Filter, & Shunt Efficiency (%)
CACH	Complete Assembly Component Height (m)
CACL	Complete Assembly Component Length (m)
CACPEM	Complete Assembly Coldplate Based Enclosure Mass (kg)
CACV	Complete Assembly Component Volume (m^3)
CACW	Complete Assembly Component Width (m)
CMM	Control and Monitoring Mass (kg)
CMP	Control and Monitoring Power (Watts)
CPT	Coldplate Temperature (°C)
CRTD	Coldplate to Radiator Temperature Delta (°C)
EFE	EMI Filter Efficiency at 100° C (%)
EFET	EMI Filter Efficiency at Coldplate Temperature (%)
EFM	EMI Filter Mass (kg)
FSE	Fully Shunted Efficiency (%)
NSS	Number of Shunt Switch Elements
PWMF	Pulse-Width-Modulation Frequency (kHz)

Table 23 (cont)
Alternator Speed Regulator Model
Variable Definitions

RA	Radiator Area (m^2)
RAM	Radiator Mass (kg)
RST	Radiator Sink Temperature (K)
SMCH	Single Module Component Height (m)
SMCL	Single Module Component Length (m)
SMCPEM	Single Module Coldplate Based Enclosure Mass (kg)
SMCV	Single Module Component Volume (m^3)
SMCW	Single Module Component Width (m)
SPO	Shunt Power Output (kWe)
SRAM	Speed Regulator Available Modules
SREM	Speed Regulator Electronics Mass (kg)
SRF	Shunt Redundancy Factor (%)
SRM	Speed Regulator Mass w/o Radiator (kg)
SRMR	Speed Regulator Mass with Radiator (kg)
SVO	Shunt Voltage Output (Vrms)
SRRM	Speed Regulator Required Modules
SRSM	Speed Regulator Specific Mass w/o Radiator (kg/kWe)
SRSMR	Speed Regulator Specific Mass with Radiator (kg/kWe)
SSE	Shunt Switch Efficiency at 100° C (%)
SSET	Shunt Switch Efficiency at Coldplate Temperature (%)
SSM	Shunt Switch Mass (kg)

3.7 Parasitic Load Radiator

The parasitic load radiator (PLR) operates in conjunction with the speed regulator to dissipate excess power. Due to its thermal inertia, the reactor can not respond quick enough to changes in load. Consequently, faster responding devices, the speed regulator and PLR, are required to control power delivery to the engines and regulate alternator speed. The PLR should be designed to dissipate all alternator power, since this situation may occur prior to engine startup and if the switchgear unit input RBI opens to isolate a fault.

The PLR model is based on a single sided, flat plate radiator. It contains numerous resistive elements that are fabricated from Nichrome V and connected in a delta configuration. Beryllium oxide was used to insulate them from the radiator plate because of its light weight, high temperature capability, and good thermal conductivity. The Nichrome V wire elements operate at a high temperature, 1255 K was used for this point design, and transfer their heat to a carbon-carbon plate that is radiating to space. Carbon-carbon was utilized for the radiator plate because of its light weight, high temperature capabilities, and structural strength. A coating would be applied to the radiating surface of the carbon-carbon plate to improve its emissivity. The structural members that support the PLR are also constructed from carbon-carbon.

Application Notes: The PLR model is intended to be used in conjunction with the speed regulator model. It is designed to be used over the same power and voltage range as the speed regulator in any application using 3-phase ac power. A 3-phase circuit can be connected in either a delta or wye configuration. Delta was selected for this application because the PLR can continue to dissipate power, albeit unevenly, even if one of the phases fails open. This is referred to as an open delta.

Model Specifics: The logic employed during the development of the PLR model is shown in the flow chart in Figure 17. The selected outputs, surface area, mass, and specific mass represent a best estimate of the users needs. Other parameters are available. They can be obtained by changing the print routine that accesses the Fortran common block. The basic model functions are shown in the middle column, and the inputs are listed in the two boxes on the left. Default values are provided for these inputs, but the user is free to change any of these values as long as they stay within the specified model limits.

Table 24 lists the acceptable input ranges and recommended values. The notes identify input parameters typically provided by other modules. The material constants utilized in the PLR model are based on Nichrome V resistive elements and a carbon-carbon radiator plate. Calculations indicated these materials had the best combination of mass, thermal, and electrical characteristics. It is not intended for the operator to use alternate materials, but it can be done by inserting the appropriate resistivity and density factors. The 120% redundancy factor was selected on the basis of preliminary analyses that indicated it was the best tradeoff between enhanced reliability and added mass.

The variables and constants utilized in the PLR model are listed in Table 25 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix G. This subroutine is located on the accompanying computer disk under the file name "ACPLR.FOR".

PARASITIC LOAD RADIATOR (PLR) FLOW CHART

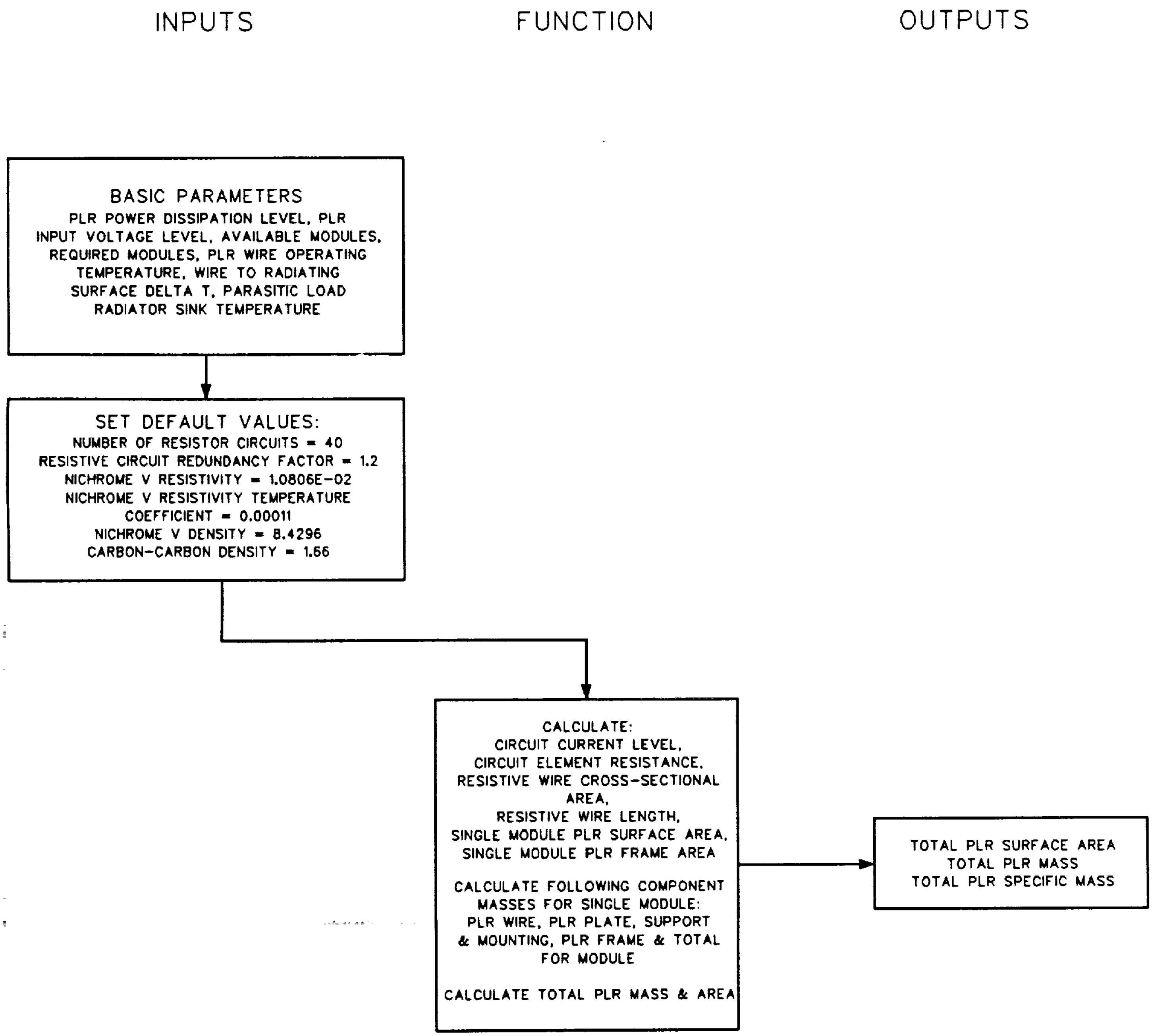


Figure 17

Table 24
Parasitic Load Radiator Model
Input Parameter Ranges

Parasitic Load Radiator Input Parameter	Recommended Input Range
PLR Power Dissipation Level	100 kWe to 10 MWe
PLR Input Voltage Level	200 to 10,000 Vrms
Available PLR Modules	Equal to or Greater than Required Modules
Required PLR Modules	No Limit
PLR Wire Operating Temperature	500 to 1350 K 1255 K Suggested as Initial Value
Wire to Radiating Surface Temperature Delta	50 to 150 K 100 K is Recommended
PLR Sink Temperature	See Note 1 247.67 K Calculated for LEO
Number of Resistive Circuits	20 to 100 40 is Suggested
Resistive Circuit Redundancy Factor	100 to 150% 120% is Recommended

1. The PLR sink temperature (PST) will normally be obtained from the heat rejection module (CR-191132). If the PMAD module is run separately, the PST must be calculated for the environment being studied. The value for LEO is 247.67 K.

Table 25
Parasitic Load Radiator Model
Variable Definitions

APM	Available Parasitic Load Radiator Modules
CC	Circuit Current Level (Amps)
CCD	Carbon-Carbon Density (g/cm^3)
CER	Circuit Element Resistance (ohms)
ND	Nichrome V Density (g/cm^3)
NR	Nichrome V Resistivity (ohms-cm^2/meter)
NRC	Number of Resistive Circuits
NRTC	Nichrome V Resistivity Temperature Coefficient (/°C)
PI	π (3.1416)
PIV	PLR Input Voltage Level (Vrms)
PPD	PLR Power Dissipation Level (kWe)
PST	Parasitic Load Radiator Sink Temperature (K)
PWOT	PLR Wire Operating Temperature (K)
RCRF	Resistive Circuit Redundancy Factor (%)
RPM	Required Parasitic Load Radiator Modules
RWD	Resistive Wire Diameter (cm)
RWL	Resistive Wire Length (m)
RWXA	Resistive Wire Cross Sectional Area (cm^2)
SMFA	Single Module PLR Frame Area (m^2)
SMFM	Single Module PLR Frame Mass (kg)

Table 25 (cont)
Parasitic Load Radiator Model
Variable Definitions

SMPA	Single Module Parasitic Load Radiator Surface Area (m^2)
SMPLRM	Single Module Parasitic Load Radiator Mass (kg)
SMPM	Single Module PLR Plate Mass (kg)
SMSM	Single Module PLR Support & Mounting Mass (kg)
SMWM	Single Module PLR Wire Mass (kg)
TPLRA	Total Parasitic Load Radiator Surface Area (m^2)
TPLRM	Total Parasitic Load Radiator Mass (kg)
TPLRSM	Total Parasitic Load Radiator Specific Mass (kg/kWe)
WRTD	Wire to Radiating Surface Temperature Delta (K)

3.8 Litz Wire Transmission Line

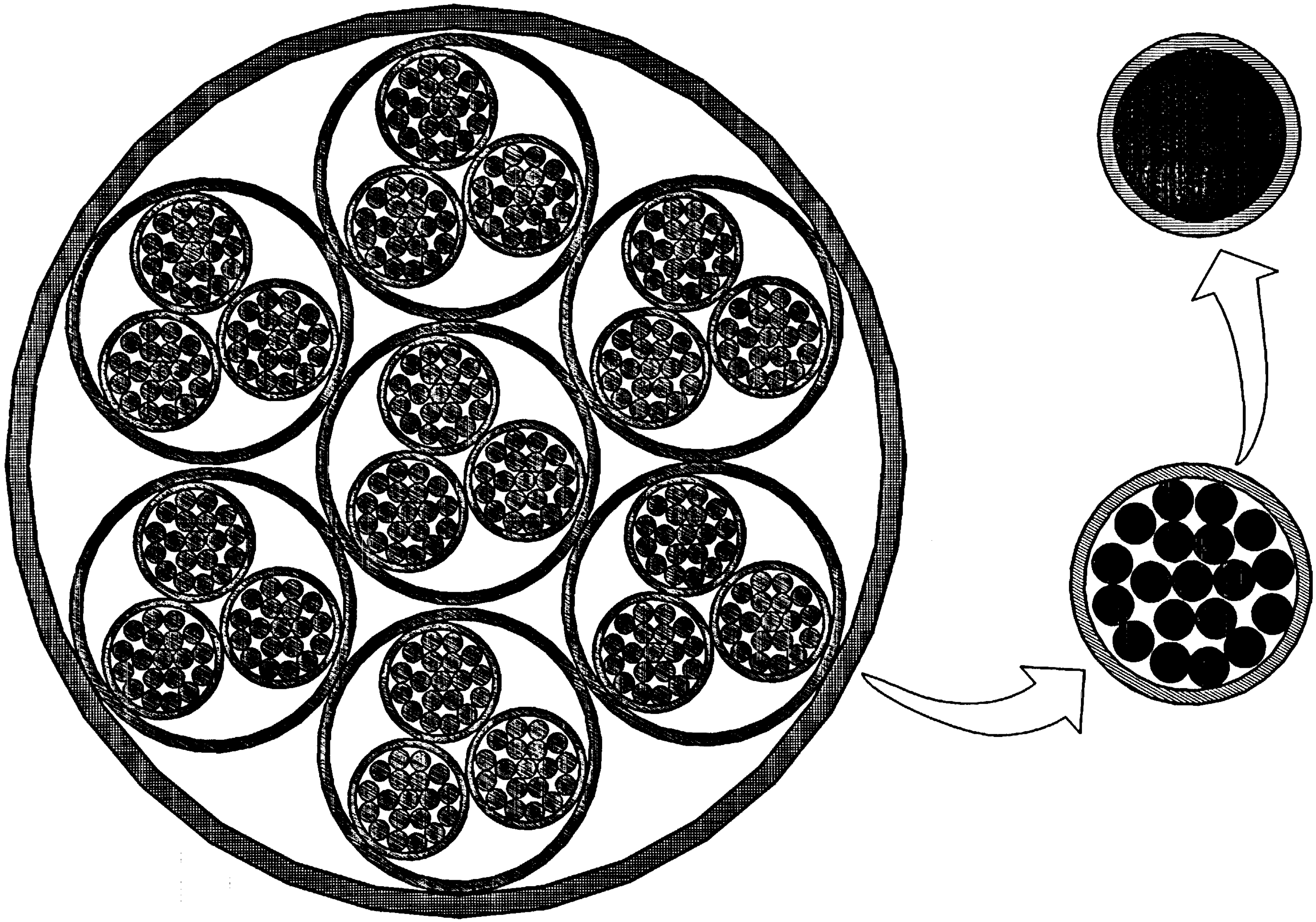
Transmission lines will be used in the PMAD system to conduct power between the following components: alternator to switchgear unit, speed regulator to PLR, switchgear unit to adjacent switchgear unit, and switchgear unit to PPU. There are several possible transmission line constructions, but the litz wire configuration was modelled because it is a low inductance, low ac resistance design that is capable of operating over a wide frequency range. (The program funding and duration precluded the development of additional transmission line models, but it is recommended for future work.) Even at the relatively low frequencies used in this model, 60 Hz to 5 kHz, skin effect losses and line inductance are a concern. They become even more critical at higher frequencies because they are a function of frequency.

The skin effect is a phenomenon that occurs in ac transmission due to the rapidly changing current intensity. It arises from the fact that the inductance encountered by the current is higher at the center of the wire than at the periphery. This causes an uneven current density over the conductor cross section; the current density is a minimum at the wire center and a maximum at the periphery. The net result is an increase in the effective resistance of the conductor and higher losses. This effect becomes more pronounced as the conductor size and frequency increase.

Another issue in ac transmission line design is line inductance. The energy stored in a transmission line is proportional to its inductance; consequently, a highly inductive line can make power switching and fault interruption more difficult. The stored energy must be controlled and dissipated by the switch. A large inductive reactance also results in a large reactive power demand. As a result the current levels in the system rise, causing higher I^2R losses, and necessitating larger conductors in the transmission lines, power conditioning components, and alternators. This effect is further compounded as conductor size increases, because it causes the line inductance to increase. In addition to increasing the PMAD system mass, the power source must be oversized to feed the reactive power demand. From a system viewpoint, it is important to minimize line inductance and maximize the PMAD system power factor.

The litz wire transmission line construction was specifically developed to reduce skin effect losses and line inductance. Figure 18 shows the internal construction of a seven bundle litz wire cable. Litz wire contains numerous wire strands, each individually insulated and packed in a conductor bundle. Because each strand is insulated, the conductor behaves like many small wires run in parallel. This dramatically reduces skin effect losses because the useful conductor cross section of several individual strands is much larger than that of a single large conductor. However, the cable mass is increased due to the added weight of this wire strand insulation. The litz wire cable is partitioned into multiple bundles to decrease the conductor separation distance, since it is a large determinant of the line inductance. Ideally, to minimize line inductance, the conductors in a 3-phase circuit should occupy the same space. Clearly this is impossible; however, reducing the conductor size does reduce the separation distance and thus the line inductance.

LITZCBLE
4-27-92



Modelled Litz Wire Cable Construction
Figure 18

Because the litz wire model is based on physical principles, it exhibits the influences of skin effect losses and line inductance and allows the user to evaluate steps aimed at improving the transmission line design. Some general procedures for reducing skin effect losses and line inductance are listed in the section entitled "Application Notes". Generally, if the transmission line model calculates an excessive mass or will not converge, it indicates that the selected input parameters are impractical and it would be extremely difficult to fabricate an actual cable that is suitable for these particular conditions.

Application Notes: The litz wire transmission line model is designed to work satisfactorily over the entire power, voltage, and frequency range. However, there are combinations of input parameters that will cause problems. Specifying a fairly high frequency (greater than 1.5 kHz) in conjunction with a low voltage (less than 2000 Vrms) and a long transmission line length (greater than 150 meters) may lead to poor results. To determine why an impractical value was calculated or identify the cause of a divergence error, first look at the calculated circuit power factor value. If it is below 0.8, this particular transmission line design is highly inductive and most likely not practical. Failure of the model to converge will almost always be marked by a very low power factor, 0.7 or less. It is necessary to change the input parameters to obtain an acceptable model output and a good cable design. The following steps are offered as a guide in determining appropriate and effective design input changes. It is assumed that the designated transmission line length is based on definite spacecraft design requirements and it can not be readily changed; however, if this is not true it is always desirable to shorten the line length since it will always improve transmission efficiency and reduce cable mass. It is recommended that the following steps be tried in the order they are listed.

1. Consider increasing the transmission line voltage. (This may necessitate selecting the Option #2 PPU design.) This change is particularly effective if the transmission line length is long, greater than 150 meters, but it will also help if the line is required to operate at a high frequency.

2. If the line length is greater than 100 meters and the specified frequency is greater than 1.5 kHz, it may be necessary to change the number of bundles from 7 to 17. This will reduce the line inductance, but it will increase the line mass and conductor temperature due to the added insulation. Conversely, if a low frequency is specified, it may be possible to realize mass and temperature benefits by utilizing one bundle.

3. The final step is to separate the transmission line into multiple lines using the ATC and RTC factors. For example, a single 3 MWe line can be broken into three 1 MWe lines by making ATC and RTC both equal to 3.

Model Specifics: The flow chart in Figure 19 shows the logic employed during the development of the litz wire transmission line model. The outputs in the right hand column represent a best estimate of the users needs and additional parameters are available. This data is in a Fortran common block and it can

NEP PMAD TRANSMISSION LINE FLOW CHART

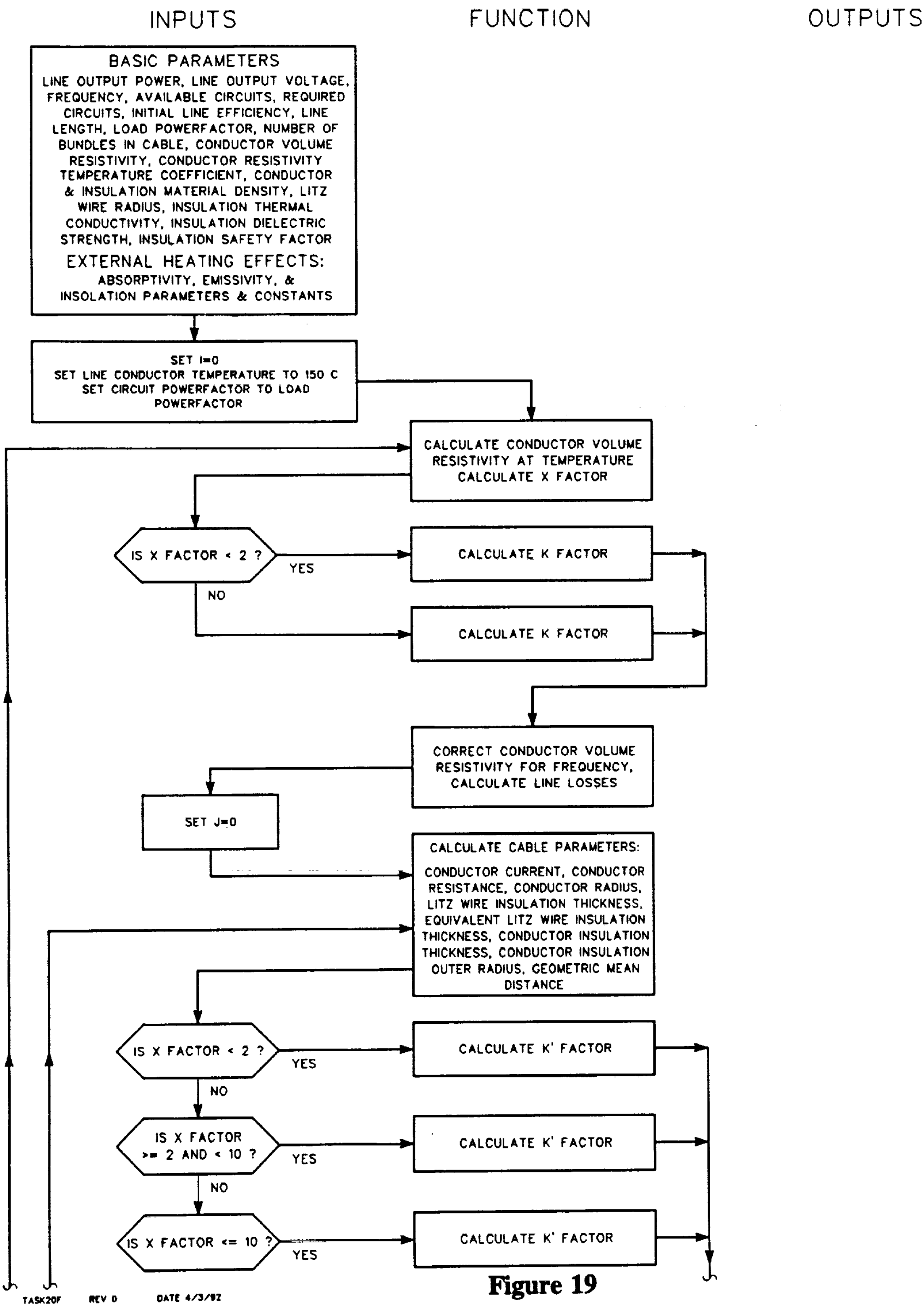


Figure 19

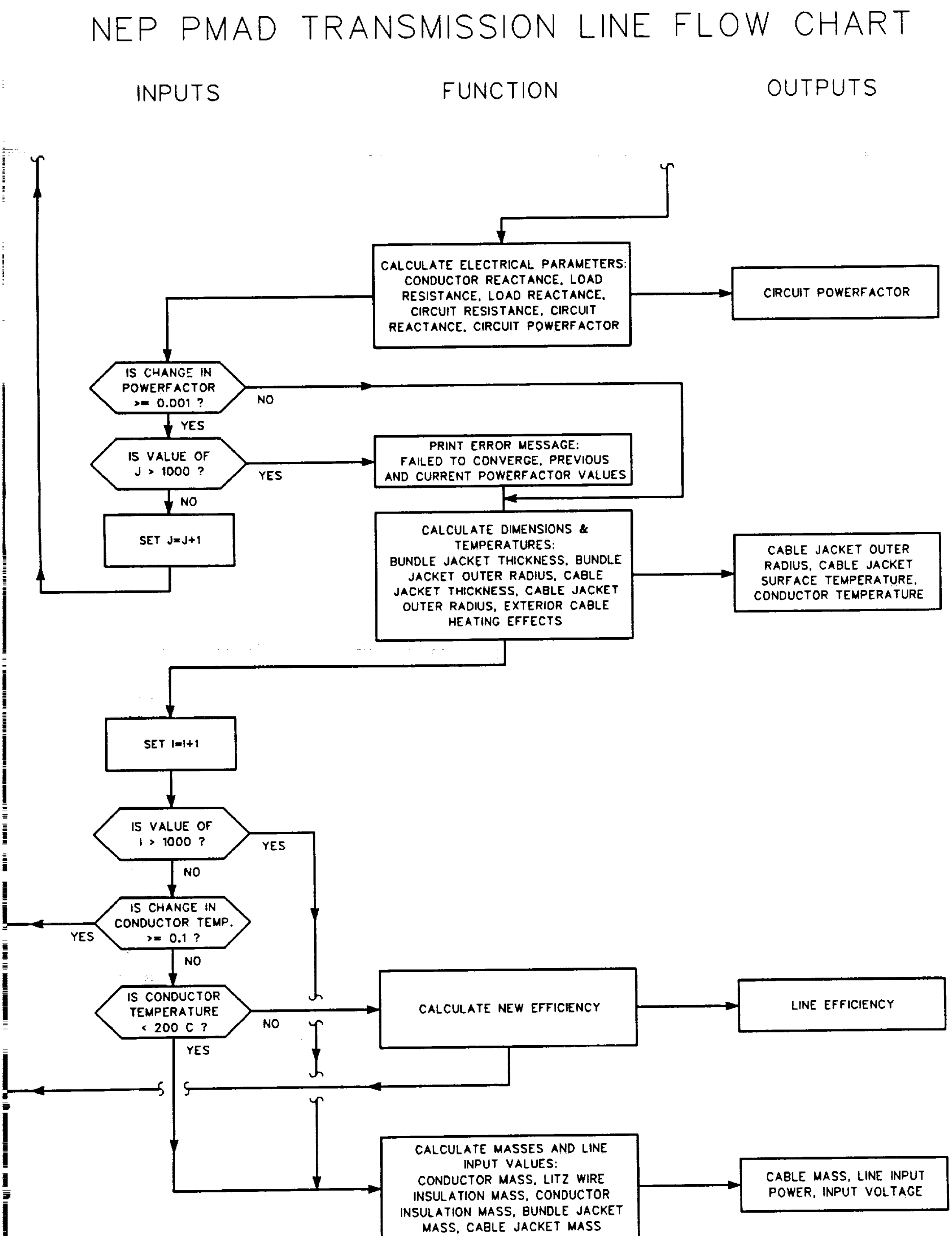


Figure 19 (cont)

TASK20C REV 0 DATE 4/3/92

be accessed by modifying the print routine. The basic model operations are shown in the middle column, and the inputs are listed in the left column. Default values are provided for each of these inputs, but the user can change any of these values as long as they stay within the specified model limits. The model allows a wide range of input parameters, but using values outside the ranges defined in Table 26 may result in errors and it is not recommended. The notes identify input parameters normally obtained from other modules.

The results of the Task Order 14 contract and its follow-on were factored into the transmission line model to reduce the number of options requiring evaluation (Ref. II-1, II-2). For example, aluminum conductors were selected over copper ones. Analyses showed that the mass of an aluminum conductor would be about half that of a copper conductor under comparable conditions. Although the resistivity of aluminum is approximately 66% higher, its density is about 30% of copper. The density-resistivity product is the important parameter in selecting the minimum mass conductor material, and calculations showed an aluminum line would be half the mass of a copper one ($1.66 \times 0.30 \approx 0.50$). Other materials, such as silver, beryllium, or molybdenum, have an even higher density-resistivity product. An aluminum conductor would be about 60% larger than a copper one, but this was considered to be a minor factor in designing a transmission line. Finally, individuals have expressed concerns about terminating aluminum conductors because of their cold flow tendencies. New termination methods and hardware appear to have solved these problems. In fact, aluminum conductors and buses have become the norm in high power terrestrial switchgear units.

There are several insulations that might be suitable for transmission line cables; however, polyimide (trade name Kapton) was selected because it offers a good combination of thermal, electrical, radiation, and mechanical properties (Ref. III-1). A Kapton jacket is mechanically superior to Teflon because it is a tough, flexible insulation that is highly resistant to abrasion. It can be applied in a thin layer on wire strands; consequently, the resulting cable construction is light weight and small in diameter. Kapton also has a high dielectric strength and good thermal conductivity. Due to the close proximity of a reactor, a transmission line insulation must be highly resistant to radiation and capable of operating at high temperatures. Test results indicate that Kapton can operate at 200° C for over ten years and the weight loss due to outgassing will be under 3%. It can also withstand high radiation levels and is rated for a total dose of 10^8 Rads gamma.

Due to the complicated construction of the litz wire cable, detailed thermal calculations would be very complex and computer intensive. To simplify these calculations, it was assumed that all conductor losses would originate from a single conductor located in the center of the cable. The calculated cross sectional area of this conductor is equal to the combined areas of all the individual litz wire stands. The litz wire, bundle jacket, and cable jacket insulations were assumed to be made from Kapton and they were consolidated to form a single jacket. The calculated mass of this jacket was equivalent to the summed masses of the individual insulations, and its thickness corresponded to the combined thicknesses of the separate insulations. It is clear that a model based on this simplified construction will not calculate temperatures as precisely as a comprehensive thermal model, and detailed thermal modelling should be performed when funding allows. However, this simplified analysis technique should yield comparable values and allow the user to determine representative cable masses and operating conditions.

The variables and constants utilized in the litz wire transmission line model are listed in Table 27 in alphabetical order. A complete listing of the Fortran source code is presented in Appendix H. This subroutine is located on the accompanying computer disk under the file name "LWTRLN.FOR".

Table 26
Litz Wire Transmission Line Model
Input Parameter Ranges

Transmission Line Input Parameter	Recommended Input Range
Output Power Level	10 kWe to 10 MWe
Output Voltage Level	1000 to 10,000 Vrms
Transmission Line Efficiency	80 to 99.999%
Transmission Line Length	25 to 300 meters
Alternator Operating Frequency (See Note 1)	60 Hz to 5 kHz 0.8 kHz is Recommended
Available Transmission Circuits	Equal to or Greater than Required Circuits
Required Transmission Circuits	No Limit
Number of Bundles	1, 7, or 17
Load Power Factor	0.80 to 1.00
Solar Radiation Level (See Note 2)	343 to 5488 w/m^2 LEO value is 1372 w/m^2
Earth Infrared Radiation Level (See Note 2)	0 to 237 w/m^2 LEO value is 237 w/m^2
Cable-Earth View Factor (See Note 2)	0 to 1.0 LEO value is 0.8
Albedo (See Note 2)	0 to 0.5 LEO value is 0.3

1. The alternator operating frequency (AOF) will normally be obtained from the power conversion module (CR-191134 or CR-191135). If the PMAD module is run separately, AOF must be input.

2. These values will normally be obtained from the heat rejection module (CR-191132). The values for LEO (400 km orbit) are: solar insolation, 1372 w/m^2; earth infrared, 237 w/m^2; cable-earth view factor, 0.8; and albedo, 0.3.

Table 27
Transmission Line Model Variable Definitions

ALBD	Albedo
AMD	Aluminum Mass Density (g/cm^3)
AOF	Alternator Operating Frequency (kHz)
ARTC	Aluminum Resistivity Temperature Coefficient (/°C)
ATC	Available Transmission Circuits
AVR	Aluminum Volume Resistivity at 20°C and 0 Hz (Ohm-m)
AVRF	Aluminum Volume Resistivity at Temperature and Frequency
AVRT	Aluminum Volume Resistivity at Conductor Temperature
BJM	Bundle Jacket Mass (kg)
BJOR	Bundle Jacket Outer Radius (cm)
BJT	Bundle Jacket Thickness (cm)
CABI	Cable Absorptivity (Infrared)
CABS	Cable Absorptivity (Solar)
CCUR	Conductor Current (Amps)
CEM	Cable Emissivity
CEVF	Cable-Earth View Factor
CIM	Conductor Insulation Mass (kg)
CIOR	Conductor Insulation Outer Radius (cm)
CIT	Conductor Insulation Thickness (cm)
CJM	Cable Jacket Mass (kg)
CJOR	Cable Jacket Outer Radius (cm)

Table 27 (cont)
Transmission Line Model Variable Definitions

CJST	Cable Jacket Surface Temperature (K)
CJT	Cable Jacket Thickness (cm)
CM	Cable Mass (kg)
COM	Conductor Mass (cm)
CRAD	Conductor Radius (cm)
CREA	Conductor Reactance (Ohms)
CRES	Conductor Resistance (Ohms)
CRP	Circuit Resistance per Phase (Ohms)
CXP	Circuit Reactance per Phase (Ohms)
ECHE	External Cable Heating Effects (w/m^2)
ELWT	Equivalent Litz Wire Insulation Thickness (cm)
GMD	Geometric Mean Distance between Conductors (cm)
IDS	Insulation Dielectric Strength (V/mil)
IDSF	Insulation Dielectric Strength Safety Factor
IMD	Insulation Mass Density (g/cm^3)
ITC	Insulation Thermal Conductivity (w/m-K)
KF	K Factor
KPF	K' Factor
LPF	Load Power Factor
LRP	Load Resistance per Phase (Ohms)
LWIM	Litz Wire Insulation Mass (kg)

Table 27 (cont)
Transmission Line Model Variable Definitions

LWIT	Litz Wire Insulation Thickness (cm)
LWR	Litz Wire Radius (cm)
LXP	Load Reactance per Phase (Ohms)
NOB	Number of Bundles
PF	Circuit Power Factor
QEIR	Earth Infrared Radiation Level (w/m^2)
QSOL	Solar Radiation Level (w/m^2)
RTC	Required Transmission Circuits
SBC	Stefan-Boltzmann Constant (w/m^2-K^4)
TLCT	Transmission Line Conductor Temperature (°C)
TLE	Transmission Line Efficiency (%)
TLIP	Transmission Line Input Power Level (kWe)
TLIV	Transmission Line Input Voltage (Vrms)
TLL	Transmission Line Length (m)
TLOP	Transmission Line Output Power Level (kWe)
TLOV	Transmission Line Output Voltage (Vrms)
TLPL	Transmission Line Power Losses (kWe)
XF	X Factor

3.9 Electronics Radiator

Since all NEP vehicle power conditioning components will require cooling, algorithms were developed to estimate the size and mass of the electronics radiator. These algorithms were based on a flat-plate radiator that rejects heat to space from both sides, and are valid for the following ranges or variables:

1. Heat dissipation levels ranging from 10 kWt to 1 MWt,
2. Coldplate temperatures ranging from 50 to 250° C,
3. An operating life of 10 years,
4. Environments ranging from low earth orbit (LEO) to interplanetary space, and
5. A technology time frame of 2005 to 2020.

The technology time frame largely determines the radiator construction and materials. The selected radiator design features were:

1. Water is the heat pipe working fluid,
2. Carbon-Carbon construction with a Monel liner,
    - Fin thickness = 0.05 cm,
    - Pipe wall thickness = 0.100 cm,
    - Liner thickness = 0.0075 cm.
3. Radiation emissivity control coating,
    - Emissivity = 0.9,
    - Absorptivity = 0.2 (solar)

Based on the above specified requirements and selected design features, the following algorithms were developed.

$$RA = (14.80E+09*PD)/((Tcp-16.67)^4-Ts^4)$$

$$RM = 3.418*RA$$

where: RA = Radiator flat plate area (one-side) (sq-meters),
PD = Required heat rejection capacity (kWt),
Tcp = Coldplate operating temperature (K),
Ts = Heat sink temperature (247.67 K),
RM = Radiator mass (kg).

4.0 Conclusions and Recommendations

The PMAD models documented in this report are capable of evaluating the effect on component parameters of a wide range of power levels, voltages, and frequencies. Options are available for assessing ion and MPD thrusters, and single and counter rotating alternators. Because there is the potential for the utilization of high temperature electronics, the model also allows the use of coldplate temperatures ranging from 60 to 200° C. While this will allow an initial assessment of high temperature electronics, it is important to realize that the operating characteristics of these devices are poorly defined and it is difficult at this time to determine their true impact. Based on the selected inputs, the end-to-end PMAD model will supply total PMAD system mass, specific mass, end-to-end efficiency, and the total electronics radiator area. Additional component modelling data are located in a Fortran common block and they can be accessed by modifying the print output subroutine.

The transmission line configuration modelled during this study is based on a litz wire construction. While this construction is suitable for a wide range of frequencies, it is primarily suited for high frequency operation. There are several other transmission line constructions, such as hollow conductor and ribbon cable, that should be evaluated since they may offer mass and performance gains. To develop these models in the most economical manner, it is recommended that an ac transmission line report authored by Dr. Loyde Gordon be consulted. This report should have been recently received by NASA LeRC. It is important to utilize this report because the models developed by Dr. Gordon are well documented and exhibit high fidelity.

The litz wire transmission line model contained in this report is relatively simple due to the complexity and cost of developing a detailed thermal model. The calculation steps in a complete thermal model would also occupy considerable computer time. Clearly, a thermal model based on a simplified construction will not calculate temperatures as precisely as a thermal model based on a complete construction; therefore, a detailed model should be constructed to test the validity of this simplified analysis technique. The litz wire transmission line model contained in this report should also be compared with the litz wire model presumed to be in Dr. Gordon's ac transmission line report to test its accuracy.

A near-term NEP vehicle may use an SP-100 thermoelectric power source. Later vehicles may utilize a thermionic power source. The output from thermoelectric and thermionic power sources, low voltage dc, is totally different from the 3-phase ac provided by a rotary alternator. Therefore, it is necessary to conduct studies to determine the best PMAD approach for these types of power sources. Based on these studies, PMAD models should be developed to compare different architecture configurations, perform system tradeoffs, and determine PMAD mass and efficiency as a function of power, voltage, and frequency if ac distribution is utilized. Because thermoelectric and thermionic power sources have similar electrical characteristics it may be possible to perform a single PMAD study involving the two power sources. The practicality of this approach would depend primarily on the proposed power levels and projected time periods for the two power sources.

The present PMAD codes contain algorithms designed to calculate the masses of the thruster PPU assemblies and radiators. However, certain thruster codes may already include the associated PPU masses or it may be desirable only to calculate the PMAD component masses on the power generation side of the thruster buses. This can be accomplished by inputing a PPU identifier that will direct the code to zero out the PPU component and radiator masses. Although a skilled Fortran programmer is required to implement and debug the actual code changes, the following general code modifications are suggested:

1) Near the beginning of fortran subroutine "**PMAD.FOR**", the comment line headed by "IDPPU", a statement indicating "0=no PPU assembly or radiator" should be added.

2) After the variable definition section of fortran subroutine "**PMAD.FOR**", the comment line stating "IDPPU should equal 1, 2, or 3" must be modified to include 0. The following execution line should include "IDPPU .NE. 0", and "IDPPU=3" should be changed to "IDPPU=0".

3) Near the end of fortran subroutine "**PMAD.FOR**", and immediately before the execution line "EEPE=PPE*PSTLE*SWE*SATLE" the following line should be added "If IDPPU=0, PPE=1".

4) Near the end of fortran subroutine "**PMAD.FOR**", and immediately before the execution line beginning "TPCM=APC*(NTC*PPM+..." the following line should be added "If IDPPU=0, PPM=0".

5) Near the end of fortran subroutine "**PMAD.FOR**", and immediately before the execution line beginning "TERM=APC*(NTC*PPRAM+..." the following line should be added "If IDPPU=0, PPRAM=0".

These code modifications are intended to remove the PPU mass and efficiency values from the system mass and efficiency totals; however, the programmer should verify these changes are accurate and that all necessary executable modifications are identified. It may also be necessary for the programmer to modify certain print statements to ensure they print the proper values.

References

II-1 Meisner, John W. "Power Conditioning Assessment for Nuclear, Solar Electric Propulsion." Task Order 14 Final Report, Rockwell International, Rocketdyne Division. NASA Contract Number NAS3-25808, July 1991 (Currently Unreleased).

II-2 Metcalf, Kenneth J. "Power Conditioning Architecture Assessment for Nuclear Electric Propulsion", Task Order 14 Follow-On Presentation of Results, Rockwell International, Rocketdyne Division. NASA Contract Number NAS3-25808, February 1992.

III-1 Du Pont. "Kapton", A brochure containing the electrical, mechanical, thermal, and chemical properties of the polyimide film Kapton.

A-1 Thome, Frank and Donald King. "A Summary of High-Temperature Electronics Research and Development." 9th Symposium on Space Nuclear Power Systems, January 1992, Vol. I, pp. 254-259.

A-2 Neudeck, Philip and Lawrence Matus. "An Overview of Silicon Carbide Device Technology." 9th Symposium on Space Nuclear Power Systems, January 1992, Vol. I, pp. 246-253.

A-3 Fink, Donald and H. Wayne Beaty. "Standard Handbook for Electrical Engineers", Eleventh Edition. New York, N.Y.: McGraw-Hill Book Company, 1978.

A-4 Wong, See-pok. "Loss in Switching Transistors vs. Hybrid Substrate Temperature." Facsimile Transmission from Space Power Incorporated, 1988.

A-5 Wieserman, William; Gene Schwarze, and Janis Niedra. "Comparison of High Frequency, High Temperature Core Loss and B-H Loop Characteristics of an 80 Ni-Fe Crystalline Alloy and Two Iron-Based Amorphous Alloys." 8th Symposium on Space Nuclear Power Systems, January 1991, Vol. III, pp. 974-981.

A-6 AVX Corporation. "Ceramic Advanced Products", A brochure containing characteristic information on ceramic capacitors prepared by the AVX Corporation.

APPENDIX A

Component Temperature-Efficiency Algorithms

Component Efficiency-Temperature Algorithms

The efficiency of a component is calculated by multiplying the efficiencies of the stages together and subtracting the parasitic power demands. The power required to operate the control and monitoring hardware is termed parasitic power and it does not vary much with the component power level. Consequently, components rated for high power levels are more efficient than ones designed for low power. The efficiency of the stages, however, does change as the operating temperature of the component rises. Therefore, a component designed for high temperature operation will typically be less efficient than one designed for lower temperatures. This occurs because the resistivity of almost all elements, conductors, transformer windings, connections, switches, diodes, etc., rises with temperature. The only exception is that transformer core losses decline with temperature. Because of this effect, algorithms were developed to adjust component efficiency with temperature. Higher component operating temperatures are being investigated because they reduce the mass of the electronics radiators. The radiator calculations utilize the component coldplate temperature; hence, the radiator area and mass are automatically recalculated when the coldplate temperature is changed.

A four step process was used to develop algorithms relating component efficiency to temperature: (1) the main elements in a component were identified, (2) their losses were determined as a function of temperature, (3) the losses attributable to each of these elements were calculated for representative components, and (4) algorithms relating efficiency to temperature were developed for components based on their respective loss allocations. The power handling devices in a component are primarily composed of four elements, copper conductors, semiconductors, magnetic materials, and capacitors. Existing temperature-resistance equations, data sheets, and technical papers were consulted to obtain information relating losses to temperature. This data was utilized to generate algorithms for each of these elements. Loss breakdowns were then obtained for selected components to determine the losses attributable to each of these elements. Based on these loss breakdowns, and the algorithms previously developed for the elements, algorithms were generated for a complete component. These algorithms are for representative components and they are general in nature. They should only be utilized to identify efficiency-temperature trends, and not be used to determine the losses of a specific component at a particular temperature.

The rationale supporting these algorithms assumes that component developments will result in not only higher efficiency operation, but allow higher operating temperatures as well. However, advanced materials are required to achieve substantially higher temperature operation. Since it takes approximately 15 to 20 twenty years to develop new power component materials, applied technology developments over the next ten years will concentrate primarily on enhancing the capabilities of present materials. This will lead to innovative constructions that utilize current materials to achieve superior characteristics. An example of this approach is the silicon-on-insulator (SOI) technology currently being evaluated for use in power devices. Since this design approach reduces the leakage currents that limit device operating temperatures and radiation exposure, SOI devices are capable of operating at higher temperatures and radiation levels. However, these devices are limited to 200° C, and will probably need to operate at significantly lower temperatures if high reliability and long life are crucial. After including these factors and the thermal resistance from the coldplate to the device, actual component coldplate temperatures will probably range from 80 to 120° C.

Although this represents a considerable improvement over present day coldplate temperatures of 30 to 60° C, higher coldplate temperatures are desired to further reduce radiator mass. Advanced heat sink designs incorporating new materials such as carbon-carbon will lower the thermal resistance and enable higher coldplate temperatures without increasing device junction temperatures. If carbon-carbon is oriented correctly it exhibits a higher thermal conductivity than copper, and its specific weight of 1.66 g/cm^3 is 19% of copper and 61% of aluminum. Furthermore, since the removal of waste heat is the limiting factor in higher density electronics packaging, utilizing carbon-carbon should reduce component volumes. This will result in shorter internal conductor lengths and reduce conductor losses.

Current transformer and inductor materials are acceptable for envisioned high temperature, high radiation environments. However, advanced capacitor design approaches are required. Ceramic and glass dielectric capacitors can tolerate relatively high temperatures and radiation levels; however, they will require additional development to operate at temperatures above 200° C and radiation levels exceeding 10^7 Rad (Si) and 10^{15} n/cm^2. Energy storage density improvements are also needed to reduce the mass and volume of ceramic and glass dielectric capacitors.

Presently, certain semiconductor technologies are being developed chiefly for high temperature, high radiation environments. Four of these, gallium arsenide (GaAs), silicon carbide (SiC), diamond, and field emitter arrays (FEAs), are receiving considerable attention and they will be briefly discussed (Ref. A-1). GaAs is already used in high speed analog and digital circuits; however, present GaAs power devices exhibit excessive leakage currents at temperatures exceeding about 175° C. If GaAs power devices can be fully developed, they should be suitable for junction temperatures up to 250° C and radiation dosages of 10^8 Rad (Si) and 10^{15} n/cm^2. SiC technology is less mature than GaAs, but these devices will be able to operate in higher temperature, $\approx$600° C, higher radiation environments (Ref. A-2). Research has resulted in the fabrication of simple diodes, MOSFETs, and BJTs; however, the operating life of these devices has been severely limited by ohmic contact and semiconductor-insulation boundary degradation. Diamond semiconductors hold great promise because the thermal conductivity of diamond, 20 W/cm-K, is better than copper, and its bandgap energy of 5.5 eV indicates operating temperatures of 900° C are possible. However, the diamond semiconductor technology is very immature and basic research is being conducted to improve substrate growth techniques and reduce defects. FEAs are vacuum microelectronic devices that consist of an array of emitter tips that provide an electron flow across a gap by means of field emission alone. These devices should be very radiation hard and suitable for very high temperature environments. The current densities possible with these devices also make them candidates for power applications.

The losses occurring in a conductor are determined by the formula I^2R, where I is the current level and R is the resistance of the conductor. If the current level remains constant, the conductor losses become a function of resistance. When the conductor resistance changes with temperature, the losses in the conductor change proportionally. The following formula is used to calculate the resistance of a copper conductor at different operating temperatures (Ref. A-3).

$$R_T=1.7241*[1+0.00393*(T-20)]$$

where: R_T - Resistance at the conductor temperature
1.7241 - Resistance of copper at 20° C in $\mu\Omega\cdot cm$
0.00393 - copper temperature-resistance coefficient at 20° C
T - conductor temperature in degrees C

This formula was used to calculate resistance values for a copper conductor normalized about 100° C. From these normalized values, the following algorithm was developed. It calculates the percent change in losses in a copper conductor as a function in temperature.

$$CUL=(0.75+0.0025*CPT)*CUL_{100}$$

where: CUL - Copper conductor losses for specified coldplate temperature
CPT - Coldplate temperature in degrees C
CUL_{100} - Copper conductor losses for 100° C coldplate temperature

A single algorithm was developed to generate a common loss-temperature trend for different semiconductor switches and materials. Because high temperature semiconductor materials are in the early stages of development, the operating characteristics of proposed devices are largely undefined. Therefore, their operating characteristics at higher temperatures were estimated by extrapolating from present silicon based device operating data. This approach is probably optimistic because the primary material under consideration, SiC, exhibits lower electron and hole mobility than silicon and thus would be expected to have a poorer efficiency. However, a slightly optimistic approach does allow one to more easily determine the potential of SiC devices. Furthermore, the change in resistivity as a function of temperature for silicon and SiC based semiconductors should be similar, and it was considered impractical to develop different algorithms for the many different materials and devices.

The device selected for this algorithm was a metal-oxide-semiconductor field-effect-transistor (MOSFET) rated for 800 V and having a drain to source on-resistance of 0.8 ohms (Ref. A-4). The losses were determined for an operating frequency of 20 kHz and a current level of 2.8 amps. Several devices would be paralleled to handle large currents. MOSFETs are common devices and this application is consistent with a NEP vehicle PMAD system. The algorithm, shown below, calculates the percent change in losses for a temperature range of 60 to 200° C. It is normalized to yield a value of 1 at 100° C.

$$SL=(0.43+0.00571*CPT)*SL_{100}$$

where: SL - Semiconductor losses for specified coldplate temperature
CPT - Coldplate temperature in degrees C
SL_{100} - Semiconductor losses for 100° C coldplate temperature

Transformers and inductors contain a core that is utilized to conduct magnetic flux. As with any element, losses occur during operation; however, the losses in a core decline with temperature. Using test data generated by the University of Pittsburgh while under contract to NASA LeRC, an algorithm relating core losses to temperature was developed (Ref. A-5). For the algorithm development a single core material, supermalloy, was used. Supermalloy is widely used for high frequency, high power applications because it exhibits low core losses and has a high thermal conductivity. Since this is consistent with proposed NEP vehicle PMAD requirements, it was considered to be a good material for modelling purposes. The algorithm developed from this data is shown below.

$$CL=(1.1+0.001*CPT)*CL_{100}$$

where: CL - Core losses for specified coldplate temperature
CPT - Coldplate temperature in degrees C
CL_{100} - Core losses for 100° C coldplate temperature

The final device that required an algorithm relating losses to temperature is a capacitor. For this process, the characteristics of a ceramic capacitor were selected (Ref. A-6). Ceramic capacitors are utilized in several components for the SSF electrical power system due to their low mass and high reliability. They can also be used in both dc and ac applications and they are suitable for relatively high radiation, high temperature applications. Because these characteristics are desirable in a NEP vehicle PMAD application, it is presumed that ceramic capacitors will be utilized in many components. The algorithm developed from the normalized ceramic capacitor data is shown below.

$$CPL=(0.26+0.00741*CPT)*CPL_{100}$$

where: CPL - Capacitor losses for specified coldplate temperature
CPT - Coldplate temperature in degrees C
CPL_{100} - Capacitor losses for 100° C coldplate temperature

Figure 20 compares the normalized efficiencies of these four elements at temperatures ranging from 60 to 200° C. Again it is stressed that these algorithms are for representative devices only, and the characteristics of certain devices may vary considerably from this generic data. The algorithm results will be general in nature and the algorithms themselves should only be used to determine efficiency-temperature trends and not specific values.

The next step in producing efficiency-temperature algorithms for complete components is to determine the losses that are attributable to the various devices. For this process, the loss breakdowns of representative components, such as the SSF main inverter units, were used. The loss allocations presented in Table 28 were generated from this effort. The temperature-resistance properties are the same for the internal component conductors and the transformer and inductor windings because these elements are all fabricated from copper. However, the losses shown in Table 28 were broken out separately for clarity.

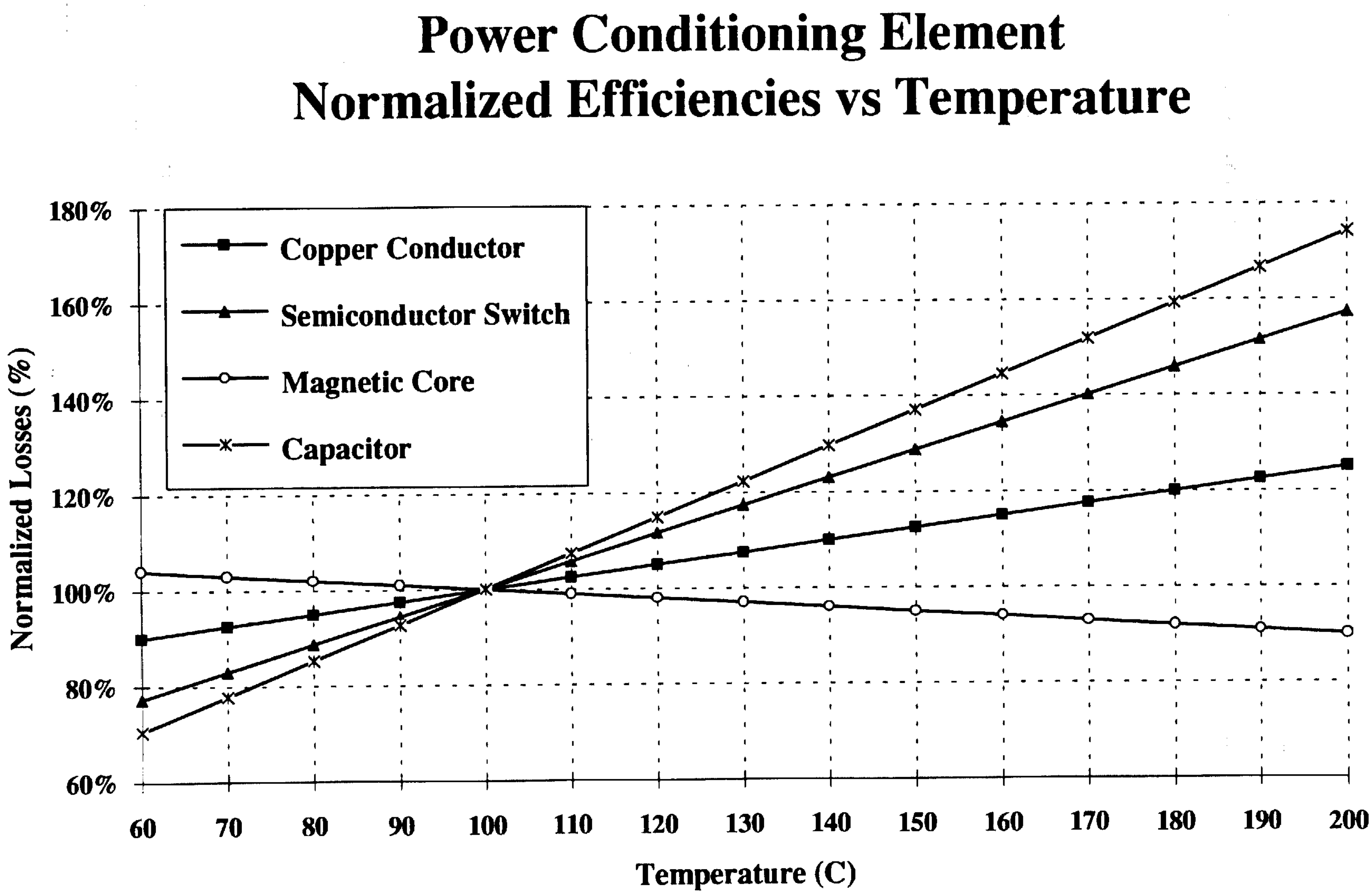


Figure 20

10/9/92

Table 28
Component Loss Allocations

Component Stage	Copper Conductor Losses (%)	Switch or Diode Losses (%)	Copper Winding Losses (%)	Magnetic Core Losses (%)	Capacitor Losses (%)	Relay Contact Losses (%)
Inverter	10	70	10	5	5	0
Transformer	0	0	60	40	0	0
Rectifier	20	80	0	0	0	0
Filter	10	0	40	20	30	0
RBI/RPC	50	0	0	0	0	50

Utilizing the loss allocation percentages shown in Table 28 and their associated device algorithms, algorithms were developed for the component stages. These algorithms determine the change in component efficiency as a function temperature. They were generated by multiplying the loss percentages and the coefficients in the device algorithms together. The algorithms for the inverter, transformer, rectifier, filter, and RBI/RPC stages are shown below.

Inverter: CSET=1-(1-CSE)*(0.593+0.00408*CPT)

Transformer: TSET=1-(1-TSE)*(0.89+0.0011*CPT)

Rectifier: RSET=1-(1-RSE)*(0.526+0.00475*CPT)

Filter: FSET=1-(1-FSE)*(0.82+0.0018*CPT)

RBI/RPC: RBET=1-(1-RBE)*(0.675+0.00325*CPT)

where: CSET - Chopper stage efficiency at the coldplate temperature (%)
CSE - Chopper stage efficiency at 100° C (%)
CPT - Coldplate temperature in degrees C
TSET - Transformer stage efficiency at the coldplate temperature (%)
TSE - Transformer stage efficiency at 100° C (%)
RSET - Rectifier stage efficiency at the coldplate temperature (%)
RSE - Rectifier stage efficiency at 100° C (%)
FSET - Filter stage efficiency at the coldplate temperature (%)
FSE - Filter stage efficiency at 100° C (%)
RBET - RBI/RPC efficiency at the coldplate temperature (%)
RBE - RBI/RPC efficiency at 100° C (%)

These temperature corrected efficiencies were incorporated into the component models and used to adjust the calculated end-to-end efficiency of the complete component. This efficiency determines the total component power losses, and affects the calculated size of the associated electronics radiator. Finally, because these corrected efficiencies interact, it caused minor adjustments in the masses of the component stages.

APPENDIX B

End-to-End PMAD Model

Also includes
Temporary Driver Module,
Common Block Module,
and
Print Output Module

```
      SUBROUTINE PMAD
C
C =====================================================================
C
C    PMAD SYSTEM DESIGN CODE
C
C    Revised: 4/27/1992      tcn
C
C    Author:  Ken Metcalf,  (818) 586-3976
C
C Inputs:
C  TOP LEVEL:
C    AOF     Alternator Operating Frequency (kHz)
C    APC     Available PMAD Channels
C    CPT     Electronics Coldplate Temperature (C)
C    CRTD    Electronics Coldplate to Radiator Temperature Delta (C)
C    KRA     Variable to Select Counter Rotating Alternators
C    IDPPU   Type of PPU (1=ion w/o transformer; 2=ion w/ transformer;
C                    3=mpd PPU)
C    NAC     Number of Alternators per PMAD Channel
C    NTC     Number of Thrusters per PMAD Channel
C    PMADPO  PMAD System Power Output (kWe)
C    PPUVI   Power Processing Unit Input Voltage (Vrms)
C    RPC     Required PMAD Channels
C    RST     Electronics Radiator Sink Temperature (K)
C  ALL PPU:
C     PPAM    Power Processing Unit Available Modules
C     PPRM    Power Processing Unit Required Modules
C     IFE     Power Processing Unit Input Filter Efficiency (frac)
C     RF      Ripple Factor (frac)
C  PPU1 & PPU2:
C     BOV     Beam Supply Output Voltage (Vdc)
C     DOV     Discharge Supply Output Voltage (Vdc)
C     AOV     Accelerator Supply Output Voltage (Vdc)
C     NOV     Neutralizer Supply Output Voltage (Vdc)
C     ATE     Accelerator Power Supply Transformer Efficiency (frac)
C     ARE     Accelerator Power Supply Rectifier Efficiency (frac)
C     AFE     Accelerator Power Supply Filter Efficiency (frac)
C     BRE     Beam Power Supply Rectifier Efficiency (frac)
C     BFE     Beam Power Supply Filter Efficiency (frac)
C     DRE     Discharge Power Supply Rectifier Efficiency (frac)
C     DFE     Discharge Power Supply Filter Efficiency (frac)
C     NFE     Neutralizer Power Supply Filter Efficiency (frac)
C     NRE     Neutralizer Power Supply Rectifier Efficiency (frac)
C PPU1:
C     DTE     Discharge Power Supply Transformer Efficiency (frac)
C     NTE     Neutralizer Power Supply Transformer Efficiency (frac)
C PPU2:
C     BTE     Beam Power Supply Transformer Efficiency (fract)
C     DT1E    Discharge Power Supply Transformer #1 Efficiency (fract)
C     DT2E    Discharge Power Supply Transformer #2 Efficiency (fract)
C     NT1E    Neutralizer Power Supply Transformer #1 Efficiency (frac)
C     NT2E    Neutralizer Power Supply Transformer #2 Efficiency (frac)
C PPU3:
C     PPOV    Power Processing Unit Output Voltage Level (Vrms)
```

```
C     TE     Transformer Efficiency (frac)
C     RE     Rectifier Efficiency (frac)
C     OFE    Output Filter Efficiency (frac)
C  TRANSMISSION LINE:
C    TLE  (= 0.98)  Transmission Line Efficiency
C    TLL  (= 150.)  Transmission Line Length, m
C    ATC  (=   1.)  Available Transmission Circuits
C    RTC  (=   1.)  Required Transmission Circuits
C    NOB  (=   7.)  Number of Bundles
C    LPF  (=   .9)  Load Power Factor
C  AC SWITCHGEAR:
C     RBE    RBI Unit Efficiency at 100 C (fraction)
C     SWAM   Switchgear Available Modules
C     SWRM   Switchgear Required Modules
C  PHASE LOCK TRANSFORMER:
C     PTAM   Phase Lock Transformer Available Modules
C     PTPP   Phase Lock Transformer Power Percentage (fraction)
C     PTRM   Phase Lock Transformer Required Modules
C     TSE    Transformer Stage Efficiency at 100 C (%)
C  ALTERNATOR SPEED REGULATOR:
C     SRAM   Speed Regulator Available Modules
C     SRRM   Speed Regulator Required Modules
C     NSS    Number of Shunt Switch Elements
C     SRF    Shunt Redundancy Factor (frac)
C     PWMF   Pulse-Width-Modulation Frequency (kHz)
c     BCE    Bus Conductor Efficiency at 100 C (frac)
C     SSE    Shunt Switch Efficiency at 100 C (frac)
C     EFE    EMI Filter Efficiency at 100 C (frac)
C  PARASITIC LOAD RADIATOR:
C     APM    Available Parasitic Load Radiator Modules
C     RPM    Required Parasitic Load Radiator Modules
C     PWOT   PLR Wire Operating Temperature (K)
C     WRTD   Wire to Radiating Surface Temperature Delta (K)
C     PST    Parasitic Load Radiator Sink Temperature (K)
C     CCD    Carbon-Carbon Density (g/cm3)
C     ND     Nichrome V Density (g/cm3)
C     NR     Nicrome V Resistivity (ohms-cm2/meter)
C     NRTC   Nicrome V Resistivity Temperature Coefficient (/C)
C
C
C  Outputs:
C     EEPE   End-to-End PMAD System Efficiency (%)
C     TERA   Total Electronics Radiator Area (m2)
C     TERM   Total Electronics Radiator Mass (kg)
C     TPCM   Total Power Conditioning Component Mass (kg)
C     TPM    Total PMAD System Mass (kg)
C     TPSM   Total PMAD System Specific Mass (kg/kWe)
C     TTLM   Total Transmission Line Mass (kg)
C
C ==========================================================
C
      INCLUDE "COMMONS.FOR"
C
C
C     IDPPU SHOULD BE 1, 2, OR 3.  SET TO 3 OTHERWISE
```

```
C
      IF (IDPPU .NE. 1 .AND. IDPPU .NE. 2 .AND. IDPPU .NE. 3) IDPPU=3
C
C     CHECK FOR VALIDITY OF NO. OF PMAD CHANNELS REQUIRED
C
      IF (RPC .GT. APC) THEN
         RPC=APC
         WRITE (6,99001) RPC
99001    FORMAT (/1X,'* WARNING! INPUT INVALID RPC IN PMAD. ',
     &           ' SET RPC = APC = ', F3.0/)
      ENDIF
C
C     CHECK FOR VALID NO. OF ALTERNATOR (EVEN NAC IS REQUIRED IF KRA=1)
C
      NACHAF=NAC/2.
      IF (KRA.EQ.1 .AND. NAC.GT. 2.*NACHAF) THEN
         NAC=NAC+1.
         WRITE (6,99002) NAC
99002    FORMAT (/1X,'* WARNING! INVALID INPUT NAC IN PMAD. ',
     &          ' SET NO. OF ALTERNATORS = ', F3.0/)
      ENDIF

C *************  POWER PROCESSING UNIT (PPU) design  *****************
C     (PPU input voltage, PPIV, is specified for ionpu2 & mpdppu.
C      PPIV is calculated for ionpu1---PPU w/o transformer )
C
C
C     Power Processing Unit Input Power (kwe) & Voltage (Vrms)
C
      PPIP=PMADPO/RPC/NTC
      IF (IDPPU.NE.1) PPIV=PPUVI
      IF ( IDPPU.EQ.1 ) CALL IONPU1
      IF ( IDPPU.EQ.2 ) CALL IONPU2
      IF ( IDPPU.EQ.3 ) CALL MPDPPU
C
C ********  PPU-to-Switchgear TRANSMISSION LINE design  ********
C
      PSTLOP=PPIP
      PSTLOV=PPIV

      TLOP=PSTLOP
      TLOV=PSTLOV
      TLL=PSTLL
      TLE=PSTLE
      ATC=PSATC
      RTC=PSRTC
      NOB=PSNOB
      LPF=PSLPF

      CALL LWTRLN

      PSTLM=CM
      PSTLIP=TLIP
      PSTLIV=TLIV
      PSCJOR=CJOR
```

```
      PSCJST=CJST
      PSTLCT=TLCT
      PSTLE=TLE
      PSPF=PF
C
C ******************  SWITCHGEAR design  **********************
C
C     Switchgear Unit Numbers of Input and Output RBIs
C
      NIRB = NAC
      NORB = NTC
C
C     Output RBI Output  Power (kwe) & Voltage (Vrms)
C
      ORBOP=PSTLIP
      ORBOV=PSTLIV

      CALL ACSWGR

      SWIBIP=IRBIP
      SWIBIV=IRBIV
      SWXBIP=XRBIP
      SWXBIV=XRBIV
C
C ******  Switchgear-to-Switchgear TRANSMISSION LINE design   ******
C
      SSTLOP=SWXBIP
      SSTLOV=SWXBIV

      TLOP=SSTLOP
      TLOV=SSTLOV
      TLL=SSTLL
      TLE=SSTLE
      ATC=SSATC
      RTC=SSRTC
      NOB=SSNOB
      LPF=SSLPF

      CALL LWTRLN

      SSTLM=CM
      SSTLIP=TLIP
      SSTLIV=TLIV
      SSCJOR=CJOR
      SSCJST=CJST
      SSTLCT=TLCT
      SSTLE=TLE
      SSPF=PF
C
C ******  Alternator-to-Switchgear TRANSMISSION LINE design   ******
C
      SATLOP=SWIBIP
      SATLOV=SWIBIV

      TLOP=SATLOP
```

```
      TLOV=SATLOV
      TLL=SATLL
      TLE=SATLE
      ATC=SAATC
      RTC=SARTC
      NOB=SANOB
      LPF=SALPF

      CALL LWTRLN

      SATLM=CM
      SATLIP=TLIP
      SATLIV=TLIV
      SACJOR=CJOR
      SACJST=CJST
      SATLCT=TLCT
      SATLE=TLE
      SAPF=PF
C
C     ALTERNATOR OUTPUT power (kwe) & voltage (Vrms)
C
      APO=SATLIP
      AVO=SATLIV
C
C ***************** PHASE LOCK TRANSFORMER design    ***************
C
      IF (KRA .EQ. 1) THEN

        CALL TRNFMR

C
C     BYPASS TRANSFORMER IF COUNTER ROTATING ALTERNATORS IS NOT SELETED
C
      ELSE
        PTRA=0.
        PTM=0.
        PTRAM=0.
      ENDIF
C
C ************** ALTERNATOR SPEED REGULATOR  design    ***************
C
      CALL SPDREG

        SRSPO=SPO
        SRSVO=SVO
C
C ********* Shunt regulator to PLR TRANSMISSION LINE design  *********
C     (Known input power & voltage.  Calculate output power & Voltage)

      SPTLIP=SRSPO
      SPTLIV=SRSVO
      ISP=0
C
C     ASSUME INITIAL VALUES FOR SPTLOP & SPTLOV
C
```

```
      IF (SPTLE .EQ. 0.) SPTLE = 0.85
170   SPTLOP=SPTLIP*SPTLE
      SPTLOV=SPTLIV*SPTLE

      TLOP=SPTLOP
      TLOV=SPTLOV
      TLL=SPTLL
      TLE=SPTLE
      ATC=SPATC
      RTC=SPRTC
      NOB=SPNOB
      LPF=SPLPF

      CALL LWTRLN

C
C     ADJUST SPTLE UNTIL DELTAT CONVERGED WITHIN .001%
C
      DELTAT=SPTLE-TLE
      IF (ABS(DELTAT) .GT. 1.E-5) THEN
        ISP=ISP+1
        IF (ISP .LE. 50) THEN
          SPTLE=TLE
          GOTO 170
        ENDIF
        WRITE (*,*) ' WARNING IN PMAD! SPTLE ITERATIONS EXCEED 50'
      ENDIF

      SPTLIP=TLIP
      SPTLIV=TLIV
      SPTLM=CM
      SPCJOR=CJOR
      SPCJST=CJST
      SPTLCT=TLCT
      SPTLE=TLE
      SPPF=PF

      SPTLOP=TLOP
      SPTLOV=TLOV

C
C *************** PARASITIC LOAD RADIATOR design ***************
C
C     PLR Power Dissipation Level (kWe) & Input Voltage Level (Vrms)
C
      PPD=SPTLOP
      PIV=SPTLOV
C
C     PLR No. of Resistive Circuits & Resistive Circuit Redundancy Fact
C
      NRC=NSS
      RCRF=SRF
C
C     SIZE & WEIGH THE PLR
C
```

```
      CALL ACPLR
C****************************** SUMMARY   ****************************
C
C      PMAD SYSTEM END-TO-END EFFICIENCY
C
      EEPE=PPE*PSTLE*SWE*SATLE
C
C      PMAD SYSTEM ELECTRONICS RADIATOR AREA, M**2
C
      TERA=APC*(NTC*PPRA + SWRA + NAC/2.*PTRA + NAC*SRRA)
C
C      PMAD SYSTEM TOTAL POWER CONDITIONING COMPONENT MASS, KG
C
      TPCM=APC*(NTC*PPM + SWM + NAC/2.*PTM + NAC*(SRM+TPLRM))
C
C      PMAD SYSTEM TOTAL TRANSMISSION LINE MASS, KG
C
      TTLM=APC*(NTC*PSTLM + SSTLM + NAC*(SATLM+SPTLM))
C
C      PMAD SYSTEM ELECTRONICS RADIATOR MASS, KG
C
      TERM=APC*(NTC*PPRAM + SWRAM + NAC/2.*PTRAM + NAC*SRRAM)
C
C      TOTAL PMAD SYSTEM  MASS, KG
C
      TPM=TPCM + TTLM + TERM
C
C      TOTAL PMAD SYSTEM  SPECIFIC MASS, KG/KWE
C
      TPSM=TPM/(RPC*NTC*PPOP)
C
C
      RETURN
      END
```

```
      PROGRAM MAIN
C
C ==========================================================
C
C    DRIVER FOR KEN METCALF'S PMAD SYSTEM OR COMPONENT MODELS
C
C    IDCOMP = 0: End-to-End NEP PMAD System Model
C    IDCOMP = 1: Ion Thruster PPU Model (w/o Beam Supply Transformer)
C    IDCOMP = 2: Ion Thruster PPU Model (with Beam Supply Transformer)
C    IDCOMP = 3: MPD Thruster Power Processing Unit (PPU) Model
C    IDCOMP = 4: Transmission Line Model
C    IDCOMP = 5: AC Switchgear Unit Model
C    IDCOMP = 6: Phase Lock Transformer Model
C    IDCOMP = 7: Alternator Speed Regulator Model
C    IDCOMP = 8: AC Parasitic Load Radiator Model
C
C    Revised: 5/05/1992 jam
C
C ==========================================================
C
C
      INCLUDE "COMMONS.FOR"

      LOGICAL DEBUG
      CHARACTER*12 FILIN
      CHARACTER*12 FILOUT, FILDMP
      CHARACTER*4 CHARS(18), BLANK
C
C
      NAMELIST /COMTYP/ IDCOMP, IDEBUG
      NAMELIST /INPUTS/ CPT , CRTD , RST , AOF,
     1 PPIV, PPOV, PPIP, PPAM, PPRM, BOV, DOV, AOV, NOV, RF,
     2 IFE, BRE, BFE, DTE, DRE, DFE, ATE, ARE, AFE, NTE, NRE, NFE,
     3 BTE, DT1E, DT2E, NT1E, NT2E, TE, RE, OFE,
     4 TLOP , TLOV , TLL , ATC , RTC , NOB , LPF , TLE,
     5 NIRB, NORB, ORBOP, ORBOV, RBE, SWAM, SWRM,
     6 APO, AVO, PTAM, PTPP, PTRM, TSE,
     7 SRAM, SRRM, NSS, SRF, PWMF, BCE, SSE, EFE,
     8 PPD , PIV , APM , RPM , PWOT , WRTD , PST ,
     & NRC , RCRF , NR , NRTC , ND , CCD
      NAMELIST /INPMAD/ CPT , CRTD , RST , AOF,
     o PMADPO, PPUVI, APC, RPC, NAC, NTC, KRA, IDPPU,
     1 PPOV, PPAM, PPRM, BOV, DOV, AOV, NOV, RF,
     2 IFE, BRE, BFE, DTE, DRE, DFE, ATE, ARE, AFE, NTE, NRE, NFE,
     3 BTE, DT1E, DT2E, NT1E, NT2E, TE, RE, OFE,
     4 PSTLL , PSATC , PSRTC , PSNOB , PSLPF , PSTLE,
     b SSTLL , SSATC , SSRTC , SSNOB , SSLPF , SSTLE,
     c SATLL , SAATC , SARTC , SANOB , SALPF , SATLE,
     d SPTLL , SPATC , SPRTC , SPNOB , SPLPF , SPTLE,
     5 RBE, SWAM, SWRM,
     6 PTAM, PTPP, PTRM, TSE,
     7 SRAM, SRRM, NSS, SRF, PWMF, BCE, SSE, EFE,
     8 APM , RPM , PWOT , WRTD , PST , NR , NRTC , ND , CCD
C
      DATA BLANK/' '/
```

```
      DATA IDCOMP/1/ , IDEBUG/1/
C
C
C****** read inputs from a data file  *******
C
       CALL SYSTEM ("CLS")
       CALL SYSTEM ("DIR/W *.*")

 100  WRITE (*,*) 'Name of local input data file?  '
      READ (*,99001) FILIN
C
C                  PRINT MAIN HEADER TO SCREEN
C
      CALL SYSTEM ("CLS")
      WRITE (*,1000)
 1000 FORMAT (' ╓┬┬┬┬─────────────────────────────────────────────────────'
     2  '────────────────────────────────────────────────────┬┬┬┬╖ '/
     3  ' ║ │ │ │              PMAD Component '
     4  '& Systems Model               │ │ │ ║ '/
     5  ' ║ │ │ │              Rockwell Internat'
     6  'ional Corporation             │ │ │ ║ '/
     7  ' ║ │ │ │                  Rocketdyne'
     8  ' Division                     │ │ │ ║ '/
     9  ' ║ │ │ │                Ken Metcalf, '
     o  '(818) 586-3976                │ │ │ ║ '/
     1  ' ║ │ │ │                  Revised: '
     2  '05 May 92                     │ │ │ ║ '/
     3  ' ║ │ │ └─────────────────────────────────────────'
     4  '─────────────────────────────────────────┘ │ │ ║ '/
     5  ' ║ │ └──────────────────────────────────────────'
     6  '───────────────────────────────────────────┘ │ ║ '/
     7  ' ║ └────────────────────────────────────────────'
     8  '─────────────────────────────────────────────┘ ║ ')
      WRITE (*,1002)
 1002 FORMAT (' ╙────────────────────────────────────────────────────────'
     2  '───────────────────────────────────────────────────────╜ '//)
C
C       Open Files for Input, output, and dump(debug purpose) data
C
      OPEN (10,FILE=FILIN,FORM='FORMATTED',STATUS='OLD',ERR=200)
      REWIND 10
      JP = index(FILIN,'.')
      IF (JP .EQ. 0) JP = index(FILIN,' ')
      IF (JP .GT. 9) JP = 9
        FILOUT(1:JP-1) = FILIN(1:JP-1)
        FILOUT(JP:JP+3)='.out'
        OPEN (13,FILE=FILOUT)
        REWIND 13
        FILDMP(1:JP-1) = FILIN(1:JP-1)
        FILDMP(JP:JP+3) = '.dmp'
        OPEN (UNIT=11,FILE=FILDMP)
        REWIND 11
      GOTO 300
 200  WRITE (*,*) 'ERROR IN OPENING FILE OR FILE NOT EXIST' , FILIN
      WRITE (*,*) ' TYPE 1 TO CONTINUE AND 0 TO END.'
```

```
      READ (*,*) KONT
      IF ( KONT.EQ.0 ) GOTO 400
      GOTO 100
300   READ (10,320) (CHARS(I),I=1,18)
320   FORMAT (18A4)
      IF (CHARS(1).EQ.'NAME') GO TO 350
      IF (CHARS(1).EQ.'STOP' .OR. CHARS(1).EQ.'stop') GOTO 370
      IF (CHARS(1).EQ.BLANK) GO TO 300
350   READ (10,COMTYP)
      IF (IDCOMP.NE.0) READ (10,INPUTS)
      IF (IDCOMP.EQ.0) READ (10,INPMAD)
C*******************************************************
      IF ( IDCOMP.EQ.0 ) CALL PMAD
      IF ( IDCOMP.EQ.1 ) CALL IONPU1
      IF ( IDCOMP.EQ.2 ) CALL IONPU2
      IF ( IDCOMP.EQ.3 ) CALL MPDPPU
      IF ( IDCOMP.EQ.4 ) CALL LWTRLN
      IF ( IDCOMP.EQ.5 ) CALL ACSWGR
      IF ( IDCOMP.EQ.6 ) CALL TRNFMR
      IF ( IDCOMP.EQ.7 ) CALL SPDREG
      IF ( IDCOMP.EQ.8 ) CALL ACPLR
C*******************************************************
C
C
C     Output TO SCREEN & FILE ID#13
C
      CALL PRINTO (IDCOMP)
C
C
C     Parameter Dump To File 11
C
      DEBUG = .FALSE.
      IF ( IDEBUG.NE.0 ) DEBUG = .TRUE.
      IF ( DEBUG ) THEN
        WRITE (11,99004)
        WRITE (11,COMTYP)
        WRITE (11,INPUTS)
        WRITE (11,INPMAD)
      ENDIF
      GOTO 300
C*******************************************************
  370 CONTINUE
      CLOSE (10)
C
C     OPTION TO RUN ANOTHER CASE
C
C      WRITE (*,*) ' TYPE 1 TO CONTINUE AND 0 TO END.'
C      READ (*,*) KONT
C      IF ( KONT.NE.0 ) GOTO 100
 400  WRITE (*,99002) FILOUT
      IF (DEBUG) WRITE (*,99003) FILDMP
      CLOSE (11)
      CLOSE (13)
99001 FORMAT (A12)
99002 FORMAT (/1X,'     Output File: ',A12/)
```

```
99003 FORMAT (/1X,'Debug Input Print: ',A12/)
99004 FORMAT (//1X,'INPUT NAMELIST:')
      END
C ***********************************************************************
      BLOCKDATA PUINIT
C
C     4/16/92
C     Default Values
C
      INCLUDE "COMMONS.FOR"
C
C     Default Values for PMAD system
C
      DATA PMADPO/30000./,PPUVI/5000./, APC,RPC/2*3./, NAC/2./, NTC/4./,
     &     KRA/1/, IDPPU/1/
     & PSATC/1./,PSRTC/1./,PSTLL/10./,PSLPF/.9/,PSNOB/7./,PSTLE/.85/,
     & SSATC/1./,SSRTC/1./,SSTLL/5./,SSLPF/.9/,SSNOB/7./,SSTLE/.85/,
     & SAATC/1./,SARTC/1./,SATLL/150./,SALPF/.9/,SANOB/7./,SATLE/.85/,
     & SPATC/48./,SPRTC/40./,SPTLL/10./,SPLPF/.9/,SPNOB/1./,SPTLE/.85/
C
C     Primary User Input Parameters for power processing units
C
      DATA CPT/100./, CRTD/16.67/ , RST/247.67/ , AOF/0.8/
      DATA PPIP/2500./ , PPAM/1./ , PPRM/1./ , BOV/1800./ , DOV/30./ ,
     &     AOV/500./ , NOV/20./ , RF/0.05/
      DATA PPIV/5000./ , PPOV/300./
C
C     Secondary Primary Input Parameters for PPU
C
      DATA IFE/0.995/ , BRE/0.98/ , BFE/0.995/ , DTE/0.99/ ,
     &     DRE/0.9725/ , DFE/0.992/ , ATE/0.99/ , ARE/0.98/ ,
     &     AFE/0.995/ , NTE/0.99/ , NRE/0.955/ , NFE/0.99/
      DATA BTE/0.99/ , DT1E , DT2E/2*0.99/ , NT1E , NT2E/2*0.99/
      DATA TE/0.99/ , RE/0.98/ , OFE/0.995/
C
C     Default Inputs for Transmission Line Module
C
      DATA TLOP/5000./, TLOV/1367./, ATC,RTC/2*1./, TLE/.9800/
      DATA TLL/150./, LPF/.9/, NOB/7./
C
C      User Input Parameters for AC Switchgear Unit
C
      DATA NIRB/2./, NORB/4./, ORBOP/2500./, ORBOV/5000./
      DATA RBE/0.9985/, SWAM/1./, SWRM/1./
C
C       User Input Parameters for Phase Lock Transformer
C
      DATA APO,AVO/2*5000./, PTPP/0.02/, PTAM/1./, PTRM/1./, TSE/0.99/
C
C       User Input Parameters for alternator Speed Regulator model
C
      DATA SRAM/1./, SRRM/1./, NSS/40./, SRF/1.2/
      DATA PWMF/20./, BCE/0.9965/, SSE/0.9945/, EFE/0.9993/
C
C       User Input Parameters for AC Parasitic Load Radiator Model
```

```
C
      DATA PPD/5000./, PIV/5000./, APM/1./, RPM/1./,
     &    PWOT/1255./, WRTD/100./, PST/247.67/
      DATA NRC/40./, RCRF/1.2/, NR/1.0806E-02/, NRTC/0.00011/,
     &    ND/8.4296/, CCD/1.66/
      END
```

```
C COMMONS.FOR
C 4/14/92
C
      REAL NSS
      REAL NOB, LPF
      REAL IRBIP, IRBIV, IRBM, IRBOP, IRBOV, NIRB, NORB
      REAL ND , NR , NRC , NRTC
      REAL IFE , NFE , NOV, NRE , NTE , NT1E , NT2E
      REAL NAC, NTC
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /PMADI/ PMADPO, PPUVI, APC, RPC, NAC, NTC, KRA, IDPPU
      COMMON /PMADO/ EEPE, TERA, TPCM, TTLM, TERM, TPM, TPSM
C
      COMMON /PPUIN/ PPIP, PPAM, PPRM, RF, IFE
      COMMON /PPUI12/ BOV, DOV, AOV, NOV, ATE, ARE, AFE, BRE, BFE,
     2            DRE, DFE, NRE, NFE
      COMMON /PPUI1/  DTE ,NTE
      COMMON /PPUI2/  BTE , DT1E , DT2E , NT1E , NT2E
      COMMON /PPU123/ PPIV
      COMMON /PPUI3/ PPOV , TE , RE , OFE
      COMMON /PPUOUT/ PPM, PPSM, PPMR, PPSMR, PPE, PPBE, PPOP,
     &            PPRAM, PPRA, PPCACV, PPCACH, PPCACW, PPCACL
C
      COMMON /TRANIO/ TLOP, TLOV, TLL, ATC, RTC, NOB, LPF,
     o            CM , TLIP , TLIV , CJOR , CJST , TLCT , TLE , PF
      COMMON /TRANSL/
     1      PSTLOP, PSTLOV, PSTLL, PSATC, PSRTC, PSNOB, PSLPF,
     &       PSTLM, PSTLIP, PSTLIV, PSCJOR, PSCJST, PSTLCT, PSTLE, PSPF,
     2      SSTLOP, SSTLOV, SSTLL, SSATC, SSRTC , SSNOB, SSLPF,
     &       SSTLM, SSTLIP, SSTLIV, SSCJOR, SSCJST, SSTLCT, SSTLE, SSPF,
     3      SATLOP, SATLOV, SATLL, SAATC, SARTC, SANOB, SALPF,
     &       SATLM, SATLIP, SATLIV, SACJOR, SACJST, SATLCT, SATLE, SAPF,
     4      SPTLOP, SPTLOV,  SPTLL, SPATC, SPRTC, SPNOB, SPLPF,
     &       SPTLM, SPTLIP, SPTLIV, SPCJOR, SPCJST, SPTLCT, SPTLE, SPPF
      COMMON /ACSWIO/ NIRB, NORB, ORBOP, ORBOV, RBE, SWAM, SWRM,
     o            IRBIP, IRBIV, IRBM, IRBOP, IRBOV, ORBM,
     &             XRBIP, XRBIV, XRBM, XRBOP, XRBOV,
     o            SWM, SWSM, SWMR, SWSMR, SWE
     &             , SWRAM, SWRA, SWCACV, SWCACH, SWCACW, SWCACL
      COMMON /TRNREG/ APO , AVO
      COMMON /TRNFIO/ PTAM , PTPP , PTRM , TSE ,
     o            PTM , PTSM , PTMR , PTSMR , PTE
     &             , PTRAM, PTRA, PTCACV, PTCACH, PTCACW, PTCACL
      COMMON /SREGIO/ SRAM, SRRM, NSS, SRF, PWMF, BCE, SSE, EFE,
     o            SPO, SVO, SRM, SRSM, SRMR, SRSMR, FSE
     &             , SRRAM, SRRA, SRCACV, SRCACH, SRCACW, SRCACL
      COMMON /RADIO / PPD , PIV , APM , RPM , PWOT , WRTD , PST ,
     i            NR , NRTC , ND , CCD ,
     i            NRC , RCRF ,
     o            TPLRA , TPLRM , TPLRSM
```

```
      SUBROUTINE PRINTO (IDCOMP)
C
C =============================================================
C
C     PRINT OUTPUT FOR KEN METCALF'S PMAD system & component MODELS
C     TO SCREEN ID#6 & FILE ID#13
C
C     IDCOMP = 0: End-to-End NEP PMAD System Model
C     IDCOMP = 1: Ion Thruster PPU Model (w/o Beam Supply Transformer)
C     IDCOMP = 1: Ion Thruster PPU Model (w/o Beam Supply Transformer)
C     IDCOMP = 2: Ion Thruster PPU Model (with Beam Supply Transformer)
C     IDCOMP = 3: MPD Thruster Power Processing Unit (PPU) Model
C     IDCOMP = 4: Transmission Line Model
C     IDCOMP = 5: AC Switchgear Unit Model
C     IDCOMP = 6: Phase Lock Transformer Model
C     IDCOMP = 7: Alternator Speed Regulator Model
C     IDCOMP = 8: AC Parasitic Load Radiator Model
C
C     Revised: 17 Apr 92 (JAM)
C
C =============================================================
C
      INCLUDE "COMMONS.FOR"
      CHARACTER*1  PAGF
      CHARACTER*20 PPUTYP(3)
      LOGICAL OFILE
C
C      DATA ISCRN/6/, IFILO/13/
      DATA IPRT/0/
      DATA PPUTYP /'Ion w/o Transformer', 'Ion w/ Transformer ',
     &            '       MPD          '/
C
C        PAGF = CHAR(12)
         PAGF = '1'
C
      IPRT=IPRT+1
      IF (IPRT .GT. 1) WRITE (13,99049) PAGF
C
C      OUTPUT TO SCREEN(IU=6) THEN TO FILE #13
C
      OFILE = .FALSE.
      IU=13
C      DO 200 IU=6,13,7
        IF (IU.EQ.13) OFILE = .TRUE.
        WRITE (IU,99050)
        WRITE (IU,99051)
        IF ( IDCOMP.EQ.0 ) WRITE (IU,99000)
        IF ( IDCOMP.EQ.1 ) WRITE (IU,99001)
        IF ( IDCOMP.EQ.2 ) WRITE (IU,99002)
        IF ( IDCOMP.EQ.3 ) WRITE (IU,99003)
        IF ( IDCOMP.EQ.4 ) WRITE (IU,99004)
        IF ( IDCOMP.EQ.5 ) WRITE (IU,99005)
        IF ( IDCOMP.EQ.6 ) WRITE (IU,99006)
        IF ( IDCOMP.EQ.7 ) WRITE (IU,99007)
        IF ( IDCOMP.EQ.8 ) WRITE (IU,99008)
```

```
      WRITE (IU,99052)
C
C      OUTPUTS FOR End-to-End NEP PMAD System Model
C
      IF (IDCOMP .EQ. 0) THEN
        IF (IDPPU.NE.1) WRITE (IU,99059) PPUVI
        WRITE (IU,99060) PMADPO, AOF,
     &       APC, RPC, NAC, NTC, KRA, PPUTYP(IDPPU)
        WRITE (IU,99019) CPT, CRTD, RST
        WRITE (IU,99075) TERA,TERM,TPCM,TTLM,TPM,TPSM,EEPE*100.
        WRITE (IU,99051)
C
        IF (OFILE) WRITE (13,99049) PAGF
        WRITE (IU,99051)
        WRITE (IU,99007)
        WRITE (IU,99051)
        WRITE (IU,99017) SRAM, SRRM, APO, AVO, NSS, SRF*100.,
     &               PWMF, BCE*100., SSE*100., EFE*100.
        WRITE (IU,99027) SRM, SRSM, SRMR, SRSMR, FSE*100.
        WRITE (IU,99030) SRRAM, SRRA, SRCACV, SRCACH, SRCACW, SRCACL
        WRITE (IU,99037) SPO, SVO
        WRITE (IU,99051)
        WRITE (IU,99073)
        WRITE (IU,99051)
        WRITE (IU,99074)
     4  SPTLOP, SPTLOV,  SPTLL, SPATC, SPRTC, SPNOB, SPLPF,
     &   SPTLIP,SPTLIV, SPTLM, SPCJOR,SPCJST,SPTLCT,SPTLE*100.,SPPF
        WRITE (IU,99051)
C
        IF (OFILE) WRITE (13,99049) PAGF
        WRITE (IU,99051)
        WRITE (IU,99008)
        WRITE (IU,99051)
        WRITE (IU,99018) PPD, PIV, APM, RPM, PWOT, WRTD, PST,
     i              NRC, RCRF*100., NR, NRTC, ND, CCD,
     o              TPLRA , TPLRM , TPLRSM
        WRITE (IU,99051)
        IF (KRA.EQ.1) THEN
          WRITE (IU,99006)
          WRITE (IU,99051)
          WRITE (IU,99016) PTAM,PTRM,APO,AVO,PTPP*100.,TSE*100.
          WRITE (IU,99026) PTM, PTSM, PTMR, PTSMR, PTE*100.
          WRITE (IU,99030) PTRAM,PTRA,PTCACV,PTCACH,PTCACW,PTCACL
          WRITE (IU,99051)
        ENDIF
C
        IF (OFILE) WRITE (13,99049) PAGF
        WRITE (IU,99051)
        WRITE (IU,99072)
        WRITE (IU,99051)
        WRITE (IU,99074) SATLOP,SATLOV,SATLL,SAATC,SARTC,SANOB,SALPF
     3  ,SATLIP,SATLIV, SATLM, SACJOR,SACJST,SATLCT,SATLE*100.,SAPF
        WRITE (IU,99051)
        WRITE (IU,99071)
        WRITE (IU,99051)
```

```
      WRITE (IU,99074) SSTLOP,SSTLOV,SSTLL,SSATC,SSRTC,SSNOB,SSLPF
    2 ,SSTLIP,SSTLIV, SSTLM, SSCJOR,SSCJST,SSTLCT,SSTLE*100.,SSPF
      WRITE (IU,99051)
C
      IF (OFILE) WRITE (13,99049) PAGF
      WRITE (IU,99051)
      WRITE (IU,99005)
      WRITE (IU,99051)
      WRITE (IU,99015) SWAM,SWRM,NIRB,NORB,RBE*100.,ORBOP,ORBOV
      WRITE (IU,99035) XRBIP, XRBIV
      WRITE (IU,99025) SWM, SWSM, SWMR, SWSMR, SWE*100.
      WRITE (IU,99030) SWRAM,SWRA,SWCACV,SWCACH,SWCACW,SWCACL
      WRITE (IU,99051)
      WRITE (IU,99070)
      WRITE (IU,99051)
      WRITE (IU,99074) PSTLOP,PSTLOV,PSTLL,PSATC,PSRTC,PSNOB,PSLPF
    1 ,PSTLIP,PSTLIV, PSTLM, PSCJOR,PSCJST,PSTLCT,PSTLE*100.,PSPF
      WRITE (IU,99051)
C
      IF (OFILE) WRITE (13,99049) PAGF
      WRITE (IU,99051)
      IF (IDPPU.EQ.1 ) WRITE (IU,99001)
      IF (IDPPU.EQ.2 ) WRITE (IU,99002)
      IF (IDPPU.EQ.3 ) WRITE (IU,99003)
      WRITE (IU,99051)
      WRITE (IU,99061) PPAM, PPRM, IFE*100., RF*100.
      IF (IDPPU.EQ.3) THEN
        WRITE (IU,99065) TE*100.,RE*100.,OFE*100.,
     &          PPIP,PPIV,PPOV, PPOP
      ELSE
        WRITE (IU,99062) BOV,DOV,AOV,NOV,
     &          ARE*100.,AFE*100.,ATE*100., BRE*100.,BFE*100.
      ENDIF
      IF (IDPPU.EQ.1) WRITE (IU,99063) DRE*100.,DFE*100.,DTE*100.,
     &     NRE*100.,NFE*100.,NTE*100.,PPIP,PPIV,PPOP
      IF (IDPPU.EQ.2) WRITE (IU,99064) BTE*100.,
     &     DRE*100.,DFE*100.,DT1E*100.,DT2E*100.,
     &     NRE*100.,NFE*100.,NT1E*100.,NT2E*100., PPIP,PPIV,PPOP

      WRITE (IU,99020) PPM , PPSM , PPMR , PPSMR , PPE*100.
      IF (IDPPU.NE.3)  WRITE (IU,99021) PPBE*100.
      WRITE (IU,99030) PPRAM, PPRA, PPCACV, PPCACH, PPCACW, PPCACL
     ENDIF
C
C   OUTPUTS FOR Ion POWER PROCESSING UNIT w/o Beam Supply Transformer
C
    IF (IDCOMP .EQ. 1) THEN
      WRITE (IU,99009) AOF, PPIP
      WRITE (IU,99061) PPAM, PPRM, IFE*100., RF*100.
      WRITE (IU,99062) BOV,DOV,AOV,NOV,
     &          ARE*100.,AFE*100.,ATE*100., BRE*100.,BFE*100.
      WRITE (IU,99063) DRE*100.,DFE*100.,DTE*100.
     &          ,NRE*100.,NFE*100.,NTE*100., PPIP, PPIV,PPOP
      WRITE (IU,99019) CPT, CRTD, RST
      WRITE (IU,99020) PPM , PPSM , PPMR , PPSMR , PPE*100.
```

```
        WRITE (IU,99021) PPBE*100.
        WRITE (IU,99030) PPRAM, PPRA, PPCACV, PPCACH, PPCACW, PPCACL
      ENDIF
C
C     OUTPUTS FOR Ion POWER PROCESSING UNIT with Beam Supply Transformer
C
      IF (IDCOMP .EQ. 2) THEN
        WRITE (IU,99029) PPIV
        WRITE (IU,99009) AOF, PPIP
        WRITE (IU,99061) PPAM, PPRM, IFE*100., RF*100.
        WRITE (IU,99062) BOV,DOV,AOV,NOV,
     &               ARE*100.,AFE*100.,ATE*100., BRE*100.,BFE*100.
        WRITE (IU,99064) BTE*100.,
     &          DRE*100.,DFE*100.,DT1E*100.,DT2E*100.,
     &          NRE*100.,NFE*100.,NT1E*100.,NT2E*100., PPIP,PPIV,PPOP
        WRITE (IU,99019) CPT, CRTD, RST
        WRITE (IU,99020) PPM , PPSM , PPMR , PPSMR , PPE*100.
        WRITE (IU,99021) PPBE*100.
        WRITE (IU,99030) PPRAM, PPRA, PPCACV, PPCACH, PPCACW, PPCACL
      ENDIF
C
C     OUTPUTS FOR MPD POWER PROCESSING UNIT
C
      IF ( IDCOMP.EQ.3 ) THEN
        WRITE (IU,99029) PPIV
        WRITE (IU,99009) AOF, PPIP
        WRITE (IU,99061) PPAM, PPRM, IFE*100., RF*100.
        WRITE (IU,99065) TE*100.,RE*100.,OFE*100.,PPIP,PPIV,PPOV,PPOP
        WRITE (IU,99019) CPT, CRTD, RST
        WRITE (IU,99020) PPM , PPSM , PPMR , PPSMR , PPE*100.
        WRITE (IU,99030) PPRAM, PPRA, PPCACV, PPCACH, PPCACW, PPCACL
      ENDIF
C
C     PRINT OUTPUTS FOR Transmission Line Model
C
      IF (IDCOMP .EQ. 4) THEN
        WRITE (IU,99014) AOF
        WRITE (IU,99074) TLOP,TLOV,TLL,ATC,RTC,NOB,LPF,
     o       TLIP , TLIV , CM, CJOR , CJST , TLCT , TLE*100. , PF
      ENDIF
C
C     PRINT OUTPUTS FOR AC SWITCHGEAR UNIT
C
      IF (IDCOMP .EQ. 5) THEN
        WRITE (IU,99015) SWAM,SWRM,NIRB,NORB,RBE*100.,ORBOP,ORBOV
        WRITE (IU,99019) CPT, CRTD, RST
        WRITE (IU,99025) SWM, SWSM, SWMR, SWSMR, SWE*100.
        WRITE (IU,99030) SWRAM, SWRA, SWCACV, SWCACH, SWCACW, SWCACL
      ENDIF
C
C     PRINT OUTPUTS FOR Phase Lock Transformer Model
C
      IF (IDCOMP .EQ. 6) THEN
        WRITE (IU,99014) AOF
        WRITE (IU,99016) PTAM, PTRM, APO, AVO, PTPP*100., TSE*100.
```

```
         WRITE (IU,99019) CPT, CRTD, RST
         WRITE (IU,99026) PTM, PTSM, PTMR, PTSMR, PTE*100.
         WRITE (IU,99030) PTRAM, PTRA, PTCACV, PTCACH, PTCACW, PTCACL
      ENDIF
C
C     PRINT OUTPUTS FOR  Alternator Speed Regulator Model
C
      IF (IDCOMP .EQ. 7) THEN
         WRITE (IU,99017) SRAM, SRRM, APO, AVO, NSS, SRF*100.,
     &         PWMF, BCE*100., SSE*100., EFE*100.
         WRITE (IU,99019) CPT, CRTD, RST
         WRITE (IU,99027) SRM, SRSM, SRMR, SRSMR, FSE*100.
         WRITE (IU,99030) SRRAM, SRRA, SRCACV, SRCACH, SRCACW, SRCACL
      ENDIF
C
C     PRINT OUTPUTS FOR AC Parasitic Load Radiator Model
C
      IF (IDCOMP .EQ. 8) THEN
         WRITE (IU,99018) PPD , PIV , APM , RPM , PWOT , WRTD , PST ,
     i                NRC , RCRF*100. , NR , NRTC , ND , CCD ,
     o                TPLRA , TPLRM , TPLRSM
      ENDIF
C
C     PRINT OUTPUTS FOR ALL INDIVIDUAL MODELS
C
      WRITE (IU,99051)

C200  CONTINUE
      RETURN
C
C
99049 FORMAT (A1)
99050 FORMAT (1H1)
99051 FORMAT (
     &7X,'*****************************************************************')
99052 FORMAT (
     &7X,'*                                                       *'/
     &7X,'*           Rockwell International Corporation          *'/
     &7X,'*                  Rocketdyne Division                  *'/
     &7X,'*                  Revised: 17 Apr 92                   *'/
     &7X,'*****************************************************************'/)
99000 FORMAT (
     &7X,'*            An End-to-End NEP PMAD System              *'/
     &7X,'*             (Radiator Designed for LEO)               *')
99001 FORMAT (
     &7X,'*        Ion Thruster Power Processing Unit (PPU)       *'/
     &7X,'*             (w/o Beam Supply Transformer)             *'/
     &7X,'*             (Radiator Designed for LEO)               *')
99002 FORMAT (
     &7X,'*        Ion Thruster Power Processing Unit (PPU)       *'/
     &7X,'*             (with Beam Supply Transformer)            *'/
     &7X,'*             (Radiator Designed for LEO)               *')
99003 FORMAT (
     &7X,'*        MPD Thruster Power Processing Unit (PPU)       *'/
     &7X,'*             (Radiator Designed for LEO)               *')
```

```
99004 FORMAT (
    &7X,'*              Transmission Line Design              *')
99070 FORMAT(
    &7X,'*        PPU-to-Switchgear TRANSMISSION LINE          *')
99071 FORMAT(
    &7X,'*      Switchgear-to-Switchgear TRANSMISSION LINE     *')
99072 FORMAT(
    &7X,'*      Alternator-to-Switchgear TRANSMISSION LINE     *')
99073 FORMAT(
    &7X,'*      Shunt-Regulator-to-PLR TRANSMISSION LINE       *')
99005 FORMAT (
    &7X,'*                 AC Switchgear Unit                 *'/
    &7X,'*            (Radiator Designed for LEO)             *')
99006 FORMAT (
    &7X,'*               Phase Lock Transformer               *'/
    &7X,'*            (Radiator Designed for LEO)             *')
99007 FORMAT (
    &7X,'*             Alternator Speed Regulator             *'/
    &7X,'*            (Radiator Designed for LEO)             *')
99008 FORMAT (
    &7X,'*          AC Parasitic Load Radiator (PLR)          *'/
    &7X,'*            (Radiator Designed for LEO)             *')
99059 FORMAT (
    &7X,'Power Processing Unit Input Voltage ....... ',F9.2,' Vrms')
99060 FORMAT (
    &7X,'PMAD System Power Output ................... ',F9.3,' kwe'/
    &7X,'Alternator Operating Frequency ............ ',F9.3,' kHz'/
    &7X,'Available PMAD Channels .................. ',F9.0/
    &7X,'Required PMAD Channels ................... ',F9.0/
    &7X,'Number of Alternators per PMAD Channel ..... ',F9.0/
    &7X,'Number of Thrusters per PMAD Channel ....... ',F9.0/
    &7X,'Counter Rotating Alternators Flag? (1=Yes)  ',I9/
    &7X,'Type of Power Processing Unit? ............ ',A20)
99061 FORMAT (/
    &7X,'PPU Available Modules ..................... ',F9.0/
    &7X,'PPU Required Modules ...................... ',F9.0/
    &7X,'PPU Input Filter Efficiency ................ ',F9.2,' %'/
    &7X,'Ripple Factor ............................ ',F9.2,' %')
99062 FORMAT (
    &7X,'Beam Supply Output Voltage ................ ',F9.2,' Vdc'/
    &7X,'Discharge Supply Output Voltage ........... ',F9.2,' Vdc'/
    &7X,'Accelerator Supply Output Voltage ......... ',F9.2,' Vdc'/
    &7X,'Neutralizer Supply Output Voltage ......... ',F9.2,' Vdc'/
    &7X,'Accelerator Power Supply Rectifier Effi..... ',F9.2,' %'/
    &7X,'Accelerator Power Supply Filter Efficiency . ',F9.2,' %'/
    &7X,'Accelerator Power Supply Transformer Effi... ',F9.2,' %'/
    &7X,'Beam Power Supply Rectifier Efficiency  ... ',F9.2,' %'/
    &7X,'Beam Power Supply Filter Efficiency ....... ',F9.2,' %')
99063 FORMAT (
    &7X,'Discharge Power Supply Rectifier Efficiency  ',F9.2,' %'/
    &7X,'Discharge Power Supply Filter Efficiency ... ',F9.2,' %'/
    &7X,'Discharge Power Supply Transformer Effi..... ',F9.2,' %'/
    &7X,'Neutralizer Power Supply Rectifier Effi..... ',F9.2,' %'/
    &7X,'Neutralizer Power Supply Filter Efficiency  ',F9.2,' %'/
    &7X,'Neutralizer Power Supply Transformer Effi... ',F9.2,' %'/
```

```
     &7X,'PPU Input Power Level ..................... ',F9.3,' kwe'//
     &7X,'PPU Input Voltage Level ................... ',F9.2,' Vrms'/
     &7X,'PPU Output Power Level .................... ',F9.3,' kwe'/)
99064 FORMAT (
     &7X,'Beam Power Supply Transformer Efficiency ... ',F9.2,' %'/
     &7X,'Discharge Power Supply Rectifier Effi....... ',F9.2,' %'/
     &7X,'Discharge Power Supply Filter Efficiency ... ',F9.2,' %'/
     &7X,'Discharge Power Supply Transformer #1 Effi.. ',F9.2,' %'/
     &7X,'Discharge Power Supply Transformer #2 Effi.. ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Rectifier Effi..... ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Filter Efficiency . ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Transformer #1 Effi ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Transformer #2 Effi ',F9.2,' %'/
     &7X,'PPU Input Power Level ..................... ',F9.3,' kwe'/
     &7X,'PPU Input Voltage Level ................... ',F9.2,' Vrms'//
     &7X,'PPU Output Power Level .................... ',F9.3,' kwe'/)
99065 FORMAT (
     &7X,'Transformer Efficiency .................... ',F9.2,' %'/
     &7X,'Rectifier Efficiency ...................... ',F9.2,' %'/
     &7X,'Output Filter Efficiency .................. ',F9.2,' %'/
     &7X,'PPU Input Power Level ..................... ',F9.3,' kwe'/
     &7X,'PPU Input Voltage Level ................... ',F9.2,' Vrms'/
     &7X,'PPU Output Voltage Level .................. ',F9.2,' Vrms'//
     &7X,'PPU Output Power Level .................... ',F9.3,' kwe'/)
99074 FORMAT (
     &7X,'Transmission Line Output Power Level ....... ',F9.3,' kWe'/
     &7X,'Transmission Line Output Voltage .......... ',F9.2,' Vrms'/
     &7X,'Transmission Line Length .................. ',F9.2,' m'/
     &7X,'Available Transmission Circuits ........... ',F9.0/
     &7X,'Required Transmission Circuits ............ ',F9.0/
     &7X,'Number of Bundles ......................... ',F9.0/
     &7X,'Load Power Factor ......................... ',F9.2//
     &7X,'Transmission Line Input Power ............. ',F9.3,' kWe'/
     &7X,'Transmission Line Input Voltage ........... ',F9.2,' Vrms'//
     &7X,'Transmission Line Mass .................... ',F9.3,' kg'/
     &7X,'Cable Jacket Outer Radius ................. ',F9.4,' cm'/
     &7X,'Cable Jacket Surface Temperature ........... ',F9.2,' K'/
     &7X,'Transmission Line Conductor Temperature .... ',F9.2,' deg C'/
     &7X,'Transmission Line Efficiency .............. ',F9.2,' %'/
     &7X,'Circuit Power Factor ...................... ',F9.4/)
99075 FORMAT (
     &7X,'Total Electronics Radiator Area ........... ',F9.4,' m2'/
     &7X,'Total Electronics Radiator Mass ........... ',F9.3,' kg'/
     &7X,'Total Power Conditioning Component Mass   . ',F9.3,' kg'/
     &7X,'Total Transmission Line Mass ............. ',F9.3,' kg'/
     &7X,'Total PMAD System Mass .................... ',F9.3,' kg'/
     &7X,'Total PMAD System Specific Mass ........... ',F9.4,' kg/kWe'/
     &7X,'End-to-End PMAD System Efficiency   ........ ',F9.2,' %'/)

99029 FORMAT (
     &7X,'Power Processing Unit Input Voltage Level .. ',F9.2,' Vrms')
99009 FORMAT (
     &7X,'Power Processing Unit Available Modules .... ',F9.0/
     &7X,'Power Processing Unit Required Modules  .... ',F9.0/
     &7X,'Alternator Operating Frequency ............ ',F9.3,' kHz'/
```

```
     &7X,'PPU Input Power Output Level ............. ',F9.3,' kwe'/
     &7X,'Ripple Factor ............................ ',F9.2,' %')
99010 FORMAT (
     &7X,'Beam Supply Output Voltage ................ ',F9.2,' Vdc'/
     &7X,'Discharge Supply Output Voltage ........... ',F9.2,' Vdc'/
     &7X,'Accelerator Supply Output Voltage ......... ',F9.2,' Vdc'/
     &7X,'Neutralizer Supply Output Voltage ......... ',F9.2,' Vdc')
99011 FORMAT (
     &7X,'PPU Input Filter Efficiency ................ ',F9.2,' %'/
     &7X,'Beam Power Supply Rectifier Efficiency   ... ',F9.2,' %'/
     &7X,'Beam Power Supply Filter Efficiency ....... ',F9.2,' %'/
     &7X,'Discharge Power Supply Transformer Effi ... ',F9.2,' %'/
     &7X,'Discharge Power Supply Rectifier Efficiency  ',F9.2,' %'/
     &7X,'Discharge Power Supply Filter Efficiency ... ',F9.2,' %'/
     &7X,'Accelerator Power Supply Transformer Effi... ',F9.2,' %'/
     &7X,'Accelerator Power Supply Rectifier Effi..... ',F9.2,' %'/
     &7X,'Accelerator Power Supply Filter Efficiency   ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Transformer Effi... ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Rectifier Effi..... ',F9.2,' %'/
     &7X,'Neutralizer Power Supply Filter Efficiency   ',F9.2,' %')
99014 FORMAT (
     &7X,'Alternator Operating Frequency ........... ',F9.3,' kHz')
99015 FORMAT (/
     &7X,'Switchgear Available Modules ............. ',F9.0/
     &7X,'Switchgear Required Modules ............... ',F9.0/
     &7X,'Number of Input Remote Bus Isolators (RBIs)  ',F9.0/
     &7X,'Number of Output RBIs ...................... ',F9.0/
     &7X,'RBI Unit Efficiency at 100 deg C .......... ',F9.2,' %'/
     &7X,'Output RBIs Output Power Level ............ ',F9.3,' kwe'/
     &7X,'Output RBIs Output Voltage Level .......... ',F9.2,' Vrms')
99035 FORMAT (/
     &7X,'Switchgear Cross Tie RBI Input Power ....... ',F9.3,' kWe'/
     &7X,'Switchgear Cross Tie RBI Input Voltage ..... ',F9.2,' Vrms')
99018 FORMAT (/
     &7X,'PLR Power Dissipation Level ............. ',F9.3,' kwe'/
     &7X,'Parasitic Load Radiator Input Voltage Level  ',F9.2,' Vrms'/
     &7X,'Available Parasitic Load Radiator Modules .. ',F9.0/
     &7X,'Required Parasitic Load Radiator Modules  .. ',F9.0/
     &7X,'PLR Wire Operating Temperature ........... ',F9.2,' K'/
     &7X,'Wire to Radiating Surface Temperature Delta  ',F9.2,' K'/
     &7X,'Parasitic Load Radiator Sink Temperature  .. ',F9.2,' K'/
     &7X,'Required No. of Nichrome V Circuits   ...... ',F9.2/
     &7X,'Resistive Circuit Redundancy Factor ....... ',F9.2,' %'/
     &7X,'Nichrome V Resistivity   .................. ',E9.4,
     &                                              ' ohm-cm2/m'/
     &7X,'Nichrome V Resistivity Temp Coefficient .... ',E9.4,' /deg C'/
     &7X,'Nichrome V Density  ...................... ',F9.4,' g/cm3'/
     &7X,'Carbon-Carbon Density ..................... ',F9.4,' g/cm3'//
     &7X,'Total Parasitic Load Radiator Surface Area   ',F9.4,' m2'/
     &7X,'Total Parasitic Load Radiator Mass ........ ',F9.3,' kg'/
     &7X,'Total Parasitic Load Radiator Specific Mass  ',F9.4,' kg/kw'/)
99019 FORMAT (
     &7X,'Coldplate Temperature ..................... ',F9.2,' deg C'/
     &7X,'Coldplate to Radiator Temperature Delta .... ',F9.2,' deg C'/
     &7X,'Radiator Sink Temperature ................ ',F9.2,' K'/)
```

```
99020 FORMAT (
    &7X,'PPU Mass w/o  Radiator ..................... ',F9.3,' kg'/
    &7X,'PPU Specific Mass w/o  Radiator ........... ',F9.4,' kg/kw'/
    &7X,'PPU Mass with Radiator .................... ',F9.3,' kg'/
    &7X,'PPU Specific Mass with Radiator ........... ',F9.4,' kg/kw'/
    &7X,'PPU Efficiency ............................ ',F9.2,' %')
99021 FORMAT (
    &7X,'PPU Beam Supply Efficiency Measure ......... ',F9.2,' %')
99025 FORMAT (/
    &7X,'Switchgear Unit Mass w/o  Radiator ........ ',F9.3,' kg'/
    &7X,'Specific Mass w/o  Radiator ................ ',F9.4,' kg/kw'/
    &7X,'Switchgear Unit Mass with Radiator ........ ',F9.3,' kg'/
    &7X,'Specific Mass with Radiator ................ ',F9.4,' kg/kw'/
    &7X,'Switchgear Unit Efficiency ................ ',F9.2,' %')
99016 FORMAT (/
    &7X,'Phase Lock Transformer Available Modules ... ',F9.0/
    &7X,'Phase Lock Transformer Required Modules .... ',F9.0/
    &7X,'Alternator Power Output ................... ',F9.3,' kwe'/
    &7X,'Alternator Voltage Output ................. ',F9.2,' Vrms'/
    &7X,'Phase Lock Transformer Power Percentage .... ',F9.2,' %'/
    &7X,'Transformer Stage Efficiency at 100 deg C    ',F9.2,' %')
99026 FORMAT (/
    &7X,'Phase Lock Transformer Mass w/o  Radiator    ',F9.3,' kg'/
    &7X,'Transformer Specific Mass w/o  Radiator ... ',F9.4,' kg/kw'/
    &7X,'Phase Lock Transformer Mass with Radiator .. ',F9.3,' kg'/
    &7X,'Transformer Specific Mass with Radiator ... ',F9.4,' kg/kw'/
    &7X,'Total Transformer Efficiency ............. ',F9.2,' %')
99017 FORMAT (/
    &7X,'Speed Regulator Available Modules ......... ',F9.0/
    &7X,'Speed Regulator Required Modules .......... ',F9.0/
    &7X,'Alternator Power Output ................... ',F9.3,' kwe'/
    &7X,'Alternator Voltage Output ................. ',F9.2,' Vrms'/
    &7X,'Number of Shunt Switch Elements ........... ',F9.2/
    &7X,'Shunt Redundancy Factor ................... ',F9.2,' %'/
    &7X,'Pulse-Width-Modulation Frequency .......... ',F9.3,' kHz'/
    &7X,'Bus Conductor Efficiency at 100 C ......... ',F9.2,' %'/
    &7X,'Shunt Switch Efficiency at 100 C .......... ',F9.2,' %'/
    &7X,'EMI Filter Efficiency at 100 C ........... ',F9.2,' %')
99027 FORMAT (/
    &7X,'Speed Regulator Mass w/o  Radiator ......... ',F9.3,' kg'/
    &7X,'Regulator Specific Mass w/o  Radiator ...... ',F9.4,' kg/kw'/
    &7X,'Speed Regulator Mass with Radiator ......... ',F9.3,' kg'/
    &7X,'Regulator Specific Mass with Radiator ...... ',F9.4,' kg/kw'/
    &7X,'Fully Shunted Efficiency .................. ',F9.2,' %')
99037 FORMAT (
    &7X,'Shunt Power Output ........................ ',F9.3,' kwe'/
    &7X,'Shunt Voltage Output ...................... ',F9.2,' Vrms'/)
99030 FORMAT (/
    &7X,'Radiator Mass .............................. ',F9.3,' kg'/
    &7X,'Radiator Area .............................. ',F9.4,' m2'/
    &7X,'Complete Assembly Component Volume ......... ',F9.6,' m3'/
    &7X,'Complete Assembly Component Height ......... ',F9.2,' m'/
    &7X,'Complete Assembly Component Width .......... ',F9.2,' m'/
    &7X,'Complete Assembly Component Length ......... ',F9.2,' m'/)
     END
```

APPENDIX C

Ion Power Processing Unit
w/o Beam Power Supply Transformer Model

```
      SUBROUTINE IONPU1
      REAL IFET , IFM , NCCM , NFET , NFM , NOP, NRET, NRM, NTET, NTM
      REAL IFE , NFE , NOV , NRE , NTE
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /PPUIN/ PPIP, PPAM, PPRM, RF, IFE
      COMMON /PPUI12/ BOV, DOV, AOV, NOV, ATE, ARE, AFE, BRE, BFE,
     2              DRE, DFE, NRE, NFE
      COMMON /PPUI1/  DTE ,NTE
      COMMON /PPU123/ PPIV
      COMMON /PPUOUT/ PPM, PPSM, PPMR, PPSMR, PPE, PPBE, PPOP
     &              , RAM, RA , CACV , CACH , CACW , CACL
C
C================================================================
C
C     Ion Power Processing Unit Model
C     - w/o Beam Power Supply Transformer
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92    tcn
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C================================================================
C
C  Inputs:
C     PPIP    Power Processing Unit Input Power Level (kWe)
C     PPAM     Power Processing Unit Available Modules
C     PPRM     Power Processing Unit Required Modules
C     BOV     Beam Supply Output Voltage (Vdc)
C     DOV     Discharge Supply Output Voltage (Vdc)
C     AOV     Accelerator Supply Output Voltage (Vdc)
C     NOV     Neutralizer Supply Output Voltage (Vdc)
C     AOF     Alternator Operating Frequency (kHz)
C     RF     Ripple Factor (frac)
C     CPT     Coldplate Temperature (deg C)
C     CRTD     Coldplate to Radiator Temperature Delta (deg C)
C     RST     Radiator Sink Temperature (deg Kelvin)
C     IFE     Power Processing Unit Input Filter Efficiency (frac)
C     ATE     Accelerator Power Supply Transformer Efficiency (frac)
C     ARE     Accelerator Power Supply Rectifier Efficiency (frac)
C     AFE     Accelerator Power Supply Filter Efficiency (frac)
C     BRE     Beam Power Supply Rectifier Efficiency (frac)
C     BFE     Beam Power Supply Filter Efficiency (frac)
C     DTE     Discharge Power Supply Transformer Efficiency (frac)
C     DRE     Discharge Power Supply Rectifier Efficiency (frac)
C     DFE     Discharge Power Supply Filter Efficiency (frac)
C     NTE     Neutralizer Power Supply Transformer Efficiency (frac)
C     NRE     Neutralizer Power Supply Rectifier Efficiency (frac)
C     NFE     Neutralizer Power Supply Filter Efficiency (frac)
C
C  Outputs:
C     PPIV     Power Processing Unit Input Voltage Level (Vrms)
C     PPOP     Power Processing Unit Total Output Power (kwe)
C     PPM     Power Processing Unit Mass w/o Radiator (kg)
C     PPMR     Power Processing Unit Mass with Radiator (kg)
C     PPSM     Power Processing Unit Specific Mass w/o Radiator (kg/kw)
```

```
C     PPSMR   Power Processing Unit Specific Mass with Radiator (kg/kw)
C     PPE     Power Processing Unit Efficiency (frac)
C     PPBE    Power Processing Unit Beam Supply Effi Measure (frac)
C     RAM     Radiator MASS (KG)
C     RA      Radiator Area (m2)
C     CACV    Complete Assembly Component Volume (m3)
C     CACH    Complete Assembly Component Height (m)
C     CACW    Complete Assembly Component Width (m)
C     CACL    Complete Assembly Component Length (m)
C
C==================================================================
C
C    Primary User Input Parameters for
C    Ion Power Processing Unit w/o Transformer
C
C     PPIP = 2500.
C     PPAM = 1.
C     PPRM = 1.
C     BOV = 1800.
C     DOV = 30.
C     AOV = 500.
C     NOV = 20.
C     AOF = 0.8
C     RF = 0.05
C     CPT = 100.
C     CRTD = 16.67
C     RST = 247.67
C
C    Secondary Primary User Input Parameters for
C    Ion Power Processing Unit w/o Transformer
C     ***RECOMMENDED DEFAULT VALUES***
C
C     IFE = 0.995
C     BRE = 0.98
C     BFE = 0.995
C     DTE = 0.99
C     DRE = 0.9725
C     DFE = 0.992
C     ATE = 0.99
C     ARE = 0.98
C     AFE = 0.995
C     NTE = 0.99
C     NRE = 0.955
C     NFE = 0.99
C
C
C     MAKE SURE REQUIRED MODULES <= AVAILABLE MODULES
C
      IF (PPRM .GT. PPAM) PPRM=PPAM
C
C     Power Supply Stage Efficiency Calculations at Coldplate Temp
C
      IFET = 1. - (1.-IFE)*(0.82+0.0018*CPT)
      BRET = 1. - (1.-BRE)*(0.526+0.00475*CPT)
      BFET = 1. - (1.-BFE)*(0.82+0.0018*CPT)
```

```
      DTET = 1. - (1.-DTE)*(0.89+0.0011*CPT)
      DRET = 1. - (1.-DRE)*(0.526+0.00475*CPT)
      DFET = 1. - (1.-DFE)*(0.82+0.0018*CPT)
      ATET = 1. - (1.-ATE)*(0.89+0.0011*CPT)
      ARET = 1. - (1.-ARE)*(0.526+0.00475*CPT)
      AFET = 1. - (1.-AFE)*(0.82+0.0018*CPT)
      NTET = 1. - (1.-NTE)*(0.89+0.0011*CPT)
      NRET = 1. - (1.-NRE)*(0.526+0.00475*CPT)
      NFET = 1. - (1.-NFE)*(0.82+0.0018*CPT)
C
C     Power Processing Unit Input Voltage Calculation
C
      PPIV = BOV/BFET/BRET/1.35/IFET
C
C     Power Processing Unit Control and Monitoring Power Demand EquN
C
      CMP = PPAM*79.4*(PPIP/PPRM)**0.1
C
C     Power Processing Unit Efficiency Equations
C
      PPE = ((PPIP*IFET-CMP/1000.)
     &     *(0.9629*BRET*BFET+0.036*DTET*DRET*DFET+
     &     0.001*ATET*ARET*AFET+0.0001*NTET*NRET*NFET))/PPIP
      PPBE = 0.9629*PPE
C     PPSE = ((PPIP*IFET)
C    &     *(0.9629*BRET*BFET+0.036*DTET*DRET*DFET+0.001*ATET*ARET*
C    &     AFET+0.0001*NTET*NRET*NFET))/PPIP
C
C     Power Processing Unit Power Division Equations
C
      BOP = PPIP*0.9629*PPE
      DOP = PPIP*0.036*PPE
      AOP = PPIP*0.001*PPE
      NOP = PPIP*0.0001*PPE
C
C     Power Processing Unit Total Output Power Calculation
C
      PPOP = BOP + DOP + AOP + NOP
C
C     RATIO OF AVAILABLE PPU MODULES/REQUIRED PPU MODULES
C
      RATMOD = PPAM/PPRM
C
C     Power Processing Unit Input Ac Filter Mass Equation
C
      IFM = 0.0105*((1.-0.995)/(1.-IFE))*RATMOD*(PPIP*IFET)
     &     *(PPIP*IFET/PPRM)**(-0.03)*(AOF/20.)**(-0.6)
C
C     Beam Power Supply Mass Equations
C
      BRM = 0.175*((EXP(0.006/(1.-BRE)))/1.35)*RATMOD*(BOP/BFET)
     &     *(BOP/PPRM/BFET)**(-0.04)*(BOV/BFET/(BOV/BFET-2.))
     &     **7*EXP(BOV/BFET/40000.)
      BFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-BFE))
     &     *RATMOD*BOP*(BOV**(-0.7)+0.0015)*(6.7/AOF)
```

```
C
C     Discharge Power Supply Mass Equations
C
      DTM = 2.5*((EXP(0.003/(1.-DTE)))/1.35)*RATMOD*(DOP/DFET/DRET)
     &     *((DOP/PPRM/DFET/DRET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(DOV/1.35/DFET/DRET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      DRM = 0.175*((EXP(0.006/(1.-DRE)))/1.35)*RATMOD*(DOP/DFET)
     &     *(DOP/PPRM/DFET)**(-0.04)*(DOV/DFET/(DOV/DFET-2.))
     &     **7*EXP(DOV/DFET/40000.)
      DFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-DFE))
     &     *RATMOD*DOP*(DOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Accelerator Power Supply Mass Equations
C
      ATM = 2.5*((EXP(0.003/(1.-ATE)))/1.35)*RATMOD*(AOP/AFET/ARET)
     &     *((AOP/PPRM/AFET/ARET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(AOV/1.35/AFET/ARET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      ARM = 0.175*((EXP(0.006/(1.-ARE)))/1.35)*RATMOD*(AOP/AFET)
     &     *(AOP/PPRM/AFET)**(-0.04)*(AOV/AFET/(AOV/AFET-2.))
     &     **7*EXP(AOV/AFET/40000.)
      AFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-AFE))
     &     *RATMOD*AOP*(AOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Neutralizer Power Supply Mass Equations
C
      NTM = 2.5*((EXP(0.003/(1.-NTE)))/1.35)*RATMOD*(NOP/NFET/NRET)
     &     *((NOP/PPRM/NFET/NRET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(NOV/1.35/NFET/NRET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      NRM = 0.175*((EXP(0.006/(1.-NRE)))/1.35)*RATMOD*(NOP/NFET)
     &     *(NOP/PPRM/NFET)**(-0.04)*(NOV/NFET/(NOV/NFET-2.))
     &     **7*EXP(NOV/NFET/40000.)
      NFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-NFE))
     &     *RATMOD*NOP*(NOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Power Processing Unit Conductor and Connector Equations
C
      FCONV = (3.**0.5/2.)*0.028
      BCCM = RATMOD*(FCONV*((BOP*1000.)/BOV)
     &      +FCONV*(((BOP*1000.)/BFET/BRET/IFET)/PPIV))
      DCCM = RATMOD*(FCONV*((DOP*1000.)/DOV)
     &      +FCONV*(((DOP*1000.)/DFET/DRET/DTET/IFET)/PPIV))
      ACCM = RATMOD*(FCONV*((AOP*1000.)/AOV)
     &      +FCONV*(((AOP*1000.)/AFET/ARET/ATET/IFET)/PPIV))
      NCCM = RATMOD*(FCONV*((NOP*1000.)/NOV)
     &      +FCONV*(((NOP*1000.)/NFET/NRET/NTET/IFET)/PPIV))
C
C     Power Processing Unit Control and Monitoring Mass Equation
C
      CMM = PPAM*(2.+2.5*(PPIP/PPRM)**0.3+0.75*(PPIP/PPRM)**0.3)
C
C     Power Processing Unit Electronics Mass Equation
C
```

```
      PPEM = IFM + BRM + BFM + DTM + DRM + DFM + ATM + ARM + AFM + NTM +
     &      NRM + NFM + BCCM + DCCM + ACCM + NCCM + CMM
C
C    Power Processing Unit Volume and Dimension Eqns (Single Module)
C
      SMCV = (PPEM/PPAM)/(0.342*1000.)
      SMCH = 0.7*SMCV**0.3333
      SMCW = 1.1*SMCV**0.3333
      SMCL = 1.3*SMCV**0.3333
C
C    Power Processing Unit Vol & Dimension Eqns (Complete Assembly)
C
      CACV = PPEM/(0.342*1000.)
      CACH = SMCH
      CACW = PPAM*SMCW
      CACL = SMCL
C
C    Power Processing Unit Enclosure Equations
C
      SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
      CACPEM = PPAM*SMCPEM
C
C    Power Processing Unit Radiator Equations
C
      RA = RATMOD*(1.48E+10*(PPIP-PPIP*PPE)/((CPT-CRTD+273.)**4-RST**4))
      RAM = 3.418*RA
C
C    Power Processing Unit Mass Summary Equations
C
      PPM = PPEM + CACPEM
      PPMR = PPEM + CACPEM + RAM
      PPSM = PPM/PPOP
      PPSMR = PPMR/PPOP
C
C    Print PPU Masses, Specific Masses, Efficiencies, Radiator Area,
C    Assembly Vol & Dimensions
C
C     PPM , PPSM , PPMR , PPSMR , PPE , PPBE , RA , CACV , CACH ,
C    &     CACW , CACL
      RETURN
      END
```

APPENDIX D

Ion Power Processing Unit
with Beam Power Supply Transformer Model

```
      SUBROUTINE IONPU2
      REAL IFET , IFM , NCCM , NFET , NFM , NIV , NOP , NRET , NRM ,
     &   NT1ET , NT1M , NT2ET , NT2M
      REAL IFE , NFE , NOV , NRE , NT1E , NT2E
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /PPUIN/ PPIP, PPAM, PPRM, RF, IFE
      COMMON /PPUI12/ BOV, DOV, AOV, NOV, ATE, ARE, AFE, BRE, BFE,
     2           DRE, DFE, NRE, NFE
      COMMON /PPUI2/  BTE , DT1E , DT2E , NT1E , NT2E
      COMMON /PPU123/ PPIV
      COMMON /PPUOUT/ PPM, PPSM, PPMR, PPSMR, PPE, PPBE, PPOP,
     &           RAM, RA, CACV, CACH, CACW, CACL
C
C==================================================================
C
C     Ion Power Processing Unit Model
C     - with Beam Power Supply Transformer
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92      tcn
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C==================================================================
C
C Inputs:
C    PPIV   Power Processing Unit Input Voltage Level (Vrms)
C    PPIP   Power Processing Unit Input Power Level (kWe)
C    PPAM   Power Processing Unit Available Modules
C    PPRM   Power Processing Unit Required Modules
C    BOV    Beam Supply Output Voltage (Vdc)
C    DOV    Discharge Supply Output Voltage (Vdc)
C    AOV    Accelerator Supply Output Voltage (Vdc)
C    NOV    Neutralizer Supply Output Voltage (Vdc)
C    AOF    Alternator Operating Frequency (kHz)
C    RF     Ripple Factor (frac)
C    CPT    Coldplate Temperature (deg C)
C    CRTD   Coldplate to Radiator Temperature Delta (deg C)
C    RST    Radiator Sink Temperature (deg Kelvin)
C    IFE    Power Processing Unit Input Filter Efficiency (fract)
C    ATE    Accelerator Power Supply Transformer Efficiency (fract)
C    ARE    Accelerator Power Supply Rectifier Efficiency (fract)
C    AFE    Accelerator Power Supply Filter Efficiency (fract)
C    BTE    Beam Power Supply Transformer Efficiency (fract)
C    BRE    Beam Power Supply Rectifier Efficiency (fract)
C    BFE    Beam Power Supply Filter Efficiency (fract)
C    DT1E   Discharge Power Supply Transformer #1 Efficiency (fract)
C    DT2E   Discharge Power Supply Transformer #2 Efficiency (fract)
C    DRE    Discharge Power Supply Rectifier Efficiency (fract)
C    DFE    Discharge Power Supply Filter Efficiency (fract)
C    NT1E   Neutralizer Power Supply Transformer #1 Efficiency (frac)
C    NT2E   Neutralizer Power Supply Transformer #2 Efficiency (frac)
C    NRE    Neutralizer Power Supply Rectifier Efficiency (fract)
C    NFE    Neutralizer Power Supply Filter Efficiency (fract)
C
C Outputs:
```

```
C     PPOP    Power Processing Unit Total Output Power (kwe)
C     PPM     Power Processing Unit Mass w/o Radiator (kg)
C     PPMR    Power Processing Unit Mass with Radiator (kg)
C     PPSM    Power Processing Unit Specific Mass w/o Radiator (kg/kw)
C     PPSMR   Power Processing Unit Specific Mass with Radiator (kg/kw)
C     PPE     Power Processing Unit Efficiency (fract)
C     PPBE    Power Processing Unit Beam Supply Effi Measure (fract)
C     RAM     Radiator MASS (KG)
C     RA      Radiator Area (m2)
C     CACV    Complete Assembly Component Volume (m3)
C     CACH    Complete Assembly Component Height (m)
C     CACW    Complete Assembly Component Width (m)
C     CACL    Complete Assembly Component Length (m)
C
C=====================================================================
C
C    Primary User Input Parameters for Ion PPU with Transformer
C     PPIP = 2500
C     PPIV = 5000
C     PPAM = 1
C     PPRM = 1
C     BOV = 1800
C     DOV = 30
C     AOV = 500
C     NOV = 20
C     AOF = 0.8
C     RF = 0.05
C     CPT = 100
C     CRTD = 16.67
C     RST = 247.67
C    Secondary Primary User Input Parameters for Ion PPU w/ Transformer
C    *** Recommended Default Values ***
C     IFE = 0.995
C     BTE = 0.99
C     BRE = 0.98
C     BFE = 0.995
C     DT1E = 0.99
C     DT2E = 0.99
C     DRE = 0.9725
C     DFE = 0.992
C     ATE = 0.99
C     ARE = 0.98
C     AFE = 0.995
C     NT1E = 0.99
C     NT2E = 0.99
C     NRE = 0.955
C     NFE = 0.99
C      Power Supply Stage Efficiency Calculations at Coldplate Temp
C
      IFET = 1. - (1.-IFE)*(0.82+0.0018*CPT)
      BTET = 1. - (1.-BTE)*(0.89+0.0011*CPT)
      BRET = 1. - (1.-BRE)*(0.526+0.00475*CPT)
      BFET = 1. - (1.-BFE)*(0.82+0.0018*CPT)
      DT1ET = 1. - (1.-DT1E)*(0.89+0.0011*CPT)
      DT2ET = 1. - (1.-DT2E)*(0.89+0.0011*CPT)
```

```
      DRET = 1. - (1.-DRE)*(0.526+0.00475*CPT)
      DFET = 1. - (1.-DFE)*(0.82+0.0018*CPT)
      ATET = 1. - (1.-ATE)*(0.89+0.0011*CPT)
      ARET = 1. - (1.-ARE)*(0.526+0.00475*CPT)
      AFET = 1. - (1.-AFE)*(0.82+0.0018*CPT)
      NT1ET = 1. - (1.-NT1E)*(0.89+0.0011*CPT)
      NT2ET = 1. - (1.-NT2E)*(0.89+0.0011*CPT)
      NRET = 1. - (1.-NRE)*(0.526+0.00475*CPT)
      NFET = 1. - (1.-NFE)*(0.82+0.0018*CPT)
C
C     PPU Control and Monitoring Power Demand Equation
C
      CMP = PPAM*79.4*(PPIP/PPRM)**0.1
C
C     Power Processing Unit Efficiency Equations
C
      EFFTRM = 0.9629*BTET*BRET*BFET + 0.0360*DT1ET*DT2ET*DRET*DFET +
     &        0.0010*ATET*ARET*AFET + 0.0001*NT1ET*NT2ET*NRET*NFET
      PPE = ((PPIP*IFET-CMP/1000.)*EFFTRM)/PPIP
C     PPSE = ((PPIP*IFET)*EFFTRM)/PPIP
      PPBE = 0.9629*PPE
C
C     Power Processing Unit Power Division Equations
C
      BOP = PPIP*0.9629*PPE
      DOP = PPIP*0.036*PPE
      AOP = PPIP*0.001*PPE
      NOP = PPIP*0.0001*PPE
C
C     Power Processing Unit Total Output Power Calculation
C
      PPOP = BOP + DOP + AOP + NOP
C
C     Discharge & Neutralizer Power Supply Intermediate Voltage Calcs
C
      DIV = (PPIV*IFET)/(((PPIV*IFET)/(DOV/1.35/DFET/DRET))**0.5)
      NIV = (PPIV*IFET)/(((PPIV*IFET)/(NOV/1.35/NFET/NRET))**0.5)
C
C     RATIO OF AVAILABLE PPU MODULES/REQUIRED PPU MODULES
C
      RATMOD = PPAM/PPRM
C
C     Power Processing Unit Input Ac Filter Mass Equation
C
      IFM = 0.0105*((1.-0.995)/(1.-IFE))*RATMOD*(PPIP*IFET)
     &     *(PPIP*IFET/PPRM)**(-0.03)*(AOF/20.)**(-0.6)
C
C     Beam Power Supply Mass Equations
C
      BTM = 2.5*((EXP(0.003/(1.-BTE)))/1.35)*RATMOD*(BOP/BFET/BRET)
     &     *((BOP/PPRM/BFET/BRET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(BOV/1.35/BFET/BRET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      BRM = 0.175*((EXP(0.006/(1.-BRE)))/1.35)*RATMOD*(BOP/BFET)
     &     *(BOP/PPRM/BFET)**(-0.04)*(BOV/BFET/(BOV/BFET-2.))
```

```
     &     **7*EXP(BOV/BFET/40000.)
      BFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-BFE))
     &     *RATMOD*BOP*(BOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Discharge Power Supply Mass Equations
C
      DT1M = 2.5*((EXP(0.003/(1.-DT1E)))/1.35)
     &     *RATMOD*(DOP/DFET/DRET/DT2ET)
     &     *((DOP/PPRM/DFET/DRET/DT2ET)**(-0.25)
     &     *EXP(PPIV*IFET/200000.)*EXP(DIV/200000.)*AOF**(-0.47)
     &     +(AOF/300.)**1.4)
      DT2M = 2.5*((EXP(0.003/(1.-DT2E)))/1.35)*RATMOD*(DOP/DFET/DRET)
     &     *((DOP/PPRM/DFET/DRET)**(-0.25)*EXP(DIV/200000.)
     &     *EXP(DOV/1.35/DFET/DRET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      DRM = 0.175*((EXP(0.006/(1.-DRE)))/1.35)*RATMOD*(DOP/DFET)
     &     *(DOP/PPRM/DFET)**(-0.04)*(DOV/DFET/(DOV/DFET-2.))
     &     **7*EXP(DOV/DFET/40000.)
      DFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-DFE))
     &     *RATMOD*DOP*(DOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Accelerator Power Supply Mass Equations
C
      ATM = 2.5*((EXP(0.003/(1.-ATE)))/1.35)*RATMOD*(AOP/AFET/ARET)
     &     *((AOP/PPRM/AFET/ARET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(AOV/1.35/AFET/ARET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      ARM = 0.175*((EXP(0.006/(1.-ARE)))/1.35)*RATMOD*(AOP/AFET)
     &     *(AOP/PPRM/AFET)**(-0.04)*(AOV/AFET/(AOV/AFET-2.))
     &     **7*EXP(AOV/AFET/40000.)
      AFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-AFE))
     &     *RATMOD*AOP*(AOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Neutralizer Power Supply Mass Equations
C
      NT1M = 2.5*((EXP(0.003/(1.-NT1E)))/1.35)
     &     *RATMOD*(NOP/NFET/NRET/NT2ET)
     &     *((NOP/PPRM/NFET/NRET/NT2ET)**(-0.25)
     &     *EXP(PPIV*IFET/200000.)*EXP(NIV/200000.)*AOF**(-0.47)
     &     +(AOF/300.)**1.4)
      NT2M = 2.5*((EXP(0.003/(1.-NT2E)))/1.35)*RATMOD*(NOP/NFET/NRET)
     &     *((NOP/PPRM/NFET/NRET)**(-0.25)*EXP(NIV/200000.)
     &     *EXP(NOV/1.35/NFET/NRET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      NRM = 0.175*((EXP(0.006/(1.-NRE)))/1.35)*RATMOD*(NOP/NFET)
     &     *(NOP/PPRM/NFET)**(-0.04)*(NOV/NFET/(NOV/NFET-2.))
     &     **7*EXP(NOV/NFET/40000.)
      NFM = 2.3*(1./(RF/0.01)**0.5)*((1.-0.995)/(1.-NFE))
     &     *RATMOD*NOP*(NOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Power Processing Unit Conductor and Connector Equations
C
      FCONV = (3.**0.5/2)*0.028
      BCCM = RATMOD*(FCONV*((BOP*1000.)/BOV)
     &     +FCONV*(((BOP*1000.)/BFET/BRET/BTET/IFET)/PPIV))
```

```
      DCCM = RATMOD*(FCONV*((DOP*1000.)/DOV)
     &      +FCONV*(((DOP*1000.)/DFET/DRET/DT2ET/DT1ET/IFET)/PPIV))
      ACCM = RATMOD*(FCONV*((AOP*1000.)/AOV)
     &      +FCONV*(((AOP*1000.)/AFET/ARET/ATET/IFET)/PPIV))
      NCCM = RATMOD*(FCONV*((NOP*1000.)/NOV)
     &      +FCONV*(((NOP*1000.)/NFET/NRET/NT2ET/NT1ET/IFET)/PPIV))
C
C   Power Processing Unit Control and Monitoring Mass Equation
C
      CMM = PPAM*(2.+2.5*(PPIP/PPRM)**0.3+0.75*(PPIP/PPRM)**0.3)
C
C   Power Processing Unit Electronics Mass Equation
C
      PPEM = IFM + BTM + BRM + BFM + DT1M + DT2M + DRM + DFM + ATM +
     &      ARM + AFM + NT1M + NT2M + NRM + NFM + BCCM + DCCM + ACCM +
     &      NCCM + CMM
C
C   PPU Volume and Dimension Equations (Single Module)
C
      SMCV = (PPEM/PPAM)/(0.342*1000.)
      SMCH = 0.7*SMCV**0.3333
      SMCW = 1.1*SMCV**0.3333
      SMCL = 1.3*SMCV**0.3333
C
C   PPU Volume and Dimension Equations (Complete Assembly)
C
      CACV = PPEM/(0.342*1000.)
      CACH = SMCH
      CACW = PPAM*SMCW
      CACL = SMCL
C
C   Power Processing Unit Enclosure Equations
C
      SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
      CACPEM = PPAM*SMCPEM
C
C   Power Processing Unit Radiator Equations
C
      RA = RATMOD*(1.48E+10*(PPIP-PPIP*PPE)/((CPT-CRTD+273.)**4-RST**4))
      RAM = 3.418*RA
C
C   Power Processing Unit Mass Summary Equations
C
      PPM = PPEM + CACPEM
      PPMR = PPEM + CACPEM + RAM
      PPSM = PPM/PPOP
      PPSMR = PPMR/PPOP
C     Print PPU Masses, Specific Masses, Efficiencies,
C     Radiator Area, Assembly Volume and Dimensions
C     PRINT PPM , PPSM , PPMR , PPSMR , PPE , PPBE , RA , CACV ,
C    & CACH , CACW , CACL
      RETURN
      END
```

APPENDIX E

MPD Power Processing Unit Model

```
      SUBROUTINE MPDPPU
      REAL IFET , IFM
      REAL IFE
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /PPUIN/ PPIP, PPAM, PPRM, RF, IFE
      COMMON /PPU123/ PPIV
      COMMON /PPUI3/ PPOV , TE , RE , OFE
      COMMON /PPUOUT/ PPM, PPSM, PPMR, PPSMR, PPE, PPBE, PPOP,
     &              RAM, RA , CACV , CACH , CACW , CACL
C
C==============================================================
C
C     MPD Power Processing Unit Model
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92      tcn
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C==============================================================
C
C  Inputs:
C     PPIV    Power Processing Unit Input Voltage Level (Vrms)
C     PPOV    Power Processing Unit Output Voltage Level (Vrms)
C     PPIP    Power Processing Unit Input Power Level (kWe)
C     PPAM    Power Processing Unit Available Modules
C     PPRM    Power Processing Unit Required Modules
C     AOF     Alternator Operating Frequency (kHz)
C     RF      Ripple Factor (frac)
C     CPT     Coldplate Temperature (deg C)
C     CRTD    Coldplate to Radiator Temperature Delta (deg C)
C     RST     Radiator Sink Temperature (deg Kelvin)
C     IFE     Power Processing Unit Input Filter Efficiency (frac)
C     TE      Transformer Efficiency (frac)
C     RE      Rectifier Efficiency (frac)
C     OFE     Output Filter Efficiency (frac)
C
C  Outputs:
C     PPOP    Power Processing Unit Total Output Power (kwe)
C     PPM     Power Processing Unit Mass w/o Radiator (kg)
C     PPMR    Power Processing Unit Mass with Radiator (kg)
C     PPSM    Power Processing Unit Specific Mass w/o Radiator (kg/kw)
C     PPSMR   Power Processing Unit Specific Mass with Radiator (kg/kw)
C     PPE     Power Processing Unit Efficiency (frac)
C     RAM     Radiator MASS (KG)
C     RA      Radiator Area (m2)
C     CACV    Complete Assembly Component Volume (m3)
C     CACH    Complete Assembly Component Height (m)
C     CACW    Complete Assembly Component Width (m)
C     CACL    Complete Assembly Component Length (m)
C
C==============================================================
C
C     Primary User Input Parameters for MPD Power Processing Unit
C     PPIP = 2500
C     PPIV = 5000
```

```
C     PPOV = 300
C     PPAM = 1
C     PPRM = 1
C     AOF = 0.8
C     RF = 0.05
C     CPT = 100
C     CRTD = 16.67
C     RST = 247.67
C      Secondary Primary User Input Parameters for MPD PPU
C        *** Recommended Default Values ***
C     IFE = 0.995
C     TE = 0.99
C     RE = 0.98
C     OFE = 0.995
C
C     Power Supply Stage Efficiency Calculations at Coldplate Temp
C
      IFET = 1. - (1.-IFE)*(0.82+0.0018*CPT)
      TET = 1. - (1.-TE)*(0.89+0.0011*CPT)
      RET = 1. - (1.-RE)*(0.526+0.00475*CPT)
      OFET = 1. - (1.-OFE)*(0.82+0.0018*CPT)
C
C     Power Processing Unit Control and Monitoring Power Demand Equn
C
      CMP = PPAM*79.4*(PPIP/PPRM)**0.1
C
C     Power Processing Unit Efficiency Equations
C
      PPE = ((PPIP*IFET-CMP/1000.)*(TET*RET*OFET))/PPIP
C     PPSE = IFET*TET*RET*OFET
C
C     Power Processing Unit Output Power Calculation
C
      PPOP = PPIP*PPE
C
C     RATIO OF AVAILABLE PPU MODULES/REQUIRED PPU MODULES
C
      RATMOD = (PPAM/PPRM)
C
C     Power Processing Unit Power Stages Mass Equations
C
      IFM = 0.0105*((1.-0.995)/(1.-IFE))*RATMOD*(PPIP*IFET)
     &     *(PPIP*IFET/PPRM)**(-0.03)*(AOF/20.)**(-0.6)
      TM = 2.5*((EXP(0.003/(1.-TE)))/1.35)*RATMOD*(PPOP/OFET/RET)
     &     *((PPOP/PPRM/OFET/RET)**(-0.25)*EXP(PPIV*IFET/200000.)
     &     *EXP(PPOV/1.35/OFET/RET/200000.)*AOF**(-0.47)+(AOF/300.)
     &     **1.4)
      RM = 0.175*((EXP(0.006/(1.-RE)))/1.35)*RATMOD*(PPOP/OFET)
     &     *(PPOP/PPRM/OFET)**(-0.04)*(PPOV/OFET/(PPOV/OFET-2.))
     &     **7*EXP(PPOV/OFET/40000.)
      OFM = 2.3*(1/(RF/0.01)**0.5)*((1.-0.995)/(1.-OFE))
     &     *RATMOD*PPOP*(PPOV**(-0.7)+0.0015)*(6.7/AOF)
C
C     Power Processing Unit Conductor and Connector Equation
C
```

```
      FCONV = (3.**0.5/2.)*0.028
      CCM = RATMOD*(FCONV*((PPOP*1000.)/PPOV)+FCONV*((PPIP*1000.)/PPIV))
C
C     Power Processing Unit Control and Monitoring Mass Equation
C
      CMM = PPAM*(2.+2.5*(PPIP/PPRM)**0.3+0.75*(PPIP/PPRM)**0.3)
C
C     Power Processing Unit Electronics Mass Equation
C
      PPEM = IFM + TM + RM + OFM + CCM + CMM
C
C     Power Processing Unit Vol & Dimension Equations (Single Module)
C
      SMCV = (PPEM/PPAM)/(0.342*1000.)
      SMCH = 0.7*SMCV**0.3333
      SMCW = 1.1*SMCV**0.3333
      SMCL = 1.3*SMCV**0.3333
C
C     Power Processing Unit Vol & Dimension Eqns (Complete Assembly)
C
      CACV = PPEM/(0.342*1000.)
      CACH = SMCH
      CACW = PPAM*SMCW
      CACL = SMCL
C
C     Power Processing Unit Enclosure Equations
C
      SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
      CACPEM = PPAM*SMCPEM
C
C     Power Processing Unit Radiator Equations
C
      RA = RATMOD*(1.48E+10*(PPIP-PPIP*PPE)/((CPT-CRTD+273)**4-RST**4))
      RAM = 3.418*RA
C
C     Power Processing Unit Mass Summary Equations
C
      PPM = PPEM + CACPEM
      PPMR = PPEM + CACPEM + RAM
      PPSM = PPM/PPOP
      PPSMR = PPMR/PPOP
C       Print PPU Masses, Specific Masses, Efficiency,
C       Radiator Area, Assembly Volume and Dimensions
C         Print PPM, PPSM, PPMR, PPSMR, PPE, RA, CACV, CACH, CACW, CACL
      RETURN
      END
```

APPENDIX F

AC Switchgear Unit Model

```
      SUBROUTINE ACSWGR
      REAL IRBIP, IRBIV, IRBM, IRBOP, IRBOV, NIRB, NORB
      COMMON /ACSWIO/ NIRB, NORB, ORBOP, ORBOV, RBE, SWAM, SWRM,
     o IRBIP, IRBIV, IRBM, IRBOP, IRBOV, ORBM,
     & XRBIP, XRBIV, XRBM, XRBOP, XRBOV,
     & SWM, SWSM, SWMR, SWSMR, SWE
     & , RAM, RA, CACV, CACH, CACW, CACL
      COMMON /INALL/ CPT, CRTD, RST, AOF
C
C=================================================================
C
C     AC Switchgear Unit Model
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92   tcn
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C=================================================================
C
C  Assumptions:
C      1) All output remote bus isolators (RBIs) will have the same
C         rating; consequently, a single power level, ORBOP,
C         is specified.
C      2) All output RBIs will operate at the same voltage;
C         consequently, a single voltage level, ORBOV, is specified.
C      3) The efficiency of the switchgear bus is 99.9%
C
C  Inputs:
C     NIRB    Number of Input RBIs
C     NORB    Number of Output RBIs
C     ORBOP   Output RBI Output Power Level (kWe)
C     ORBOV   Output RBI Output Voltage Level (Vrms)
C     RBE     RBI Unit Efficiency at 100 C (fraction)
C     SWAM    Switchgear Available Modules
C     SWRM    Switchgear Required Modules
C     CPT     Coldplate Temperature (deg C)
C     CRTD    Coldplate to Radiator Temperature Delta (deg C)
C     RST     Radiator Sink Temperature (deg Kelvin)
C
C  Outputs:
C     XRBIP   Cross Tie RBI Input Power Level (kWe)
C     XRBIV   Cross Tie RBI Input Voltage Level (Vrms)
C     XRBOP   Cross Tie RBI Output Power Level (kWe)
C     XRBOV   Cross Tie RBI Output Voltage Level (Vrms)
C     XRBM    CROSS TIE RBI Mass (KG)
C     IRBIP   Input RBI Input Power Level (kWe)
C     IRBIV   Input RBI Input Voltage Level (Vrms)
C     IRBM    Mass of one Input RBI (kg)
C     IRBOP   Input RBI Output Power Level (kWe)
C     IRBOV   Input RBI Output Voltage Level (Vrms)
C     ORBM    Mass of one Output RBI (kg)
C     SWM     Switchgear Unit Mass w/o Radiator (kg)
C     SWMR    Switchgear Unit Mass with Radiator (kg)
C     SWSM    Switchgear Unit Specific Mass w/o Radiator (kg/kwe)
C     SWSMR   Switchgear Unit Specific Mass with Radiator (kg/kwe)
```

```
C     SWE     Switchgear Unit Efficiency (fraction)
C     RA      Radiator Area (m2)
C     RAM     Radiator MASS (KG)
C     CACV    Complete Assembly Component Volume (m3)
C     CACH    Complete Assembly Component Height (m)
C     CACW    Complete Assembly Component Width (m)
C     CACL    Complete Assembly Component Length (m)
C
C=====================================================================
C
C     User Input Parameters for AC Switchgear Unit
C     NIRB = 2.
C     NORB = 4.
C     ORBOP = 2500.
C     ORBOV = 5000.
C     RBE = 0.9985.
C     SWAM = 1.
C     SWRM = 1.
C     CPT = 100.
C     CRTD = 16.67
C     RST = 247.67
C
C
C     BE SURE THAT required modules <= available modules
C
      IF (SWRM .GT. SWAM ) SWRM=SWAM
C
C     RBI Efficiency Correction at Coldplate Temperature
C
      RBET = 1. - (1.-RBE)*(0.675+0.00325*CPT)
C
C     Switchgear Unit Bus Power Calculation
C
      SWBP = (NORB*ORBOP)/RBET
C
C     Switchgear Unit Control and Monitoring Power Demand Equation
C
      CMP = SWAM*79.4*(SWBP/SWRM)**0.1
C
C     COMBINED RBI & BUS SECTION EFFICIENCY
C     (The efficiency of the switchgear bus is assumed to be 99.9%)
C
      RBSE = RBET*0.999*RBET
C
C     Switchgear Unit Efficiency Calculations
C
      SWE = (NORB*ORBOP)/(((NORB*ORBOP)/RBET/0.999+CMP/1000.)/RBET)
C
C     Switchgear Unit RBI Power Calculations
C
      IRBOP = (SWBP/0.999+CMP/1000.)/NIRB
      XRBOP = (SWBP/0.999+CMP/1000.)
      IRBIP = IRBOP/RBET
      XRBIP = XRBOP/RBET
C
```

```
C     Switchgear Unit Voltage Calculations
C
      SWBV = ORBOV/RBET
      IRBOV = SWBV/0.999
      XRBOV = IRBOV
      IRBIV = ORBOV/RBSE
      XRBIV = IRBIV
C
C     RBI Unit Mass Calculations
C
      ORBM = 0.135*((EXP(0.0008/(1.-RBE)))/1.7)*(SWAM/SWRM)
     &      *ORBOP*(ORBOP/SWRM)**(- 0.15)*(ORBOV/200.)**0.05
      IRBM = 0.135*((EXP(0.0008/(1.-RBE)))/1.7)*(SWAM/SWRM)
     &      *IRBOP*(IRBOP/SWRM)**(- 0.15)*(IRBOV/200.)**0.05
      XRBM = 0.135*((EXP(0.0008/(1.-RBE)))/1.7)*(SWAM/SWRM)
     &      *XRBOP*(XRBOP/SWRM)**(- 0.15)*(XRBOV/200.)**0.05
C
C     Switchgear Unit Conductor and Connector MASS Calculation
C
      CCM = (SWAM/SWRM)*((3.**0.5/2.)*0.056*(SWBP*1000.)/SWBV)
C
C     Switchgear Unit Control and Monitoring Mass Calculation
C
      CMM = SWAM*(2.+2.5*(SWBP/SWRM)**0.3+0.75*(SWBP/SWRM)**0.3)
C
C     Switchgear Unit Electronics Mass Calculation
C
      SWEM = (NIRB*IRBM) + (NORB*ORBM) + XRBM + CCM + CMM
C
C     Single Module Switchgear Unit Volume and Dimension Calculations
C
      SMCV = (SWEM/SWAM)/(0.342*1000.)
      SMCH = 0.7*SMCV**0.3333
      SMCW = 1.1*SMCV**0.3333
      SMCL = 1.3*SMCV**0.3333
C
C     Complete Assembly Switchgear Unit Volume & Dimension Calculations
C
      CACV = SWEM/(0.342*1000.)
      CACH = SMCH
      CACW = SWAM*SMCW
      CACL = SMCL
C
C     Switchgear Unit Enclosure Calculations
C
      SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
      CACPEM = SWAM*SMCPEM
C
C     Switchgear Unit Radiator Calculations
C
      RA = (SWAM/SWRM)
     &    *(1.48E+10*((NIRB*IRBIP)-(NORB*ORBOP))/((CPT-CRTD+273.)
     &    **4-RST**4))
      RAM = 3.418*RA
C
```

```
C     Ac Switchgear Unit Mass Summary Calculations
C
      SWM = SWEM + CACPEM
      SWSM = SWM/(NORB*ORBOP)
      SWMR = SWEM + CACPEM + RAM
      SWSMR = SWMR/(NORB*ORBOP)
C       Print Switchgear Masses, Specific Masses, Efficiency,
C       Radiator Area, Assembly Volume and Dimensions
C       PRINT SWM, SWSM, SWMR, SWSMR, SWE, RA, CACV, CACH, CACW, CACL
      RETURN
      END
```

APPENDIX G

Phase Lock Transformer Model

```
      SUBROUTINE TRNFMR
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /TRNREG/ APO , AVO
      COMMON /TRNFIO/ PTAM , PTPP , PTRM , TSE ,
     o                PTM , PTSM , PTMR , PTSMR , PTE
     &                , RAM, RA , CACV , CACH , CACW , CACL
C
C==================================================================
C
C     Phase Lock Transformer Model
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92    tcn
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C==================================================================
C
C  Inputs:
C     AOF    Alternator Operating Frequency (kHz)
C     APO    Alternator Power Output (kWe)
C     AVO    Alternator Voltage Output (Vrms)
C     CPT    Coldplate Temperature (deg C)
C     CRTD   Coldplate to Radiator Temperature Delta (deg C)
C     PTAM   Phase Lock Transformer Available Modules
C     PTPP   Phase Lock Transformer Power Percentage (fraction)
C     PTRM   Phase Lock Transformer Required Modules
C     RST    Radiator Sink Temperature (deg Kelvin)
C     TSE    Transformer Stage Efficiency at 100 C (%)
C
C  Outputs:
C     PTM    Phase Lock Transformer Mass w/o Radiator (kg)
C     PTSM   Phase Lock Transformer Specific Mass w/o Radiator (kg/kWe)
C     PTMR   Phase Lock Transformer Mass with Radiator (kg)
C     PTSMR  Phase Lock Transformer Specific Mass w/ Radiator (kg/kWe)
C     PTE    Phase Lock Transformer Efficiency (fraction)
C     RAM    Radiator MASS (KG)
C     RA     Radiator Area (m2)
C     CACV   Complete Assembly Component Volume (m3)
C     CACH   Complete Assembly Component Height (m)
C     CACW   Complete Assembly Component Width (m)
C     CACL   Complete Assembly Component Length (m)
C
C==================================================================
C
C     User Input Parameters for Phase Lock Transformer
C      APO=5000
C      AVO=5000
C      PTPP=0.02
C      PTAM=1
C      PTRM=1
C      AOF=0.8
C      TSE=0.99
C      CPT=100
C      CRTD=16.67
C      RST=247.67
```

```
C
C
C    BE SURE THAT required modules <= available modules
C
     IF (PTRM .GT. PTAM ) PTRM=PTAM
C
C    Phase Lock Transformer Power Output Calculation
C
     PTPO = PTPP*APO
C
C    Phase Lock Transformer Control & Monitoring Power Demand Calc
C
     CMP = PTAM*47.6*(PTPO/PTRM)**0.1
C
C    Phase Lock Transformer Efficiency Calculations
C
     TSET = 1. - (1.-TSE)*(0.89+0.0011*CPT)
     PTE = PTPO/(PTPO/TSET+CMP/1000.)
C
C    Transformer Stage Mass Calculation
C
     TSM = 2.5*((EXP(0.003/(1.-TSE)))/1.35)*(PTAM/PTRM)
    &      *PTPO*((PTPO/PTRM)**(-0.25)*EXP(AVO/100000.)*AOF**(-0.47)
    &      +(AOF/300.)**1.4)
C
C    Phase Lock Transformer Conductor and Connector Mass Calculation
C
     CCM = (PTAM/PTRM)*((3.**0.5/2.)*0.056*(PTPO*1000.)/AVO)
C
C    Phase Lock Transformer Control and Monitoring Mass Calculation
C
     CMM = PTAM*(2.+0.83*(PTPO/PTRM)**0.3+0.25*(PTPO/PTRM)**0.3)
C
C    Phase Lock Transformer Electronics Mass Calculation
C
     PTEM = TSM + CCM + CMM
C
C    Phase Lock Transformer Single Module Volume & Dimension Calc
C
     SMCV = (PTEM/PTAM)/(0.342*1000.)
     SMCH = 0.7*SMCV**0.3333
     SMCW = 1.1*SMCV**0.3333
     SMCL = 1.3*SMCV**0.3333
C
C    Phase Lock Transformer Complete Assembly Volume & Dimension Calc
C
     CACV = PTEM/(0.342*1000.)
     CACH = SMCH
     CACW = PTAM*SMCW
     CACL = SMCL
C
C    Phase Lock Transformer Enclosure Calculations
C
     SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
     CACPEM = PTAM*SMCPEM
```

```
C
C     Phase Lock Transformer Radiator Calculations
C
      RA = (PTAM/PTRM)*(1.48E+10*(PTPO/PTE-PTPO))
     &     /((CPT-CRTD+273.)**4-RST**4)
      RAM = 3.418*RA
C
C     Phase Lock Transformer Mass Summary Calculations
C
      PTM = PTEM + CACPEM
      PTSM = PTM/PTPO
      PTMR = PTEM + CACPEM + RAM
      PTSMR = PTMR/PTPO
C       Print Phase Lock Transformer Masses, Specific Masses,
C       Efficiency, Radiator Area, Assembly Volume and Dimensions
C       Print PTM, PTSM, PTMR, PTSMR, PTE, RA, CACV, CACH, CACW, CACL
      RETURN
      END
```

APPENDIX H

Speed Regulator Model

```
      SUBROUTINE SPDREG
      REAL NSS
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /TRNREG/ APO , AVO
      COMMON /SREGIO/ SRAM, SRRM, NSS, SRF, PWMF, BCE, SSE, EFE,
     o              SPO, SVO, SRM, SRSM, SRMR, SRSMR, FSE
     &              , RAM, RA , CACV , CACH , CACW , CACL
C
C================================================================
C
C     Alternator Speed Regulator Model
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  13 April 92
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C================================================================
C
C  Inputs:
C     APO    Alternator Power Output (kWe)
C     AVO    Alternator Voltage Output (Vrms)
C     SRAM   Speed Regulator Available Modules
C     SRRM   Speed Regulator Required Modules
C     NSS    Number of Shunt Switch Elements
C     SRF    Shunt Redundancy Factor (frac)
C     PWMF   Pulse-Width-Modulation Frequency (kHz)
c     BCE    Bus Conductor Efficiency at 100 C (frac)
C     SSE    Shunt Switch Efficiency at 100 C (frac)
C     EFE    EMI Filter Efficiency at 100 C (frac)
C     CPT    Coldplate Temperature (deg C)
C     CRTD   Coldplate to Radiator Temperature Delta (deg C)
C     RST    Radiator Sink Temperature (deg Kelvin)
C
C  Outputs:
C     SPO    Shunt Power Output (kWe)
C     SVO    Shunt Voltage Output (Vrms)
C     SRM    Speed Regulator Mass w/o Radiator (kg)
C     SRSM   Speed Regulator Specific Mass w/o Radiator (kg/kWe)
C     SRMR   Speed Regulator Mass with Radiator (kg)
C     SRSMR  Speed Regulator Specific Mass w/ Radiator (kg/kWe)
C     FSE    Fully Shunted Efficiency (fraction)
C     RAM    Radiator MASS (KG)
C     RA     Radiator Area (m2)
C     CACV   Complete Assembly Component Volume (m3)
C     CACH   Complete Assembly Component Height (m)
C     CACW   Complete Assembly Component Width (m)
C     CACL   Complete Assembly Component Length (m)
C
C================================================================
C
C     Primary User Input Parameters for Speed Regulator
C     APO = 5000
C     AVO = 5000
C     SRAM = 1
C     SRRM = 1
```

```
C     CPT = 100
C     CRTD = 16.67
C     RST = 247.67
C      Secondary User Input Parameters for Speed Regulator
C       *** Recommended Default Values ***
C     NSS = 40
C     SRF = 1.2
C     PWMF = 20
C     BCE = 0.9965
C     SSE = 0.9945
C     EFE = 0.9993
C
C
C    BE SURE THAT required modules <= available modules
C
     IF (SRRM .GT. SRAM ) SRRM=SRAM
C
C    Speed Regulator Control and Monitoring Power Demand Calculation
C
     CMP = SRAM*79.4*(APO/SRRM)**0.1
C
C    BUS CONDUCTOR EFFICIENCY AT COLDPLATE TEMP
C
     BCET = 1. - (1.-BCE)*(0.75+0.0025*CPT)
C
C    EMI FILTER EFFICIENCY AT COLDPLATE TEMP
C
     EFET = 1. - (1.-EFE)*(0.82+0.0018*CPT)
C
C    SHUNT SWITCH EFFICIENCY AT COLDPLATE TEMP
C
     SSET = 1. - (1.-SSE)*(0.526+0.00475*CPT)
C
C    FULLY SHUNTED EFFICIENCY
C
     FSE = ((APO-CMP/1000)*BCET*EFET*SSET)/APO
C
C    COMBINED BUS, FILTER, AND SHUNT Efficiency
C
     BFSE = BCET*EFET*SSET
C
C    Speed Regulator Shunt Output Calculations
C
     SPO = APO*FSE
     SVO = AVO*BFSE
C
C    Bus and Connector Mass Calculation
C
     BCM = (SRAM/SRRM)*((1.-0.9965)/(1.-BCE))
    &     *SRF*((3**0.5/2.)*0.056*(APO*1000.)/AVO)
C
C    EMI Filter Mass Calculation
C
     EFM = 0.0105*((1.-0.9993)/(1.-EFE))*(SRAM/SRRM)*SRF*(SPO/SSET)
    &     *(SPO/SRRM/NSS/SSET)**(-0.03)*(PWMF/20.)**(-0.6)
```

```
C
C    Shunt Switch Mass Calculation
C
     SSM = 0.15*((EXP(0.001/(1.-SSE)))/1.2)*(SRAM/SRRM)
    &      *SRF*SPO*(SPO/SRRM/NSS)**(-0.04)*(SVO/(SVO-2.))
    &      **7*EXP(SVO/40000.)
C
C    Speed Regulator Control and Monitoring Mass Calculation
C
     CMM = SRAM*(2.+2.5*(APO/SRRM)**0.3+0.75*(APO/SRRM)**0.3)
C
C    Speed Regulator Electronics Mass Calculation
C
     SREM = BCM + EFM + SSM + CMM
C
C    Speed Regulator Single Module Volume and Dimension Calculations
C
     SMCV = (SREM/SRAM)/(0.342*1000.)
     SMCH = 0.7*SMCV**0.3333
     SMCW = 1.1*SMCV**0.3333
     SMCL = 1.3*SMCV**0.3333
C
C    Speed Regulator Complete Assembly Volume & Dimension Calculations
C
     CACV = SREM/(0.342*1000.)
     CACH = SMCH
     CACW = SRAM*SMCW
     CACL = SMCL
C
C    Speed Regulator Enclosure Calculations
C
     SMCPEM = 44.26*SMCV**0.6666 + 10.25*(SMCL*SMCW)
     CACPEM = SRAM*SMCPEM
C
C    Speed Regulator Radiator Calculations
C
     RA = (SRAM/SRRM)*(1.48E+10*(APO-FSE*APO))
    &    /((CPT-CRTD+273.)**4-RST**4)
     RAM = 3.418*RA
C
C    Speed Regulator Mass Summary Calculations
C
     SRM = SREM + CACPEM
     SRSM = SRM/SPO
     SRMR = SREM + CACPEM + RAM
     SRSMR = SRMR/SPO
C    Print Shunt Regulator Masses, Specific Masses, Efficiency,
C    Radiator Area, Assembly Volume and Dimensions
C    Print SRM, SRSM, SRMR, SRSMR, FSE, RA, CACV, CACH, CACW, CACL
     RETURN
     END
```

APPENDIX I

Parasitic Load Radiator Model

```
      SUBROUTINE ACPLR
      REAL ND , NR , NRC , NRTC
      COMMON /RADIO / PPD , PIV , APM , RPM , PWOT , WRTD , PST ,
     i              NR , NRTC , ND , CCD ,
     i              NRC , RCRF ,
     o              TPLRA , TPLRM , TPLRSM
C
C=====================================================================
C
C     AC Parasitic Load Radiator Model
C     - Radiator Equations Set for LEO (400 km orbit)
C
C     - Last Revised:  14 April 92
C
C     - Author:  Ken Metcalf,  (818) 586-3976
C=====================================================================
C
C  Assumptions:
C        1) Nichrome V wire mass includes 50% extra mass for
C         bonding & insulating materials
C        2) Radiator plates are 2-.5 mm flat & corrugated C-C plates
C      3) Radiator frame, braces & structural supports are 1mm thick CC
C      4) Radiation efficiency = 0.873
C      5) Radiator surface emissivity = 0.90
C
C  Inputs:
C     PPD    PLR Power Dissipation Level (kWe)
C     PIV    PLR Input Voltage Level (Vrms)
C     APM    Available Parasitic Load Radiator Modules
C     RPM    Required Parasitic Load Radiator Modules
C     PWOT   PLR Wire Operating Temperature (K)
C     WRTD   Wire to Radiating Surface Temperature Delta (K)
C     PST    Parasitic Load Radiator Sink Temperature (K)
C     CCD    Carbon-Carbon Density (g/cm3)
C     ND     Nichrome V Density (g/cm3)
C     NR     Nicrome V Resistivity (ohms-cm2/meter)
C     NRC    Number of Resistive Circuits
C     RCRF   Resistive Circuit Redundancy Factor (FRACT)
C     NRTC   Nicrome V Resistivity Temperature Coefficient (/C)
C
C  Outputs:
C  TPLRA      Total Parasitic Load Radiator Surface Area (m2)
C  TPLRM      Total Parasitic Load Radiator Mass (kg)
C  TPLRSM     Total Parasitic Load Radiator Specific Mass (kg/kWe)
C
C=====================================================================
C
C      Primary User Input Parameters for Parasitic Load Radiator
C     PPD = 5000
C     PIV = 5000
C     APM = 1
C     RPM = 1
C     PWOT = 1255
C     WRTD = 100
C     PST = 247.67
```

```
C      Secondary User Input Parameters for Parasitic Load Radiator
C       *** Recommended Default Values ***
C     NRC = 40
C     RCRF = 1.2
C     NR = 1.0806E-02
C     NRTC = 0.00011
C     ND = 8.4296
C     CCD = 1.66
C
C
C     BE SURE THAT required modules <= available modules
C
      IF (RPM .GT. APM ) RPM=APM
C
C      Parasitic Load Radiator Circuit Calculations
C
      CC = (PPD*1000.)/RPM/NRC/3./PIV
      CER = PIV/CC
C
C      Parasitic Load Radiator Resistive Wire Calculations
C
      RWXA = CC**1.4/10500.
      RWL = (CER*RWXA)/(NR*(1.+NRTC*(PWOT-273.-20.)))
C
C     Single Module Parasitic Load Radiator Plate & Frame Area Calc
C
      SMPA = 2.*RCRF*(1.48E+10*PPD/RPM)/((PWOT-WRTD)**4-PST**4)
      SMFA = 4.*(SMPA**0.5*1.002)*(SMPA**0.5*0.02)
C
C     Single Module Parasitic Load Radiator Mass Calculations
C
      SMWM = 1.5*3.*RCRF*NRC*((RWL*100.)*RWXA)*(ND/1000.)
      RHOCC=CCD/1000.
      SMPM = 2.15*SMPA*10000.*0.05*RHOCC
      SMFM = (SMFA*10000.*0.1)*RHOCC +
     &      2.*(SMFA/4.*2.**0.5*10000.*0.1)*RHOCC
      SMSM = (SMFA/2.*10000.*0.15)*RHOCC +(SMFA*1.12*10000.*0.15)*RHOCC
C
C     Single Module Parasitic Load Radiator Mass Summary Calculation
C
      SMPLRM = SMWM + SMPM + SMFM + SMSM
C
C     Total Parasitic Load Radiator Mass Calculations
C
      TPLRA = APM*SMPA
      TPLRM = APM*SMPLRM
      TPLRSM = TPLRM/PPD
C       Print Parasitic Load Radiator Area, Mass, Specific Mass
C       Print TPLRA, TPLRM, TPLRSM
      RETURN
      END
```

APPENDIX J

Litz Wire Transmission Line Model

```
      SUBROUTINE LWTRLN
      REAL IDS , IDSF , IMD , ITC , KF , KPF
      REAL LRP , LXP , LWR , LWIT , LWIM
      REAL NOB , LPF
      COMMON /INALL / CPT , CRTD , RST, AOF
      COMMON /TRANIO/ TLOP , TLOV , TLL , ATC , RTC , NOB , LPF ,
     &               CM, TLIP , TLIV , CJOR , CJST , TLCT , TLE , PF
      DATA MAXIT/1000/ , TOLTLE/0.01/
C
C =====================================================================
C
C    Transmission Line Module
C    - 3 Phase, Aluminum Conductor
C    - Insulated Litz Wire
C    - Radiation Cooled Cable Jacket (LEO, 400 km)
C
C    Last Revised: 27 April 92        tcn
C
C    Author: Ken Metcalf, (818) 718 - 3391
C =====================================================================
C
C    User Input Parameters
C
C      Par  Default
C     Name   Value  Parameter Description
C     ----- ------  ------------------------------------
C    TLOP    5000.  Transmission Line Output Power Level, kWe
C    TLOV    1367.  Transmission Line Output Voltage, Vrms
C i/o TLE    .9800  Initial Transmission Line Efficiency (0 if unknown)
C    TLL     150.   Transmission Line Length, m
C    AOF       .8   Alternator Operating Frequency, kHz
C    ATC       1.   Available Transmission Circuits
C    RTC       1.   Required Transmission Circuits
C    NOB       7.   Number of Bundles
C    LPF       .9   Load Power Factor
C
C Outputs:
C    CM      Transmission Line Mass , kg
C    TLIP    Transmission Line Input Power, kWe
C    TLIV    Transmission Line Input Voltage, Vrms
C    CJOR    Cable Jacket Outer Radius, cm
C    CJST    Cable Jacket Surface Temperature, deg C
C    TLCT    Conductor Temperature, deg C
C i/o TLE    Transmission Line Efficiency, frac
C    PF      Circuit Power Factor, frac
C
C Notes:
C
C    TLOP and TLOV obtained from PPU or Switchgear model
C    AOF obtained from Power conversion Submodule (CR-191134 or CR-191135)
C    ATC must be equal to or greater than RTC
C    NOB must be 1., 7. or 17.
C
C    Combinations of high power (> 5 MWe), lower voltage (< 2000 Vrms),
C    and higher frequency (> 1 KHz) may cause  divergence errors.
```

```
C     Typically a circuit power factor of 0.8 or less indicates unstable
C     operation and pending divergence errors.
C     The following steps are suggested to correct these problems:
C     1) Select a higher operating voltage if possible;
C     2) Utilize a larger value for the number of bundles (NOB),
C        for example, 7 instead of 1, or 17 instead of 7;
C     3) Reduce transmission line length if practical;
C     4) Reduce the power level or break a single line into parallel
C        lines using the ATC and RTC values.
C     In general, it should be noted that transmission line divergence
C     errors may indicate the selected values are not actually practical
C     or they will result in a complex or undesirable transmission line
C     design.
C
C ==========================================================
C
      PI = 3.1415926536
C
C      BE SURE THAT RTC <= ATC
C
      IF (RTC .GT. ATC ) RTC=ATC
C
C      BE SURE THAT NOB=1, 7, OR 17.  SET NOB=7 OTHERWISE
C
      IF (NOB .NE. 1. .AND. NOB .NE. 7. .AND. NOB .NE. 17.) NOB=7.
C
C      Calculate an initial TLE
C
      CALTLE=1. - TLL/150.*5000./TLOV*0.01
      IF (TLE .LT. CALTLE) TLE=CALTLE
C
C      Aluminum Resistivity, Temperature, and Density Constants
C
      AVR = 0.028264
C      ARTC = 0.00403
      AMD = 2.703
C
C      Insulation Density, DielectriC Strength, Safety Factor Constants
C
      IMD = 1.42
      IDS = 7000.
      IDSF = 10.
C
C      Litz Wire Strand Radius (Value suitable for 60 Hz to 5 kHz)
C
      LWR = 0.016
C
C      Cable Jacket and Conductor Temperature Calculation Constants
C      Temperature Calculation Constants Suitable for LEO (400 km)
C
      CABS = 0.4
      CEM = 0.9
      CEVF = 0.8
      ALBD = 0.3
      CABI = 0.9
```

```
      QSOL = 1372.
      QEIR = 237.
      SBC = 5.67E-08
      ITC = 0.300
C
C     Calculate Transmission Line Output Parameters
C
      TLCT = 150.
      PF = LPF
      I = 0
C ********* RETURN HERE FOR TLCT and/or TLE Calculations  *******
C
C     Aluminum Volume Resistivity at Temperature
C
 100  AVRT = (AVR*(1.+0.00403*(TLCT-20.)))/1000000.
C
C     X-factor
C
      XF = 2.*PI*LWR*((2.*AOF*1000.)/(AVRT*100.*1000000000.))**0.5
C
C     K-factor
C
      IF ( XF.LT.2. ) THEN
        KF = XF*0.03908 + 1.
      ELSE
        KF = XF*0.35233163 + 0.37349673
      ENDIF
C
C     Aluminum Volume Resistivity at Temperature and Frequency
C
      AVRF = KF*AVRT
C
C     Transmission Line Power Losses
C
      TLPL = TLOP/TLE - TLOP
C
C
      J = 0
C ********* RETURN HERE FOR Power Factor PF Calculation Loop  *******
C
C     Conductor Current Level
C
 200  CCUR = ((TLOP*1000.)/RTC/NOB)/(3.**0.5*TLOV*PF)
C
C     Conductor Resistance
C
      CRES = (((TLPL/3.)*1000.)/RTC/NOB)/CCUR**2
C
C     Conductor Radius
C
      CRAD = (((AVRF*TLL)/(PI*CRES))**0.5)*100.
C
C     Litz Wire Insulation Thickness
C
      LWIT = TLOV/(IDS/0.00254)
```

```
C
C     Equivalent Litz Wire Insulation Thickness
C
      ELWT = ((CRAD**2/LWR**2)*(LWR+LWIT)**2)**0.5 - CRAD
C
C     Conductor Insulation Thickness
C
      CIT = (IDSF*TLOV)/(IDS/0.00254)
C
C     Conductor Insulation Outer Radius
C
      CIOR = CRAD + ELWT + CIT
C
C     GeometriC Mean Distance
C
      GMD = 2.*CIOR
C
C     K'-factor
C
      IF ( XF.LT.2. ) KPF = 1./EXP(XF/40.)
      IF ( XF.GE.2. .AND. XF.LT.10. ) KPF = EXP((1.7-XF)/6.)
      IF ( XF.GE.10. ) KPF = EXP(2.116/XF) - 0.985
C
C     Conductor Reactance
C
      CREA = ((2.*ALOG(GMD/CRAD)+KPF*(1./2.))*0.000000001)
     &       *(2.*PI*AOF*1000.)*(TLL*100.)
C
C     Load Resistance per Phase
C
      LRP = ((TLOP*1000.)/RTC/3.)/(NOB*CCUR)**2
C
C     Load Reactance per Phase
C
      LXP = TAN(ACOS(LPF))*LRP
C
C     Circuit Resistance per Phase
C
      CRP = LRP + (CRES/RTC/NOB)
C
C     Circuit Reactance per Phase
C
      CXP = LXP + CREA/RTC/NOB
C
C     Circuit Power Factor
C
      PFOLD = PF
      PF = COS(ATAN(CXP/CRP))
      IF ( ABS(PF-PFOLD).GT.0.001 ) THEN
        IF ( J.GT.MAXIT ) THEN
          WRITE (*,99001) PF , PFOLD
        ELSE
          J = J + 1
          GOTO 200
        ENDIF
```

```
      ENDIF
C
C     Bundle Jacket Thickness
C
      BJT = (IDSF*TLOV)/(IDS/0.00254)
C
C     Bundle Jacket Outer Radius
C
      BJOR = CIOR*(1.+2./3.**0.5) + BJT
C
C     Cable Jacket Thickness
C
      CJT = (IDSF*TLOV)/(IDS/0.00254)
C
C     Cable Jacket Outer Radius
C
      IF ( NOB.EQ.1. ) THEN
        CJOR = BJOR
      ELSEIF ( NOB.EQ.7. ) THEN
        CJOR = 3.*BJOR + CJT
      ELSE
        CJOR = 5.*BJOR + CJT
      ENDIF
C
C     Exterior Cable Heating Effects
C
      ECHE = (CABS*QSOL) + (ALBD*QSOL*CABS*CEVF) + (CABI*QEIR)
C
C     Cable Jacket Surface Temperature
C
      CJST = ((ECHE*(2.*CJOR/100.*TLL)+(TLPL*1000.))
     &       /(SBC*CEM*2.*PI*CJOR/100.*TLL))**0.25
C
C     Conductor Temperature
C
      TOLD = TLCT
      TLCT = (TLPL*1000.)
     &       *(ALOG(CJOR/(NOB**0.5*3.**0.5*CRAD))/(2.*PI*ITC*TLL))
     &       + CJST - 273.
      I = I + 1
      IF ( I.LE.MAXIT ) THEN
        IF ( ABS(TLCT-TOLD).GT.0.1 ) GOTO 100
        IF ( TLCT.GE.200. ) THEN
          TLE = ((1.-TLE)*TOLTLE) + TLE
          GOTO 100
        ENDIF
      ELSE
        WRITE (*,99002) MAXIT, TLCT, TLE
      ENDIF
C
C     Conductor Mass
C
      COM = ATC*3.*NOB*PI*CRAD**2*(TLL*100.)*(AMD/1000.)
C
C     Litz Wire Insulation Mass
```

```
C
      LWIM = ATC*3.*NOB*PI*((CRAD+ELWT)**2-CRAD**2)*(TLL*100.)
     &       *(IMD/1000.)
C
C     Conductor Insulation Mass
C
      CIM = ATC*3.*NOB*PI*((CRAD+ELWT+CIT)**2-(CRAD+ELWT)**2)*(TLL*100.)
     &       *(IMD/1000.)
C
C     Bundle Jacket Mass
C
      BJM = ATC*NOB*PI*(BJOR**2-(BJOR-BJT)**2)*(TLL*100.)*(IMD/1000.)
C
C     Cable Jacket Mass
C
      CJM = ATC*PI*(CJOR**2-(CJOR-CJT)**2)*(TLL*100.)*(IMD/1000.)
C
C     Cable Mass
C
      CM = COM + LWIM + CIM + BJM + CJM
C
C     Transmission Line Input Power
C
      TLIP = TLOP/TLE
C
C     Transmission Line Input Voltage
C
      TLIV = TLOV/TLE
C
      RETURN
99001 FORMAT (1X,'Failed to conv in lwtrln, PF=',F9.4,' PFOLD=',F9.4)
99002 FORMAT (1X,'WARNING! Exceeds',I5,'iters in lwtrln. TLCT =',F9.2,
     &        ' TLE =',F9.4)
      END
```

Report Documentation Page

National Aeronautics and Space Administration

1. Report No. NASA CR-191136	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Power Conditioning System Modelling for Nuclear Electric Propulsion		5. Report Date November 1993
		6. Performing Organization Code Rocketdyne Division Rockwell International
7. Author(s) Kenneth J. Metcalf		8. Performing Organization Report No. None
		10. Work Unit No.
9. Performing Organization Name and Address Rocketdyne Division Rockwell International Corporation 6633 Canoga Avenue Canoga Park, CA 91303		11. Contract or Grant No. NAS3-25808
		13. Type of Report and Period Covered Contractor Report Final
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, OH 44135		14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

NASA LeRC is currently developing a Fortran based model of a complete nuclear electric propulsion (NEP) vehicle that would be used for piloted and cargo missions to the Moon or Mars. The proposed vehicle design will use either a Brayton or K-Rankine power conversion cycle to drive a turbine coupled with a rotary alternator. Two thruster types are also being studied, ion and magnetoplasmadynamic (MPD). In support of this NEP model, Rocketdyne developed a power management and distribution (PMAD) subroutine that provides parametric outputs for selected alternator operating voltages and frequencies, thruster types, system power levels, and electronics coldplate temperatures.

The end-to-end PMAD model described in this report is based on the direct use of the alternator voltage and frequency for transmitting power to either ion or MPD thrusters. This low frequency transmission approach was compared with dc and high frequency ac designs, and determined to have the lowest mass, highest efficiency, highest reliability and lowest development costs. While its power quality is not as good as that provided by a high frequency system, it was considered adequate for both ion and MPD engine applications. The low frequency architecture will be used as the reference in future NEP PMAD studies.

17. Key Words (Suggested by Author(s)) Nuclear Electric Porulsion, Power Management and Distribution, Subroutines	18. Distribution Statement Unclassified - Unlimited Subject Category 44

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified		

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service. Springfield, Virginia 22161