NASA Contractor Report 182198
ARINC Research Publication 5149-11-01-4744

Space Station Electrical Power System Availability Study

(NASA-CR-182198) SPACE STATION ELECTRICAL
POWER SYSTEM AVAILABILITY STUDY Final
Contractor Report (Arinc Research Corp.)
192 p
CSCL 22B
G3/18
N89-11802
Unclas
0174586

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November 1988

Prepared for
Lewis Research Center
Under Contract C-31003-J

National Aeronautics and
Space Administration

FOREWORD

This report describes a UNIRAM preliminary reliability, availability, and maintainability study of the Space Station Electric Power System. It was performed between July 1987 and June 1988 for the System Engineering and Integration Division of NASA Lewis Research Center under USAF contract F05603-87-D-0006, Task Order S^3-N-88-01. The project engineer was Mr. Scott R. Turnquist. The principal investigators were Mr. Turnquist and Mr. Mark Twombly. Dr. James Witt made significant contributions through consultations with the authors. The authors extend their thanks to Mr. Dave Hoffman, of NASA, for his efforts in promptly answering all technical questions dealing with this study.

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SUMMARY

INTRODUCTION

ARINC Research Corporation was asked by the NASA Lewis Research Center (LeRC) System Engineering and Integration (SE&I) Division to perform a preliminary reliability, availability, and maintainability (RAM) analysis of the Space Station Electric Power System (EPS). The Space Station has a mission life of 30 years: therefore, a power system capable of repair must be designed. Precedents for on-orbit repair and maintenance of space-based systems have been set through the use of the Space Shuttle, and the development of a maintainable Space Station is based on these precedents. The concept of on-orbit maintainability is being applied to the Space Station design. The EPS is a vital part of the Space Station and on-orbit maintainability is integral to its design.

The major objective of this study was to model and analyze the EPS using the UNIRAM RAM assessment methodology. The resulting EPS model and methodology will provide NASA with tools to continue assessing EPS design variations from a RAM perspective. The analysis objectives of this study included:

- Development of baseline RAM measures for EPS power generation and distribution
- Estimation of the RAM performance of the EPS when orbital replacement unit (ORU) mean failure and repair rates are taken into account
- Assessment of the impact of ORU maintainability changes on EPS RAM performance
- Assessment of the impact of ORU reliability changes on EPS RAM performance

The UNIRAM RAM assessment methodology was used to meet these objectives. The methodology incorporates an IBM PC-based software package with RAM modeling techniques to perform system RAM assessments. The UNIRAM software package was developed by ARINC Research Corporation for the Electric Power Research Institute (EPRI) to evaluate the RAM characteristics of electric power generation systems.

The scope of the study documented in this report was defined by the major objective and two additional constraints. At the direction of NASA the ORU was defined to be the hardware indenture referred to in the UNIRAM terminology as "component level," and the values used for ORU mean time between failures (MTBF) and mean time to restore (MTTR) were estimates that allowed a wide margin for ORU MTBF and MTTR variation for sensitivity analyses. ORU MTBF variations were limited to a range between two scale factors -- 5.0 and 0.7. ORU MTTRs were assumed to have only two values -- 1,080 hours and 6 hours -- which corresponded to estimates of ORU replacement times if the ORU had to be transported from the ground or if it were available as an on-orbit spare.

Two key metrics used throughout the study are defined as follows:

- Availability (A) - A measure of the amount of time, within a given period, that a system will generate or deliver power. Another way of stating this would be that availability is the probability of producing power at any level.
- Equivalent Availability (EA) - A ratio of the power actually produced or delivered by a system to the power that would have been produced or delivered had there been no system power outages due to component failures or planned system shutdowns.

EPS RAM ASSESSMENT METHODOLOGY

Before the EPS RAM assessment was conducted, the EPS design was reviewed and an approach to the assessment was established. The review showed functional differences between the EPS power generation system and the distribution system. Figure S-1 illustrates one portion of the EPS, the power generation and distribution systems were modeled separately as a matter of convenience for the EPS RAM analyses that followed.

As illustrated in Figure S-1, EPS power is distributed to two distinct distribution subsystems: the manned core power distribution system which consists of power distribution control assemblies (PDCAs) and other ORUs, and the inner keel power distribution system which consists of power distribution control units (PDCUs) on the inner keel outside the manned core. These systems were modeled separately to allow a RAM assessment of each.

The EPS power generation system has two modes of operation that were separated into two models. During the insolar mode, the EPS draws power from the photovoltaic arrays; during the eclipse mode of operation, the EPS draws power from the batteries.

Separating the EPS power generating system into two models causes a problem. If EPS eclipse power generation were modeled as shown in Figure S-1, a fully charged battery would be inherently assumed at the beginning of each period of eclipse operation. The cross-hatched subsystems in Figure S-1 represent subsystems that must operate in an insolar period preceding the eclipse period so that the battery is fully charged at the beginning of the eclipse period. There is a finite probability that some subsystems will not be available to charge the battery, and that

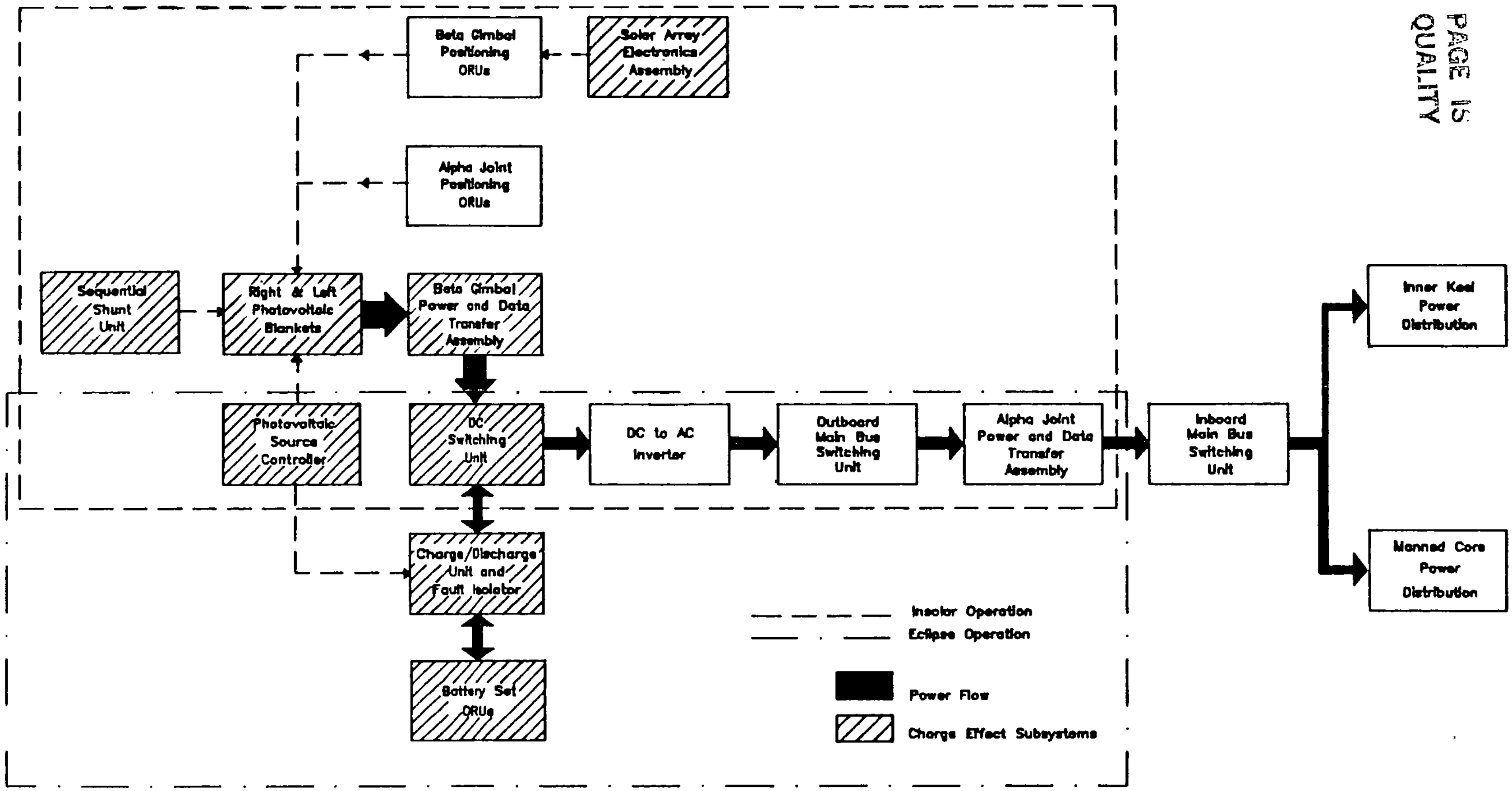

FIGURE S-1

SPACE STATION EPS BASIC POWER GENERATION BLOCK DIAGRAM unavailability would lead to lower power levels, on average, over a given period of time. The availability of these subsystems has been taken into account in the model for eclipse-period EPS power generation. These subsystems were modeled separately, and their availabilities for battery charging were calculated using the UNIRAM baseline execution option. The calculated availabilities were then inserted into the eclipse power generation model in the form of MTBFs and MTTRs in charge-effect pseudocomponents. These components effectively reduce the eclipse power availability, which reflects the probability that the battery may not be fully charged at the beginning of an eclipse period.

The EPS RAM assessment was performed in the following five steps:

- Model the EPS
- Evaluate the EPS model to determine the baseline system RAM values and component criticality rankings
- Perform assessments of EPS availability sensitivity to sparing ORUs on-orbit
- Perform assessments of EPS availability sensitivity to changes in ORU reliability and analyze expected ORU failure rates
- Integrate the power generation and power distribution system results to obtain overall EPS RAM performance measures

Each of these steps is briefly described in the following paragraphs:

Model the EPS

As shown in Figure S-2, the UNIRAM modeling methodology follows a five-step process and culminates in a UNIRAM input file, which is then analyzed using the UNIRAM software. The following paragraphs outline each step in the modeling methodology:

Develop an EPS Availability Block Diagram (ABD)

The EPS ABD is a representation of the system which shows how ORUs are interconnected from the standpoint of availability. From this standpoint, an ORU does not have to be functionally related to another ORU to have a functional dependance on it. It is this functional dependance which is shown in an ABD and not necessarily the physical connections between ORUs (for example the thermal control system is linked in series with the outboard main bus switching unit subsystem). The blocks within an ABD are basic subsytems. A basic subsystem is an aggregation of one or more components logically linked together to define how their failures can cause failure of the basic subsystem. A basic subsystem has only two output states: either it is fully operational, or it is failed.

The Space Station Power System Description Document (PSDD) and NASA LeRC personnel supplied the information necessary to derive the EPS ABDs. As noted, the EPS required four distinct ABDs, however, NASA also requested an additional evaluation of a different architecture for the

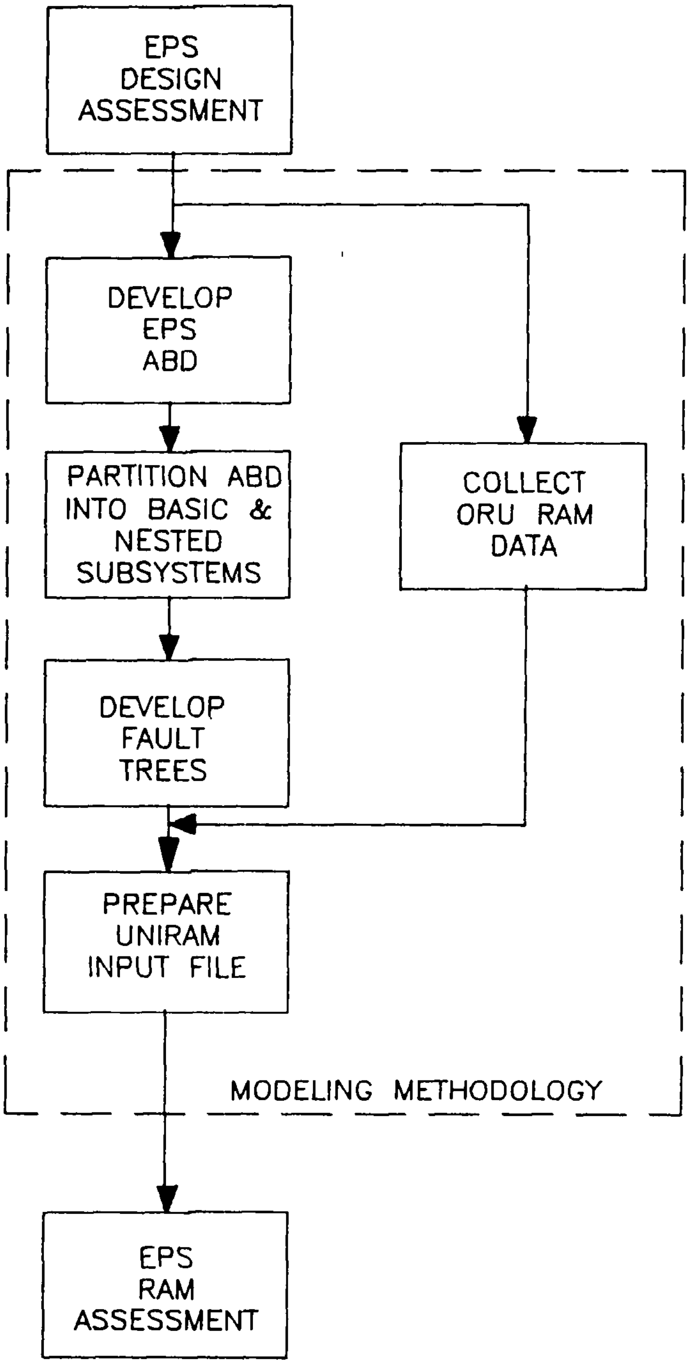

FIGURE S-2

EPS MODELING METHODOLOGY

manned core power distribution system, and that request required the development of a fifth ABD. The following ABDs were developed for the EPS:

- Photovoltaic power generation system during the insolar portion of an orbit (insolar ABD)
- Battery power generation system during the eclipse portion of an orbit (eclipse ABD)
- Manned core power distribution system with a ring PDCU architecture (power management and distribution [PMAD] ABD)
- Manned core power distribution system with a radial PDCU architecture (PMAD ABD, special case study).
- Inner keel power distribution system outside the manned core (inner keel ABD)

Partition the ABDs Into Basic and Nested Subsystems

Partitioning ABDs into basic and nested subsystems is an iterative process. The process of nesting defines the logical connections of basic and nested subsystems and thus defines the failure states of the system being modeled. The first iteration of ABD partitioning forms nested subsystems from those basic subsystems that are functionally connected in series paths. The end points of these paths are often defined by manifolds (a manifold is a point at which multiple functional paths meet). Manifolding allows multiple levels of operation that are based on failures of subsystems within the functional paths that form that manifold. This iterative process continues until the system is defined by a single nested subsystem.

The basic subsystems are nested together as follows: The parallel redundant basic subsystems are collapsed into nested subsystems (the nested subsystem logically maps a system's functional dependence on its basic subsystems). The resulting series of basic and nested subsystems is then collapsed into larger nested subsystems. Ultimately, a single nested subsystem is formed that represents the full system being modeled. Basic and nested subsystems are addressed in more detail in Section 2.3.2 of this report and in Reference 1.

Develop Fault Trees For Each Basic Subsystem

Each basic subsystem has an associated fault tree that defines the logical framework for the basic subsystem's dependence on individual ORUs for its operation. Figure S-3 illustrates the two basic fault tree types. In Figure S-3a the "and-gate" logically represents the condition where both component A and component B must fail to fail the basic subsystem. However, Figure S-3b shows through the use of an "or-gate", that the failure of either component A or component B will cause the basic subsystem to fail. These gates and special cases of them are further discussed in Reference 1.

Obtain ORU RAM Data

This step was performed concurrently with the previous two steps. NASA LeRC personnel supplied estimates of the required ORU reliabilities in the form of ORU MTBF estimates. These estimates are listed in Appendix A, Table A-1. Two estimated values were used for the ORU MTTR values. For an ORU required to be brought to orbit, an MTTR of 1,080 hours was used. This value corresponds to a 45-day Space Shuttle response time upon failure of the ORU. For an ORU that was spared on-orbit, an MTTR of 6 hours was used as a nominal on-orbit repair time.

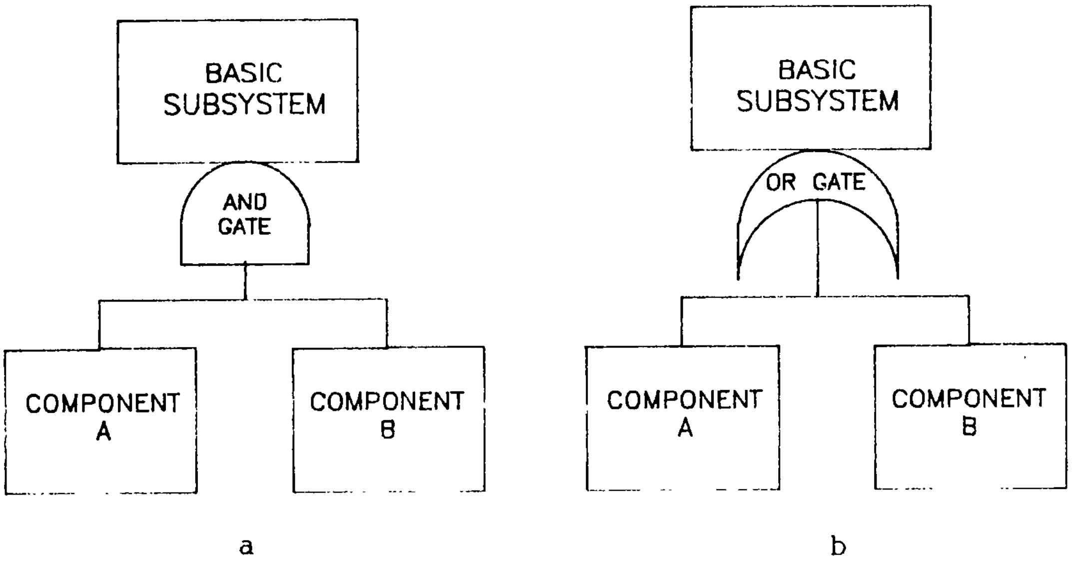

FIGURE S-3

FAULT TREE EXAMPLE

Prepare UNIRAM Input Files

The UNIRAM input files are prepared in accordance with Reference 1. The input file includes the total system capacity, the number of hours per year the system will be shut down (zero hours in the EPS models), and the number of basic subsystem definitions to follow. The basic subsystem definition incorporates the ORU definitions, the fault tree logic, and the capacity of the basic subsystem. The ORU definitions contain the ORU MTBF and MTTR data. Another data entry for each component is the time, in hours, that the component's basic subsystem can function after the component has failed. This surge capability was used for the Beta positioning ORUs to show that loss of these components is not significant until a given period of time has passed. The surge time increases the basic subsystem's effective MTBF value. The nested subsystem definitions follow those of the basic subsystem to form the UNIRAM model input file.

Evaluate the EPS Model to Determine the Baseline System RAM Data and Component Criticality Rankings

The UNIRAM software was used to perform baseline analyses of each of the system models. The analyses included system availabilities and equivalent availabilities; system output power levels (states) and their associated state probabilities; and ORU criticality ranking, which ranks ORUs by their effect on system equivalent availability if they were perfectly available. Other analyses to determine the effects of ORU MTBF and MTTR variation on a given system model were performed, using the EPS models.

Perform Assessments of EPS Availability Sensitivity to Sparing ORUs On-Orbit

The sparing sensitivity analyses determined the effects on the system of sparing ORUs either on-ground or on-orbit. Eight ORUs had a significant impact on system availability or equivalent availability when spared on-orbit; they are designated in this report as the eight critical ORUs. These eight ORUs also had significant impact on the reliability sensitivity analyses.

Perform Assessments of EPS Availability Sensitivity to Changes in ORU Reliability and Analyze Expected ORU Failure Rates

The reliability and reliability sensitivity analyses performed on each of the models were similar to the sparing sensitivity analyses. However, instead of using a single change in ORU reliabilities, the ORU MTBFs were scaled individually and universally over a range of 0.7 to 5.0 times their baseline MTBF values. Again, the eight critical ORUs had more impact on system equivalent availabilities than did other ORUs.

An analysis was performed to determine the expected number of ORU failures per year. For the baseline EPS, the expected number of ORU failures per year was 35; as anticipated, when the MTBFs of all ORUs were doubled, that value dropped to 18. When only the eight critical ORU MTBFs were doubled, the expected failure rate was 29 ORUs per year. Because of system ORU redundancy, not all of these expected ORU failures would require immediate replacement. For example, a failure of a photovoltaic source controller (PVSC) would not require immediate repair, because the PVSC is dually redundant.

Combine the Output States of the Power Generation System Models with the Output States of the Power Distribution System Model to Integrate the EPS Model Results

After the analyses were completed on each of the system models, the power generation system results were combined with the power distribution system results. The combination provided an indication of the RAM performance of the EPS from each of the power generation systems to a load in the PMAD system. The insolar, the eclipse without charge effects and eclipse with charge effects baseline output states were combined with those of PMAD. Each combination resulted in a range of system output states through a load PDCA (PDCA-L3). In each combination, three analysis scenarios were used: all ORU MTTRs equal 1,080 hours, all ORUs are spared on-orbit and the eight critical ORUs are spared on orbit. In every case, the effect on the ability to supply 25 kW of load from a PMAD PDCA was evaluated.

CONCLUSIONS AND RECOMMENDATIONS

The Space Station Electric Power System was modeled, and a RAM assessment was performed using the UNIRAM availability assessment methodology. As the EPS design evolves, NASA can use the resulting EPS models to assess EPS design changes on system RAM performance. The conclusions and recommendations that resulted from the EPS RAM assessments are addressed in the following paragraphs.

EPS Power Generation

From a RAM perspective, eight EPS ORUs accounted for most of the EPS RAM changes when EPS ORU reliability and maintainability parameters were varied. These ORUs, considered critical to EPS operation, are:

- Alpha Joint Power and Data Transfer Assembly
- Beta Gimbal Power and Data Transfer Assembly
- Charge/Discharge Unit
- Power Distribution Control Unit
- Power Management Controller
- Sequential Shunt Unit
- Solar Array Electronics Assembly
- Thermal Control Plate

These ORUs are possible candidates for on-orbit sparing; however, further analyses based on ORU cost, weight, and volume considerations must be performed to determine which ORUs should be spared.

Table S-1 presents the equivalent availabilities and the availabilities for the system variations considered in this study. The system variations are listed in order of descending system equivalent availability. The equivalent availability change among the system variations is large (a maximum difference of 13.99 percent), and the availability change among the system variations is small (a maximum difference of 0.08 percent). EPS equivalent availability is sensitive to both ORU reliability and maintainability.

TABLE S-1

SYNOPSIS OF EPS ORU SPARING AND RELIABILITY SENSITIVITY ANALYSIS

System Variation	EA(%)	A(%)
Insolar		
Spare All ORUs	99.77	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	98.08	>99.99
Increase All ORU MTBFs by Factor of Five	97.78	>99.99
Spare Eight Critical ORUs	96.20	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	95.83	>99.99
Double All ORU MTBFs	94.53	99.98
Double Eight Critical ORU MTBFs	93.74	99.98
Baseline System Results	89.35	99.92
Eclipse without Charge Effects		
Spare All ORUs	99.94	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	98.49	>99.99
Increase All ORU MTBFs by Factor of Five	97.86	>99.99
Spare Eight Critical ORUs	96.96	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	95.48	>99.99
Double All ORU MTBFs	94.70	99.98
Double Eight Critical ORU MTBFs	93.23	99.98
Baseline System Results	89.58	99.92
Eclipse with Charge Effects		
Spare All ORUs	99.85	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	96.24	>99.99
Increase All ORU MTBFs by Factor of Five	94.69	>99.99
Spare Eight Critical ORUs	92.55	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	89.04	>99.99
Double All ORU MTBFs	87.22	99.98
Double Eight Critical ORU MTBFs	83.89	99.98
Baseline System Results	75.96	99.92

EPS Power Management and Distribution System

The RAM assessment showed that there is little or no difference between PDCAs when considering the availability of power from any given PDCA in the PMAD system. The baseline availability of the PMAD system is 99.98 percent, but ORU on-orbit sparing and reliability changes increased the availability to greater than 99.99 percent. Since there are 28 PDCUs in the manned core, the only PMAD ORU considered viable as a potential on-orbit spare was the PDCU.

A baseline analysis of the inner keel power distribution system was also performed. The availability of power from an inner keel PDCU was97.90 percent when ORU MTTRs were 1,080 hours. When a PDCU was spared on-orbit, the availability of power from a PDCU on the inner keel increased to 99.99 percent.

EPS Integrated System

Table S-2 presents the equivalent availabilities, the probabilities of power levels below minimum life-support levels, and the probabilities of zero output states for the EPS integrated system analyses. Since the PMAD system was modeled as delivering power to a perfectly available 25 kW load (33.33 percent of 75 kW, which is the total system capacity), the equivalent availability data are on a scale of 33.33 percent. EPS integrated system analyses were also performed for sparing only the eight critical ORUs on-orbit. The results of these analyses were the same as the results for sparing all ORUs on-orbit (MTTR = 6). With no on-orbit sparing of ORUs, there is a finite probability that the EPS power output will fall below minimum life-support levels.

The total number of ORUs used to model the EPS was 418. The expected average annual failure rate is 35 ORUs per year.

TABLE S-2

EPS INTEGRATED SYSTEM RESULTS

System Combination	Equivalent Availability (%)		Probability of Less Than Minimum Life-Support		Probability of Zero Output State	
	MTTR=1,080	MTTR=6	MTTR=1,080	MTTR=6	MTTR=1,080	MTTR=6
PMAD and Insolar	33.29	33.33	0.0010	<0.0001	0.0010	<0.0001
PMAD and Eclipse (No Charge Effects)	33.29	33.33	0.0010	<0.0001	0.0010	<0.0001
PMAD and Eclipse	33.25	33.33	0.0015	<0.0001	0.0010	<0.0001

Recommendations

As this study was performed, the following further analyses were identified as necessary:

- An analysis of the EPS, taking into consideration various distributed power load scenarios should be performed. The initialanalysis used a single 25-kW load at the output of the distributionsystem, but a subsequent evaluation would not only distribute the single 25-kW load to other PDCUs in the manned core, but would alsoaccount for the insolation period system load represented by the EPS battery charge. If possible, load-shedding ranking factors should be used to determine the availability of power to each load under the ranking criteria. Ultimately, this study would provide information on the EPS ability to supply power in various load configurations.

- An analysis incorporating the lifetime data associated with the EPS batteries and photovoltaic arrays should be performed. This analysis would center on the use of a distribution function, such as the Weibull, to determine yearly MTBF values. The values would then be used in several UNIRAM analyses to study the decrease in EPS performance as the battery packs and photovoltaic arrays degrade with age. This analysis would also yield an expected annual ORU failure rate that would increase as the lifetimes of the batteries and photovoltaic arrays are reached.

- RAM analyses of individual ORUs, taking into consideration the parts makeup within the ORU, should be performed . These analyses would provide possible output states and state probabilities for the ORU. The states and state probabilities would then be incorporated into a system analysis for a more precise indication of system RAM performance using actual capabilities of selected ORUs.

- An ORU parts-type evaluation similar to a MIL-HDBK-217E (Ref. 2) analysis should be performed on selected ORUs. This analysis should include the previously identified eight critical ORUs. The purpose of the analysis would be to establish more accurate predictions of the ORU MTBFs.

- Analyses specific to selecting an optimum on-orbit level of ORU spares for the EPS should be performed. These analyses would consider such constraints as: EPS RAM considerations, ORU mass, volume, cost to lift, and the requirements for ORU spares testing while ORUs are on-orbit.

- An in-depth analysis of EPS maintainability should be performed. It should use expected ORU failure rates and on-orbit sparing scenarios as well as the proposed EPS intravehicular activity (IVA)and extravehicular activity (EVA) budgets allowed for EPS maintenance. The analysis results would identify possible maintenance strategies to trade IVA and EVA hours for degraded levels of system performance and would determine the adequacy of the IVA and EVA budgets as they relate to various levels of system performance.

- An EPS testability analysis should be performed to determine if the current ORU packaging and test point distribution is adequate to isolate faults to at least individual ORUs.

GLOSSARY OF
ABBREVIATIONS AND ACRONYMS

A	Availability
ABD	Availability Block Diagram
CDU	Charge/Discharge Unit
DC-RBI	dc Remote Bus Isolator
DCSU	dc Switch Unit
DOD	Depth of Discharge
EA	Equivalent Availability
EPRI	Electric Power Research Institute
EPS	Electric Power System
EVA	Extravehicular Activity
EFOR	Equivalent Forced Outage Rate
FOH	Forced Outage Hours
FOR	Forced Outage Rate
HAB	Habitation Module
IVA	Intravehicular Activity
LAB	Laboratory Module
LeRC	Lewis Research Center
LPVB	Left Photovoltaic Blanket
MTBF	Mean Time Between Failure
MTTR	Mean Time to Restore
NASA	National Aeronautics and Space Administration
OMBSU	Outboard Main Bus Switch Unit
ORU	Orbital Replacement Unit
Pd	Power Degradation
PDCA	Power Distribution Control Assembly
PDCU	Power Distribution Control Unit
PDT	Power Data Transfer
PSDD	Power System Description Document
PMAD	Power Management and Distribution
PMC	Power Management Controller

Photovoltaic
Photovoltaic Source Controller

Reliability, Availability, and Maintainability
Right Photovoltaic Blanket
Reserve Shutdown Hours

Solar Array Electronics
System Engineering and Integration
Scheduled Outage Hours
Sequential Shunt Unit

Thermal Control System
Thermal Control Plate

Unit Reliability, Availability, and Maintainability

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

ARINC Research Corporation was tasked by the NASA Lewis Research Center (LeRC) System Engineering and Integration (SE&I) Division to perform a reliability, availability, and maintainability (RAM) analysis of the Space Station Electric Power System (EPS). The Space Station has a mission life of 30 years; therefore, a power system capable of repair must be designed. Precedents for on-orbit repair and maintenance of space-based systems have been set due to the use of the Space Shuttle, and the development of a maintainable Space Station is based on these precedents. The concept of on-orbit maintainability is being applied to the Space Station design. The EPS is a vital part of the Space Station and on-orbit maintainability is integral to its design.

The major objective of this study was to model and analyze the EPS using the UNIRAM RAM assessment methodology. The resulting EPS model and methodology will provide NASA with tools to continue assessing EPS design variations from a RAM perspective. The analysis objectives of this study included:

- Development of baseline RAM measures for EPS power generation and distribution

- Estimation of the RAM performance of the EPS when orbital replacement unit (ORU) mean failure and repair rates are taken into account

- Assessment of the impact of ORU maintainability changes on EPS RAM performance

- Assessment of the impact of ORU reliability changes on EPS RAM performance

The UNIRAM RAM assessment methodology was used to meet these objectives. This methodology incorporates an IBM PC-based software package with RAM modeling techniques to perform system RAM assessments. The UNIRAM software package was developed by ARINC Research Corporation for the Electric Power Research Institute (EPRI) to evaluate the RAM characteristics of electric power generation systems.

1.2 SCOPE

This report documents the application of the UNIRAM methodology to the EPS and the preliminary analysis results. It applies to the Phase 1 EPS design as defined by the Power System Description Document (PSDD), dated July 1987, and its revisions (as mentioned in the Space Station Electric Power System Proposal) through March 1988. This excludes the solar dynamic system and incorporates two additional photovoltaic modules on each side of the Space Station. The study was predominantly defined by its major objective. However, two other limitations were placed upon the RAM assessment. At the direction of NASA, the ORU was defined as the component level for this study. This means that when an ORU fails, it will not produce, pass, or control system power in any manner. In addition, the values used for ORU mean time between failures (MTBF) and mean time to restore (MTTR) were based on NASA estimates as listed in Appendix A, Table A-1. The values were obtained from discussions with NASA LeRC personnel and from Reference 3. Since they are estimates, there was wide margin within which the ORU MTBFs could be varied for sensitivity analyses. An upper-limit MTBF scale factor of 5.0 and a lower-limit scale factor of 0.7 were used. Also, the ORU MTTR data were represented by only two values. An ORU MTTR of 1,080 hours (45 days) was used, which corresponds to an estimate of the mean amount of time it would take to bring a replacement ORU from the ground to orbit. The other MTTR used was 6 hours, which corresponds to an estimate of the mean time it will take to replace an ORU that is spared on-orbit.

1.3 REPORT ORGANIZATION

This report is organized into four chapters and four appendixes. Chapter Two describes each of the steps in the analysis methodology. Chapter Three presents the results of the analyses. Chapter Four provides conclusions and recommendations based on the results of the analyses. The appendixes present modeling information (Appendix A), data generated during the analyses (Appendix B), references (Appendix C), and definitions of terms and concepts used in this report (Appendix D).

CHAPTER TWO

EPS RAM ASSESSMENT METHODOLOGY

2.1 APPROACH

An initial examination of the EPS design revealed the following modeling considerations:

- The Space Station EPS has two types of power generating systems and a power distribution system. The distribution system has been functionally separated from the power generation system.
- The power distribution system has two points of output: (1) the manned core distribution system and (2) the inner keel distribution system (outside the manned core but inside the alpha joints).
- The EPS power generation system is operated in two modes: (1) eclipse period operation and (2) insolar period operation. Each of these operating modes has a different power source. During eclipse operation, the EPS draws power from the batteries. During the insolar period, the EPS draws power from the photovoltaic panel arrays.
- The photovoltaic and battery power generating systems are assumed to generate power exclusively of one another over any given orbit.

Figure 2-1 is a functional diagram of EPS power generation and distribution from a single photovoltaic module. The modeling considerations led to the determination that multiple RAM models were needed to completely model the EPS; therefore, an assessment approach using multiple models for the EPS RAM analysis was also required. This approach modeled the four specific systems identified in the considerations above: the photovoltaic power generation system, the eclipse power generation system, the manned core distribution system and, the inner keel distribution system. Also, there were special cases of interest that required their own models, as discussed in Section 2.3.1.

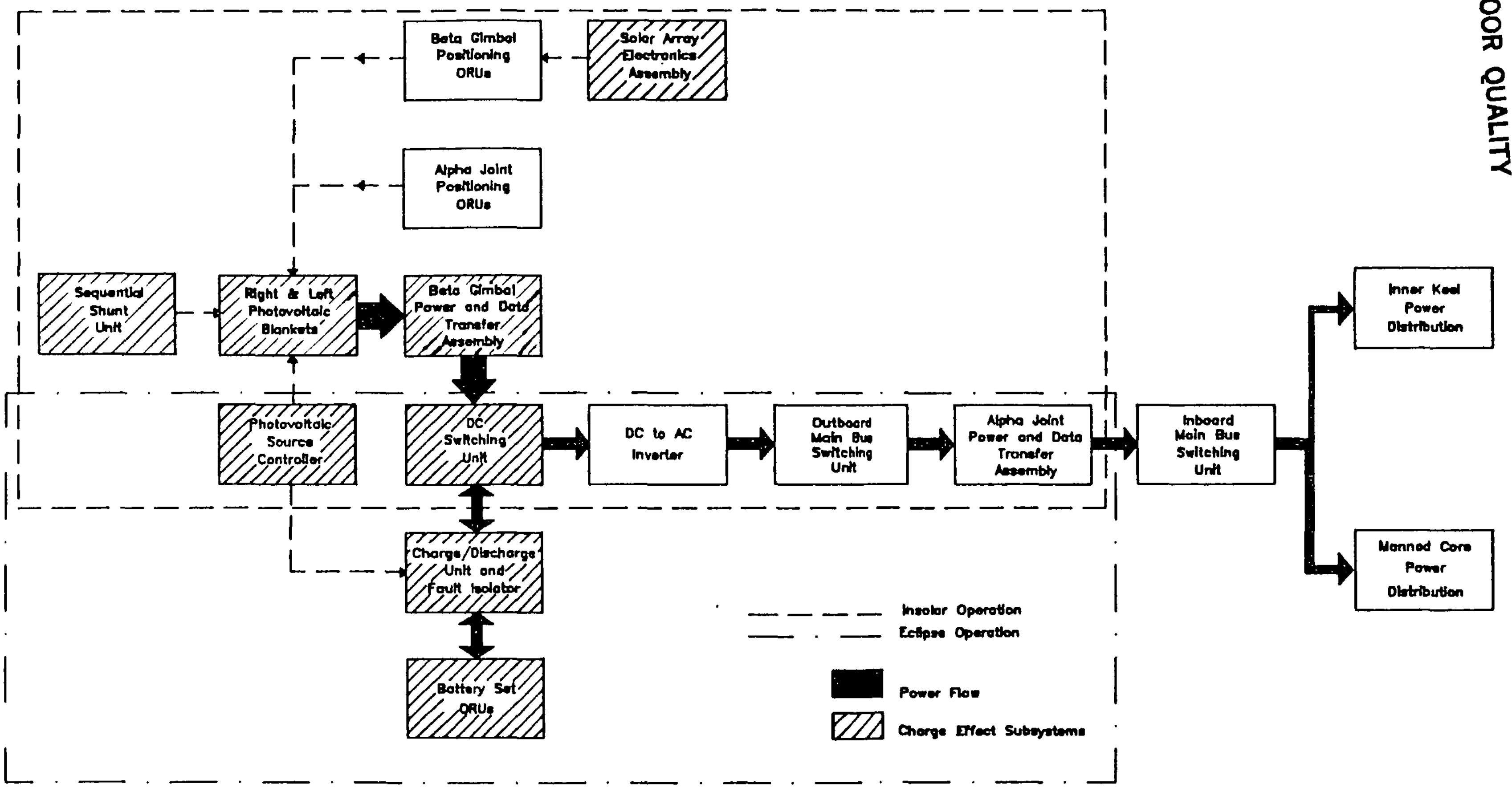

FIGURE 2-1

SPACE STATION EPS BASIC POWER GENERATION BLOCK DIAGRAM

2.2 METHODOLOGY

Two key metrics were used to quantify the RAM of the EPS. They are defined as follows:

- Availability (A) - A measure of the amount of time, within a given period, that a system will generate or deliver power. Another way of stating this would be that availability is the probability of producing power at any level. UNIRAM calculates availability using a point-estimate technique.
- Equivalent Availability (EA) - A ratio of the power actually produced or delivered by a system to the power that would have been produced or delivered had there been no system power outages due to component failures or planned system shutdowns.

The methodology for conducting a RAM assessment of the Space Station EPS was divided into five steps:

- Model the EPS
- Evaluate the EPS model to determine the baseline system RAM values and ORU criticality rankings
- Perform assessments of EPS availability sensitivity to sparing ORUs on-orbit
- Perform assessments of EPS availability sensitivity to changes in ORU reliability and analyze expected ORU failure rates
- Integrate the power generation and power distribution system results to obtain overall EPS RAM performance measures

Sections 2.3 through 2.7 address each of these steps in detail.

2.3 MODEL THE EPS

The first step in the EPS RAM assessment methodology was to model the EPS. The UNIRAM modeling methodology permits the UNIRAM software to relate any failure or combination of failures at the ORU (component) level to the resultant loss in system power output capability (Ref. 1).

As shown in Figure 2-2, the EPS was modeled using the following five steps:

- Develop an EPS availability block diagram (ABD)
- Partition the ABDs into basic and nested subsystems
- Develop fault trees
- Obtain ORU RAM data
- Prepare UNIRAM input files

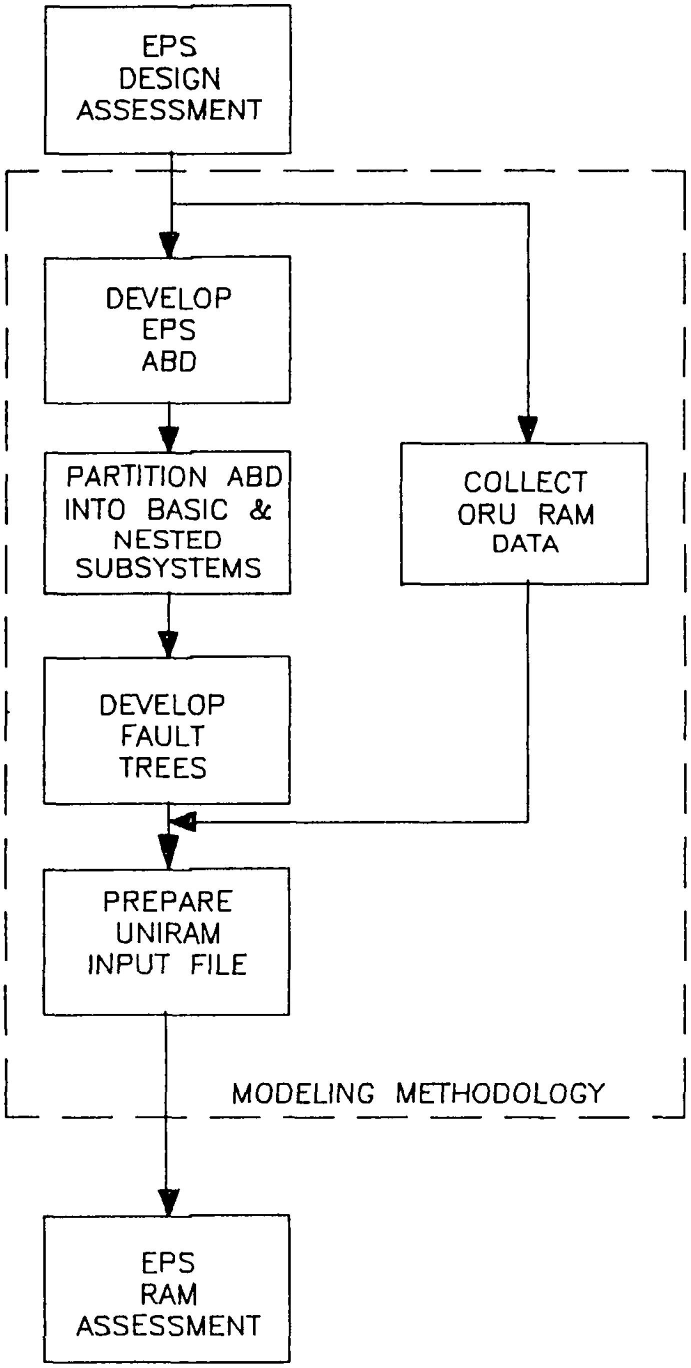

FIGURE 2-2

EPS MODELING METHODOLOGY

2.3.1 Develop an EPS Availability Block Diagram

An availability block diagram is a representation of a system which shows how components are interconnected from the standpoint of availability. From this standpoint, a component does not have to be functionally related to another component to have a functional dependance on it. It is this functional dependance which is shown in an ABD and not necessarily the physical connections between components (for example the thermal control system is linked in series with the outboard main bus switching unit subsystem). The points at which multiple functional paths meet are called manifolds. Manifolding allows multiple output states of operation based on failures within the functional paths that converge to or diverge from the manifold. Manifolds often mark the boundaries of basic subsystems or the boundaries between nested subsystems; thus, they provide information about subsystem structure (Ref. 4). Figure 2-3 is an example of an ABD for a thermal control system. The two thermal control system ORUs are on parallel paths connected by a manifold.

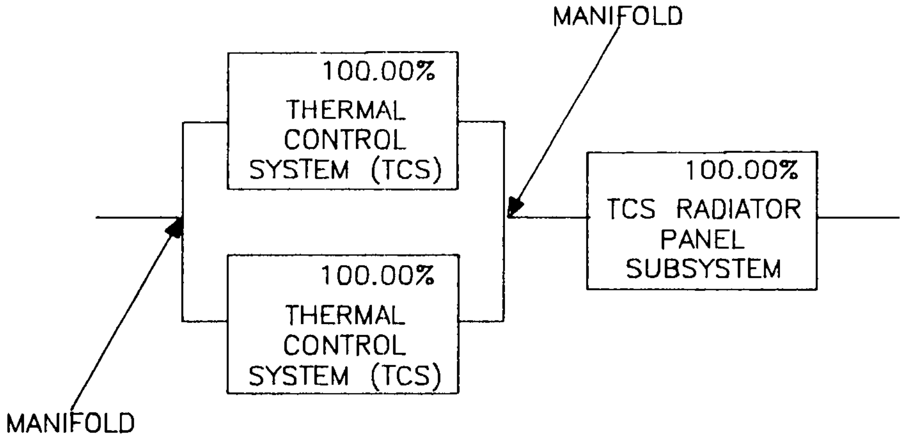

FIGURE 2-3

SAMPLE ABD OF A THERMAL CONTROL SYSTEM

The EPS has four functional and operational portions, as illustrated in Figure 2-1. For this reason and for other reasons discussed in the following paragraphs, the EPS required the following system ABDs for modeling and analysis:

- The photovoltaic power generation system during the insolar portion of an orbit (insolar ABD)
- The eclipse power generation system during the eclipse portion of an orbit (eclipse ABD)
- The power management and distribution system ABDs:
  - The manned core power distribution system through a ring PDCU architecture (PMAD ABD)

- The manned core power distribution system through a radial PDCU architecture (PMAD ABD, special case study)
- The inner keel power distribution system, outside the manned core and through the inner keel PDCUs (inner keel ABD)

The EPS has two types of power sources that operationally complement each other during a single orbit; Figure 2-1 illustrates both. It was assumed that the photovoltaic power generation system (insolar period) and the battery power generation system (eclipse period) generate power exclusively of one another; therefore, these two power generating systems were separated to form two major subsystems of the EPS. By separating them, all of the eclipse operation cycles in a given period have been collapsed into one system period of eclipse operation. Also, all of the insolar operation cycles have been collapsed into one system period of insolar operation.

To account for the availability of the ORUs required for a full battery charge during an insolation cycle that precedes a given eclipse cycle, charge-effect pseudocomponents were used in the eclipse ABD. A separate UNIRAM model (charge-effect model) was used to model the groups of ORUs required to provide a full battery charge. These ORUs are the cross-hatched ORUs in Figure 2-1. The effective MTBF and MTTR data were calculated using the baseline UNIRAM execution option with this model. These MTBF and MTTR values were then used as the charge-effect pseudocomponent data. The validity of accounting for the availability of a full battery in this way is discussed in Section A.2 of Appendix A. The eclipse period was modeled both with and without charge effects. All eclipse analyses were conducted twice - once with the charge-effect pseudocomponents set to "perfect" availability, and once using the effective MTBF and MTTR values.

The power management and distribution (PMAD) systems (Figure 2-1) were modeled separately from the two power generation systems. For analysis purposes it was convenient to separate power generation models from the PMAD system models. EPS power generation is functionally different from EPS power distribution. The EPS power generation systems have many probable output power levels (states) and require a measure of system equivalent availability. The EPS PMAD system consists of many redundant paths, each with a capacity of 25 kW. If a path is available, power is delivered to the load; therefore, PMAD has only two output states -- 25 kW and 0 kW. Since there are only two output states, availability becomes the RAM parameter of interest. In addition, the PMAD system was modeled as delivering power to a perfectly available 25-kW load.

Three ABDs were used for the PMAD system. The ring PDCU architecture ABD (PMAD ABD) is shown in Figure 2-4. The radial PDCU architecture ABD, shown in Figure 2-5, was developed for a special case study at the request of NASA (PMAD ABD, special case study), and it was used to model a radial PMAD PDCU architecture that, when analyzed, provided data for comparing the baseline RAM results of the two PMAD architectures. The inner keel distribution ABD (inner keel ABD), shown in Figure 2-6, was developed to model and determine the baseline RAM results for power distribution outside the manned core but inside the alpha joints.

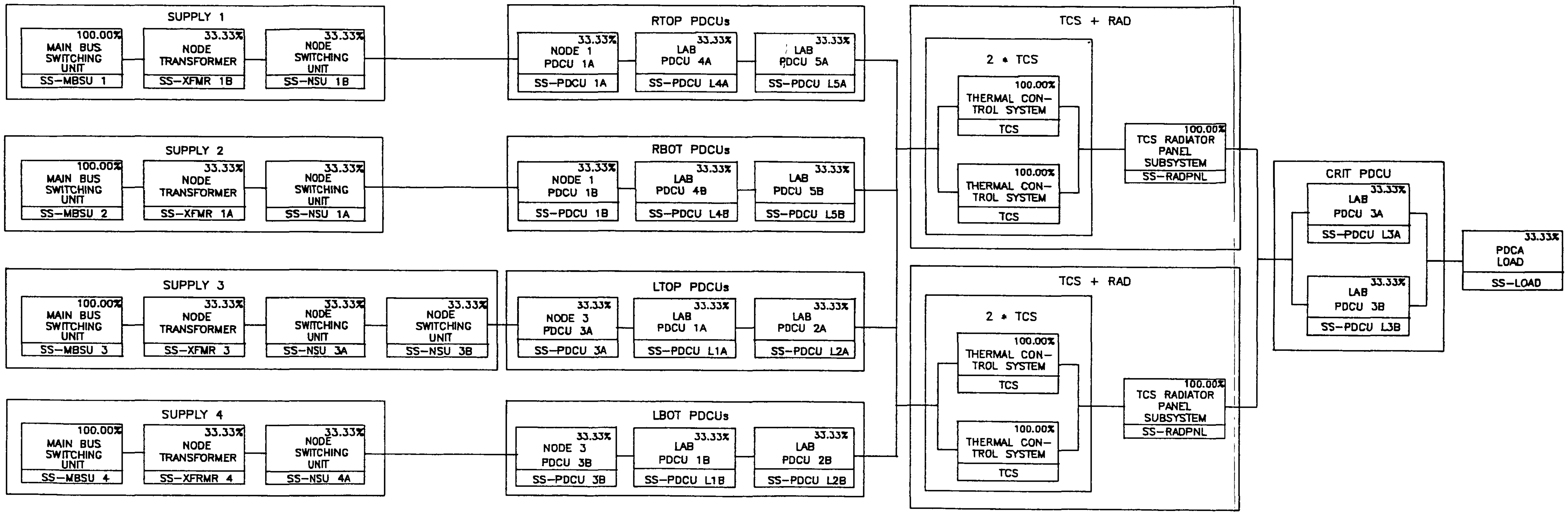

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FIGURE 2-4

PMAD AVAILABILITY BLOCK DIAGRAM
FOR RING PDCU ARCHITECTURE

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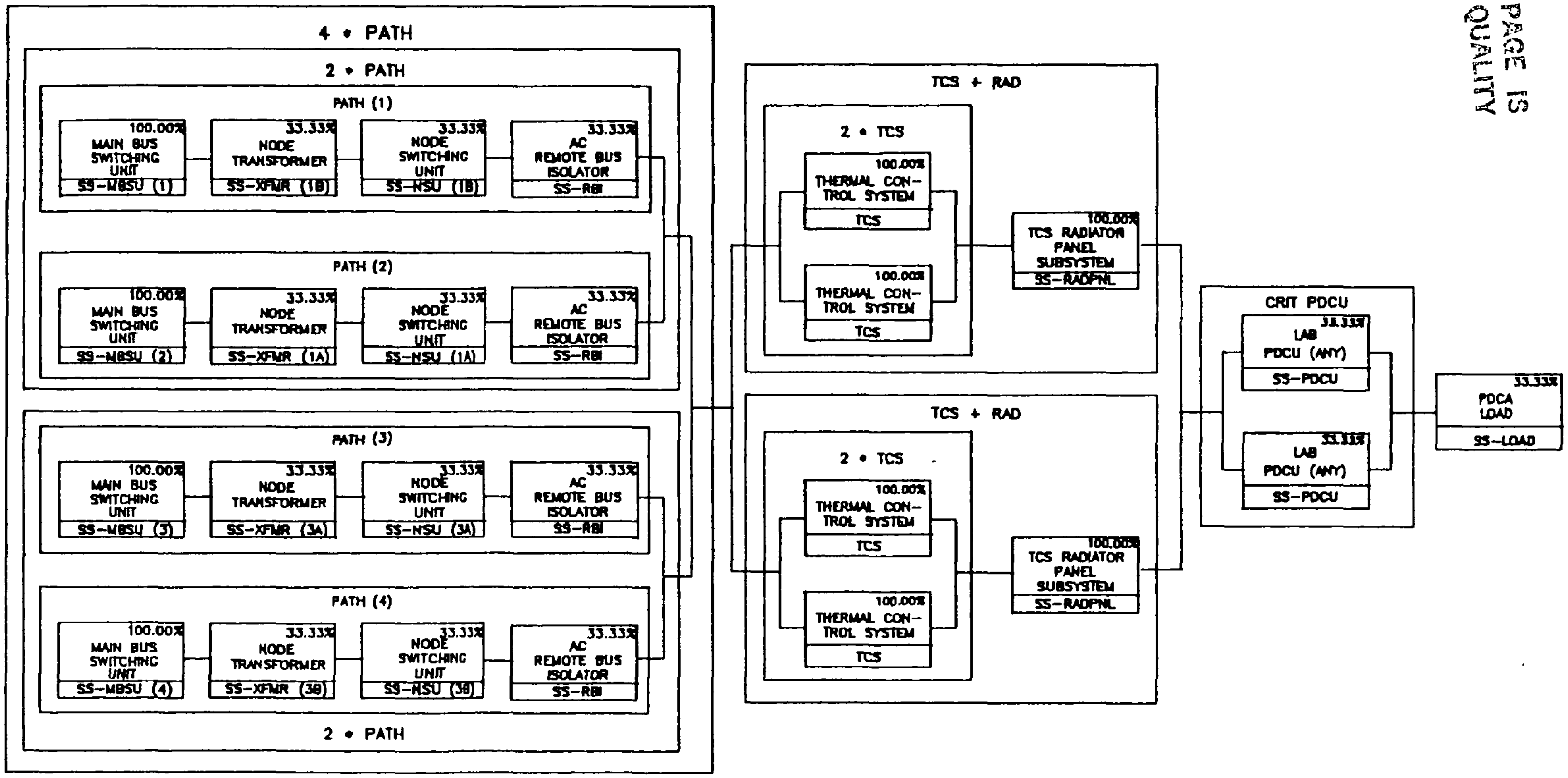

FIGURE 2-5

PMAD AVAILABILITY BLOCK DIAGRAM FOR RADIAL PDCU ARCHITECTURE

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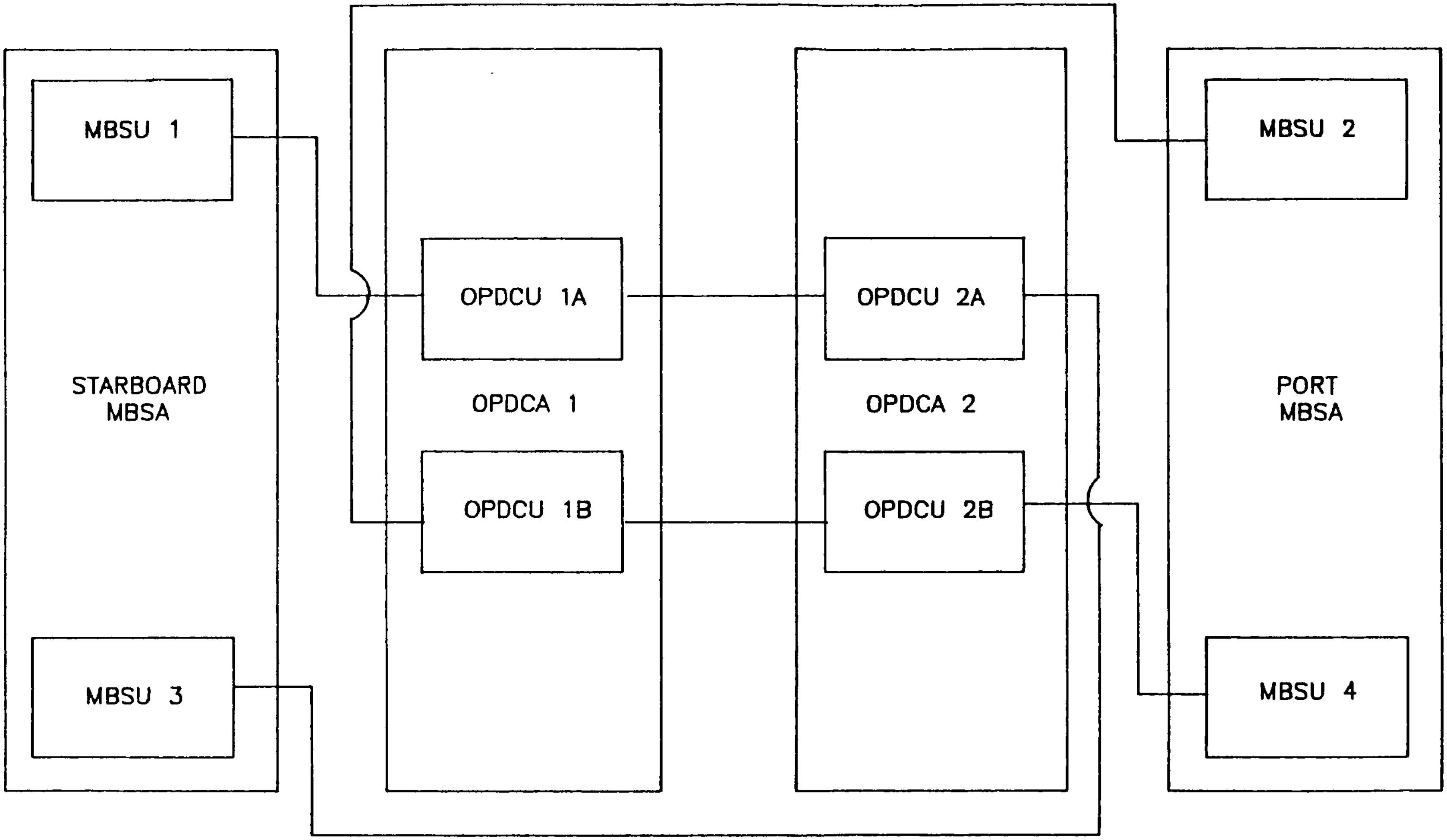

FIGURE 2-6

INNER KEEL AVAILABILITY BLOCK DIAGRAM

The EPS ABDs for each of the systems are provided in Section A.3 of Appendix A. The charge-effect model is comprised of four basic subsystems, each representing a charge-effect pseudocomponent. Fault trees for the charge effect basic subsystems are also presented in Section A.3.The ABDs were formulated on the basis of information from the Power System Description Document (PSDD, Ref. 3) and discussions with NASA LeRC personnel.

2.3.2 Partition the ABDs Into Basic and Nested Subsystems

A basic subsystem is one level of aggregation above the component level, when "component" is defined as the level at which the MTBF and MTTR data are collected or estimated. For the EPS, ORUs are considered the component level. Two components in the EPS UNIRAM models are not ORUs. At the request of NASA, the fault isolator was modeled as a component separate from its charge/discharge unit (CDU). The dc remote bus isolators (DC-RBIs), which couple the CDU to the dc switch unit (DCSU), were also modeled as separate components. Basic subsystems have only two levels of capacity -- full and zero.

A nested subsystem is an aggregation of basic subsystems and other nested subsystems. The nesting follows the manifolding in the ABD. There are two types of nested subsystems - a series configuration and a parallel configuration. A nested subsystem has two or more levels of output capability, based on the capacities and the number of subsystems nested within it.

Partitioning ABDs into basic and nested subsystems is an iterative process. The process of nesting defines the logical connections of basic and nested subsystems and thus defines the failure states of the system being modeled. The basic subsystems of the system ABDs are iteratively reduced (collapsed) into a single nested subsystem as part of the modeling process. To accomplish this reduction, serial and parallel arrangements of basic and nested subsystems are collected into progressively larger nested subsystems. The final nested subsystem contains all other subsystems and is equivalent to the full system being modeled (Ref. 1). For example, the basic subsystems shown in Figure 2-3 are nested into a single nested subsystem by combining the two thermal control systems (TCS) into a nested subsystem with a parallel configuration and then combining this nested subsystem with the TCS radiator panel subsystem into a series configuration to obtain the final nested subsystem.

2.3.3 Develop Fault Trees for Each Basic Subsystem

Every EPS basic subsystem has an associated fault tree that defines a logical framework for indicating which combinations of component failures within a basic subsystem would make that basic subsystem unavailable. Figure 2-7 illustrates the two basic fault tree types. In Figure 2-7a the "and-gate" logically represents the condition where both component A and component B must fail to fail the basic subsystem. However, Figure 2-7b shows that, through the use of an "or-gate", the failure of either component A or component B will cause the basic subsystem to fail. These gates and special cases of them are further discussed in Refference 1.

2.3.4 Obtain ORU RAM Data

Estimates of ORU MTBFs were obtained from NASA LeRC personnel and from the PSDD (refer to Appendix A). ORU MTTR data were based on the mean time it will take to bring a replacement ORU on-orbit, using the Space Shuttle. This value is assumed to be 1,080 hours (45 days). If the ORU is assumed to be spared on-orbit, the ORU MTTR is 6 hours. An ORU MTTR of 6 hours is an estimate of the mean time any ORU will require for replacement when spared on-orbit.

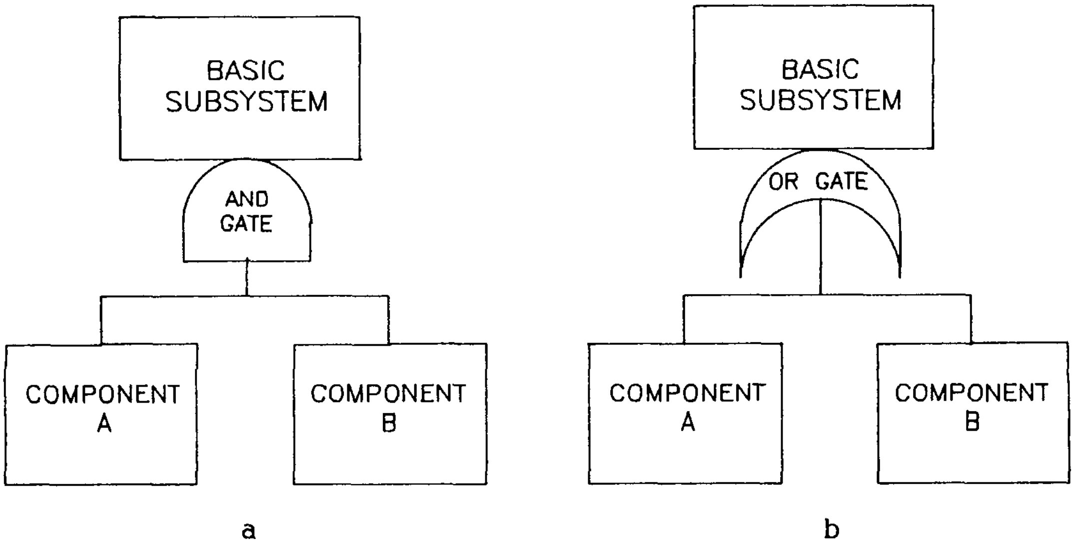

FIGURE 2-7

FAULT TREE EXAMPLE

2.3.5 Prepare UNIRAM Input Files

The UNIRAM input file describes the system model at the system, subsystem, and ORU levels. It uses the previous four modeling steps to implement the EPS models in a coded form so that the UNIRAM software can be used to determine the RAM values of the EPS models. The input file contains specific information about the availability block diagram, including subsystem nesting. The input file also includes the total system capacity, the number of hours per year the system will be shut down (zero hours in the EPS models), and the number of basic subsystem definitions to follow. The basic subsystem definition incorporates the ORU definitions, the fault tree logic, and the capacity of the basic subsystem. The ORU definitions contain the ORU MTBF and MTTR data. Another data entry for each ORU is the time, in hours, that the ORU's basic subsystem can function after the ORU has failed. This surge capability was used for the Beta positioning ORUs to show that loss of its ORUs is not significant until a given period of time has passed. The surge time increases the basic subsystem's effective MTBF value. The nested subsystem definitions follow those of the basic subsystem to form the UNIRAM model input file. The UNIRAM input files for the EPS are presented in Section A.4 of Appendix A. Refference 1 contains complete a description of the UNIRAM input file structure.

2.4 EVALUATE BASELINE EPS RAM VALUES AND ORU CRITICALITY RANKINGS

2.4.1 Initial System Availabilities, Equivalent Availabilities, and Output States

A baseline execution of UNIRAM yields predictions of system performance on the basis of the operating philosophy and expected equipment performance assumed in the modeling process (Ref. 1). The baseline UNIRAM runs were used to predict:

- The expected system output states and the probability of operation at each output state

- System performance measures, including availability, equivalent availability, forced outage rate, and equivalent forced outage rate

Two sets of baseline UNIRAM analyses were performed on all EPS models. The first set was performed with all ORU MTTRs set to 6 hours, and the second was performed with all ORU MTTRs set to 1,080 hours.

2.4.2 ORU Criticality Rankings

An important part of the EPS RAM assessment, in addition to system output states and system RAM measures, was an analysis of the system at the ORU level. UNIRAM component criticality ranking runs were performed for each model to evaluate the impact of individual ORUs on system performance. The component criticality ranking run ranks the ORUs in order of their contribution to system equivalent availability. The ranking factor is the amount of change in system equivalent availability that would be obtained if the ORU were made perfectly available. The magnitude of the ranking factor is a function of the ORU MTBF and MTTR, its throughput capacity, and its location in the system configuration (Ref. 1). When an EPS model was evaluated for its ORU criticality ranking, the ORU MTTRs were set to 1,080 hours. The ORU criticality rankings for the EPS models are listed in Appendix B.

2.5 EPS SPARING SENSITIVITY ASSESSMENTS

For this study, ORU sparing is defined as locating the spare ORU on-orbit. The effect of having a spare ORU on-orbit versus having one on-ground is a reduction in MTTR from 1,080 hours to 6 hours. Some ORUs will take fewer than 6 hours to restore, and some will take longer. An average of 6 hours was used because the change in system performance due to changes of ORU MTTRs from 12 hours to 6 hours, or from 6 hours to 3 hours, is negligible compared with the change in system performance when the spare ORU is moved from on-ground to on-orbit.

Sparing sensitivity analyses were performed on the insolar, eclipse without charge effects, eclipse with charge effects, and PMAD (ring PDCU architecture) models. The baseline component criticality rankings for each model in the analyses were used in two ways: MTTRs were varied only for ORUs with non-zero ranking factors, and the ORU rankings specified the order in which ORU MTTRs were varied. ORUs were first spared on-orbit individually and then spared on-orbit cumulatively (in order of the criticality rankings). For the eclipse model with charge effects, the procedure was first to vary the ORU MTTR in the charge-effect model to calculate the new effective MTBF and MTTR of the pseudocomponents. These MTBFs and MTTRs were then inserted into the eclipse system model. The insolar ORUs used in the charge-effect model were interspersed among the ranked eclipse ORUs on the basis of their rankings. The order of the ORU rankings in the resulting modified ORU criticality ranking supplied the order of ORU MTTR variation in the eclipse with charge-effects system model.

The output data of the previous analyses were tabulated to show the effects that sparing an ORU on-orbit has on system availability and equivalent availability. These data are listed in Appendix B. The tabulated data were examined to determine which of the ORUs have a significant impact on system availability and equivalent availability when spared on-orbit. These ORUs were considered critical and possible candidates for on-orbit sparing.

2.6 ASSESSMENT OF EPS AVAILABILITY SENSITIVITY TO ORU MTBF AND FAILURE RATE ANALYSES

The main variable in the reliability assessment and the failure rate analyses is ORU MTBF. Analyses were performed to determine the effect that varying ORU MTBFs had on system performance.

2.6.1 System Availability and Equivalent Availability

Reliability sensitivity assessments were performed on the insolar, eclipse without charge-effects, Eclipse with charge-effects, and PMAD (ring PDCU architecture) models. The MTBFs of selected ORUs in each system model were varied by scale factors from 0.7 to 5.0, and the resultant system availabilities and equivalent availabilities were tabulated. The ORUs to be analyzed were selected on the basis of their criticality rankings. In the PMAD system, only the PDCU MTBF was varied. The MTBFs of all the ORUs in each system model were then varied by scale factors from 0.7 to 5.0, and the resultant system availabilities and equivalent availabilities were tabulated. Finally, the MTBFs of the group of critical ORUs identified in the sparing sensitivity analyses were varied by scale factors from 0.7 to 5.0. The resultant tabulations of system availabilities and equivalent availabilities are listed in Appendix B.

2.6.2 Failure Rate Analyses

The EPS system ORU failure rates were calculated to determine the expected number of ORU failures in a one-year period. The results of this analysis are shown in Appendix B. The following equation was used:

$$\text{EPS system ORU failure rate} = \sum_{i=1}^{m} (t * N_i * \lambda_i)$$

where

i = component
m = total number of separate components in system
t = period of interest = 8,760 hours (1 year)
N_i = number of times the component is repeated in the system
λ_i = component failure rate (failures per hour)

2.7 INTEGRATE THE POWER GENERATION MODELS AND THE POWER DISTRIBUTION MODEL RESULTS

The various output states and state probabilities for the insolar, eclipse without charge effects, and eclipse with charge-effects models were combined with those of the PMAD (ring PDCU architecture) model to obtain the EPS integrated system results. The method used for this analysis essentially connects each power generation system with the power distribution system in a series configuration. The procedure for combining the power states is explained in the following example.

Table 2-1 presents examples of power distribution and power generation system output states and their associated output state probabilities and state power levels. For this study, power generation was assumed to be independent of power distribution. For independent systems in series, the combined system output states are found by calculating all possible combinations of the output states for the systems making up the combined system. The output state probability for each combined state is the product of the probabilities of the states being combined. Table 2-2 shows all possible combinations for the two models in Table 2-1. For the combined system, any given output state power level is the minimum power level of the two states (one for each unit in the combination) being combined. The combinations in Table 2-2 are reduced to the final combined output states in Table 2-3 by adding the state probabilities of combinations with the same output capability.

TABLE 2-1

JOINT STATE PROBABILITY EXAMPLE

(A) Sample Power Distribution Unit Output States

Output State	Output State Capability (%)	Output State Probability	Output State Power Level (kW)
1	33.33333	0.9500	25
2	0.00000	0.0500	0

(B) Sample Power Generation Unit Output States

1	100.0000	0.7500	75
2	80.0000	0.1000	60
3	60.0000	0.0500	45
4	40.0000	0.0400	30
5	20.0000	0.0300	15
6	0.0000	0.0300	0

TABLE 2-2

SAMPLE POWER DISTRIBUTION SYSTEM AND POWER GENERATION SYSTEM STATE COMBINATIONS

Output State	Output State Capability (%)	Output State Probability	Output State Power Level (kW)
A1 * B1	33.3333	0.7125	25
A1 * B2	33.3333	0.0950	25
A1 * B3	33.3333	0.0475	25
A1 * B4	33.3333	0.0380	25
A1 * B5	20.0000	0.0285	15
A1 * B6	0.0000	0.0285	0
A2 * B1	0.0000	0.0375	0
A2 * B2	0.0000	0.0050	0
A2 * B3	0.0000	0.0025	0
A2 * B4	0.0000	0.0020	0
A2 * B5	0.0000	0.0015	0
A2 * B6	0.0000	0.0015	0

TABLE 2-3

SAMPLE POWER DISTRIBUTION SYSTEM AND POWER GENERATION SYSTEM FINAL COMBINED STATES

Output State	Output State Capability (%)	Output State Probability	Output State Power Level (kW)
1	33.3333	0.8930	25
2	20.0000	0.0285	15
3	0.0000	0.0785	0

CHAPTER THREE

ANALYSIS RESULTS

The analysis methodology presented in Chapter Two provides results concerning the expected availability of the Space Station Electric Power System. In addition to baseline information, the methodology provides results for determining the effects of varying ORU reliability and maintainability on system availability. ORU reliability was varied by changing ORU MTBF. ORU maintainability was varied by reducing ORU MTTR between on-orbit sparing (MTTR = 6 hours) and on-ground sparing (MTTR = 1,080 hours). This chapter describes and discusses the results of the following:

- EPS Baseline RAM Analyses
- EPS Sparing Sensitivity Analyses
- EPS Reliability Sensitivity Analyses
- Comparison of EPS Model Reliabilities and Maintainabilities
- EPS Integrated System Evaluation
- EPS ORU Failure and Replacement Rate

The tabular data supporting all figures and data discussed in this chapter are listed in Appendix B.

3.1 EPS BASELINE RAM ANALYSES

This section discusses system availability and equivalent availability and system ORU criticality ranking

3.1.1 Insolar Baseline RAM Analysis

The baseline availability is 99.92 percent; the corresponding baseline equivalent availability is 89.35 percent. There are 61 possible output states for the insolar model; 16 of the output states have state probabilities less than 0.000001. Table 3-1 shows the Insolar system output states with output probabilities greater than 0.01. There are three output states with power levels below the 12.5 kW assumed necessary for minimum life support. The three output states yield a total probability of 0.000857 of falling below the minimum life-support level, including a zero-output state probability of 0.000783. This value is represented as a combined state in Table 3-1.

TABLE 3-1

SIGNIFICANT INSOLAR SYSTEM OUTPUT STATES

Output Capability (%)	Output State Probability	Days Per Year	Power Output (kW)
100.00	0.393899	143.77	75.0
99.69	0.053547	19.54	74.8
87.50	0.301812	110.16	65.6
87.19	0.035900	13.10	65.4
81.83	0.024162	8.82	61.4
75.00	0.104130	38.01	56.3
74.69	0.010617	3.88	56.0
62.50	0.020964	7.65	46.9
50.00	0.020530	7.49	37.5
<16.67	0.000857	0.31	<12.5

The insolar ORU criticality ranking shows that the alpha joint power data transfer assembly (Alpha-PDT) has the highest criticality ranking which is followed closely by the rankings for the beta PDT, sequential shunt unit, DC switch unit and the solar array electronics assembly. The Alpha-PDT has the highest criticality because its failure would cause a 50-percent reduction in system output capability.

3.1.2 Eclipse Baseline RAM Analysis

The eclipse power generation model was evaluated with and without taking into account the probability of a full battery charge at the beginning of the eclipse period. To account for the probability of a full battery charge at the beginning of an eclipse cycle, charge-effect pseudocomponents were incorporated at the appropriate points in the eclipse model. Section A.2 of Appendix A presents a discussion of charge-effect use and pseudocomponent location in the eclipse model. To evaluate the eclipse model without charge effects, the charge-effect pseudocomponents were made perfectly available.

For the eclipse model without charge effects, the baseline availability is 99.92 percent and the corresponding equivalent availability is 89.57 percent. There are 21 possible output states with 1 output state having a state probability less than 0.000001. Table 3-2 presents the output states with output probabilities greater than 0.01. There are four output states with power levels below the 12.5 kW necessary for minimum life support. The four output states yield a total probability of 0.000798 of falling below the minimum life-support level, including a zero-output state probability of 0.000782. This value is represented as a combined state in Table 3-2.

TABLE 3-2

SIGNIFICANT ECLIPSE SYSTEM OUTPUT STATES (WITHOUT CHARGE EFFECTS)

Output Capability (%)	Output State Probability	Days Year	Power Output (kW)
100.00	0.191128	69.76	75.0
95.00	0.288218	105.20	71.3
90.00	0.224706	82.02	67.5
85.00	0.137810	50.30	63.7
80.00	0.071631	26.15	60.0
75.00	0.033810	12.34	56.3
70.00	0.014891	5.44	52.5
50.00	0.012661	4.62	37.5
<16.67	0.000798	0.29	<12.5

For the eclipse model with charge effects, the baseline availability is again 99.92 percent. However, the corresponding equivalent availability is 75.95 percent. The decrease in equivalent availability when charge effects are considered exceeds 13 percent. The significant impact on equivalent availability when charge effects are used emphasizes the importance of the availability of a full battery charge at the beginning of the eclipse period. Availability was not affected, because charge effects reduce the availability of charge on individual battery sets. To affect availability, the probability of the zero-output state must be affected. Since there are four full battery sets in the eclipse model, even with charge effects, the probability of simultaneous failure of all batteries is still low. Hence, charge effects have no effect on availability.

Eclipse with charge effects has the same 21 possible output states as eclipse without charge effects, but the output state probabilities differ significantly. Table 3-3 lists the output states with output probabilities greater than 0.01. Eclipse with charge effects has a zero-output state probability of 0.000790. The probability of falling below the minimum life-support power level of 12.5 kW is 0.001287. Figure 3-1 illustrates why there is a significant drop in equivalent availability when charge effects are considered. Figure 3-1 is a plot of output state probabilities for the possible output power levels of eclipse with and without charge effects. On the basis of Figure 3-1, the most probable output states for eclipse with charge effects are lower than those for eclipse without charge effects. An output state probability can be interpreted as the percentage of time spent at a given output state. Since less time is spent in the higher output power states because of charge effects, equivalent availability is lower.

TABLE 3-3

SIGNIFICANT ECLIPSE SYSTEM OUTPUT STATES (WITH CHARGE EFFECTS)

Output Capability (%)	Output State Probability	Days Per Year	Power Output (kW)
100.00	0.021545	7.86	75.0
95.00	0.067433	24.61	71.3
90.00	0.113707	41.50	67.5
85.00	0.147591	53.87	63.7
80.00	0.157565	57.51	60.0
75.00	0.143823	52.50	56.3
70.00	0.116384	42.48	52.5
65.00	0.083777	30.58	48.8
60.00	0.054586	19.92	45.0
55.00	0.032362	11.81	41.3
50.00	0.021613	7.89	37.5
45.00	0.015166	5.54	33.8
<16.67	0.001287	0.47	<12.5

The ORU criticality ranking for eclipse without charge effects shows that the battery has a slightly greater ranking than the Alpha-PDT, the DC switch unit, the CDU fault isolator and the CDU for this model. Making the battery perfectly available has more impact on system equivalent availability than making the other ORUs perfectly available, because the baseline MTBF of the battery is eight years and the baseline MTBF of the other ORUs is ten years or more.

The ORU criticality ranking for Eclipse with charge effects shows that two charge-effect pseudocomponents are considered the most critical components: partial photovoltaic (PV) module charge effects and battery charge effects. Together, these two components account for almost all of the 13-percent decrease in equivalent availability resulting from the use of charge effects. This is because partial PV module charge effects and battery charge effects contain nearly all the ORUs that are incorporated in the charge-effect components. The remainder of this criticality ranking is similar to that for eclipse without charge effects.

3.1.3 PMAD Baseline RAM Analysis

Initially, baseline analyses were performed on model variations of the PMAD system in a ring architecture (Figure 3-2). The variations

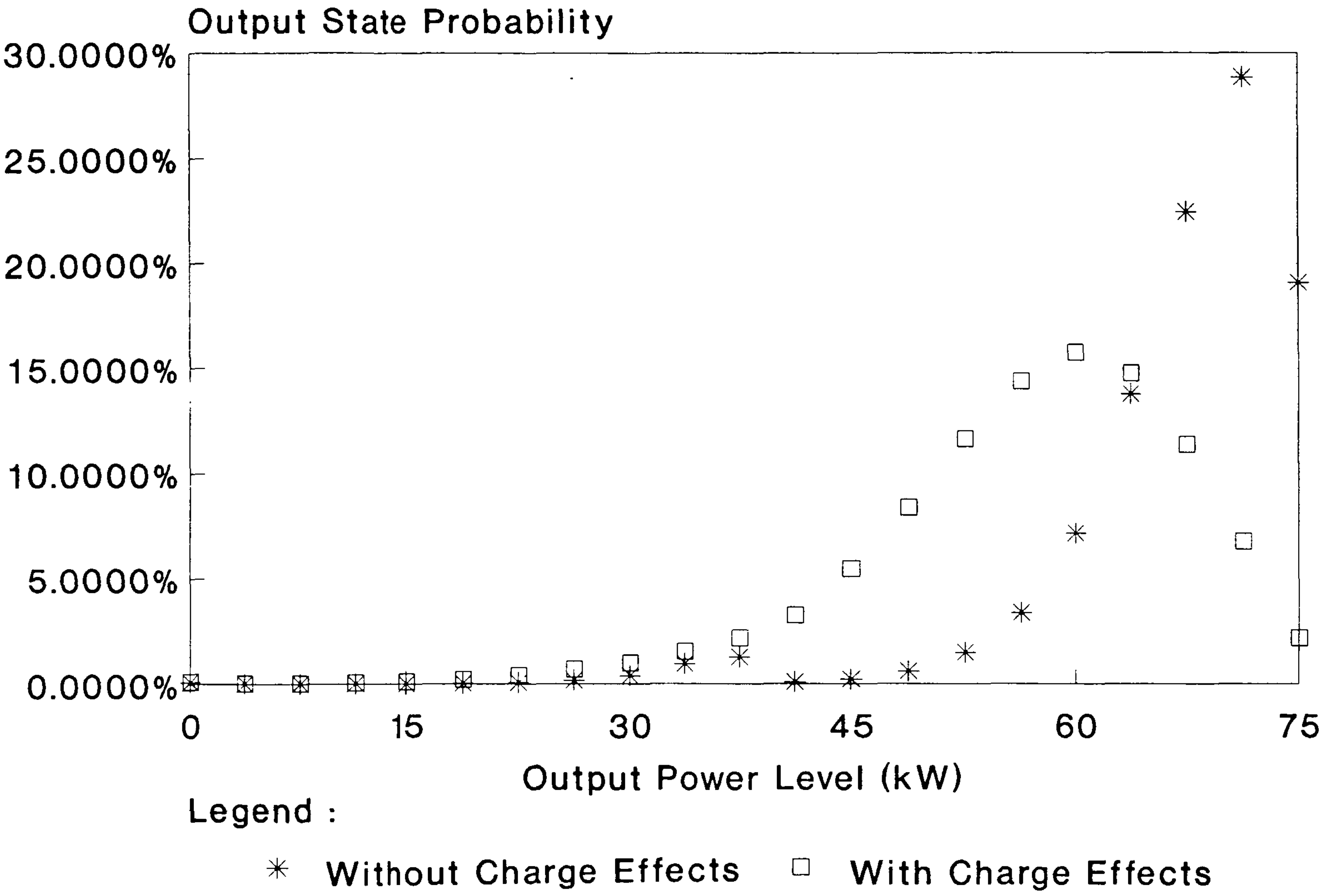

FIGURE 3-1

ECLIPSE OUTPUT STATE PROBABILITY VERSUS OUTPUT POWER LEVEL changed which PDCA was at the end of the distribution chain of PDCUs. This determined which PDCA had the least availability and equivalent availability. The laboratory module (LAB) and habitation module (HAB) distribution systems are identical relative to the UNIRAM methodology, and the LAB module was modeled. The results obtained are applicable to the HAB module as well. As shown in Figure 3-3, there is essentially no difference in availability among the PDCAs. All further analyses were performed using a PMAD configuration that modeled power flow through PDCA-L3 to a perfectly available 25-kW load, as explained in Section 2.3.1. Since the load will be distributed between all PDCAs and the other PDCAs are more available than PDCA-L3, the analysis with a 25-kW load provides lower bounds on PMAD availability and equivalent availability levels. Since the results reflect the use of the 25-kW load in the model, the perfect equivalent availability figure is 33.3333 percent (rather than 100.000 percent), because PMAD was modeled with a system capacity of 75 kW.

The baseline availability for the PMAD is 99.98 percent, and the corresponding equivalent availability is 33.33 percent. All components in the PMAD system are modeled with a 33.33 percent throughput capacity (33.33 percent of the total system capacity of 75 kW). For this reason, there were only two output states -- 25 kW and 0 kW. If a path is available, the power will be delivered to the load. Since there are only two possible output states, the probability of falling below the minimum life-support level of 12.5 kW is the same as the zero-output state probability of 0.000187.

The PDCU is the highest ranked ORU in the PMAD ORU criticality ranking. The PDCUs that make up the load center PDCA, in this case PDCUs L3A and L3B (Figure 3-2) are at the end points of the availability chain of components and, therefore, will always rank highest. The remaining ORUs have approximately the same ranking and are not expected to be of critical concern.

3.2 EPS SPARING SENSITIVITY ANALYSES

The sparing sensitivity analyses were performed to provide an indication of the importance of ORU MTTR to EPS operation. ORUs were spared on-orbit individually and cumulatively, in order of the system criticality rankings, to determine the effects on system availability and equivalent availability. The cumulative ORU on-orbit sparing results follow directly from the results obtained for individual on-orbit sparing of ORUs. Only the results of individual ORU on-orbit sparing are discussed in this section. Most of the effects of sparing ORUs on system equivalent availability are centered on eight ORUs. From a RAM perspective only, these eight ORUs could be recommended for potential on-orbit spares.

In both the insolar and eclipse models, thermal control plates (TCPs) are prominent in their effects on equivalent availability when spared on-orbit. These effects are not apparent from the criticality rankings. As long as an ORU's population in the EPS is reflected by the subsystem nesting within the unit, it is taken into account in the criticality ranking. The TCPs are not modeled such that the subsystem nesting will

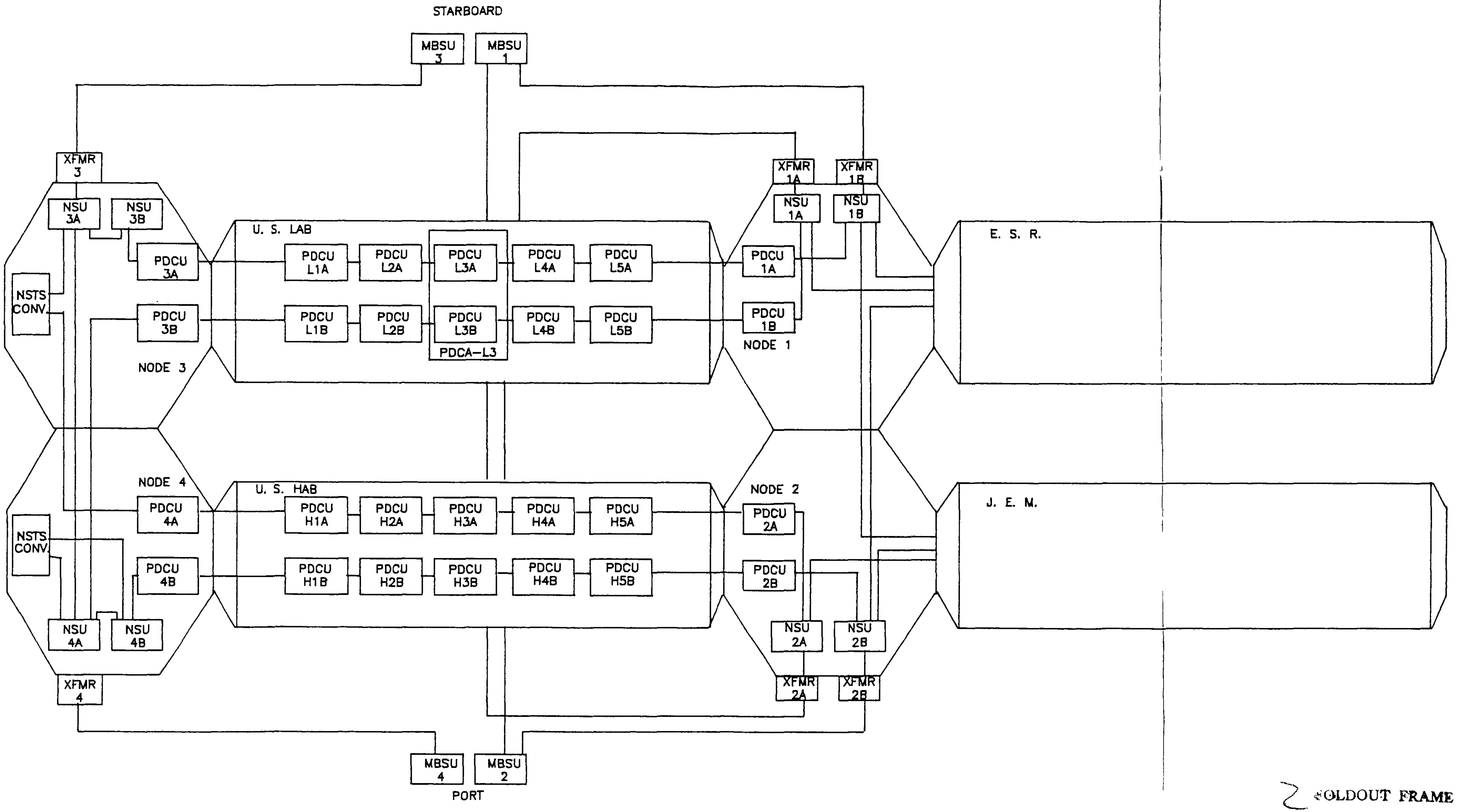

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FIGURE 3-2

PMAD RING ARCHITECTURE
FUNCTIONAL BLOCK DIAGRAM

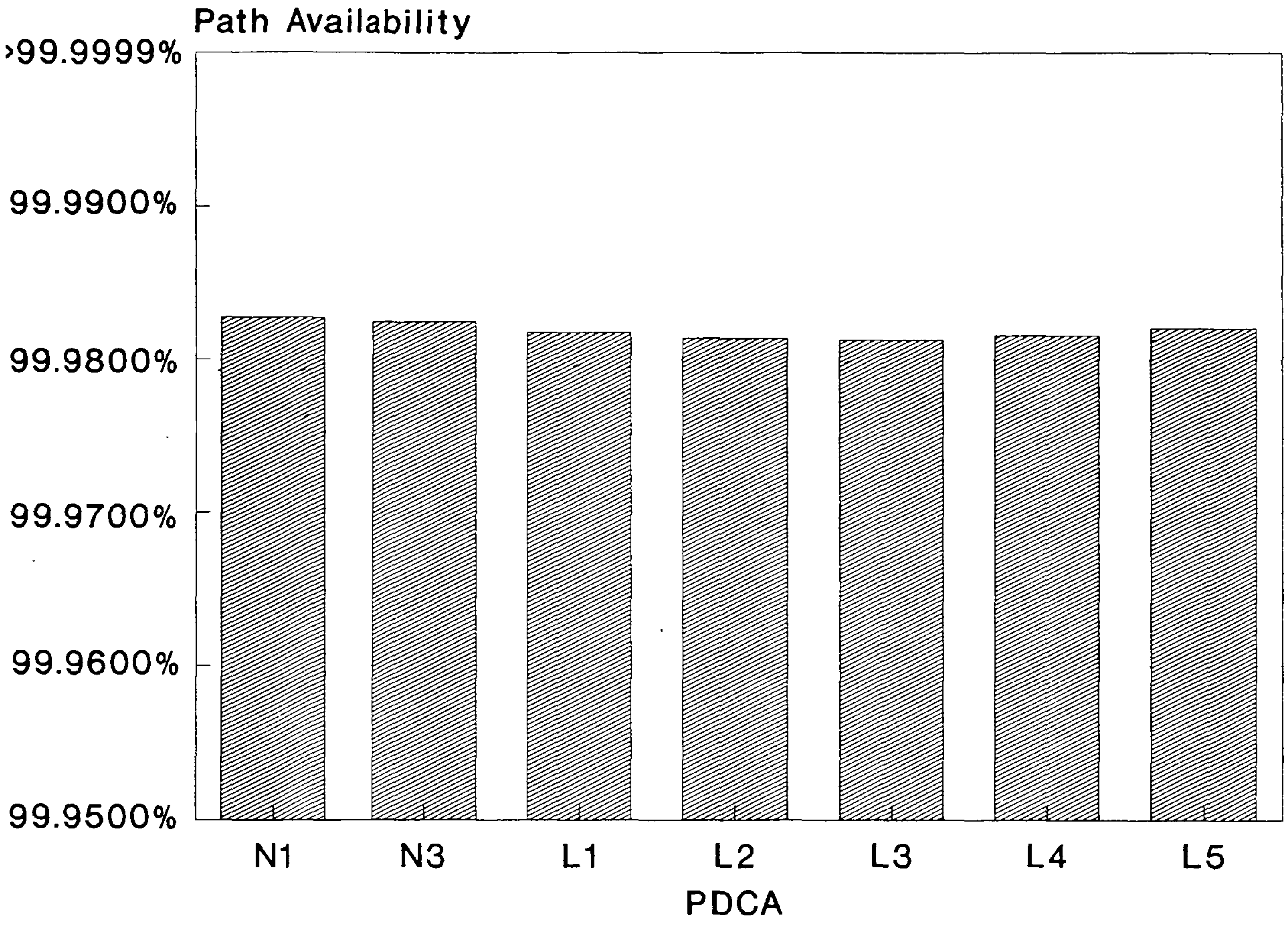


FIGURE 3-3

PMAD PATH AVAILABILITY TO EACH PDCA

account for the population of the ORU TCP. Since each TCP is within the fault tree of another ORU, UNIRAM does not evaluate a single ORU type called TCP. It evaluates, for example, a CDU-TCP or a PDCU-TCP. However, when the TCP was evaluated as a spare, all TCP MTTRs were physically changed in the UNIRAM input file. Therefore, the TCPs have an effect on equivalent availability seemingly out of proportion to their criticality rankings.

3.2.1 Insolar Sparing Sensitivity Results

Figures 3-4 and 3-5 show the effects of single ORU on-orbit sparing on system availability and equivalent availability, respectively, for the insolar model. The significant ORUs for availability are the Alpha-PDT and the power management controller (PMC). These ORUs, because of their small quantity (2) and the fact that the EPS system depends on them for operation, have the greatest probability of bringing the insolar power generation system to a zero-output level. The scale on Figure 3-4 ranges from 99.9217 percent to > 99.9999 percent, thus, the variation in availability is relatively small compared with that shown in Figure 3-5.

In Figure 3-5 two major items become apparent. First, seven ORUs have significant impact on insolar system equivalent availability: Alpha-PDT, Beta-PDT, solar array electronics (SAElec), sequential shunt unit (SSU), dc switch unit (DCSU), thermal control plates (TCPs), and right and left photovoltaic blankets (RPVB and LPVB). Second, the first five of these components (Alpha-PDT, Beta-PDT, SAElec, SSU, and DCSU) have the same amount of impact on insolar equivalent availability which allows the possibility of trade-offs on EPS level of on-orbit sparing. Trade-offs allow the possibility of taking other factors into account, such as cost, weight, and volume. The high impact that sparing TCPs have on system equivalent availability is due to the great number of TCPs in the system; 136 TCPs were modeled in the full EPS system. Many insolar system ORUs depend on TCPs for operation.

3.2.2 Eclipse Sparing Sensitivity Results

Figures 3-6 and 3-7 show the effects of single ORU on-orbit sparing on system availability and equivalent availability, respectively, for the eclipse model without charge effects. The Alpha-PDT and the PMC have the greatest impact on system availability for the same reasons as for the insolar model. Variations in availability (Figure 3-6) are small compared with variations in equivalent availability (Figure 3-7).

A comparison of Figure 3-5 with Figure 3-7 shows that there are additional similarities between insolar operation and eclipse operation without charge effects. In this case, six ORUs and ancillary components have significant impact on system equivalent availability: battery, Alpha-PDT, DCSU, fault isolator, CDU, and TCPs. As with the insolar system, the eclipse system without charge effects has several ORUs that affect equivalent availability equally when they are spared on-orbit: Alpha-PDT, DCSU, and CDU fault isolator. The TCPs have a pronounced effect again, due to their great number and their impact on the ability of ORUs in the eclipse system without charge effects to operate.

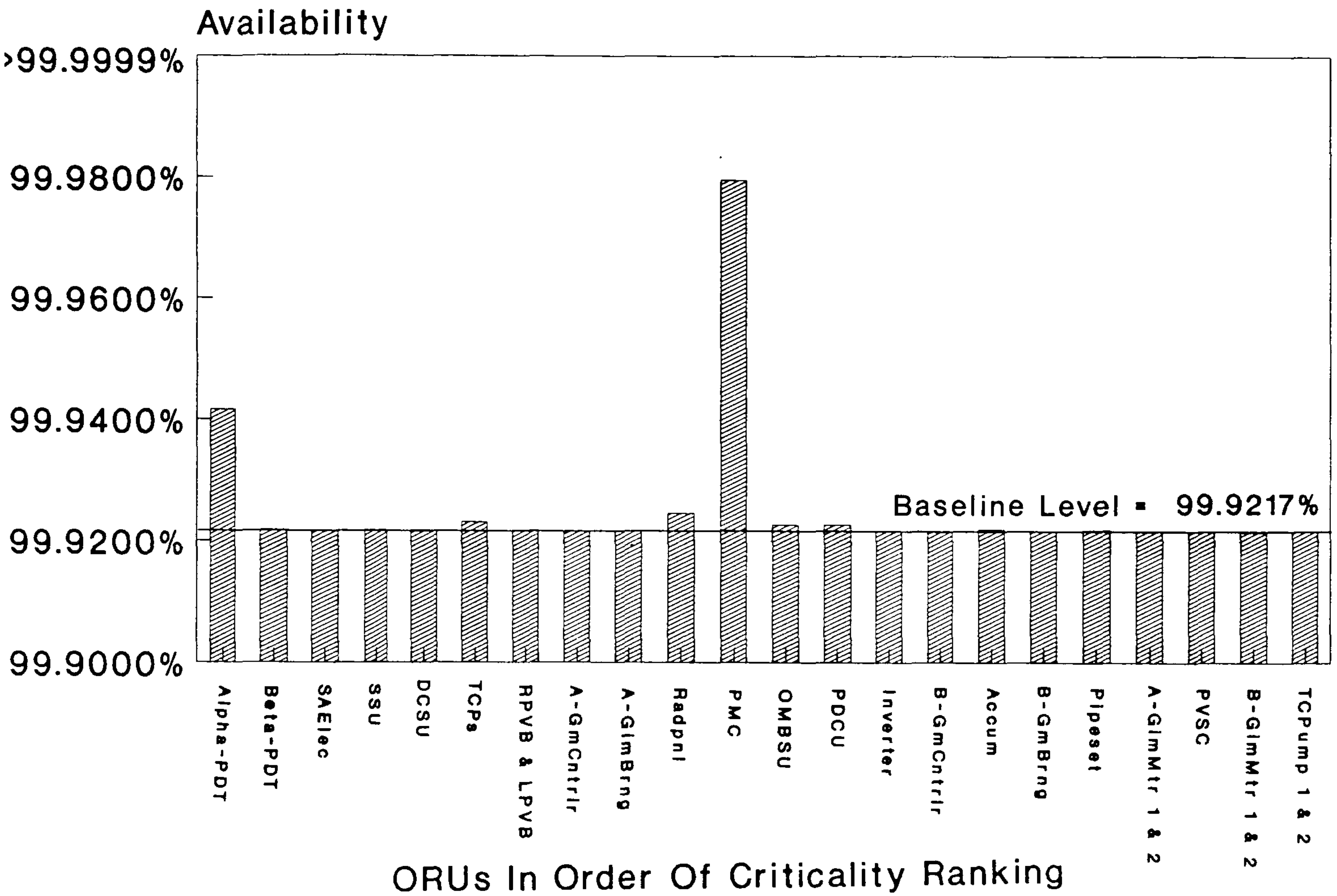


FIGURE 3-4

EFFECTS OF SINGLE ORU ORBITAL SPARING ON AVAILABILITY FOR THE INSOLAR MODEL

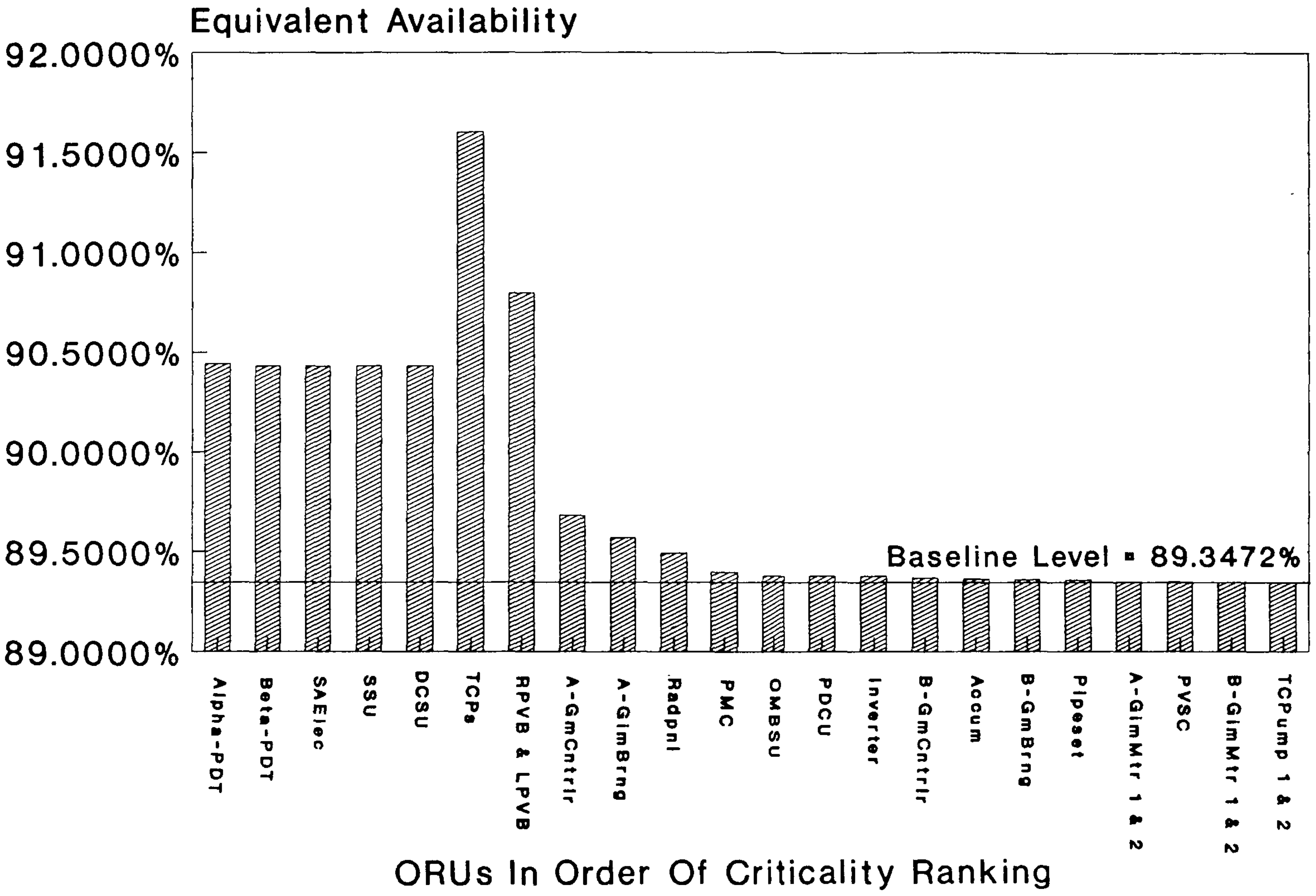


FIGURE 3-5

EFFECTS OF SINGLE ORU ORBITAL SPARING ON EQUIVALENT AVAILABILITY FOR THE INSOLAR MODEL

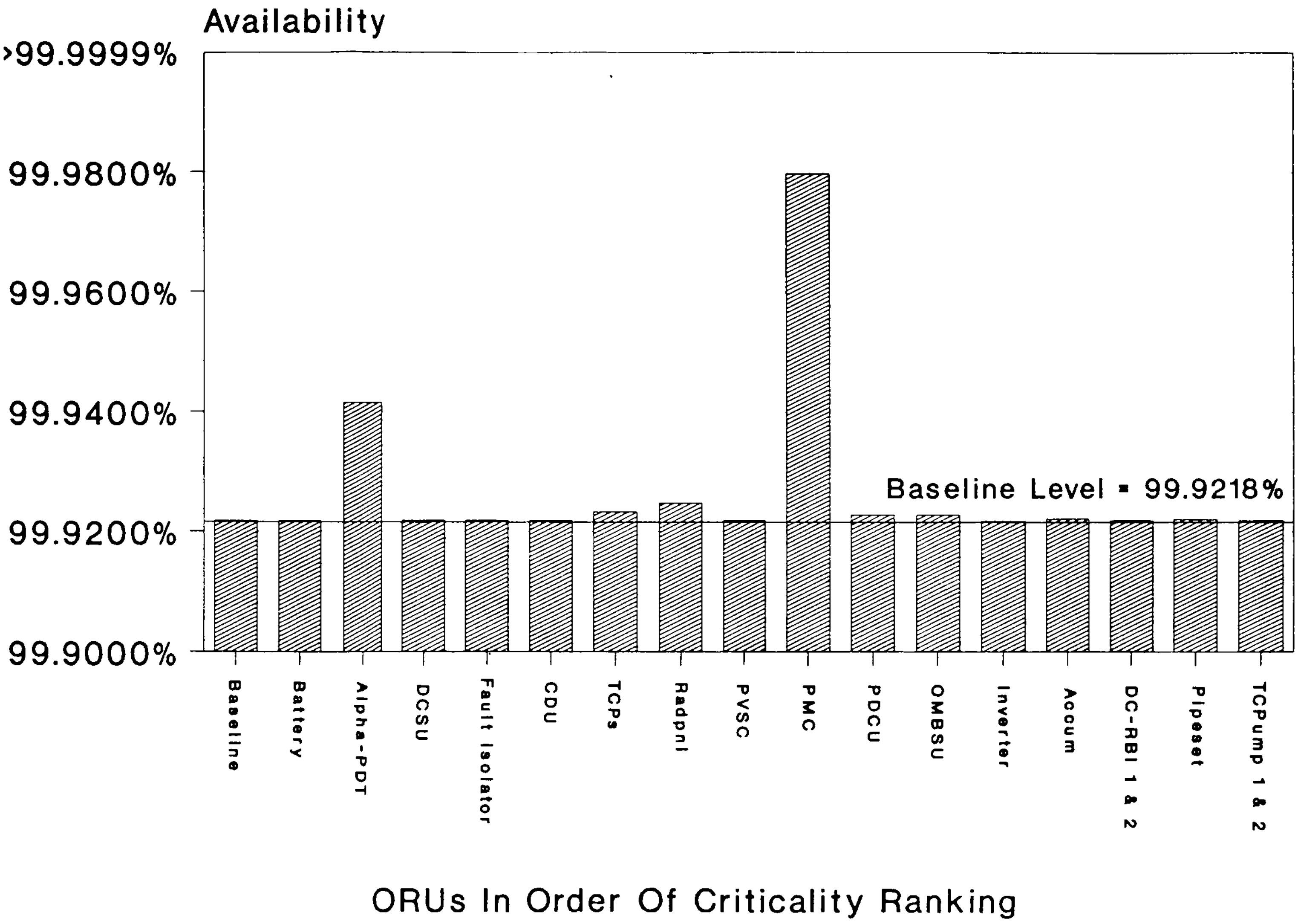


FIGURE 3-6

EFFECTS OF SINGLE ORU ORBITAL SPARING ON AVAILABILITY FOR THE ECLIPSE MODEL WITHOUT CHARGE EFFECTS

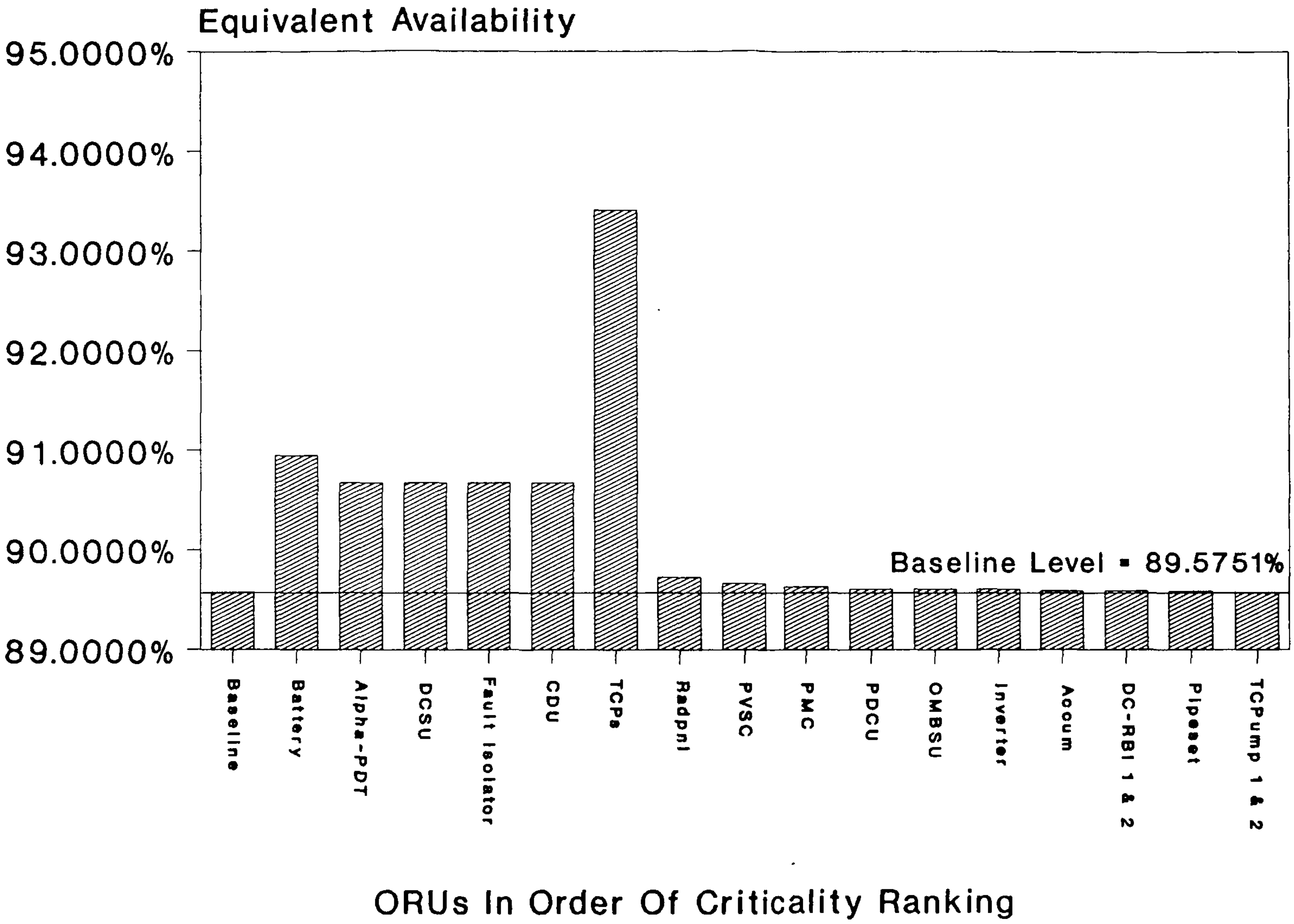


FIGURE 3-7

EFFECTS OF SINGLE ORU ORBITAL SPARING ON EQUIVALENT AVAILABILITY FOR THE ECLIPSE MODEL WITHOUT CHARGE EFFECTS

Figure 3-8 shows that the Alpha-PDT and PMC present the most significant effects on availability when spared on-orbit. However, Figure 3-9 shows that effects on equivalent availability due to on-orbit sparing of ORUs differ from those for insolar (Figure 3-5) and eclipse without charge effects (Figure 3-7) in two significant ways. First, there are now effects due to insolation period components. The Beta-PDT, SSU, SAElec, and RPVB and LPVB have significant effects on eclipse operation. Second, a greater significance is attached to the DCSU and CDU fault isolator, since these ORUs are now taken into account during both the insolation and eclipse periods of operation. When considering eclipse without charge effects, this insolation dependence was not apparent. In eclipse without charge effects (Figure 3-7) a general trade-off for ORU on-orbit sparing possibly allowed equally weighted choices between the Alpha-PDT, DCSU, and CDU fault isolator. Incorporating charge effects into the eclipse model gave the DCSU and CDU/Fault Isolator ORUs greater on-orbit sparing impact than the Alpha-PDT (Figure 3-9) thus limiting the ORU on-orbit sparing trade-off choices. The batteries have a more pronounced impact than do the Alpha-PDT and other ORUs, because the battery MTBF is less than the other ORU MTBFs (eight years versus ten years), and the batteries also have an insolation operation dependence.

3.2.3 PMAD Sparing Sensitivity Results

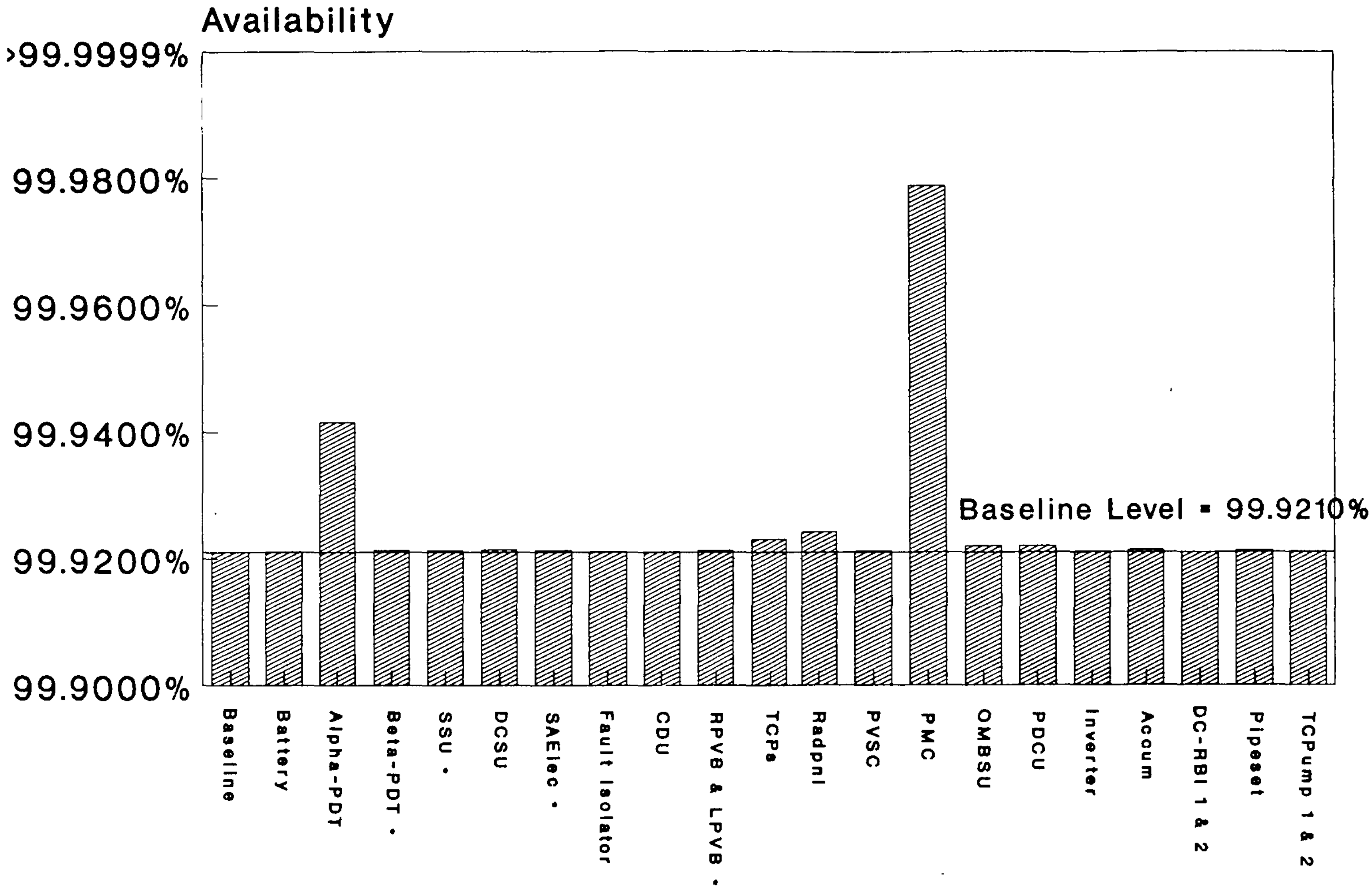
The PMAD system power distribution control unit (PDCU) is the one ORU that stands out because of its effect on PMAD system equivalent availability when spared on-orbit (Figure 3-10). The total variation is small, from 24.9950 kW (33.3271 percent) to 24.9998 kW (33.331 percent). However, from a repair point of view, because there are 28 internal PDCUs, the PDCU is the most likely ORU to need replacement; and from a maintainability perspective, the PDCU should be evaluated as an on-orbit spare.

3.2.4 On-Orbit Level of Sparing

On the basis of the previous discussion and examination of the ORU sparing analysis results, the following eight ORUs are considered the most critical from a RAM perspective and are potential choices for on-orbit spares:

- PMC - The PMC has the greatest effect on eclipse and insolar system availability, as shown in Figures 3-4, 3-6, and 3-8.

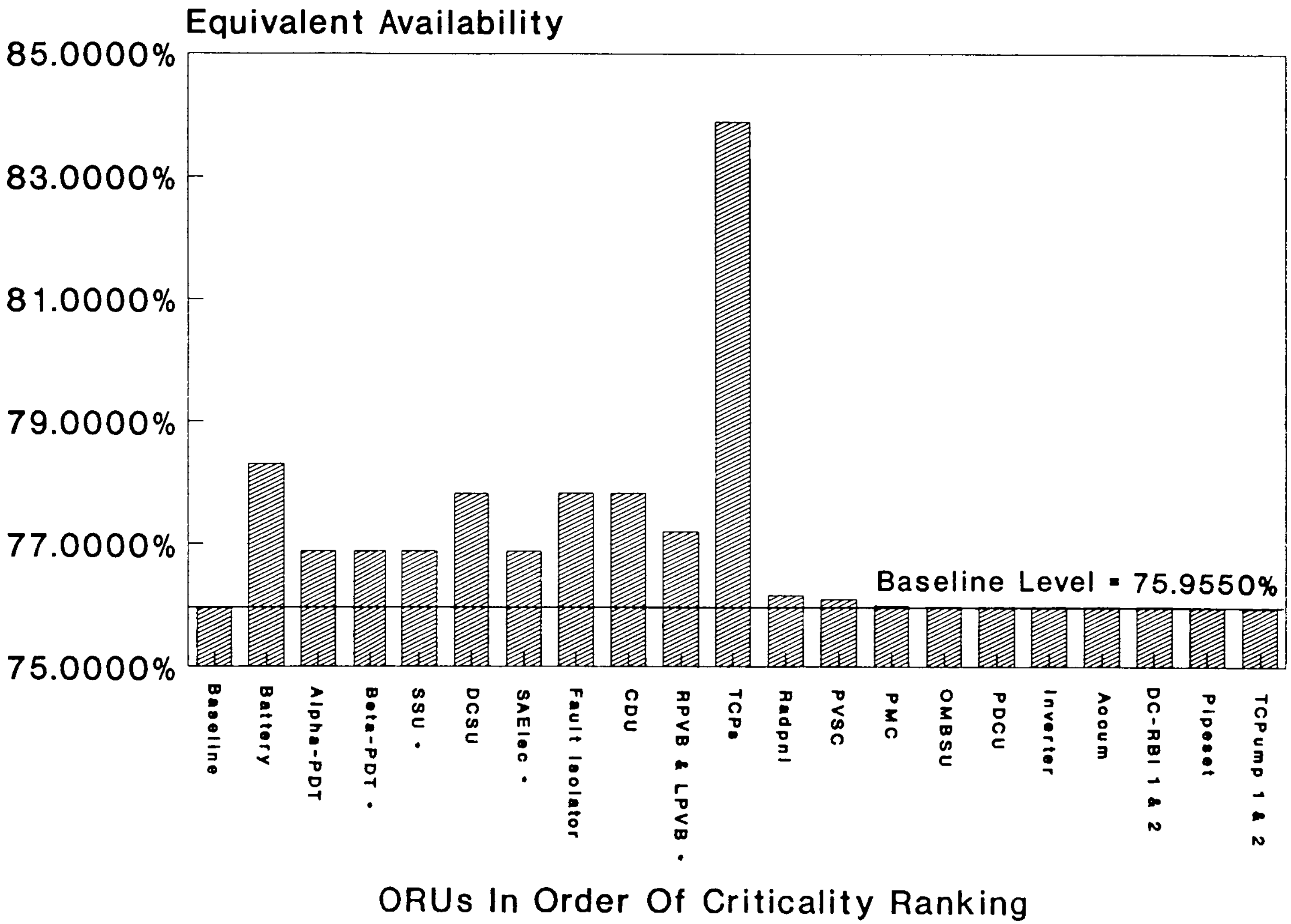
- Alpha-PDT - The Alpha-PDT has a significant effect on availability and equivalent availability (Figures 3-4 through 3-9). There is no redundancy of Alpha-PDTs, and a single point failure causes a 50-percent loss of EPS output power capability.



*Insolar ORUs In Charge Effects

FIGURE 3-8

EFFECTS OF SINGLE ORU ORBITAL SPARING ON AVAILABILITY FOR THE ECLIPSE MODEL WITH CHARGE EFFECTS



*Insolar ORUs In Charge Effects

FIGURE 3-9

EFFECTS OF SINGLE ORU ORBITAL SPARING ON EQUIVALENT AVAILABILITY FOR THE ECLIPSE MODEL WITH CHARGE EFFECTS

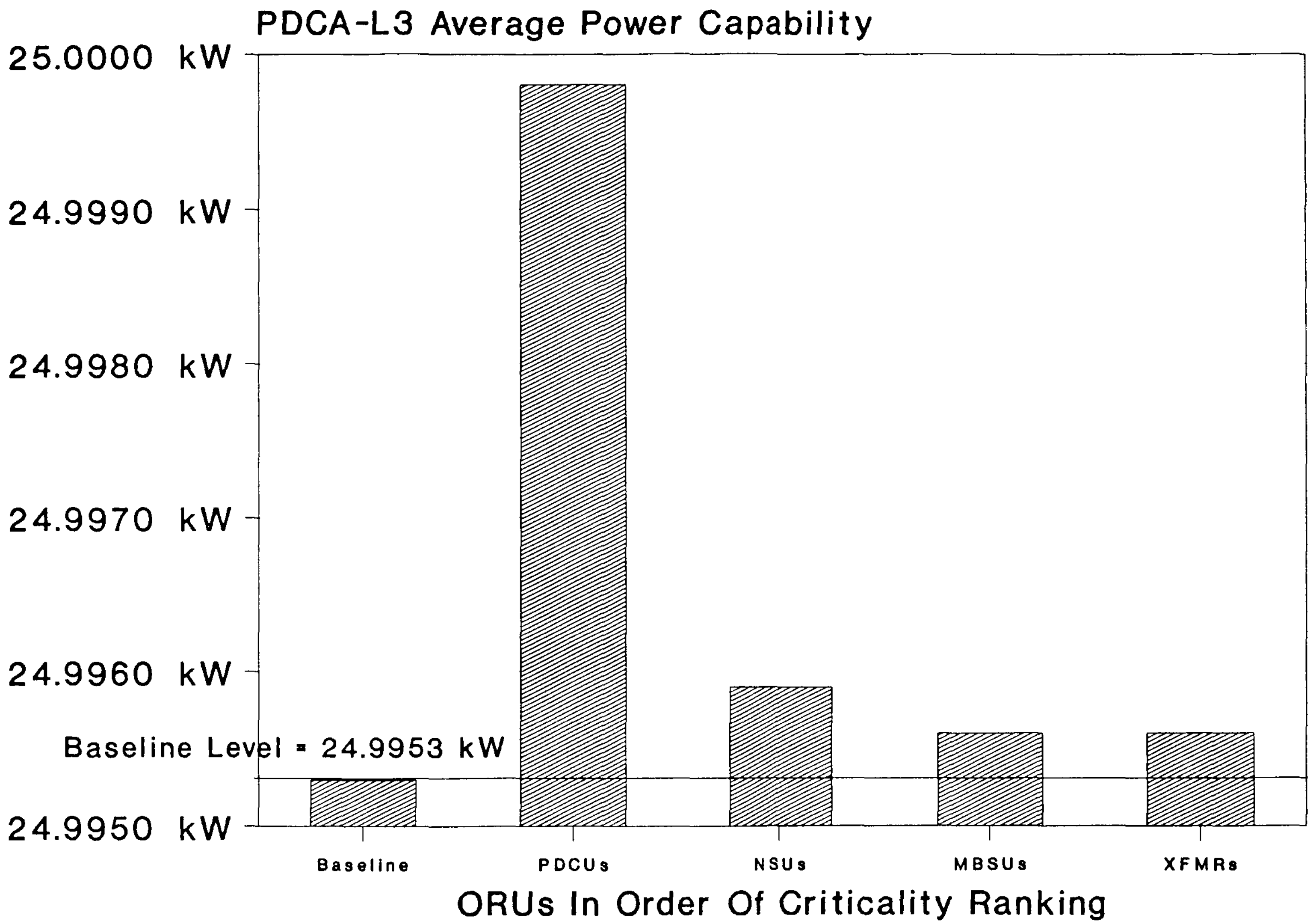


FIGURE 3-10

PMAD SINGLE ORU ORBITAL SPARING

- TCP - The TCPs have a significant impact on system equivalent availability (Figures 3-5, 3-7 and 3-9) because there are 136 of them in the total EPS system. On-orbit sparing of one TCP reduces the MTTRs of all TCPs in the system until the first TCP failure and the on-orbit spare is used. Because of the high number of TCPs, the probability of random failure of a TCP is significant.

- SAElec - A failure of an SAElec ORU will result in the loss of output power from one-half of a PV module. Eight SAElec ORUs are affected by a change in the MTTR.

- SSU - The reasoning for sparing this component is the same as that for the SAElec.

- CDU - The reasoning for sparing this component is the impact of the CDU on equivalent availability (Figures 3-7 and 3-9), when considering charge effects during eclipse operation, should rank the CDU as a more valuable on-orbit spare than the Alpha-PDT, SAElec, and SSU. When the CDU is spared, a fault isolator is also spared.

- Beta-PDT - The reasoning for sparing this component is the same as that for the SAElec.

- PDCU - On-orbit sparing of the PDCU ORU is recommended because the high ORU failure probability resulting from the large number (28) of PDCUs in the EPS.

The following ORUs were not evaluated as potential choices for on-orbit sparing:

- dc switch unit (DCSU)

- Right and left photovoltaic blankets (RPVB, LPVB)

- Battery

The DCSU was not evaluated since it is a complex series of DC remote bus isolators, the failure of which may or may not cause a total failure of the DCSU. On the other hand, the battery, RPVB and LPVB were not chosen as on-orbit spares since these ORUs fail in a predictable manner due to wearout and are therefore scheduled replacement items. All the other ORUs were not considered as spares since they contributed little to system availability when spared on-orbit.

3.3 EPS RELIABILITY SENSITIVITY ANALYSES

The reliability sensitivity analyses were performed to provide an indication of ORU MTBF importance with respect to EPS system operation. ORU MTBF sensitivity results are discussed only for those ORUs which showed a significant effect compared with the other ORUs in a given model. The effects of ORU MTBF variation on availability have not been included in this discussion, because the range of availability change is small, as shown in Figure 3-11. The results of the reliability sensitivity analyses closely follow those of the ORU sparing sensitivity analyses.

Figure 3-12 presents the variation of insolar system equivalent availability as the ORU reliability for all ORUs is scaled from 0.7 to 5.0. Also shown in Figure 3-12 are the results of varying the MTBFs of the eight critical ORUs listed in Section 3.2.4. Most of the system equivalent availability changes result from varying the eight critical ORU reliabilities. Figure 3-13 shows the insolar ORUs that have the most significant effect on equivalent availability as their reliabilities are varied -- the Alpha-PDT, Beta-PDT, SAElec, SSU, DCSU, and TCPs. These ORUs have the same relative significance, so their plots overlap. As with insolar ORU sparing, the TCPs yield the largest amount of equivalent availability increase for the amount of reliability increase because of the large number of ORUs affected by changes in the TCPs (136).

The reliability for the eclipse system without charge effects was also varied by scale factors from 0.7 to 5.0 (Figure 3-14). The results were nearly identical to those for the insolar system (Figure 3-12). The single ORU MTBF variations (Figure 3-15) also show some similarities with the insolar system (Figure 3-13). However, in Figure 3-15 the CDU MTBF variation results include scaling the CDUs associated fault isolator. Thus, its effect is about twice that of the Alpha-PDT, and the DCSU. For example, at a scale factor of 2.0 the change in equivalent availability due to a change in CDU fault isolator reliability is 1.1009 percent and that of the Alpha-PDT is 0.5488 percent. Hence, the Alpha-PDT, DCSU, CDU (without fault isolator dependence), and fault isolator have nearly the same effect on equivalent availability for the eclipse system without charge effects.

Figures 3-16 and 3-17 show the effects of single ORU reliability variation on equivalent availability for the eclipse with charge effects system. The results closely parallel those for the sparing sensitivity analysis if the doubling effect for the CDU fault isolator combination is taken into account. The ORUs with the greatest variation are the Alpha-PDT, CDU fault isolator, PDCU, TCPs, and the insolar components: Beta-PDT, SAElec, and SSU. The incorporation of charge effects increases the MTBF for the CDU fault isolator and DCSU.

Due to the redundancy of power flow paths to critical loads in the PMAD system, variations in ORU reliabilities had little effect on PMAD system availabilty measures.

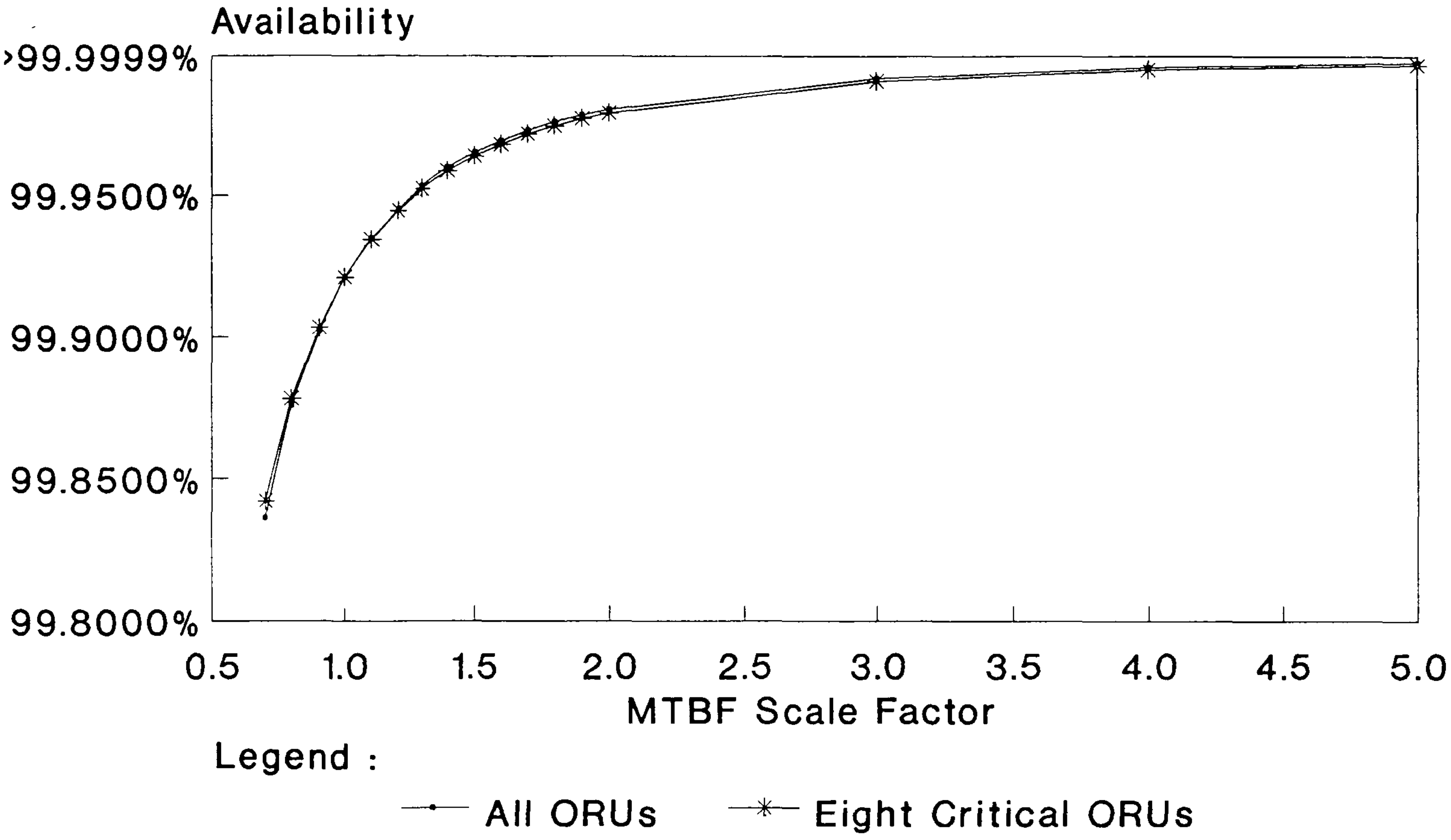


FIGURE 3-11

VARIATION OF AVAILABILITY WITH MTBF SCALE FACTOR FOR THE ECLIPSE MODEL WITH CHARGE EFFECTS

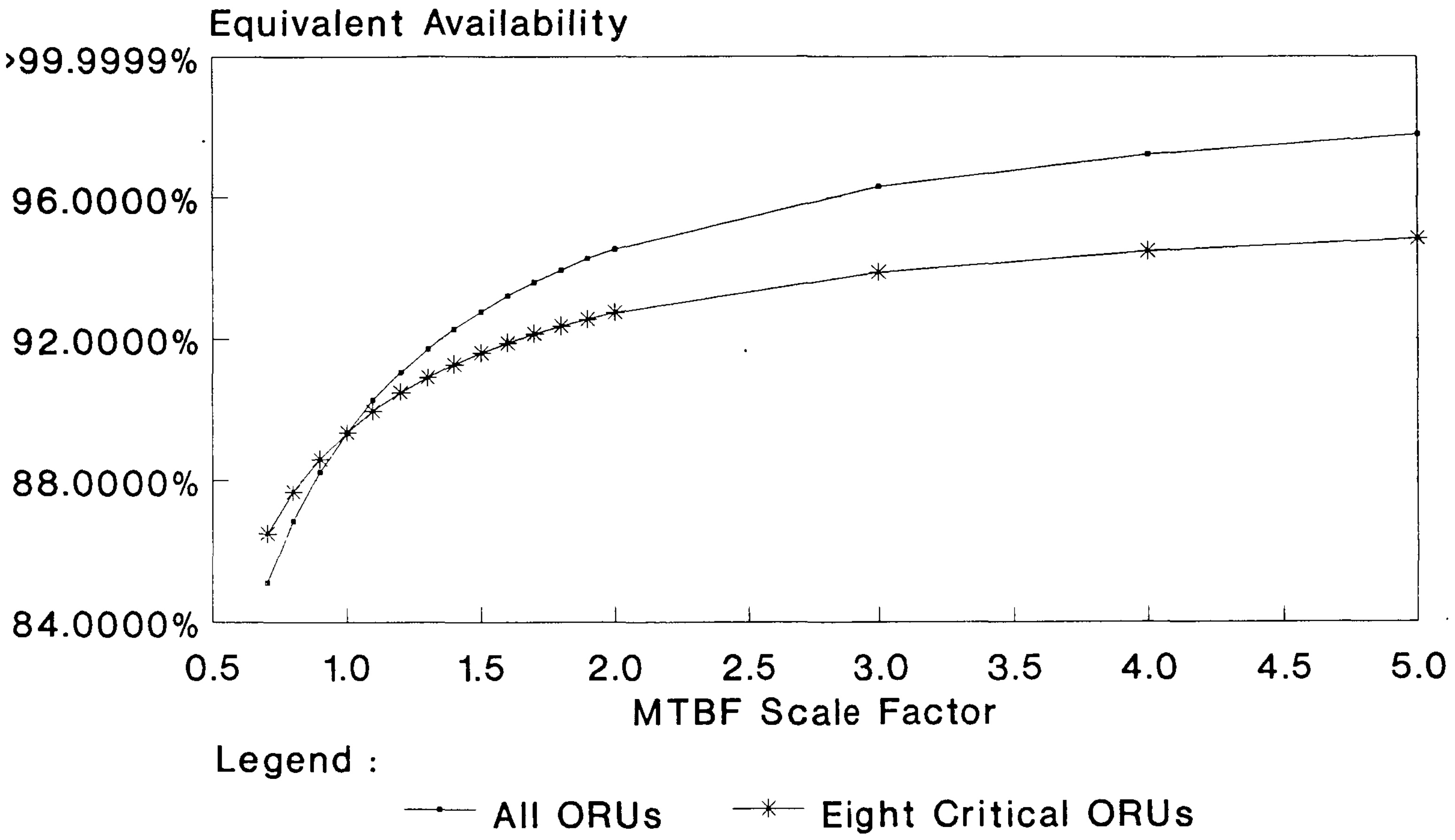


FIGURE 3-12

VARIATION OF EQUIVALENT AVAILABILITY WITH MTBF SCALE FACTOR FOR THE INSOLAR MODEL

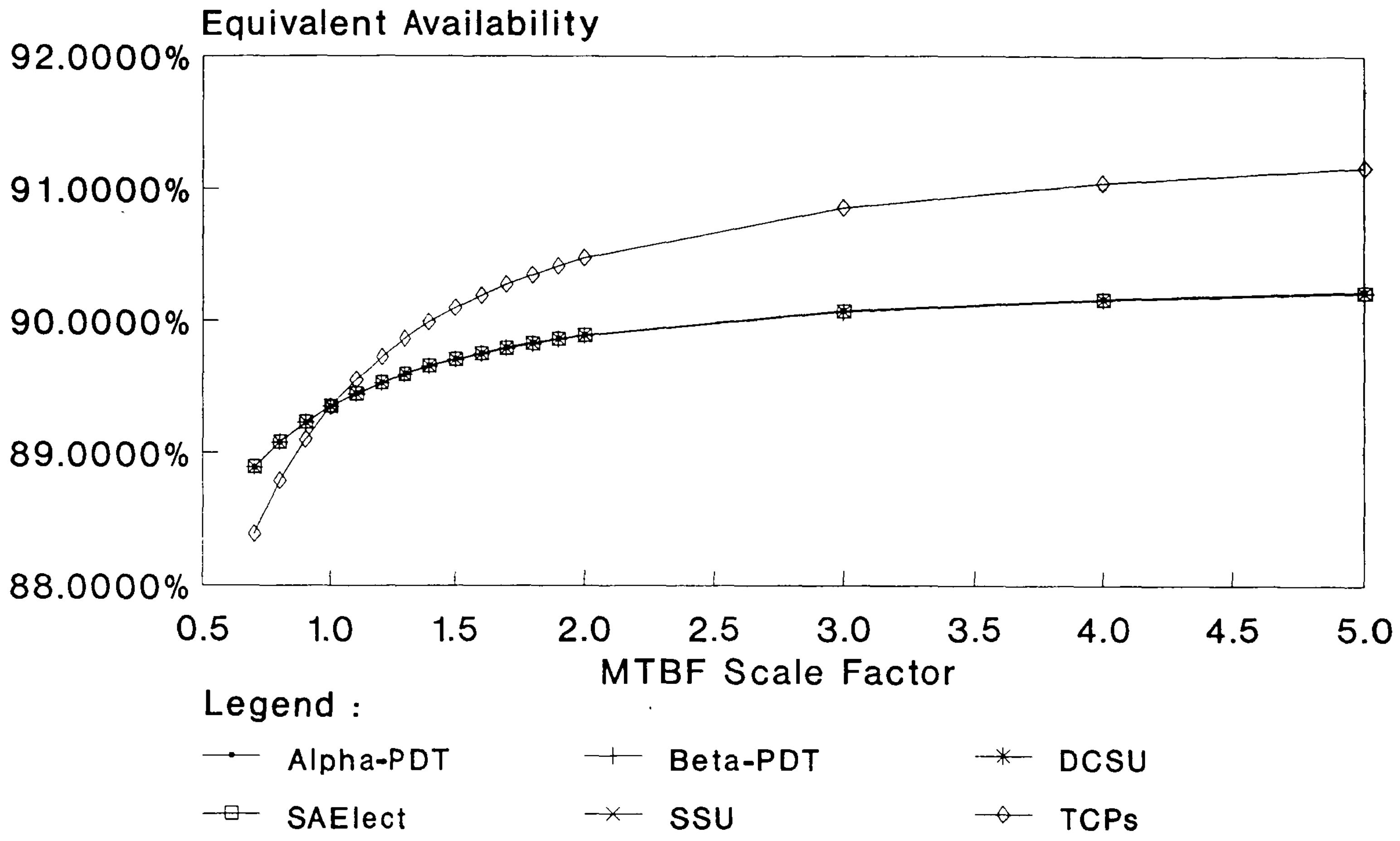


FIGURE 3-13

EFFECTS OF SINGLE ORU MTBF VARIATION ON EQUIVALENT AVAILABILITY FOR THE INSOLAR MODEL

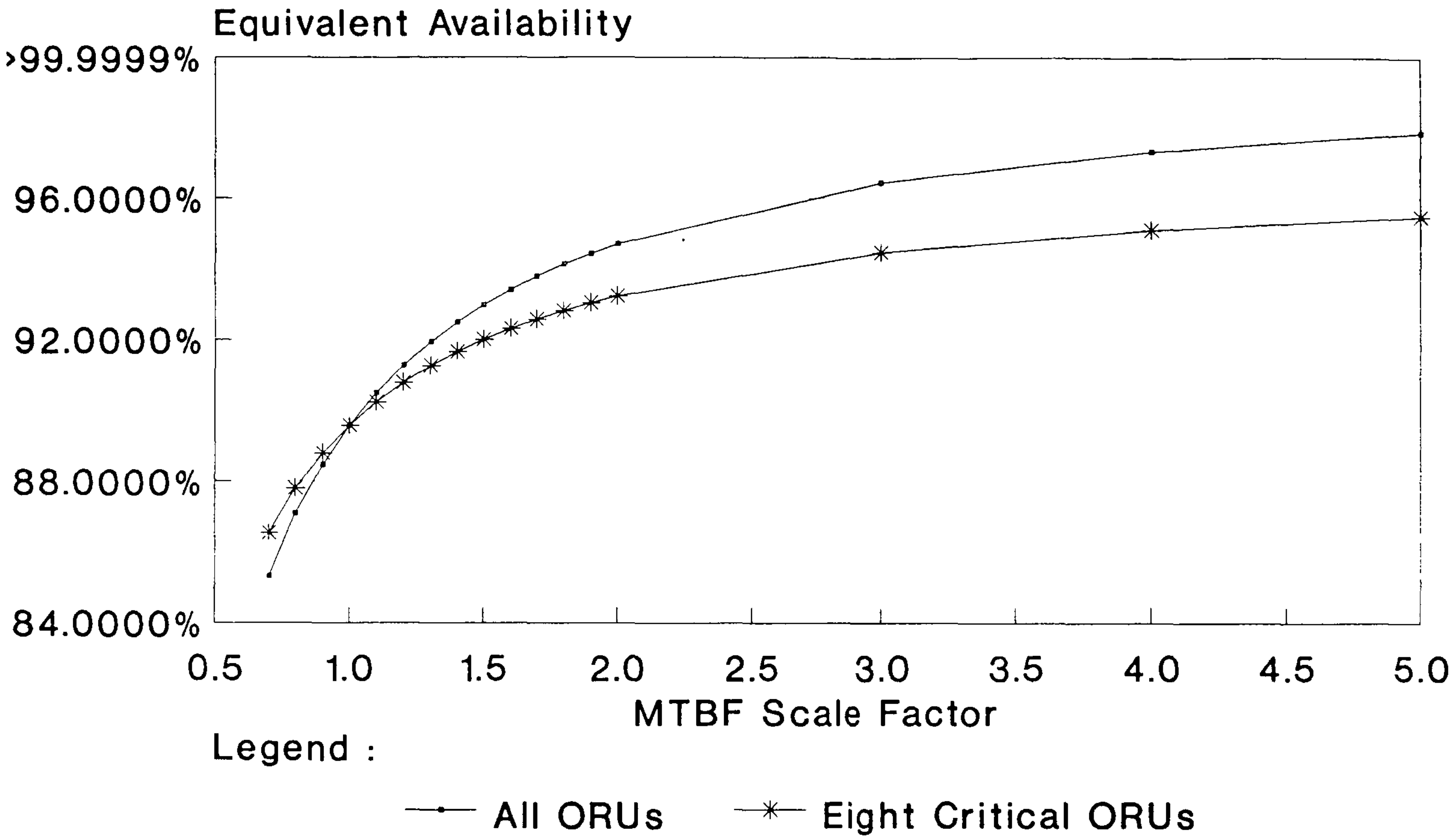


FIGURE 3-14

VARIATION OF EQUIVALENT AVAILABILITY WITH MTBF SCALE FACTOR FOR THE ECLIPSE MODEL WITHOUT CHARGE EFFECTS

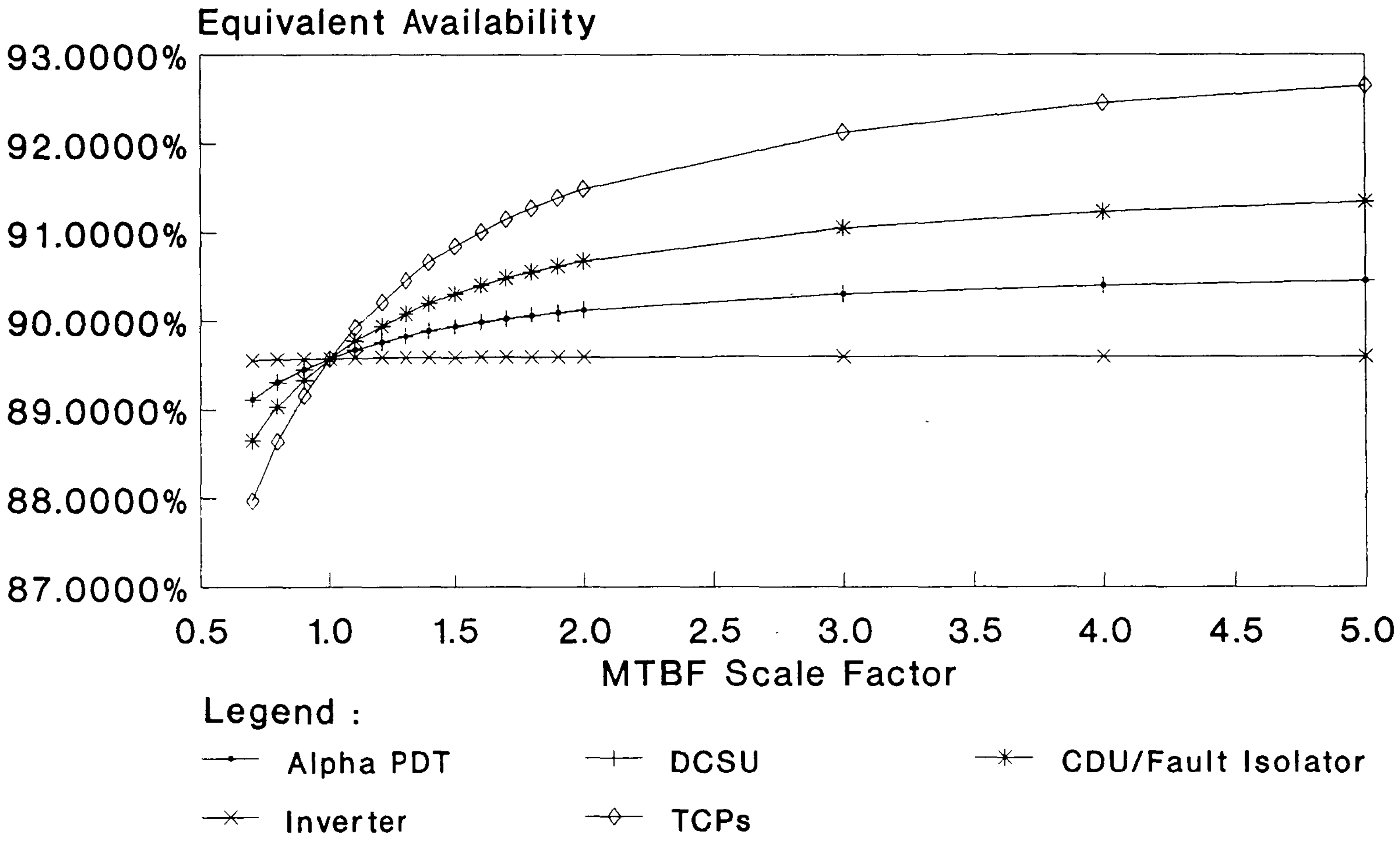


FIGURE 3-15

EFFECTS OF SINGLE ORU MTBF VARIATION ON EQUIVALENT AVAILABILITY FOR THE ECLIPSE MODEL WITHOUT CHARGE EFFECTS

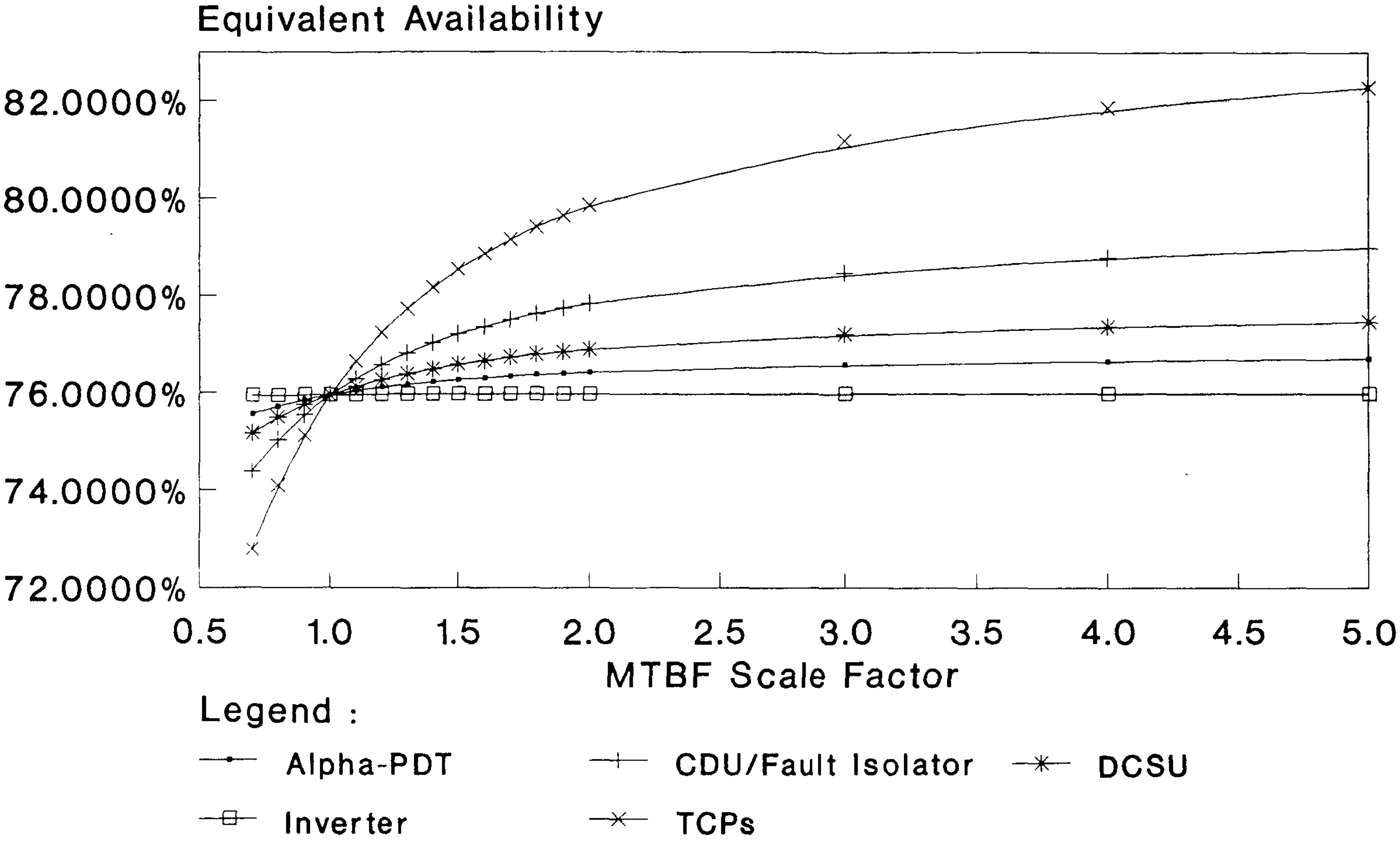
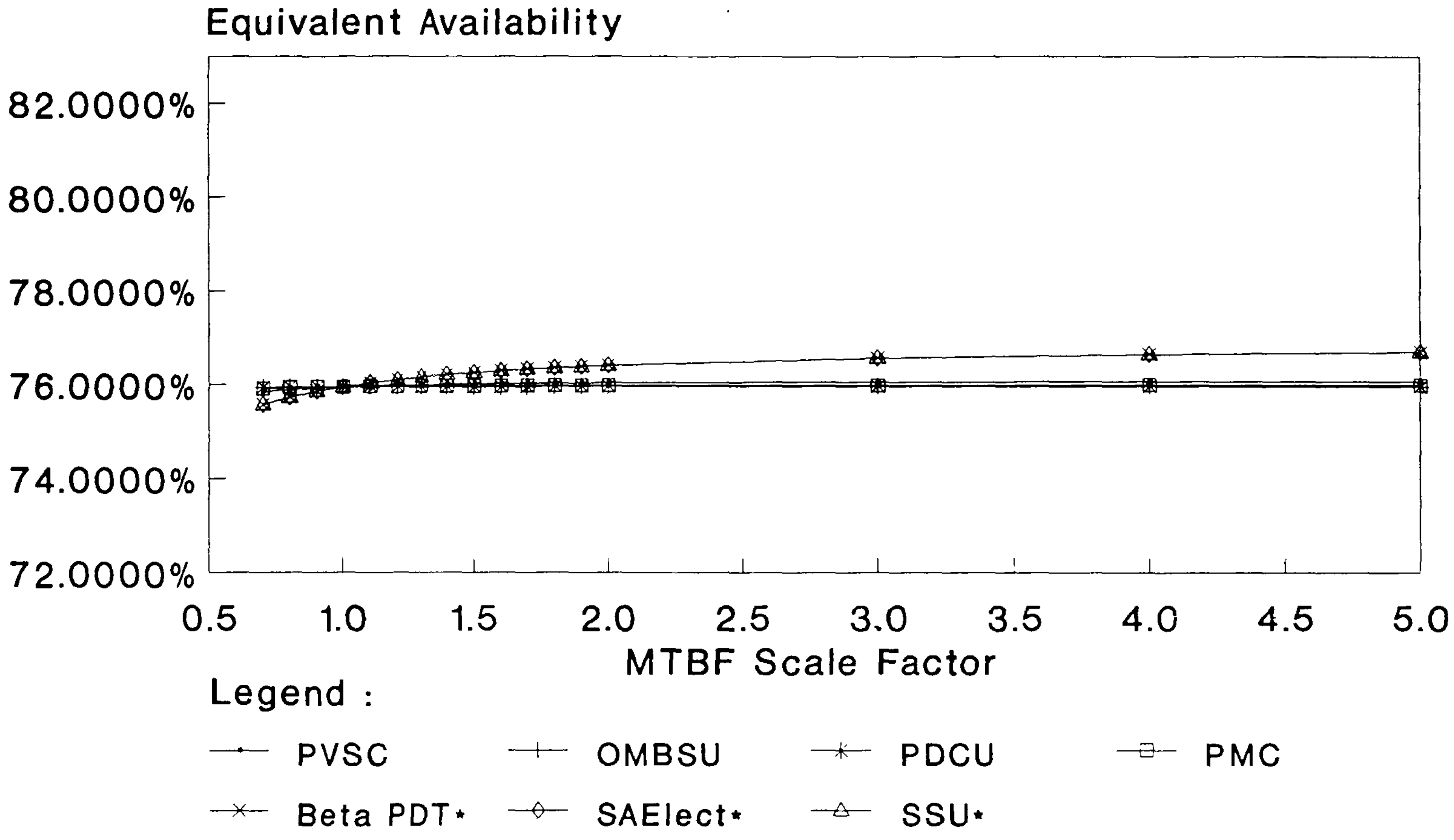


FIGURE 3-16

EFFECTS OF SINGLE ORU MTBF VARIATION ON EQUIVALENT AVAILABILITY FOR THE ECLIPSE MODEL WITH CHARGE EFFECTS (1 of 2)



*Insolar ORUs In Charge Effects

FIGURE 3-17

EFFECTS OF SINGLE ORU MTBF VARIATION ON EQUIVALENT AVAILABILITY FOR THE ECLIPSE MODEL WITH CHARGE EFFECTS (2 of 2)

3.4 COMPARISON OF RELIABILITY AND MAINTAINABILITY

3.4.1 EPS Power Generating Systems

Figures 3-18 and 3-19 provide graphic comparisons of the effects of design and operational variations of the power generating systems on availability and equivalent availability respectively. Figures 3-20 and 3-21 present the same type of comparison for PMAD only .

The scale captions for Figures 3-18 through 3-21 are defined as follows:

- MTTR = 1080: Baseline EPS ORU MTBF values were used (Section A.1 of Appendix A) with all ORU MTTRs = 1,080 hours (on-ground sparing).
- MTTR = 6: Baseline EPS ORU MTBF values were used; all ORU MTTRs = 6 hours (on-orbit sparing).
- Sparing: Baseline EPS ORU MTBF values were used; the eight critical ORU MTTRs = 6 hours; all other ORU MTTRs = 1,080 hours.
- 2*All: All EPS baseline ORU MTBFs were increased by a scale factor of 2; all ORU MTTRs = 1,080 hours.
- Sparing & 2*All: All EPS baseline ORU MTBFs were increased by a scale factor of 2; the eight critical ORU MTTRs = 6 hours; all other ORU MTTRs = 1,080 hours.
- 2*Spare: The eight critical ORU baseline MTBFs were increased by a scale factor of 2; all ORU MTTRs = 1,080 hours.

The data presented in Figure 3-18 illustrate four major items of interest:

- The availability range is relatively small (from approximately 99.92 percent to approximately 100 percent).
- There is no significant difference in the availabilities of the three models for each system variation.
- Sparing all ORUs on-orbit essentially eliminates the possibility of a zero-output state.
- Doubling the MTBFs of all ORUs has less effect on availability than the two levels of sparing.

In Figure 3-19, four items of interest are apparent:

- The amount of variation in equivalent availability between models is significant, except for the case when all ORUs are spared on-orbit.

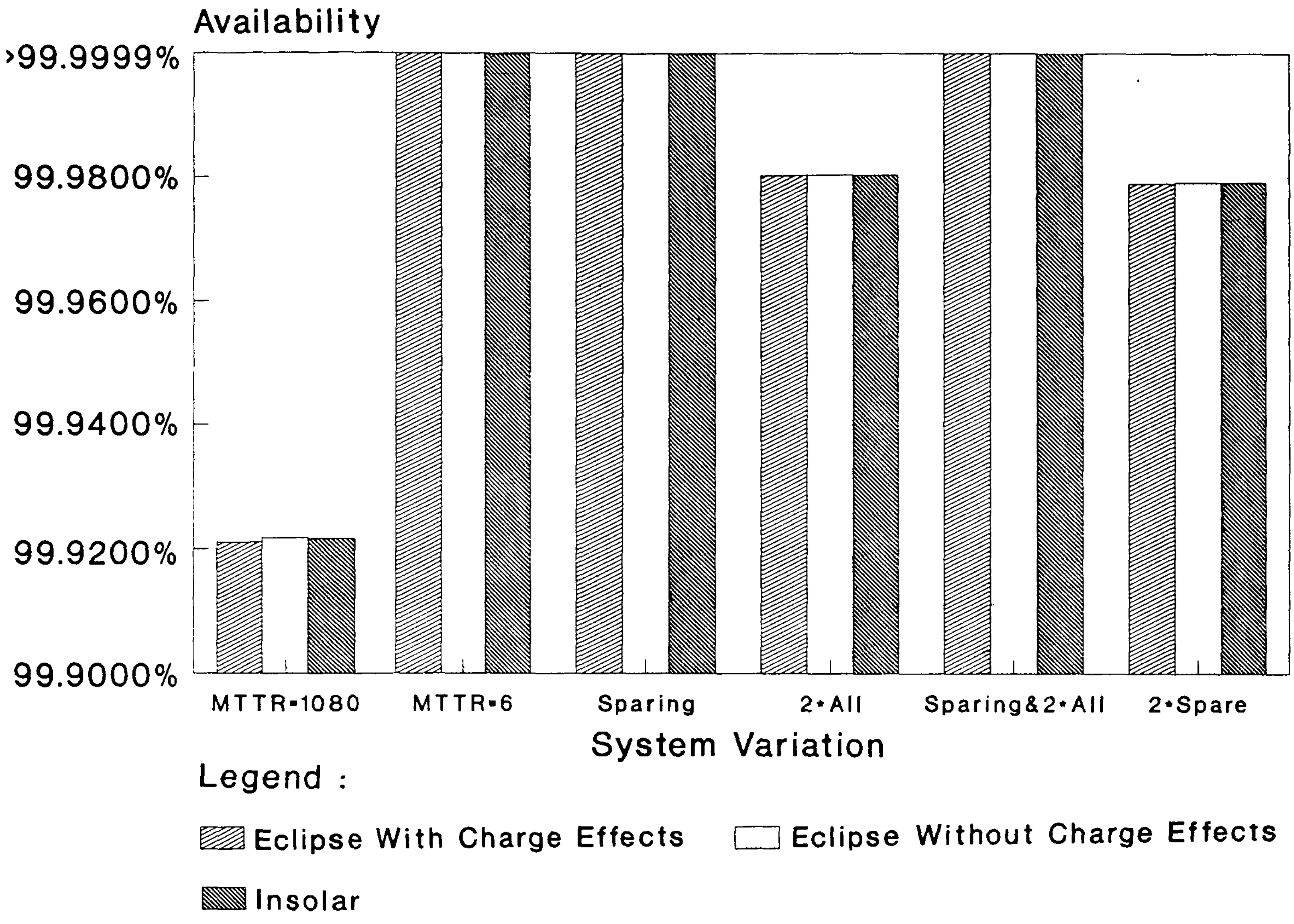


FIGURE 3-18

EFFECTS OF DESIGN AND OPERATIONAL VARIATIONS OF POWER GENERATING SYSTEMS ON AVAILABILITY

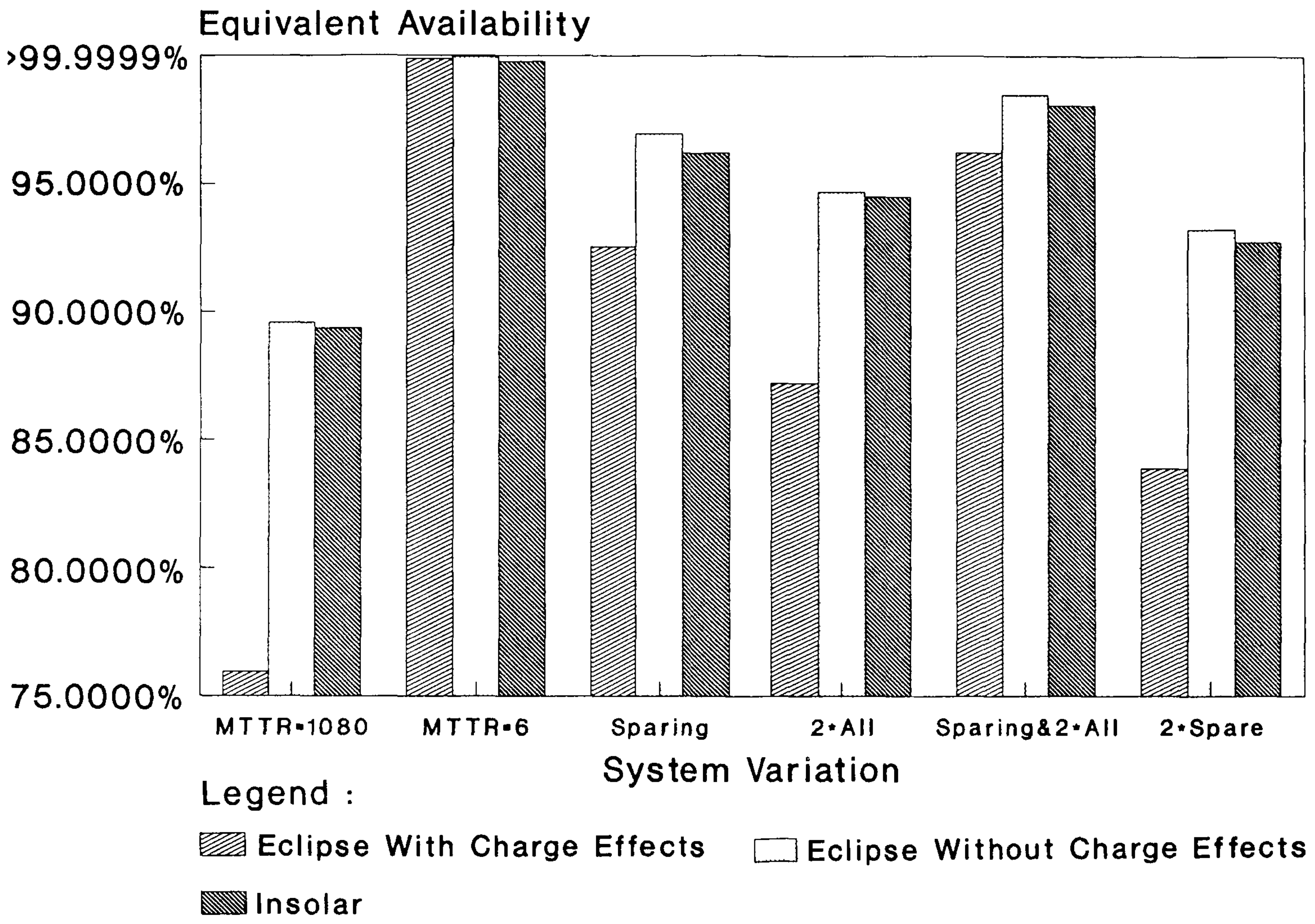


FIGURE 3-19

EFFECTS OF DESIGN AND OPERATIONAL VARIATIONS OF
POWER GENERATING SYSTEMS ON EQUIVALENT AVAILABILITY

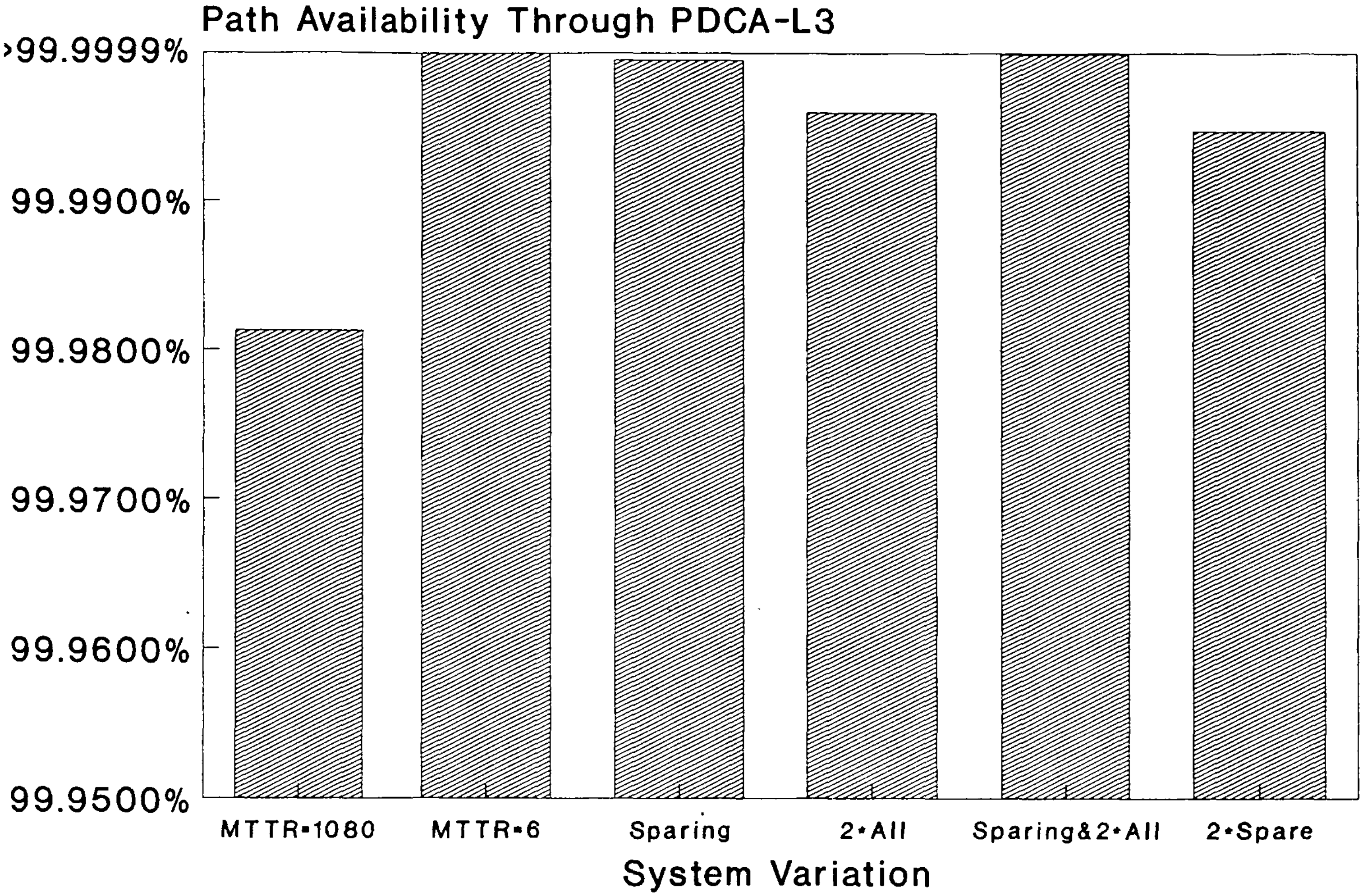


FIGURE 3-20

EFFECTS OF DESIGN AND OPERATIONAL VARIATIONS OF PMAD SYSTEM ON PATH AVAILABILITY

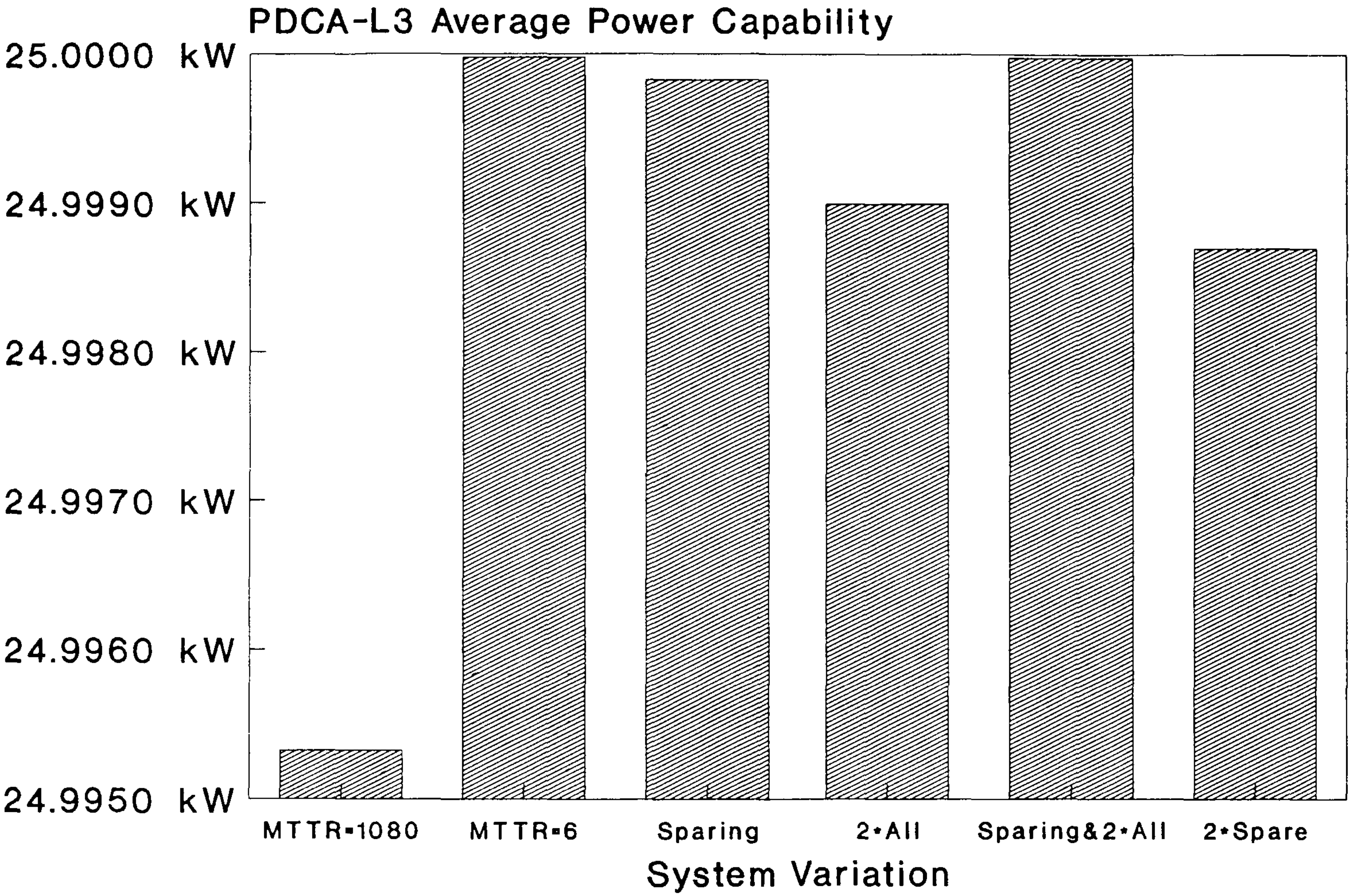


FIGURE 3-21

EFFECTS OF DESIGN AND OPERATIONAL VARIATIONS OF PMAD SYSTEM ON AVERAGE POWER CAPABILITY

- System variations of insolar and eclipse without charge effects provide approximately the same equivalent availability effects.

- The inclusion of the probability of a full battery charge in eclipse, through the use of charge effects, has significant impact on system equivalent availability, except when the eight critical ORUs are spared on-orbit and all ORU MTBFs are doubled or all ORUs are spared on-orbit.

- Doubling all ORU MTBFs has less effect than sparing only the eight critical ORUs.

3.4.2 Power Distribution System (PMAD)

In the PMAD system design and operational comparison of path availability through PDCA-L3 (Figure 3-20), the following trends are apparent:

- The variation in availability is relatively small (0.01 percent).

- Sparing all ORUs on-orbit essentially eliminates the possibility of a zero-output state.

- Sparing eight critical ORUs provides nearly all the availability change as sparing all ORUs on-orbit.

- Doubling the MTBFs of all ORUs has less effect on availability than the two levels of sparing.

3.4.2.1 Equivalent Availability

In Figure 3-21 all equivalent availability levels have been replaced with their kilowatt average power equivalents, presenting the magnitudes of variation in a more understandable form. The results are similar to those of the power generating system comparisons, with one exception. The scale over which the variations occur is small (<5 watts). Although the same trends are seen, this small scale of variation makes PMAD ORU reliability enhancements unnecessary. However, due to the number of PDCUs (28 internal to modules), the PDCUs are potential candidates for on-orbit spares.

3.4.2.2 Architecture Comparisons

Figure 3-22 provides an indication of the availability variation between the ring and radial PMAD architectures, as well as for the inner keel distribution system. The availability of either internal architecture is nearly the same and varies little, whether ORUs are spared on-orbit or on-ground. The significant deviation with the outside PDCU is due to modeling a single PDCU rather than a PDCA composed of two parallel redundant PDCUs (Figure 3-2). When ORUs are spared on-orbit, the outside PDCU availability approaches that of the internal PMAD. The same type of results are shown in Figure 3-23 for PMAD system equivalent availability.

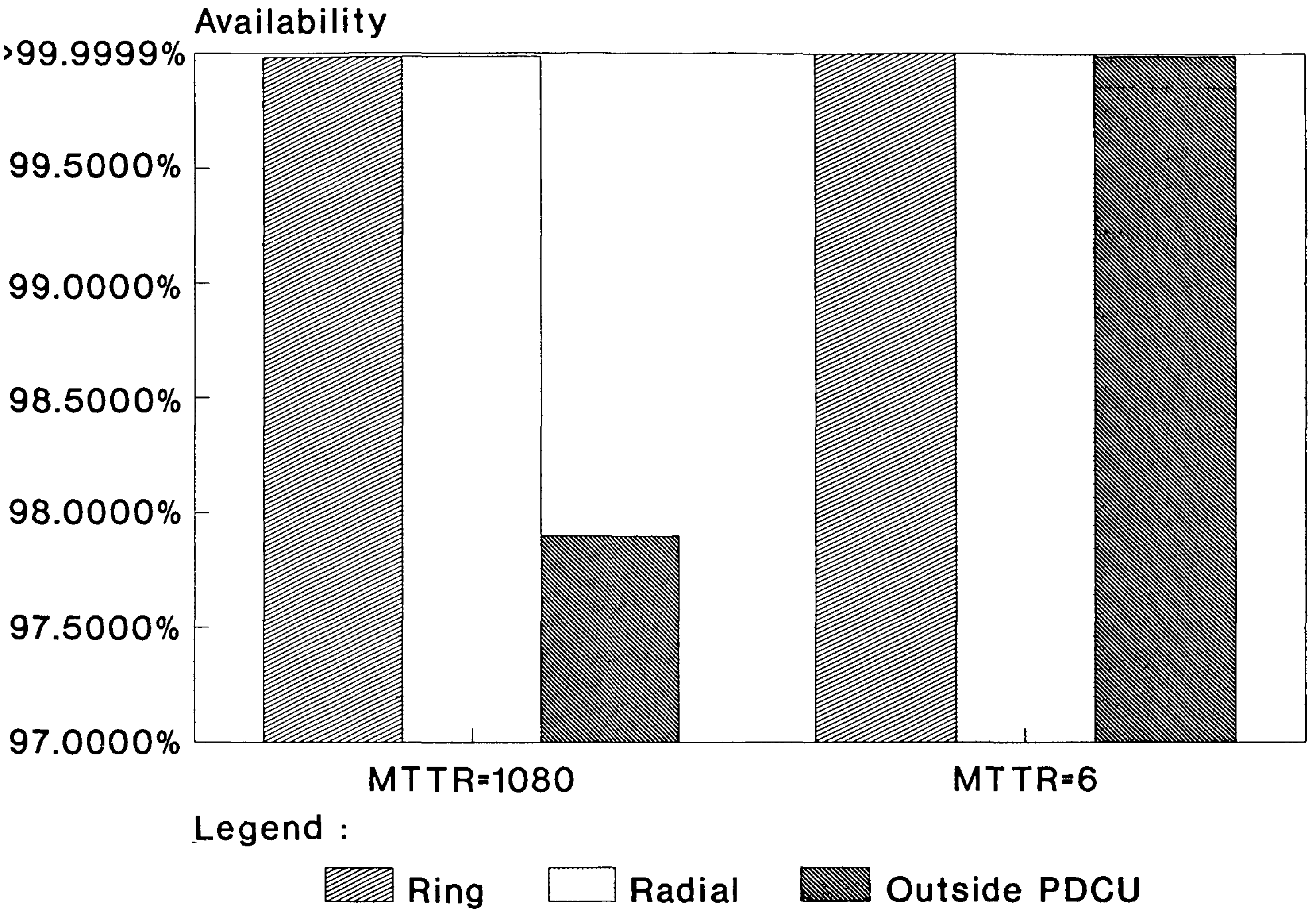


FIGURE 3-22

COMPARISON OF AVAILABILITY FOR THE PMAD MODEL CONFIGURATIONS

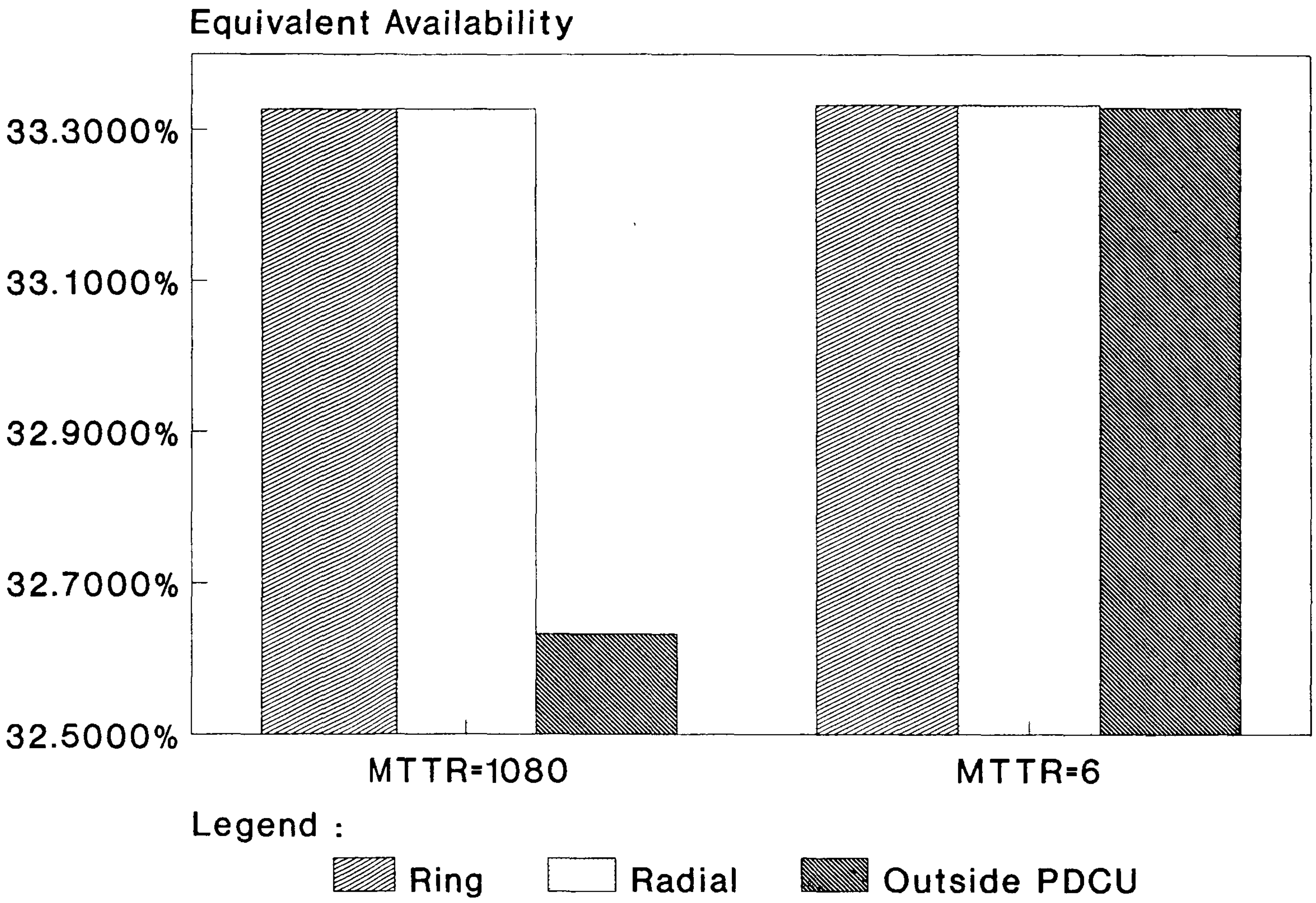


FIGURE 3-23

COMPARISON OF EQUIVALENT AVAILABILITY FOR THE PMAD MODEL CONFIGURATIONS

3.5 EPS INTEGRATED SYSTEM EVALUATION

This section provides the results of the integration of the power generating system models and the power distribution system inside the alpha joints. Three cases were evaluated for each of the three models: baseline (MTTR = 1080), on-orbit sparing of all ORUs (MTTR = 6), and sparing of the eight critical ORUs on-orbit. In each case the highest PMAD output state was 33.3333 percent (25 kW) because of the use of a 25-kW output load on PDCA-L3. The difference between PMAD alone and the integrated systems is the addition of output power states between 33.3333 percent and 0.0000 percent. These states lower system equivalent availability slightly. The relatively low state probabilities between the 33.3333 percent level and the 0.0000 percent level are driven by the power generating system redundancy. This redundancy significantly increases the probability of states above 50.0000 percent generated output and thus reduces the probability of those states below 50.0000 or 33.3333 percent. In each case, the probability of falling below the minimum life-support level of 12.5 kW increased slightly due to the effect of combining the zero-output state probabilities of the PMAD with the generating system state probabilities.

Table 3-4 presents the results of the EPS integrated system evaluation for the integrated insolar and PMAD systems. As expected, the baseline configurations have a slightly lower equivalent availability than either of the sparing scenarios -- 33.29 percent versus 33.33 percent. The average output capabilities (equivalent availability * 75 kW) vary over a range of 24.9974 kW to 24.9646 kW (0.0328 kW or 32.8 W). Either sparing scenario significantly reduces the probability of a zero-output state.

Table 3-5 presents the evaluation results for integrated eclipse without charge effects and the PMAD system. The average output capabilities vary over a range of 24.9975 kW to 24.9698 kW (0.0277 kW or 27.7 W). Either sparing scenario significantly reduces the probability of a zero-output state.

Table 3-6 presents the evaluation results for the integrated eclipse with charge effects and the PMAD system. The average output capabilities vary over a range of 24.9975 kW to 24.9341 kW (0.0634 kW or 63.4 W). Either sparing scenario significantly reduces the probability of a zero-output state.

TABLE 3-4

EPS INSOLAR PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-L3

MTTR = 1,080

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.997308	24.9975
2	31.83	0.000550	23.8725
3	25.00	0.001061	18.7500
4	24.69	0.000036	18.5175
5	24.38	0.000001	18.2850
6	12.50	0.000073	9.3750
7	12.19	0.000001	9.1425
8	0.00	0.000970	0.0000

Equivalent Availability = 33.29%
Average Power Output Capability = 24.9646 kW

MTTR = 6

1	33.33	0.999995	24.9975
2	31.83	0.000000	23.8725
3	25.00	0.000003	18.7500
4	24.69	0.000000	18.5175
5	24.38	0.000000	18.2850
6	12.50	0.000000	9.3750
7	12.19	0.000000	9.1425
8	0.00	0.000003	0.0000

Equivalent Availability = 33.33%
Average Power Output Capability = 24.9974 kW

Sparing Eight Critical ORUs

1	33.33	0.999911	24.9975
2	31.83	0.000060	23.8725
3	25.00	0.000017	18.7500
4	24.69	0.000001	18.5175
5	24.38	0.000000	18.2850
6	12.50	0.000001	9.3750
7	12.19	0.000000	9.1425
8	0.00	0.000008	0.0000

Equivalent Availability = 33.33%
Average Power Output Capability = 24.9971 kW

TABLE 3-5

EPS ECLIPSE PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-L3 (WITHOUT CHARGE EFFECTS)

MTTR = 1,080

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.998222	24.9975
2	30.00	0.000524	22.5000
3	25.00	0.000209	18.7500
4	20.00	0.000061	15.0000
5	15.00	0.000012	11.2500
6	10.00	0.000004	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000969	0.0000

Equivalent Availability = 33.29%
Average Power Output Capability = 24.9698 kW

MTTR = 6

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.999998	24.9975
2	30.00	0.000000	22.5000
3	25.00	0.000000	18.7500
4	20.00	0.000000	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000001	0.0000

Equivalent Availability = 33.33%
Average Power Output Capability = 24.9975 kW

Sparing Eight Critical ORUs

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.999973	24.9975
2	30.00	0.000008	22.5000
3	25.00	0.000009	18.7500
4	20.00	0.000001	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000008	0.0000

Equivalent Availability = 33.33%
Average Power Output Capability = 24.9972 kW

TABLE 3-6

EPS ECLIPSE PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-L3 (WITH CHARGE EFFECTS)

MTTR = 1,080

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.991804	24.9975
2	30.00	0.003766	22.5000
3	25.00	0.002011	18.7500
4	20.00	0.000945	15.0000
5	15.00	0.000337	11.2500
6	10.00	0.000133	7.5000
7	5.00	0.000027	3.7500
8	0.00	0.000977	0.0000

Equivalent Availability = 33.25%

Average Power Output Capability = 24.9341 kW

MTTR = 6

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.999996	24.9975
2	30.00	0.000000	22.5000
3	25.00	0.000003	18.7500
4	20.00	0.000000	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000003	0.0000

Equivalent Availability = 33.33%

Average Power Output Capability = 24.9975 kW

Sparing Eight Critical ORUs

Output State	Output State Capability (%)	State Probability	Output Power Level (kW)
1	33.33	0.999894	24.9975
2	30.00	0.000050	22.5000
3	25.00	0.000035	18.7500
4	20.00	0.000009	15.0000
5	15.00	0.000002	11.2500
6	10.00	0.000001	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000008	0.0000

Equivalent Availability = 33.33%

Average Power Output Capability = 24.9968 kW

The incorporation of charge effects had an impact. This is evident when comparing the integrated results for eclipse with charge effects with either the insolar or eclipse without charge effects results. The intermediate states have increased probabilities and importance, which led to the lower equivalent availabilities (average output capabilities).

3.6 EPS FAILURE AND REPLACEMENT RATE ANALYSES

The failure rate calculation methodology defined in Section 2.6.2 was used to calculate the overall system average annual ORU failure rates. As a result of these calculations, it was determined that the baseline EPS will have an expected ORU failure rate of approximately 35 ORUs and ancillary components per year. The total number of ORUs and ancillary components used in the calculation was 418, which includes 136 TCPs, 40 DC-RBIs associated with the CDUs, and 20 fault isolators. Although 35 failures per year seems high, some of the ORU failures will not need immediate attention (for example, a failure of one CDU DC-RBI does not require immediate replacement, since the CDU DC-RBIs are dually redundant). Thus the average annual repair rate may be lower.

Failure rate calculations were also performed on the analyses results used in Section 3.5, which varied ORU MTBFs. As expected, when all ORU MTBFs are doubled the failure rate is cut by half, approximately 17 ORUs per year. When the eight critical component MTBFs are exclusively doubled, the failure rate drops to 29.

CHAPTER FOUR

CONCLUSIONS AND RECOMMENDATIONS

The Space Station Electric Power System was modeled and a RAM assessment was performed using the UNIRAM assessment methodology. As the EPS design evolves, NASA Can use the resulting EPS models and evaluation to assess EPS design changes on system RAM performance as the EPS design evolves. The following sections present the specific conclusions and recommendations that resulted from the initial EPS RAM assessments, described in this report.

EPS Power Generation

From a RAM perspective, eight EPS ORUs accounted for most of the EPS RAM changes when EPS ORU reliability and maintainability parameters were varied. These ORUs, considered critical to EPS operation, and are listed as follows:

- Alpha Joint Power and Data Transfer Assembly
- Beta Gimbal Power and Data Transfer Assembly
- Charge/Discharge Unit
- Power Distribution Control Unit
- Power Management Controller
- Sequential Shunt Unit
- Solar Array Electronics Assembly
- Thermal Control Plate

These ORUs are possible candidates for on-orbit sparing; however, further analyses based on ORU cost, weight, and volume considerations must be performed to determine which ORUs should be spared.

Table 4-1 presents the equivalent availabilities and the availabilities for the system variations considered in this study. The system variations are listed in order of descending system equivalent availability. The equivalent availability change among the system variations is large (a maximum difference of 13.99 percent), and the availability change among the system variations is small (a maximum difference of 0.08 percent). EPS equivalent availability is sensitive to both ORU reliability and maintainability.

TABLE 4-1

SYNOPSIS OF EPS ORU SPARING AND RELIABILITY SENSITIVITY ANALYSIS

System Variation	EA(%)	A(%)
Insolar		
Spare All ORUs	99.77	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	98.08	>99.99
Increase All ORU MTBFs by Factor of Five	97.78	>99.99
Spare Eight Critical ORUs	96.20	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	95.83	>99.99
Double All ORU MTBFs	94.53	99.98
Double Eight Critical ORU MTBFs	93.74	99.98
Baseline System Results	89.35	99.92
Eclipse without Charge Effects		
Spare All ORUs	99.94	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	98.49	>99.99
Increase All ORU MTBFs by Factor of Five	97.86	>99.99
Spare Eight Critical ORUs	96.96	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	95.48	>99.99
Double All ORU MTBFs	94.70	99.98
Double Eight Critical ORU MTBFs	93.23	99.98
Baseline System Results	89.58	99.92
Eclipse with Charge Effects		
Spare All ORUs	99.85	>99.99
Double All ORU MTBFs and Spare Eight Critical ORUs	96.24	>99.99
Increase All ORU MTBFs by Factor of Five	94.69	>99.99
Spare Eight Critical ORUs	92.55	>99.99
Increase Eight Critical ORU MTBFs by Factor of Five	89.04	>99.99
Double All ORU MTBFs	87.22	99.98
Double Eight Critical ORU MTBFs	83.89	99.98
Baseline System Results	75.96	99.92

EPS Power Management and Distribution System

The RAM assessment showed that there is little or no difference between PDCAs when considering the availability of power from any given PDCA in the PMAD system. The baseline availability of the PMAD system is 99.98 percent, but ORU on-orbit sparing and reliability changes increased the availability to greater than 99.99 percent. Since there are 28 PDCUs in the manned core, the only PMAD ORU considered viable as a potential on-orbit spare was the PDCU.

A baseline analysis of the inner keel power distribution system was also performed. The availability of power from an inner keel PDCU was 97.90 percent when ORU MTTRs were 1,080 hours. When a PDCU was spared on-orbit, the availability of power from a PDCU on the inner keel increased to 99.99 percent.

EPS Integrated System

Table 4-2 presents the equivalent availabilities, the probabilities of power levels below minimum life-support levels, and the probabilities of zero output states for the EPS integrated system analyses. Since the PMAD system was modeled as delivering power to a perfectly available 25 kW load (33.33 percent of 75 kW, which is the total system capacity), the equivalent availability data are on a scale of 33.33 percent. EPS integrated system analyses were also performed for sparing only the eight critical ORUs on-orbit. The results of these analyses were the same as the results for sparing all ORUs on-orbit (MTTR = 6). With no on-orbit sparing of ORUs, there is a finite probability that the EPS power output will fall below minimum life-support levels.

The total number of ORUs used to model the EPS was 418. The expected average annual failure rate is 35 ORUs per year.

TABLE 4-2

EPS INTEGRATED SYSTEM RESULTS

System Combination	Equivalent Availability (%)		Probability of Less Than Minimum Life Support		Probability of Zero Output State	
	MTTR=1,080	MTTR=6	MTTR=1,080	MTTR=6	MTTR=1,080	MTTR=6
PMAD and Insolar	33.29	33.33	0.0010	<0.0001	0.0010	<0.0001
PMAD and Eclipse (No Charge Effects)	33.29	33.33	0.0010	<0.0001	0.0010	<0.0001
PMAD and Eclipse	33.25	33.33	0.0015	<0.0001	0.0010	<0.0001

Recommendations

As this study was performed, the following further analyses were identified as necessary:

- An analysis of the EPS, taking into consideration various distributed power load scenarios should be performed. The initial analysis used a single 25-kW load at the output of the distribution system, but a subsequent evaluation would not only distribute the single 25-kW load to other PDCUs in the manned core, but would also account for the insolation period system load represented by the EPS battery charge. If possible, load-shedding ranking factors should be used to determine the availability of power to each load under the ranking criteria. Ultimately, this study would provide information on the EPS ability to supply power in various load configurations.

- An analysis incorporating the lifetime data associated with the EPS batteries and photovoltaic arrays should be performed. This analysis would center on the use of a distribution function, such as the Weibull, to determine yearly MTBF values. The values would then be used in several UNIRAM analyses to study the decrease in EPS performance as the battery packs and photovoltaic arrays degrade with age. This analysis would also yield an expected annual ORU failure rate that would increase as the lifetimes of the batteries and photovoltaic arrays are reached.

- RAM analyses of individual ORUs, taking into consideration the parts makeup within the ORU, should be performed . These analyses would provide possible output states and state probabilities for the ORU. The states and state probabilities would then be incorporated into a system analysis for a more precise indication of system RAM performance using actual capabilities of selected ORUs.

- An ORU parts-type evaluation similar to a MIL-HDBK-217E (Ref. 2) analysis should be performed on selected ORUs. This analysis should include the previously identified eight critical ORUs. The purpose of the analysis would be to establish more accurate predictions of the ORU MTBFs.

- Analyses specific to selecting an optimum on-orbit level of ORU spares for the EPS should be performed. These analyses would consider such constraints as: EPS RAM considerations, ORU mass, volume, cost to lift, and the requirements for ORU spares testing while ORUs are on-orbit.

- An in-depth analysis of EPS maintainability should be performed. It should use expected ORU failure rates and on-orbit sparing scenarios as well as the proposed EPS intravehicular activity (IVA) and extravehicular activity (EVA) budgets allowed for EPS maintenance. The analysis results would identify possible maintenance strategies to trade IVA and EVA hours for degraded levels of system performance and would determine the adequacy of the IVA and EVA budgets as they relate to various levels of system performance.

- An EPS testability analysis should be performed to determine if the current ORU packaging and test point distribution is adequate to isolate faults to at least individual ORUs.

APPENDIX A

MODELING INFORMATION FOR THE SPACE STATION ELECTRIC POWER SYSTEM

A.1 ORUs USED IN THE ANALYSIS

Table A-1 lists the ORUs used in the RAM analysis of the Space Station EPS, including the ORU names, model input file acronyms, and associated reliability data.

TABLE A-1

ORUs USED IN THE SPACE STATION ELECTRIC POWER SYSTEM UNIRAM MODELS

ORU Name	Basic Subsystem Component	MTBF (Hours)	MTTR (Hours)
Solar Array Right Blanket	RPVB	131,400	--
Solar Array Left Blanket	LPVB	131,400	--
Solar Array Mast Longeron	Longeron	99,999,999*	0.01*
Solar Array Electronics Box	SAElec	87,600	--
Sequential Shunt Unit	SSU	87,600	--
Beta Gimbal Subassemblies			
Power/Data Transfer Subassembly	Beta-PDT	87,600	--
Bearing Subassembly	B-GimBrng	131,400	--
Drive Motor Subassembly	B-GimMtr	87,600	--
Controller	B-GmCntrlr	87,600	--
Alpha Joint Subassemblies			
Power/Data Transfer Subassembly	Alpha-PDT	87,600	--
Bearing Subassembly	A-GimBrng	131,400	--
Drive Motor Subassembly	A-GimMtr	87,600	--
Controller	A-GmCntrlr	87,600	--
Electrical Equipment Assembly Subassemblies			
DC Switch Unit	DCSU	87,600	--
DC/AC Inverter	Inverter	87,600	--
Outboard Main Bus Switching Unit	OMBSU	87,600	--
Power Distribution and Control Unit	PDCU	87,600	--

(continued)

TABLE A-1 (continued)

ORU Name	Basic Subsystem Component	MTBF (Hours)	MTTR (Hours)
Electrical Equipment Assembly Subassemblies (continued)			
Photovoltaic Source Controller	PVSC	43,800	--
Charge/Discharge Unit	CDU	87,600	--
CDU dc Remote Bus Isolator	DC-RBI	87,600	--
CDU Fault Isolator	Fault ISO	87,600	--
Battery	Battery	70,080	--
Power Management and Distribution System Subassemblies			
Node Transformer	Xfmr	131,400	--
Power Distribution Control Unit	PDCU	87,600	--
Outboard Main Bus Switching Unit	OMBSU	87,600	--
Main Bus Switch Unit	MBSU	87,600	--
Node Switch Unit	NSU	87,600	--
Power Management Controller	PMC	43,800	--
Thermal Control System Subassemblies			
Thermal Control Pump Unit	Pump	280,320	--
Thermal Control System Pipe Set	Pipe Set	262,800	--
Thermal Control System Accumulator	Accum	131,400	--
Radiator Panel Assembly	RadPnl	489,351	540
Thermal Control Plates	TCPs	131,400	--

*Default UNIRAM values to give ORU perfect availability

A.2 KEY ASSUMPTIONS PERTAINING TO THE SPACE STATION ELECTRIC POWER SYSTEM UNIRAM MODELS

The assumptions used to develop the system ABDs for the EPS are presented in the following subsections by the major system to which the assumptions apply.

A.2.1 EPS Assumptions

The following assumptions apply to the entire EPS:

- The ORU is the component level for UNIRAM modeling.
- ORU failures are independent.
- The MTBF values used for the EPS ORUs represent the relative differences in failure rates between ORUs.
- Nearly all actual MTTRs will be bounded between the 6 hour (on-orbit ORU sparing) and the 45 day (ground ORU sparing) MTTRs assumed in this study.
- The outboard thermal control system pumps are powered by 400 Hz ac synchronous motors, which are powered, in turn, from the inboard PV module PDCUs. The loss of both PDCUs results in the loss of all thermal control systems on a station side, outboard of the alpha joint.
- The thermal control system reservoir is included in the thermal control system fault tree because it uses a diaphragm as an interface between N_2 gas and the refrigerant. The diaphragm will be the critical failure point in the system. The reservoir MTBF is assumed to be 15 years.
- The thermal control system radiator panel assemblies are constructed so that each panel has two separate, two-phase tapered tube heat pipes. Both heat pipes must be penetrated to fail a panel. The probability of meteoroids not disabling 3 of the 12 panels over 30 years is about 0.99999938. Because of this probability, meteoroid impact will not be taken into account in the modeling results, and the panels of the radiator panel assembly are assumed to not fail. However, each panel is secured to the interface heat exchanger by a clamp assembly pressurized by a GN_2 canister. The GN_2 canister has an MTBF of 15 years, and the clamp has an MTBF of 15 years. If either fails the panel will have poor mechanical contact with the interface heat exchanger for heat transfer, and the entire panel assembly can be assumed to have failed. Over-capacity is designed into the system such that 10 or more panel assemblies can take the full heat load. A Markov process was used to determine the mean time between failure of moving from a 12-panel up state to a 9-panel up state. This process assumed an MTTR per assembly of 45 days (1,080 hours). The MTBF to the 9-panel up state was calculated as 489,351 hours (55.86 years). This MTBF was used as the radiator panel basic subsystem MTBF.
- With few exceptions, each ORU was modeled with its own thermal control plate

- The inboard PV module thermal control system cools both outboard main bus switch units (OMBSUs) for each side of the Space Station. The loss of an inboard PV module TCS is assumed to cause the loss of both OMBSUs and thus one side of the EPS.

- There is only one pair of outboard power distribution control units (PDCUs) for each side of the Space Station. Located on the inboard PV modules, the PDCUs redundantly supply ac control power to the PV modules. Consequently, the loss of the PDCUs on one side results in the loss of all thermal control system pumps outboard of the alpha joint on that side of the Space Station.

A.2.2 EPS Insolar UNIRAM Model

The following assumptions apply to the insolar UNIRAM model:

- The beta gimbal assembly positioning ORUs have been separated from the power and data transfer assembly. A derate pseudocomponent is placed around the beta positioning basic subsystem (Beta 2), corresponding to the power degradation after 45 days of positioning loss. The angular error after 45 days will be 12.80°, and total power degradation (Pd) will be

  $$Pd = P_{max} * \cos(12.80^\circ)$$

  $$Pd = P_{max} * 0.975$$

  In addition, a photovoltaic array angular error that leads to a $Pd = 0.99 * P_{max}$ is not considered significant in terms of power loss. This error corresponds to a 2.56° angular error, or approximately nine days of positioning capability loss. This nine-day period (216 hours) is inserted as surge time for the beta gimbal positioning components basic subsystem.

- A PVSC has control features which affect the positioning capability of the beta gimbals on its side of the Space Station. A PVSC derate has been incorporated to reflect the reduced power capability due to beta positioning loss for 45 days (refer to preceding assumption). In essence, this derate is a perfectly available pseudo-component with a throughput capacity of 24.375% (18.281 kw). This corresponds to 0.975 * the output power of one PV module (18.75 kw). Also, each PVSC is modeled with a 216 hour surge time for the same reason given in the preceding assumption.

- The beta gimbal positioning motors are brushless dc motors powered from the inboard PV module PDCUs. Loss of these PDCUs removes positioning capability from all beta gimbal assemblies on one side of the Space Station; however, loss of the PDCUs also shuts down the thermal control system pumps. Since the loss of these pumps is much more significant than the loss of beta positioning, the loss of beta positioning resulting from the loss of PDCUs is not modeled.

- The dc switch units(DCSUs) operate in a cross-connected manner upon failure of a dc-to-ac inverter.

- One dc-to-ac inverter is capable of handling all of the output power capability of a PV module.

- OMBSUs can be cross-connected.

- The alpha joint was modeled as a beta gimbal because no alpha joint design information was available.

- The positioning and power transfer functions of the alpha joint have been separated, as they have been with the beta gimbal. The alpha joint can be manually repositioned to the single optimum insolation period position upon loss of automatic positioning capability. This positioning leads to an average power level, over one-half orbit, of 23.87 kW. This power level is derived as follows:

  Power as a function of position P(pos) is:

  $$P(pos) = P_{max} * \sin(\theta)$$

  The average power (P_{ave}) over one-half of the orbit is:

  $$P_{ave} = 2/\pi * \int_{0}^{\pi/2} P_{max} * \sin(\theta)\, d\theta$$

  $$P_{ave} = P_{max} * 2/\pi * [-\cos(\theta)] \Big|_{0}^{\pi/2}$$

  $$P_{ave} = P_{max} * 2/\pi * [-\cos(\pi/2) + \cos(0)]$$

  $$P_{ave} = P_{max} * 2/\pi$$

  $$P_{max} = 75 \text{ kW}/2 = 37.5 \text{ kW}$$

  $$P_{ave} = 23.87 \text{ kW} = 31.83\% \text{ of total power}$$

- The photovoltaic array mast has been modeled so that the loss of one longeron will cause the loss of the mast and thus its associated solar array wing. This is a basic subsystem composed of three longerons nested below an "or" gate.

A.2.3 EPS Eclipse UNIRAM Model

The following assumptions apply to the eclipse UNIRAM model:

- The dc switch units will operate in a cross-connected manner upon failure of a dc-to-ac inverter. This mode of operation allows maximum power output from a single inverter.

- The inboard PV module TCS cools both OMBSUs for each side of the Space Station. The loss of an inboard PV module TCS is assumed to cause the loss of both OMBSUs and thus one side of the EPS.

- The loss of both photovoltaic source controllers in a module results in the loss of the ability of that module to charge the battery. After three full orbits, a battery will be fully discharged. This three-orbit full discharge is incorporated into the eclipse models as a 4.5-hour surge time. During the insolation period, the PVSC loss has no effect on PV module output.

- Each PV module has five batteries, consisting of three battery packs of 30 cells each, in series. Each battery pack has its own thermal control plate. A battery will be modeled as a basic subsystem consisting of one battery with an MTBF of eight years and three battery pack thermal control plates (TCPs) nested under an "or" gate. The batteries are modeled this way for two reasons. When a battery pack fails the entire battery will be replaced; and, if one of the battery pack TCPs fails, the battery will not be available for use.

- The battery fault isolator, located in the charge/discharge unit (CDU), will be modeled as a separate component with an MTBF of 10 years.

- The only part of the alpha joint to affect the eclipse operation of the EPS is the power and data transfer subassembly.

A.2.3.1 Charge Effect Basic Subsystems

Charge-effect basic subsystems are a recommended means to more accurately represent the availability of the EPS during eclipse operation. These basic subsystems are meant to account for the availability of the ORUs required to fully charge the batteries. The use of these charge-effect subsystems in the UNIRAM model has been a topic of discussion throughout the duration of this study. The eclipse ABD was evaluated with and without charge effects as a way of determining the upper and lower bounds of EPS eclipse availability.

The availabilities of the ORUs required for charging the battery are incorporated by first determining which ORUs are necessary to charge the battery. The ORU positions in the charge path are considered, and the ORUs are then combined in fault trees which represent the charge-effect pseudocomponents. These pseudocomponents are then modeled. The ORUs that affect the charging of a single battery are combined in charge 1, as shown in Section A.3. The ORUs that affect the ability to charge either the top or bottom battery set in a PV module are combined in charge 2. Finally, the ORUs that affect the ability of an entire PV module to charge all batteries are combined in charge 3. The charge-effect model is then assessed using the UNIRAM baseline run. The effective charge-effect pseudocomponent MTBFs and MTTRs are obtained for charges 1, 2, and 3 from the subsystem MTBF and MTTR values obtained from the baseline run. In the eclipse model with charge-effects, these values are used to account for the availability of having a fully charged battery at the beginning of the eclipse cycle.

Expected system availability during eclipse operation is the conditional availability of the eclipse system, given that it is charged, multiplied by the expectation of being charged. The expectation of being charged is the expected availability of the charging components during the insolation period, or:

$$A_E = (A_B | A_C) A_C$$

where

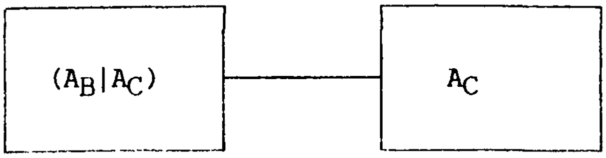
A_E is the expected eclipse system availability.

$(A_B | A_C)$ is the conditional availability of the eclipse system *given that the batteries are fully charged*

and

A_C is the expected availability of the components involved in the charge period.

Since the combination of these expectations is a product relationship, it can be represented by a "series" configured ABD, such as:



where $(A_B | A_C)$ is the existing eclipse system ABD without charge-effects, and A_C represents the availability of the components associated with a battery charge. The availability is calculated using the associated component MTBFs and MTTRs as determined by the UNIRAM evaluation of the charge-effect model. Since multiplication is distributive and commutative, A_C can be broken into pieces and distributed within $(A_B | A_C)$. This means that the charge effect components can be broken into subgroups and their associated charge effects can be distributed within the eclipse system ABD.

There are ORUs which operate both during battery charge and discharge periods. For example, the CDU operates during both charge and discharge of the battery. Since the eclipse time base is exclusive of the insolar time base, and the ORUs are assumed to have exponential failure distributions, the use of these ORUs in both the insolar and eclipse models does not double account for the effect these ORUs have on availability.

And finally, for future modeling use:

- The alpha joint charge effect pseudocomponent (Charge 4) is incorporated into the models. It would be used to incorporate the availability of the positioning ORUs of the alpha joint during charging operation.

A.2.4 EPS PMAD UNIRAM Models

The following assumptions apply to the PMAD UNIRAM models:

- Power to a PDCA does not flow through the PDCAs of a non-associated module.
- The MBSUs are not cross-connected.
- A load can be supplied from either PDCU in its associated PDCA.
- Node transformers are considered separate, in that failure of one transformer will not cause failure of the other.
- There are five PDCAs in the LAB module and five PDCAs in the HAB module.
- Upon loss of control signals or control power, PDCUs fail in an as-is condition.
- PDCU failure is assumed catastrophic such that no power will be supplied to its load and no power will flow through it to other PDCUs.
- The inner-manned core components are not cooled by thermal control plates.

A.3 SPACE STATION ELECTRIC POWER SYSTEM MODELING DIAGRAMS

The following subsections present the EPS system ABDs, functional block diagrams, and basic subsystem fault trees used to evaluate the EPS RAM characteristics. Section A.3.1 provides the insolar UNIRAM model diagrams; Section A.3.2 provides the eclipse model diagrams and charge-effect diagrams; Section A.3.3 provides the PMAD ring architecture diagrams; Section A.3.4 provides the PMAD radial architecture diagrams; and Section A.3.5 provides the inner keel PDCU ABD diagram. The insolar and eclipse models share many of the same subsystems. For this reason, the common fault trees between them and the other models have only been inserted into this report once. Therefore, Section A.3.1, the insolar model diagrams, contains nearly all of the fault tree diagrams and Section A.3.2 contains only those fault trees that are unique to the eclipse model.

A.3.1 Insolar UNIRAM Model ABD and Fault Trees

The following index lists the nested subsystem breakdowns, ABDs, and fault trees for the insolar power generation system. In general, the modeling diagrams are ordered from left to right following the basic subsystems on the insolar ABD.

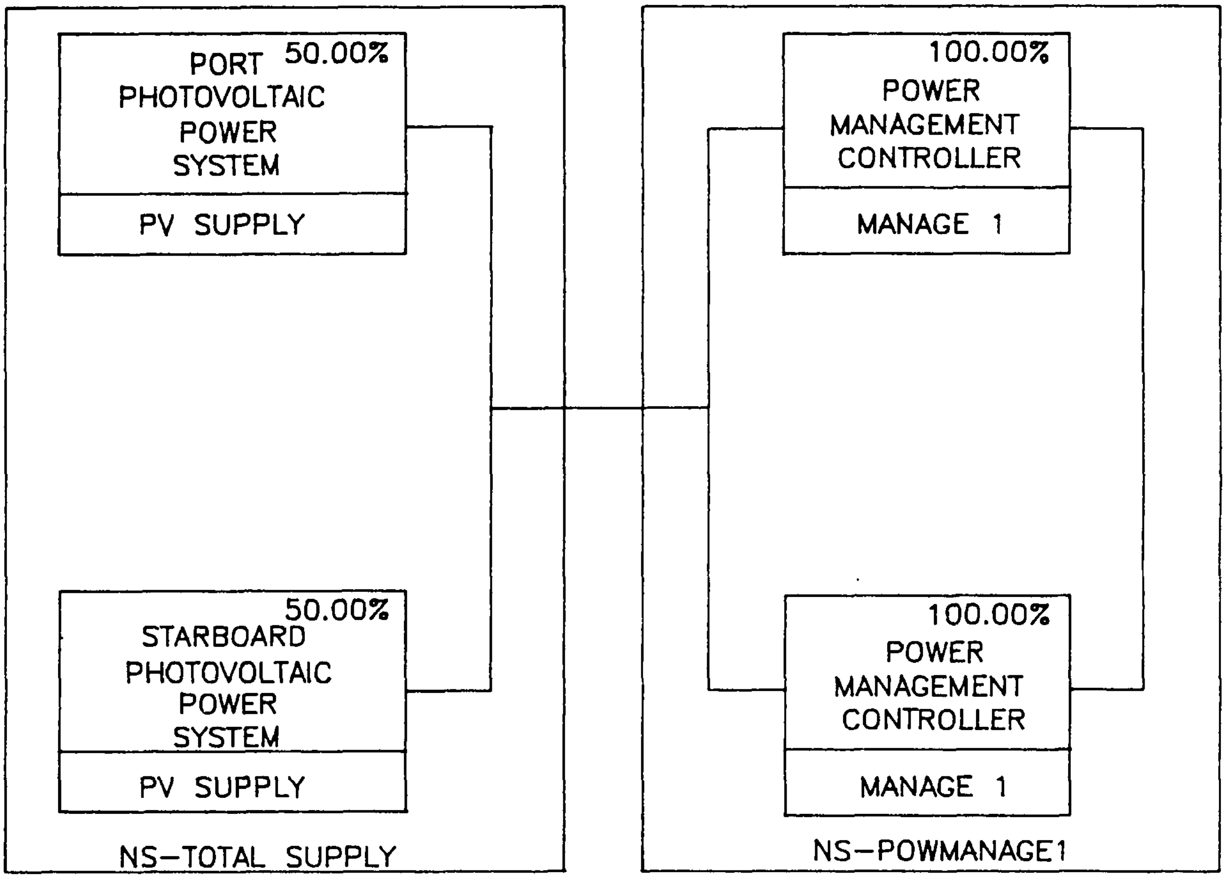


FIGURE A-1

INSOLATION POWER GENERATION NESTED SUBSYSTEM BLOCK DIAGRAM

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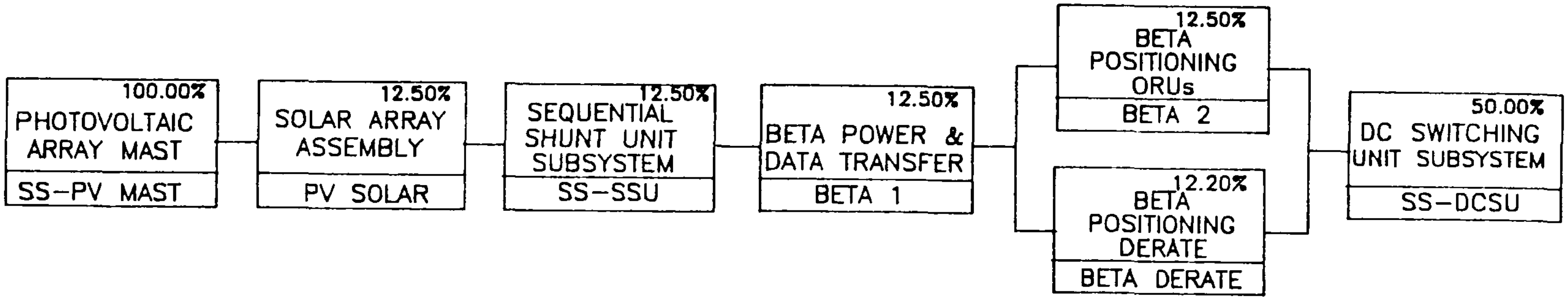

FIGURE A-3

PV MODULE/2 NESTED SUBSYSTEM BLOCK DIAGRAM

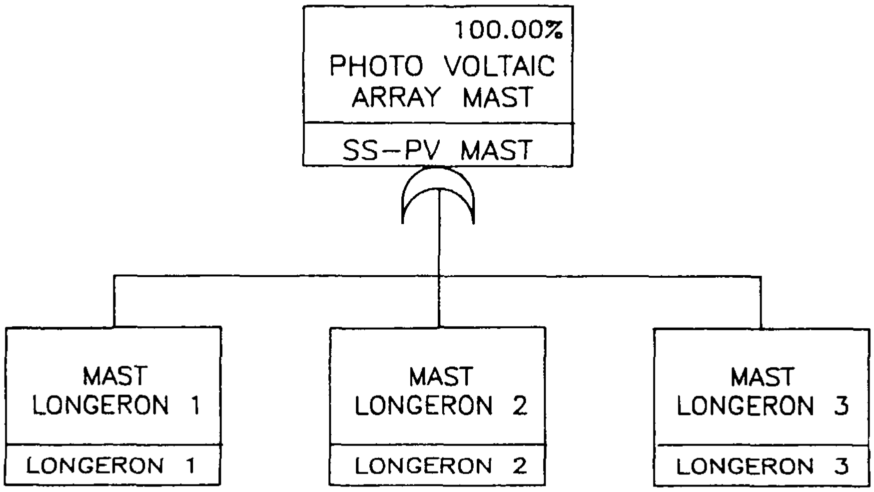

FIGURE A-4

PHOTOVOLTAIC ARRAY MAST FAULT TREE

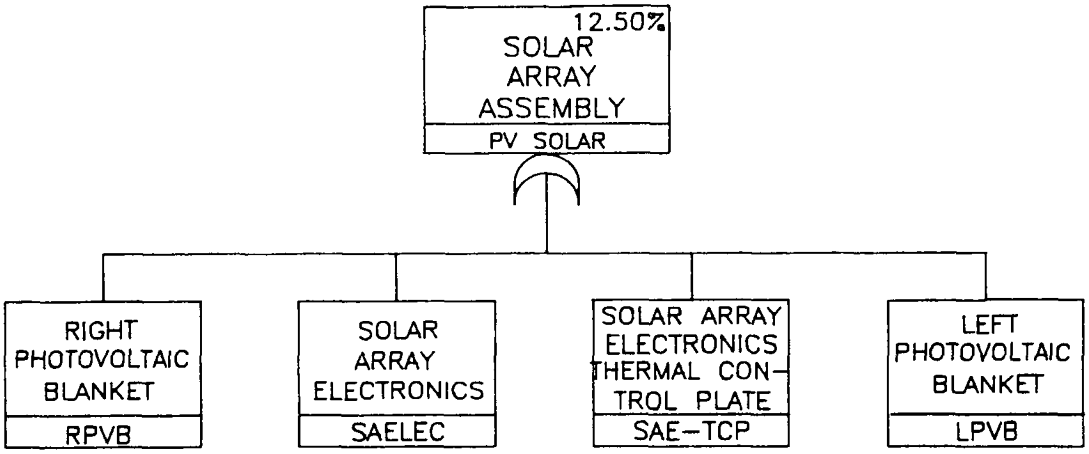

FIGURE A-5

SOLAR ARRAY ASSEMBLY FAULT TREE

C-2

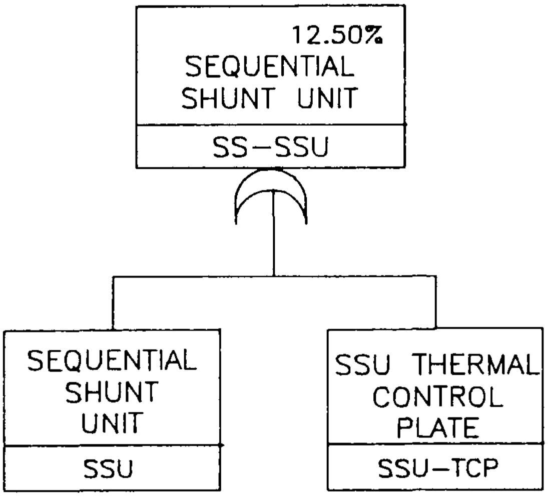

FIGURE A-6

SEQUENTIAL SHUNT UNIT SUBSYSTEM FAULT TREE

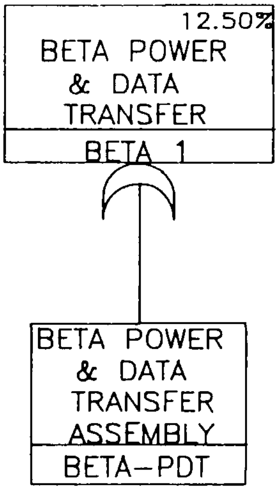

FIGURE A-7

BETA GIMBAL POWER AND DATA TRANSFER FAULT TREE

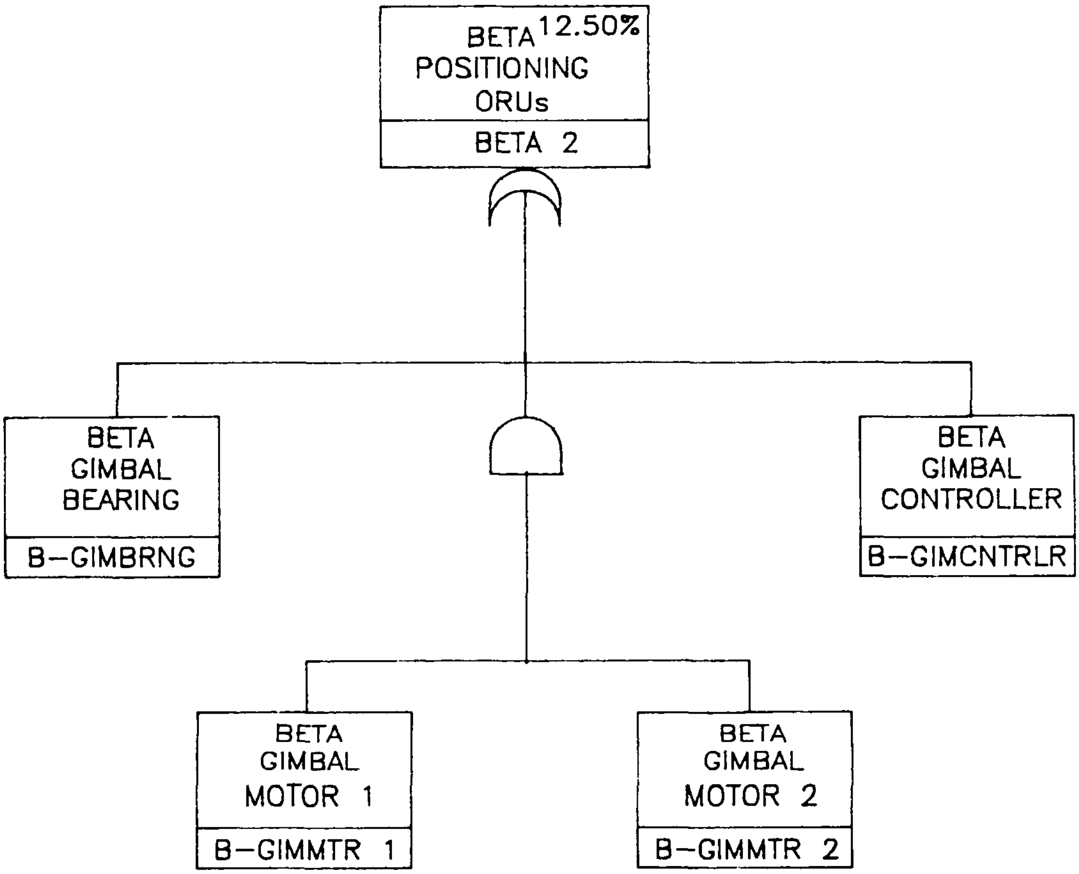

FIGURE A-8

BETA GIMBAL POSITIONING ORUs FAULT TREE

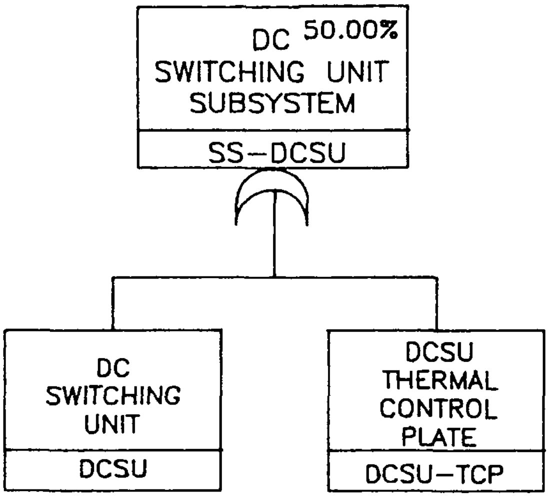

FIGURE A-9

DC SWITCHING UNIT SUBSYSTEM FAULT TREE

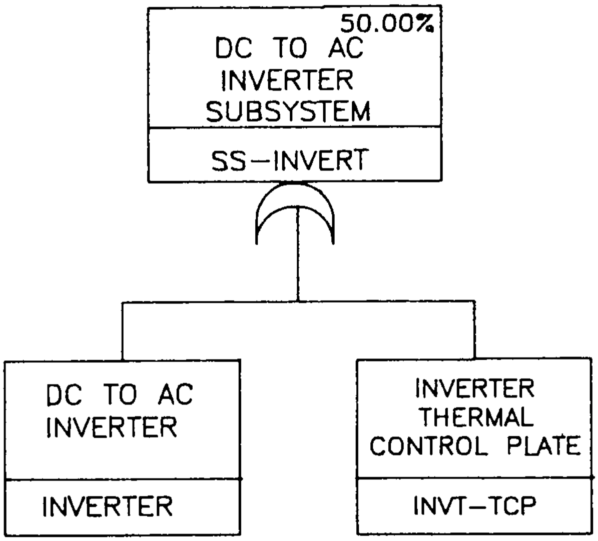

FIGURE A-10

DC TO AC INVERTER SUBSYSTEM FAULT TREE

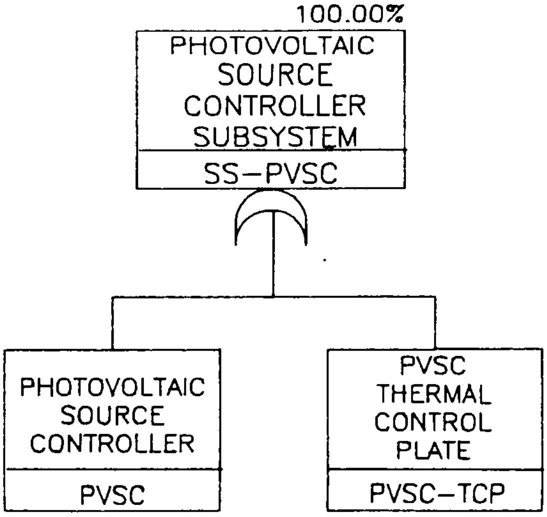

FIGURE A-11

PHOTOVOLTAIC SOURCE CONTROLLER SUBSYSTEM FAULT TREE

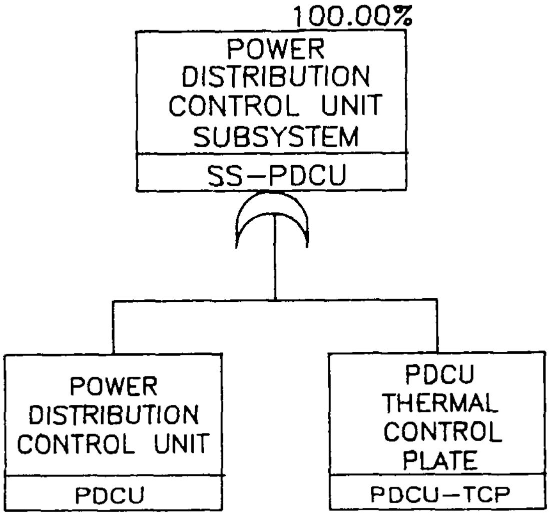

FIGURE A-12

POWER DISTRIBUTION CONTROL UNIT SUBSYSTEM FAULT TREE

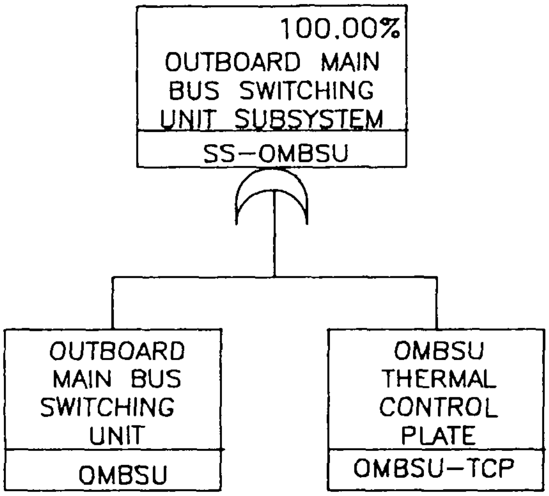

FIGURE A-13

OUTBOARD MAIN BUS SWITCHING UNIT SUBSYSTEM FAULT TREE

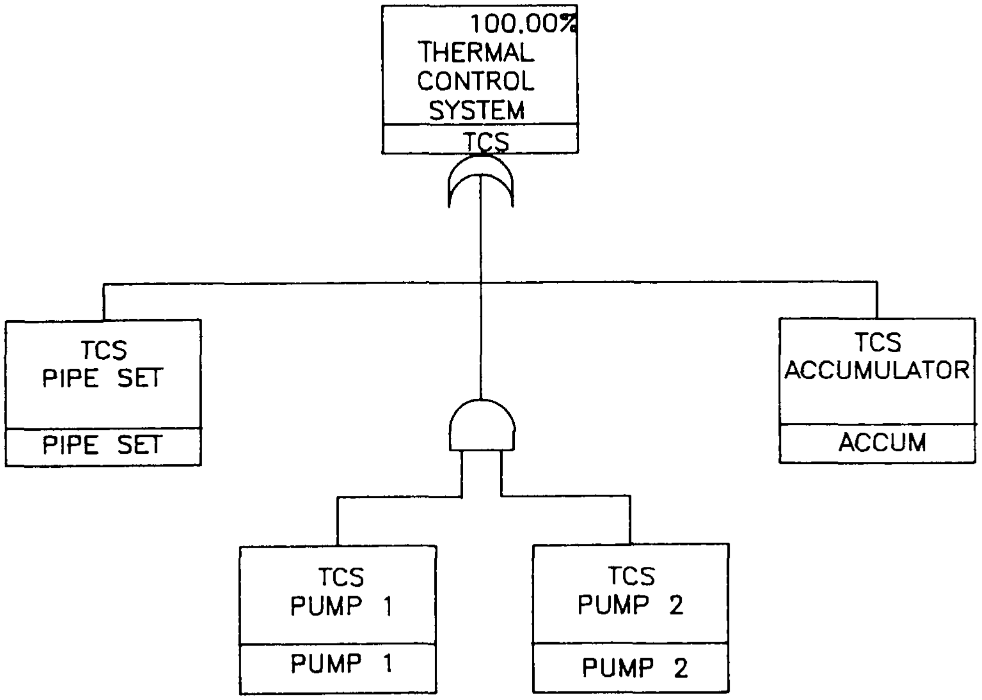

FIGURE A-14

THERMAL CONTROL SYSTEM FAULT TREE

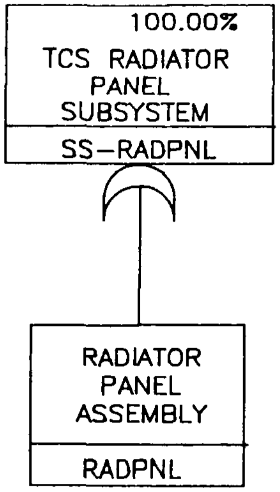

FIGURE A-15

THERMAL CONTROL SYSTEM RADIATOR PANEL SUBSYSTEM FAULT TREE

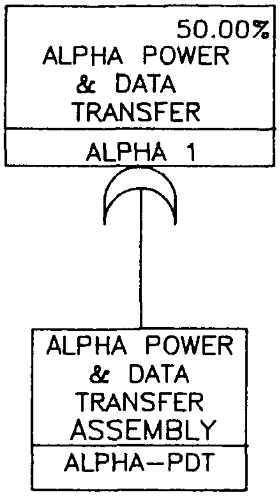

FIGURE A-16

ALPHA JOINT POWER AND DATA TRANSFER FAULT TREE

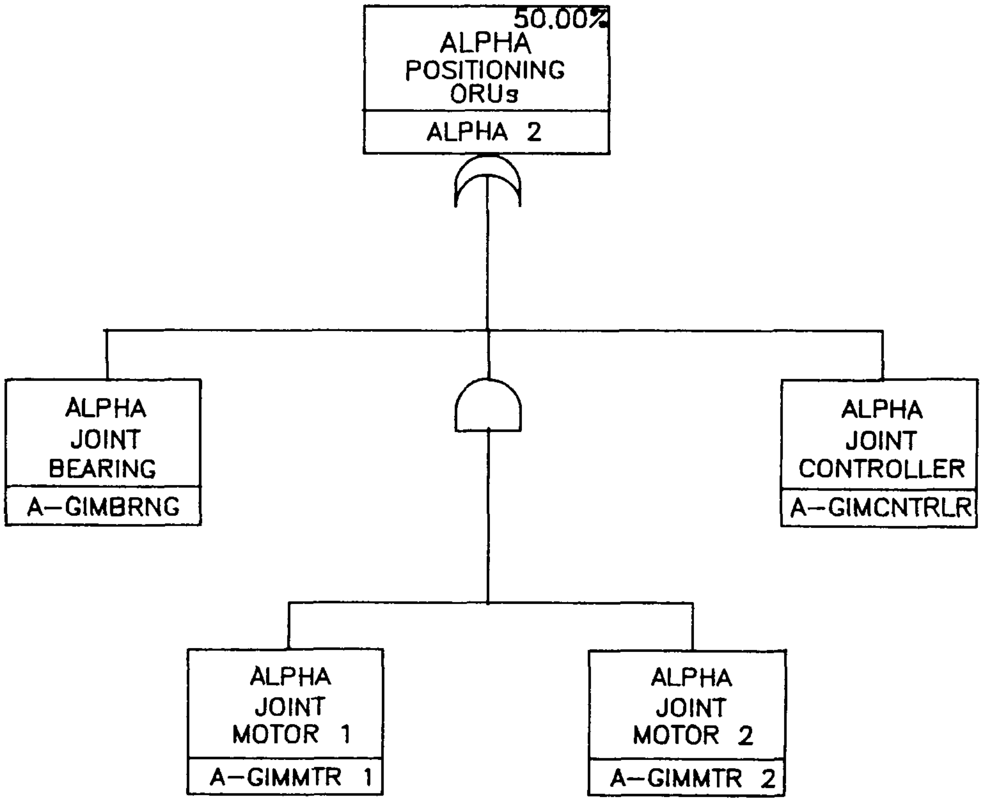

FIGURE A-17

ALPHA JOINT POSITIONING ORUs FAULT TREE

A.3.2 Eclipse UNIRAM Model ABD, Fault Trees, and Charge Effect Block Diagrams

The following section presents the modeling diagrams for the eclipse UNIRAM model. As stated previously, fault trees for basic subsystems that the eclipse model shares with the insolar model are listed in the insolar section. The index for the eclipse model figures follows.

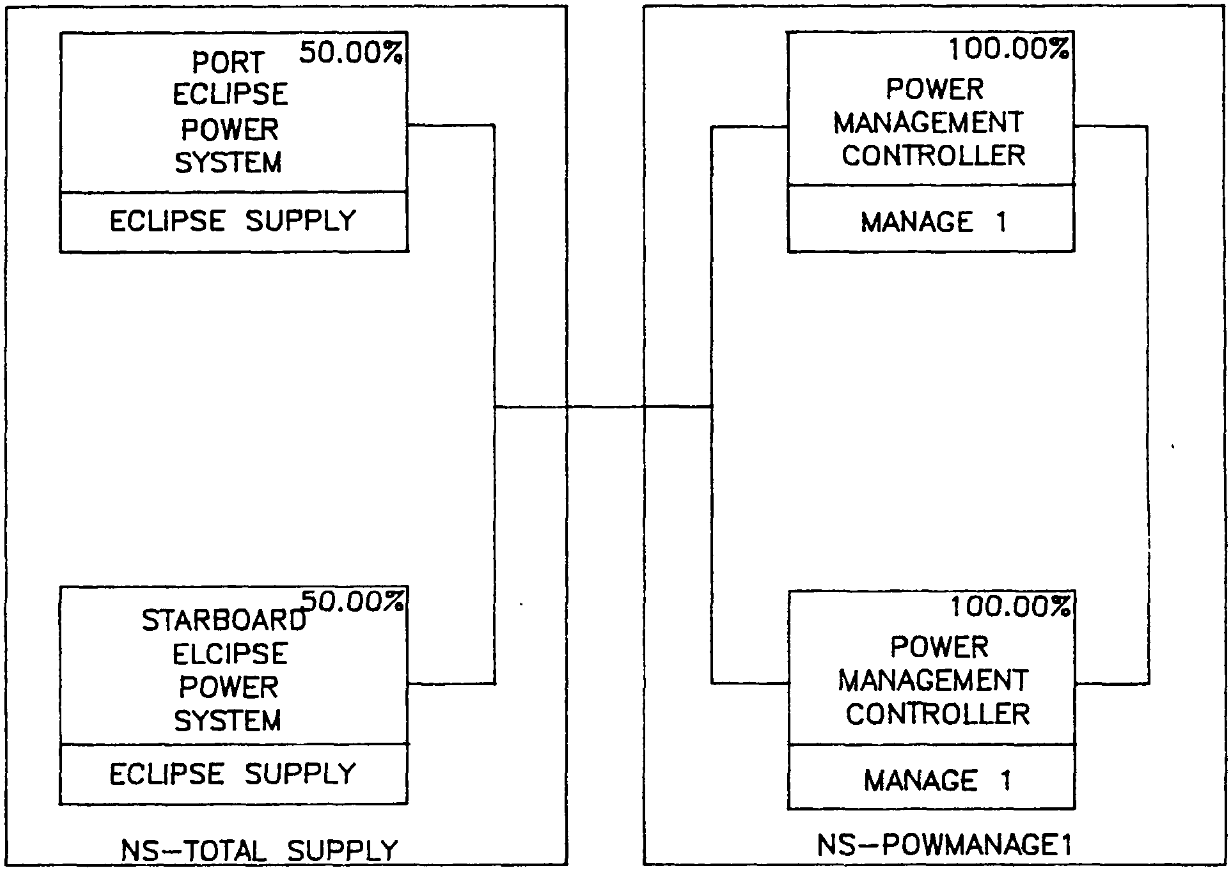

FIGURE A-18

ECLIPSE POWER GENERATION NESTED SUBSYSTEM FAULT TREE

A.3.4 PMAD Radial Architecture Model ABD and Fault Trees

Figure A-31 presents a functional block diagram of the PMAD system with a radial PDCU architecture. Figure A-32 presents the ABD of the PMAD system radial architecture that followed from Figure A-31.

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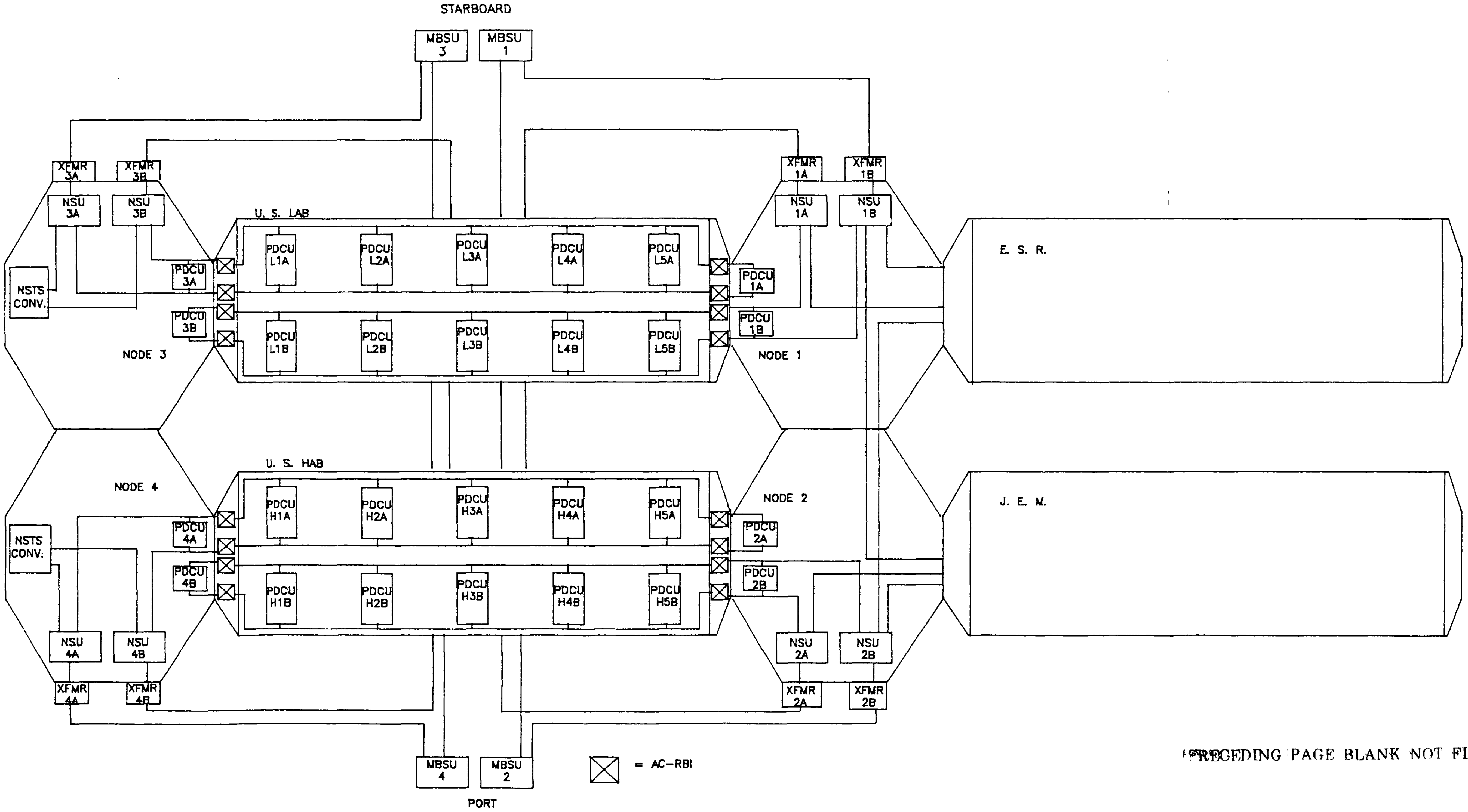
1 FOLDOUT FRAME

2 FOLDOUT FRAME



PRECEDING PAGE BLANK NOT FILMED

FIGURE A-31

PMAD RADIAL ARCHITECTURE
FUNCTIONAL BLOCK DIAGRAM

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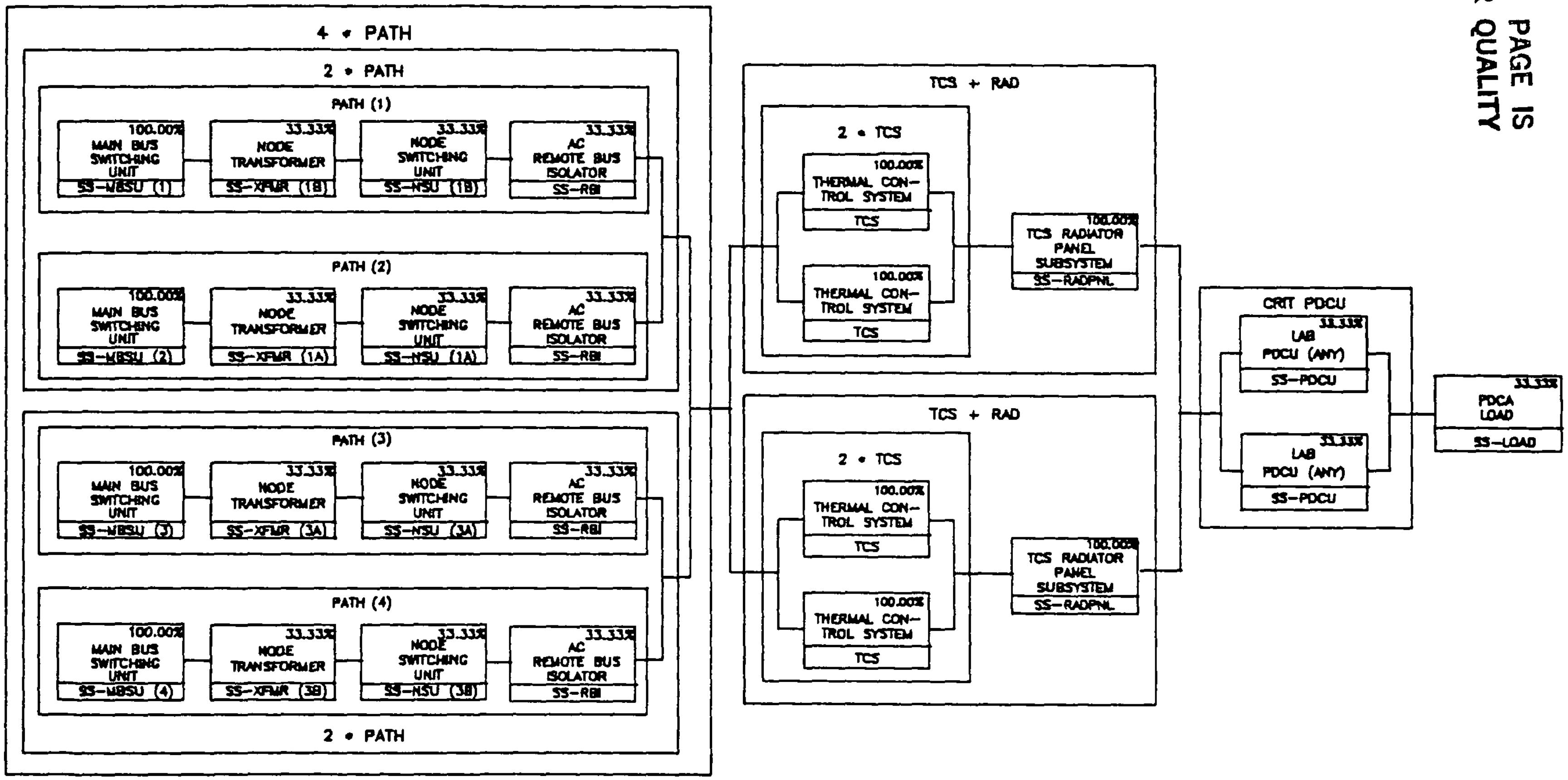

FIGURE A-32

PMAD RADIAL ARCHITECTURE
AVAILABILITY BLOCK DIAGRAM

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A.3.5 Inner Keel PDCU Model ABD

Figure A-33 presents the ABD for the inner keel power distribution system

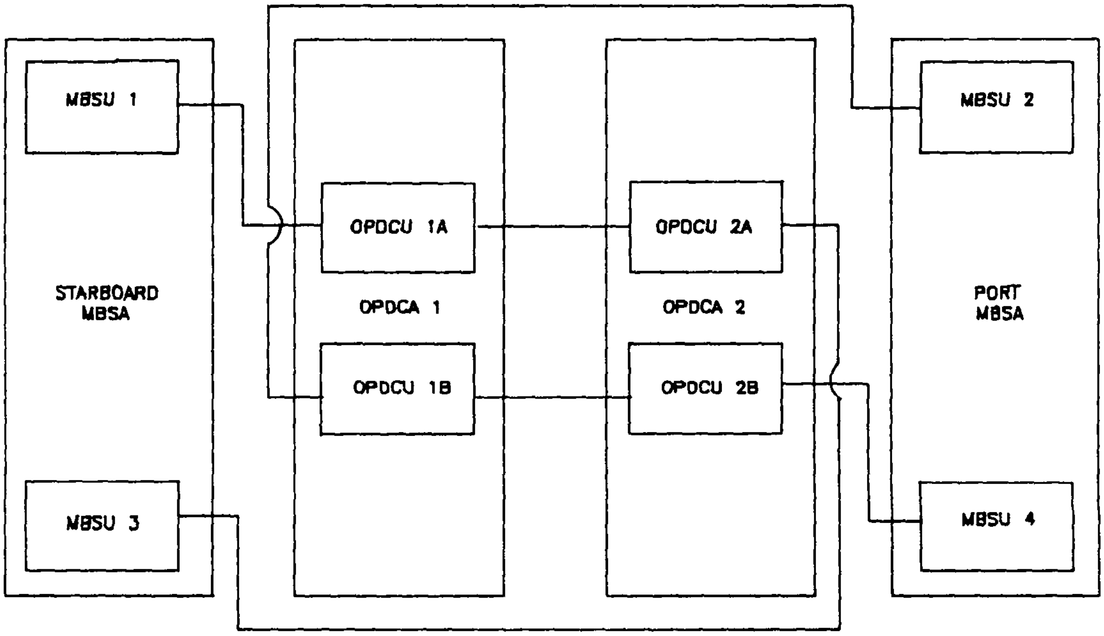

FIGURE A-33

INNER KEEL AVAILABILITY BLOCK DIAGRAM

A.4 SPACE STATION EPS UNIRAM INPUT FILES

The UNIRAM input files used for the Space Station EPS RAM analysis are listed in this section as follows:

- Section A.4.1, Insolar Model UNIRAM Input File
- Section A.4.2, Eclipse Model UNIRAM Input File
- Section A.4.3, Charge Effect UNIRAM Input File
- Section A.4.4, PMAD Ring Architecture UNIRAM Input File
- Section A.4.5, PMAD Radial Architecture UNIRAM Input File
- Section A.4.6, Inner Keel UNIRAM Input File

A.4.1 Insolar Model UNIRAM Input File

```
Power Availability 0 0 0.0750
18
SS-PV Mast
100 8 3 1
-1 0
Longeron 1
1 1 99999999 1 0.01 0
Longeron 2
1 1 99999999 1 0.01 0
Longeron 3
1 1 99999999 1 0.01 0
PVSolar
100 8 4 1
-1 0
RPVB
1 1 131400 1 1080 0
SAElec
1 1 87600 1 1080 0
SAE-TCP
1 1 131400 1 1080 0
LPVB
1 1 131400 1 1080 0
SS-SSU
100 8 2 1
-1 0
SSU
1 1 87600 1 1080 0
SSU-TCP
1 1 131400 1 1080 0
BETA1
100 8 1 0
BETA PDT
0 1 87600 1 1080 0
BETA2
100 8 4 2
-1 0
1 1
B-GimBrng
1 1 131400 1 1080 216
B-GmCntrlr
1 1 87600 1 1080 216
B-GimMtr1
2 1 87600 1 1080 216
B-GimMtr2
2 1 87600 1 1080 216
BetaDerate
97.5 8 1 0
BYPASS
0 1 99999999 1 .01 0
SS-DCSU
100 2 2 1
-1 0
```

```
DCSU
1 1 87600 1 1080 0
DCSU-TCP
1 1 131400 1 1080 0
SS-INVERT
100 3 2 1
-1 0
Inverter
1 1 87600 1 1080 0
Invt-TCP
1 1 131400 1 1080 0
SS-PVSC
100 4 2 1
-1 0
PVSC
1 1 43800 1 1080 216
PVSC-TCP
1 1 131400 1 1080 216
PVSCDerate
97.5 4 1 0
BYPASS
0 1 99999999 1 .01 0
TCS
100 1 4 2
-1 0
1 1
PipeSet
1 1 262800 1 1080 0
ACCUM
1 1 131400 1 1080 0
PUMP1
2 1 280320 1 1080 0
PUMP2
2 1 280320 1 1080 0
SS-RadPnl
100 2 1 0
RADPNL
0 1 489351 1 540 0
SS-OMBSU
100 1 2 1
-1 0
OMBSU
1 1 87600 1 1080 0
OMBSU-TCP
1 1 131400 1 1080 0
ALPHA1
100 2 1 0
ALPHA-PDT
0 1 87600 1 1080 0
ALPHA2
100 2 4 2
-1 0
1 1
```

```
A-GimBrng
1 1 131400 1 1080 0
A-GmCntrlr
1 1 87600 1 1080 0
A-GimMtr1
2 1 87600 1 1080 0
A-GimMtr2
2 1 87600 1 1080 0
AlfaDerate
63.66 2 1 0
BYPASS
0 1 99999999 1 .01 0
SS-PDCU
100 2 2 1
-1 0
PDCU
1 1 87600 1 1080 0
PDCU-TCP
1 1 131400 1 1080 0
Manage1
100 1 1 0
PMC
0 1 43800 1 1080 0
18
BetaPos
3  2
5  1
6  1
PV Mod/2
4  6
1  1
2  1
3  1
4  1
7  1
19  1
2*PV Mod/2
3  2
20  1
20  1
2*Inverts
2  1
8  2
2*PVSC
3  3
9  1
21 1
22 1
23 1
1
2*TCS
2  1
11 2
```

```
TCS&RAD
4  2
25 1
12 1
PV Mod Outbd
4  2
24 1
26 1
PV(In+Out)
3  2
24 1
27 1
PDCA
2  1
17 2
OMBSA
2  1
13 2
ALPHA Pos
3  2
15 1
16 1
ALPHA Jnt
4  2
14 1
31 1
PV Supply
4  5
26 1
28 1
29 1
30 1
32 1
PV Total
3  2
33 1
33 1
POW MANAGE
3  2
18 1
18 1
Tot System
4  2
34 1
35 1
0
0
0
```

A.4.2 Eclipse Model UNIRAM Input File

```
Eclipse Model
0 0 0.0750
16
SS-Battery
100 20 4 1
-1 0
Battery
1 1 70080 1 1080 0
Bat-TCP1
1 1 131400 1 1080 0
Bat-TCP2
1 1 131400 1 1080 0
Bat-TCP3
1 1 131400 1 1080 0
Charge1
100 20 1 0
BattCE
0 1 99999999 1 .01 0
SS-FaultIsolator
100 20 1 0
FaultIsolator
0 1 87600 1 1080 0
SS-CDU
100 20 4 2
-1 0
1 1
CDU
1 1 87600 1 1080 0
CDU-TCP
1 1 131400 1 1080
0 DC-RBI1
2 1 87600 1 1080 0
DC-RBI2
2 1 87600 1 1080 0
Charge2
15 1 1 0
PV-MOD-CE2
0 1 99999999 1 .01 0
SS-DCSU
50 1 2 1
-1 0
DCSU
1 1 87600 1 1080 0
DCSU-TCP
1 1 131400 1 1080 0
SS-PDCU
100 2 2 1
-1 0
PDCU
1 1 87600 1 1080 0
PDCU-TCP
1 1 131400 1 1080 0
```

```
SS-Invert
100 3 2 1
-1 0
Inverter
1 1 87600 1 1080 0
Invt-TCP
1 1 131400 1 1080 0
Charge3
100 4 1 0
PV-MOD-CE3
0 1 99999999 1 .01 0
SS-PVSC
100 4 2 1
-1 0
PVSC
1 1 43800 1 1080 4.5
PVSC-TCP
1 1 131400 1 1080 0
TCS
100 1 4 2
-1 0
1 1
PipeSet
1 1 262800 1 1080 0
ACCUM
1 1 131400 1 1080 0
PUMP1
2 1 280320 1 1080 0
PUMP2
2 1 280320 1 1080 0
SS-Radpnl
100 2 1 0
Radpnl
0 1 489351 1 540 0
SS-OMBSU
100 1 2 1
-1 0
OMBSU
1 1 87600 1 1080 0
OMBSU-TCP
1 1 131400 1 1080 0
ALPHA 1
100 2 1 0
ALPHA-PDT
0 1 87600 1 1080 0
Charge4
100 2 1 0
AlphaJntCE
0 1 99999999 1 .01 0
Manage 1
100 1 1 0
PMC
0 1 43800 1 1080 0
```

```
19
Battery
4  4
1  1
2  1
3  1
4  1
Top Bats
3  3
17 1
17 1
17 1
Bot Bats
3  2
17 1
17 1
Top BatPow
4  3
18 1
5  1
6  1
Bot BatPow
4  3
19 1
5  1
6  1
T&B BatPow
3  2
20 1
21 1
2*Inverters
2  1
8  2
PDCA
2  1
7  2
2*PVSC
2  1
10 2
PV Mod Inbd
4  4
9  1
22 1
23 1
25 1
2*TCS
2  1
11 2
TCS&RAD
4  2
12 1
27 1
```

```
PV Mod Outbd
4  2
26 1
28 1
PV(In+Out)
3  2
26 1
29 1
OMBSA
2  1
13 2
PV Supply
4  6
14 1
15 1
24 1
28 1
30 1
31 1
PV Total
3  2
32 1
32 1
Power Manage
2  1
16 2
Total System
4  2
33 1
34 1
0
0
0
```

A.4.3 Charge Effect UNIRAM Input File

```
Charge Effect Model
0 0 0.0750
3
Charge 1
100 1 9
2
-1
0 1
1
Battery
1 1 70080 1 1080 0
Bat-TCP1
1 1 131400 1 1080
0 Bat-TCP2
1 1 131400 1 1080
0 Bat-TCP3
1 1 131400 1 1080
0 Fault Isolator
1 1 87600 1 1080 0
CDU
1 1 87600 1 1080 0
CDU-TCP
1 1 131400 1 1080 0
DC-RBI1
2 1 87600 1 1080 0
DC-RBI2
2 1 87600 1 1080 0
Charge 2
100 1 12 5
-1 0
-1 1
-1 1
-1 1
-1 1
Longeron 1
2 1 99999999 1 0.01 0
Longeron 2
2 1 99999999 1 0.01 0
Longeron 3
2 1 99999999 1 0.01 0
RPVB
3 1 131400 1 1080 0
SAElec
3 1 87600 1 1080 0
SAE-TCP
3 1 131400 1 1080 0
LPVB
3 1 131400 1 1080 0
SSU
4 1 87600 1 1080 0
SSU-TCP
4 1 131400 1 1080 0
```

```
BETA PDT
1 1 87600 1 1080 0
DCSU
5 1 87600 1 1080 0
DCSU-TCP
5 1 131400 1 1080 0
Charge 3
100 1 13 9
-1 0
1 1
-1 2
1 3
-1 2
1 5
1 1
-1 7
-1 7
Pipset1
3 1 262800 1 1080 0
ACCUM1
3 1 131400 1 1080 0
TCPump1
4 1 280320 1 1080 0
TCPump2
4 1 280320 1 1080 0
Pipset2
5 1 262800 1 1080 0
ACCUM2
5 1 131400 1 1080 0
TCPump3
6 1 280320 1 1080 0
TCPump4
6 1 280320 1 1080 0
RADPNL
1 1 489351 1 540 0
PVSC1
8 1 43800 1 1080 0
PVSC1-TCP
8 1 131400 1 1080 0
PVSC2
9 1 43800 1 1080 0
PVSC2-TCP
9 1 131400 1 1080 0
1
Nest
4 3
1 1
2 1
3 1
0
0
0
```

A.4.4 PMAD Ring Architecture UNIRAM Input File

```
CROSS-CONNECTS
0. 0. 0.0750
30
SS-XFMR1A
100 3 1 0
XFMR1A
0 1 131400. 1 1080. 0
SS-XFMR1B
100 3 1 0
XFMR1B
0 1 131400. 1 1080. 0
SS-XFMR3
100 3 1 0
XFMR3
0 1 131400. 1 1080. 0
SS-XFMR4
100 3 1 0
XFMR4
0 1 131400. 1 1080. 0
SS-NSU1A
35 1 1 0
NSU1A
0 1 87600. 1 1080. 0
SS-NSU1B
35 1 1 0
NSU1B
0 1 87600. 1 1080. 0
SS-NSU3A
35 1 1 0
NSU3A
0 1 87600. 1 1080. 0
SS-NSU3B
35 1 1 0
NSU3B
0 1 87600. 1 1080. 0
SS-NSU4A
35 1 1 0
NSU4A
0 1 87600. 1 1080. 0
SS-MBSU1
100 1 2 1
-1 0
MBSU1
1 1 87600. 1 1080. 0
MBSU1-TCP
1 1 131400. 1 1080 0
SS-MBSU2
100 1 2 1
-1 0
```

```
MBSU2
1 1 87600. 1 1080. 0
MBSU2-TCP
1 1 131400. 1 1080 0
SS-MBSU
100 1 2 1
-1 0
MBSU3
1 1 87600. 1 1080. 0
MBSU3-TCP
1 1 131400. 1 1080 0
SS-MBSU4
100 1 2 1
-1 0
MBSU4
1 1 87600. 1 1080. 0
MBSU4-TCP
1 1 131400. 1 1080 0
TCS
100 1 4 2
-1 0
1 1
Pipeset
1 1 262800. 1 1080. 0
ACCUM
1 1 131400. 1 1080. 0
PUMP1
2 1 280320. 1 1080. 0
PUMP2
2 1 280320. 1 1080. 0
SS-RADPNL
100 1 1 0
RADPNL
0 1 489351. 1 540 0
SS-PDCU1A
100 3 1 0
PDCU1A
0 1 87600. 1 1080. 0
SS-PDCU1B
100 3 1 0
PDCU1B
0 1 87600. 1 1080. 0
SS-PDCU3A
100 3 1 0
PDCU3A
0 1 87600. 1 1080. 0
SS-PDCU3B
100 3 1 0
PDCU3B
0 1 87600. 1 1080. 0
SS-PDCUL1A
100 3 1 0
```

```
PDCUL1A
0 1 87600. 1 1080. 0
SS-PDCUL1B
100 3 1 0
PDCUL1B
0 1 87600. 1 1080. 0
SS-PDCUL2A
100 3 1 0
PDCUL2A
0 1 87600. 1 1080. 0
SS-PDCUL2B
100 3 1 0
PDCUL2B
0 1 87600. 1 1080. 0
SS-PDCUL3A
100 3 1 0
PDCUL3A
0 1 87600. 1 1080. 0
SS-PDCUL3B
100 3 1 0
PDCUL3B
0 1 87600. 1 1080. 0
SS-PDCUL4A
100 3 1 0
PDCUL4A
0 1 87600. 1 1080. 0
SS-PDCUL4B
100 3 1 0
PDCUL4B
0 1 87600. 1 1080. 0
SS-PDCUL5A
100 3 1 0
PDCUL5A
0 1 87600. 1 1080. 0
SS-PDCUL5B
100 3 1 0
PDCUL5B
0 1 87600. 1 1080. 0
SS-LOAD
100 3 1 0
LOAD
0 1 99999999. 1 .01 0
20
SUPPLY 1
 4  3
 2  1
 6  1
10  1
SUPPLY 2
 4  3
 1  1
 5  1
11  1
```

```
SUPPLY 3
 4  4
 3  1
 7  1
 8  1
12  1
SUPPLY 4
 4  3
 4  1
 9  1
13  1
RTOP
PDCUs
 4  3
16  1
26  1
28  1
RBOT PDCUs
 4  3
17  1
27  1
29  1
LTOP PDCUs
 4  3
18  1
20  1
22  1
LBOT PDCUs
 4  3
19  1
21  1
23  1
CRIT PDCU
 3  2
24  1
25  1
RT PATH T
 4  2
31  1
35  1
RT PATH B
 4  2
32  1
36  1
LFT PATH T
 4  2
33  1
37  1
LFT PATH B
 4  2
34  1
38  1
```

```
RT PATH
 3  2
40  1
41  1
LFT PATH
 3  2
42  1
43  1
PATHS COM
 3  2
44  1
45  1
DUAL TCS
 2  1
14  2
TCS/RAD
 4  2
47  1
15  1
MOD TCS
 3  2
48  1
48  1
LOAD PDCA
 4  4
30  1
39  1
46  1
49  1
0
0
0
```

A.4.5 PMAD Radial Architecture UNIRAM Input File

```
0 0 0.0750
8
SS-XFMR
100 3 1 0
XFMR
0 1 131400 1 1080 0
SS-MBSU
100 1 2 1
-1 0
MBSU
1 1 87600 1 1080 0
MBSU-TCP
1 1 131400 1 1080 0
SS-NSU
35 1 1 0
NSU
0 1 87600 1 1080 0
SS-RBI
35 1 1 0
RBI
0 1 87600 1 1080 0
SS-PDCU
100 3 1 0
PDCU
0 1 87600 1 1080 0
TCS
100 1 4 2
-1 0
1 1
Pipeset
1 1 262800 1 1080 0
ACCUM
1 1 131400 1 1080 0
TCPump1
2 1 280320 1 1080 0
TCPump2
2 1 280320 1 1080 0
SS-Radpnl
100 1 1 0
Radpnl
0 1 489351 1 540 0
SS-Load
100 3 1 0
Load
0 1 99999999 1 0.01 0
8
PDCA
2 1
5 2
Path
4 4
1 1
```

```
2 1
3 1
4 1
2*Path
3 2
10 1
10 1
4*Path
3 2
11 1
11 1
2*TCS
2 1
6 2
TCS/RAD
4 2
13 1
7 1
2*TCS/RAD
3 2
14 1
14 1
Unit Nest
4 4
8 1
9 1
12 1
15 1
0
0
0
```

A.4.6 Inner Keel UNIRAM Input File

```
Inner Keel Model
0 0 0.0750
4
SS-MBSU
100 1 2 1
-1 0
MBSU
1 1 87600 1 1080 0
MBSU-TCP
1 1 131400 1 1080 0
SS-OPDCU
100 3 2 1
-1 0
OPDCU
1 1 87600 1 1080 0
OPDCU-TCP
1 1 131400 1 1080 0
TCS
100 1 4 2
-1 0
1 1
Pipeset
1 1 262800 1 1080 0
ACCUM
1 1 131400 1 1080 0
TCPump1
2 1 280320 1 1080 0
TCPump2
2
1 280320 1 1080 0
SS-Radpnl
100 1 1 0
Radpnl
0 1 489351 1 540 0
6
Path 1
4 2
1 1
2 1
Path 1&2
3 2
1 1
5 1
2*TCS
2 1
3 2
TCS/RAD
4 2
4 1
7 1
```

APPENDIX B

SPACE STATION ELECTRIC POWER SYSTEM

TABULAR DATA RESULTS

APPENDIX B

SPACE STATION ELECTRIC POWER SYSTEM TABULAR DATA RESULTS

Appendix B contains the tabulated data compiled during the UNIRAM RAM analysis of the Space Station Electric Power System. The following tables are listed:

TABLE B-1

PMAD BASELINE RESULTS FOR PATH RELIABILITY TO EACH PDCA

PDCA	A (%)	EA (%)	FOR (%)	EFOR (%)	Average Power (Kw)
PDCA-N1	99.9828	33.3276	0.0172	66.6724	24.9957
PDCA-N3	99.9825	33.3275	0.0175	66.6725	24.9956
PDCA-L1	99.9818	33.3273	0.0182	66.6727	24.9955
PDCA-L2	99.9814	33.3271	0.0186	66.6729	24.9953
PDCA-L3	99.9813	33.3271	0.0187	66.6729	24.9953
PDCA-L4	99.9816	33.3272	0.0184	66.6728	24.9954
PDCA-L5	99.9821	33.3274	0.0179	66.6726	24.9956

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR: Equivalent Forced Outage Rate

TABLE B-2

SPACE STATION EPS BASELINE RESULTS

Model	Availability (%)	Equivalent Availability (%)	Forced Outage Rate (%)	Equivalent Forced Outage Rate (%)
Insolar	99.9217	89.3472	0.0783	10.6528
Eclipse (without charge effects)	99.9218	89.5751	0.0782	10.4249
Eclipse (with charge effects)	99.9210	75.9550	0.0790	24.0450
PMAD/PDCA-L3	99.9813	33.3271	0.0187	66.6729

TABLE B-3

INSOLAR BASELINE SYSTEM OUTPUT STATES

Plant State	Output State Probability	Output Capability	Days/ Year	Power (MW) Output
1	39.3899%	100.00%	143.77	0.0750
2	5.3547%	99.69%	19.54	0.0748
3	0.4316%	99.38%	1.58	0.0745
4	0.0224%	99.06%	0.08	0.0743
5	0.0008%	98.75%	0.00	0.0741
6	0.0000%	98.44%	0.00	0.0738
7	0.0000%	98.13%	0.00	0.0736
8	0.0000%	97.81%	0.00	0.0734
9	0.0000%	97.50%	0.00	0.0731
10	30.1812%	87.50%	110.16	0.0656
11	3.5900%	87.19%	13.10	0.0654
12	0.2480%	86.88%	0.91	0.0652
13	0.0107%	86.56%	0.04	0.0649
14	0.0003%	86.25%	0.00	0.0647
15	0.0000%	85.94%	0.00	0.0645
16	0.0000%	85.63%	0.00	0.0642
17	0.0000%	85.31%	0.00	0.0640
18	2.4162%	81.83%	8.82	0.0614
19	0.1642%	81.52%	0.60	0.0611
20	0.0077%	81.21%	0.03	0.0609
21	0.0002%	80.89%	0.00	0.0607
22	0.0000%	80.58%	0.00	0.0604
23	10.4130%	75.00%	38.01	0.0563
24	1.0617%	74.69%	3.88	0.0560
25	0.0613%	74.38%	0.22	0.0558
26	0.0021%	74.06%	0.01	0.0555
27	0.0000%	73.75%	0.00	0.0553
28	0.0000%	73.44%	0.00	0.0551
29	0.0000%	73.13%	0.00	0.0548
30	0.9256%	69.33%	3.38	0.0520
31	0.0472%	69.02%	0.17	0.0518
32	0.0015%	68.71%	0.01	0.0515
33	0.0000%	68.39%	0.00	0.0513
34	0.0371%	63.66%	0.14	0.0477
35	2.0964%	62.50%	7.65	0.0469
36	0.1781%	62.19%	0.65	0.0466
37	0.0083%	61.88%	0.03	0.0464
38	0.0002%	61.56%	0.00	0.0462
39	0.0000%	61.25%	0.00	0.0459
40	0.0000%	60.94%	0.00	0.0457
41	0.1421%	56.83%	0.52	0.0426

(Continued)

TABLE B-3 (continued)

Plant State	Output State Probability	Output Capability	Days/ Year	Power (MW) Output
42	0.0048%	56.52%	0.02	0.0424
43	0.0001%	56.21%	0.00	0.0422
44	2.0530%	50.00%	7.49	0.0375
45	0.1395%	49.69%	0.51	0.0373
46	0.0063%	49.38%	0.02	0.0370
47	0.0001%	49.06%	0.00	0.0368
48	0.0000%	48.75%	0.00	0.0366
49	0.0099%	44.33%	0.04	0.0332
50	0.0002%	44.02%	0.00	0.0330
51	0.7060%	37.50%	2.58	0.0281
52	0.0360%	37.19%	0.13	0.0279
53	0.0011%	36.88%	0.00	0.0277
54	0.0000%	36.56%	0.00	0.0274
55	0.0550%	31.83%	0.20	0.0239
56	0.1061%	25.00%	0.39	0.0188
57	0.0036%	24.69%	0.01	0.0185
58	0.0001%	24.38%	0.00	0.0183
59	0.0073%	12.50%	0.03	0.0094
60	0.0001%	12.19%	0.00	0.0091
61	0.0783%	0.00%	0.29	0.0000

TABLE B-4

INSOLAR COMPONENT CRITICALITY RANKING

Subsystem	Component	Definition	Ranking Factor
Alpha 1	Alpha-PDT	Alpha Joint Power Data Transfer Assembly	1.1014
Beta1	Beta PDT	Beta Gimbal Power Data Transfer Assembly	1.0888
SS-SSU	SSU	Sequential Shunt Unit	1.0888
SS-DCSU	DCSU	DC Switch Unit	1.0888
PVSolar	SAElec	Solar Array Electronics Assembly	1.0888
PVSolar	RPVB	Right Photovoltaic Blanket	0.7258
PVSolar	SAE-TCP	Solar Array Electronics TCP	0.7258
PVSolar	LPVB	Left Photovoltaic Blanket	0.7258
SS-SSU	SSU-TCP	Sequential Shunt Unit-TCP	0.7258
SS-DCSU	DCSU-TCP	DC Switch Unit-TCP	0.7258
Alpha 2	A-GmCntrlr	Alpha Joint Controller	0.3360
Alpha 2	A-GimBrng	Alpha Joint Bearing	0.2240
SS-RadPnl	Radpnl	Radiator Panel Assembly	0.1475
Manage 1	PMC	Power Management Controller	0.0518
SS-OMBSU	OMBSU	Outboard Main Bus Switching Unit	0.0306
SS-PDCU	PDCU	Power Distribution Control Unit	0.0306
SS-INVERT	Inverter	AC to DC Inverter	0.0304
SS-OMBSU	OMBSU-TCP	Outboard Main Bus Switching Unit-TCP	0.0233
SS-PDCU	PDCU-TCP	Power Distribution Control Unit-TCP	0.0233
SS-INVERT	Invt-TCP	AC to DC Inverter-TCP	0.0232
BETA 2	B-GmCntrlr	Beta Gimbal Controller	0.0218
TCS	Accum	Thermal Control System Accumulator	0.0177
BETA 2	B-GimBrng	Beta Gimbal Bearing	0.0145
TCS	PipeSet	Thermal Control System Pipeset	0.0110
ALPHA 2	A-GimMtr1	Alpha Joint Motor	0.0040
ALPHA 2	A-GimMtr2	Alpha Joint Motor	0.0040
SS-PVSC	PVSC	Photovoltaic Source Controller	0.0013
SS-PVSC	PVSC-TCP	Photovoltaic Source Controller-TCP	0.0006
BETA 2	B-GimMtr1	Beta Gimbal Motor	0.0002
BETA 2	B-GimMtr2	Beta Gimbal Motor	0.0002
TCS	TC Pump1	Thermal Control System Pump	0.0001
TCS	TC Pump2	Thermal Control System Pump	0.0001
SS-PV Mast	Longeron1	PV Mast Longeron	0.0000
SS-PV Mast	Longeron2	PV Mast Longeron	0.0000
SS-PV Mast	Longeron3	PV Mast Longeron	0.0000
BetaDerate	BYPASS		0.0000
PVSCDerate	BYPASS		0.0000
AlphaDerate	BYPASS		0.0000

Note: TCP = Thermal Control Plate

TABLE B-5

ECLIPSE WITHOUT CHARGE EFFECTS BASELINE SYSTEM OUTPUT STATES

Plant State	Output State Probability	Output Capability	Days/ Year	Power (MW) Output
1	19.1128%	100.00%	69.76	0.0750
2	28.8218%	95.00%	105.20	0.0713
3	22.4706%	90.00%	82.02	0.0675
4	13.7810%	85.00%	50.30	0.0637
5	7.1631%	80.00%	26.15	0.0600
6	3.3810%	75.00%	12.34	0.0563
7	1.4891%	70.00%	5.44	0.0525
8	0.5826%	65.00%	2.13	0.0488
9	0.2130%	60.00%	0.78	0.0450
10	0.0721%	55.00%	0.26	0.0413
11	1.2661%	50.00%	4.62	0.0375
12	0.9443%	45.00%	3.45	0.0338
13	0.3793%	40.00%	1.38	0.0300
14	0.1641%	35.00%	0.60	0.0263
15	0.0524%	30.00%	0.19	0.0225
16	0.0209%	25.00%	0.08	0.0188
17	0.0061%	20.00%	0.02	0.0150
18	0.0012%	15.00%	0.00	0.0113
19	0.0004%	10.00%	0.00	0.0075
20	0.0000%	5.00%	0.00	0.0038
21	0.0782%	0.00%	0.29	0.0000

TABLE B-6

ECLIPSE WITH CHARGE EFFECTS BASELINE SYSTEM OUTPUT STATES

Plant State	Output State Probability	Output Capability	Days/ Year	Power (MW) Output
1	2.1545%	100.00%	7.86	0.0750
2	6.7433%	95.00%	24.61	0.0713
3	11.3707%	90.00%	41.50	0.0675
4	14.7591%	85.00%	53.87	0.0637
5	15.7565%	80.00%	57.51	0.0600
6	14.3823%	75.00%	52.50	0.0563
7	11.6384%	70.00%	42.48	0.0525
8	8.3777%	65.00%	30.58	0.0488
9	5.4586%	60.00%	19.92	0.0450
10	3.2362%	55.00%	11.81	0.0413
11	2.1613%	50.00%	7.89	0.0375
12	1.5166%	45.00%	5.54	0.0338
13	0.9783%	40.00%	3.57	0.0300
14	0.6655%	35.00%	2.43	0.0263
15	0.3767%	30.00%	1.38	0.0225
16	0.2011%	25.00%	0.73	0.0188
17	0.0945%	20.00%	0.34	0.0150
18	0.0337%	15.00%	0.12	0.0113
19	0.0133%	10.00%	0.05	0.0075
20	0.0027%	5.00%	0.01	0.0038
21	0.0790%	0.00%	0.29	0.0000

TABLE B-7

ECLIPSE COMPONENT CRITICALITY RANKING WITHOUT CHARGE EFFECTS

Subsystem	Component	Definition	Ranking Factor
SS-Battery	Battery	Battery	1.3803
ALPHA-PDT	ALPHA 1	Alpha Joint Power Data Transfer Assembly	1.1043
SS-DCSU	DCSU	DC Switch Unit	1.1043
SS-FaultIs	Fault Iso	CDU Fault Isolator	1.1042
SS-CDU	CDU	Charge/Discharge Unit	1.1042
SS-Battery	Bat-TCP1	Battery-TCP	0.7361
SS-Battery	Bat-TCP2	Battery-TCP	0.7361
SS-Battery	Bat-TCP3	Battery-TCP	0.7361
SS-DCSU	DCSU-TCP	DC Switch Unit-TCP	0.7361
SS-CDU	CDU-TCP	Charge/Discharge Unit-TCP	0.7361
SS-Radpnl	Radpnl	Radiator Panel Assembly	0.1481
SS-PVSC	PVSC	Photovoltaic Source Controller	0.0854
Manage 1	PMC	Power Management Controller	0.0519
SS-PVSC	PVSC-TCP	Photovoltaic Source Controller-TCP	0.0399
SS-PDCU	PDCU	Power Distribution Control Unit	0.0307
SS-OMBSU	OMBSU	Outboard Main Bus Switching Unit	0.0307
SS-Invert	Inverter	AC to DC Inverter	0.0307
SS-OMBSU	OMBSU-TCP	Outboard Main Bus Switching Unit-TCP	0.0234
SS-PDCU	PDCU-TCP	Power Distribution Control Unit-TCP	0.0234
SS-Invert	Invt-TCP	AC to DC Inverter-TCP	0.0234
TCS	ACCUM	Thermal Control System Accumulator	0.0178
SS-CDU	DC-RBI1	Charge/Discharge Unit	0.0133
SS-CDU	DC-RBI2	Charge/Discharge Unit	0.0133
TCS	PipeSet	Thermal Control System Pipeset	0.0111
TCS	TC Pump1	Thermal Control System Pump	0.0001
TCS	TC Pump2	Thermal Control System Pump	0.0001
Charge 1	BattCE	Battery Charge Effects	0.0000
Charge 2	PV-MOD-CE2	Partial PV Module Charge Effects	0.0000
Charge 3	PV-MOD-CE3	Full PV Module Charge Effects	0.0000
Charge 4	AlphaJntCE	Alpha Joint Charge Effect	0.0000

Note: TCP = Thermal Control Plate

TABLE B-8

ECLIPSE COMPONENT CRITICALITY RANKING WITH CHARGE EFFECTS

Subsystem	Component	Definition	Ranking Factor
Charge 2	PV-MOD-CE2	Partial PV Module Charge Effect	7.1495
Charge 1	BattCE	Battery Charge Effect	5.7277
SS-Battery	Battery	Battery	1.1704
Alpha1	Alpha-PDT	Alpha Joint Power Data Transfer Assembly	0.9364
SS-FaultIs	Fault Iso	CDU Fault Isolator	0.9363
SS-DCSU	DCSU	DC Switch Unit	0.9363
SS-CDU	CDU	Charge/Discharge Unit	0.9363
SS-DCSU	DCSU-TCP	DC Switch Unit-TCP	0.6242
SS-Battery	Bat-TCP1	Battery-TCP	0.6242
SS-Battery	Bat-TCP2	Battery-TCP	0.6242
SS-Battery	Bat-TCP3	Battery-TCP	0.6242
SS-CDU	CDU-TCP	Charge/Discharge Unit-TCP	0.6242
Charge 3	PV-MOD-CE3	Full PV Module Charge Effect	0.1732
SS-Radpnl	Radpnl	Radiator Panel Assembly	0.1256
SS-PVSC	PVSC	Photovoltaic Source Controller	0.0724
Manage 1	PMC	Power Management Controller	0.0440
SS-PVSC	PVSC-TCP	Photovoltaic Source Controller-TCP	0.0338
SS-Invert	Inverter	AC to DC Inverter	0.0260
SS-PDCU	PDCU	Power Distribution Control Unit	0.0260
SS-OMBSU	OMBSU	Outboard Main Bus Switching Unit	0.0260
SS-OMBSU	OMBSU-TCP	Outboard Main Bus Switching Unit-TCP	0.0198
SS-PDCU	PDCU-TCP	Power Distribution Control Unit-TCP	0.0198
SS-Invert	Invt-TCP	AC to DC Inverter-TCP	0.0198
TCS	ACCUM	Thermal Control System Accumulator	0.0151
SS-CDU	DC-RBI1	DC Remote Bus Isolator	0.0113
SS-CDU	DC-RBI2	DC Remote Bus Isolator	0.0113
TCS	Pipeset	Thermal Control System Pipeset	0.0094
TCS	TC Pump1	Thermal Control System Pump	0.0000
TCS	TC Pump2	Thermal Control System Pump	0.0000
Charge 4	AlphaJntCE	Alpha Joint Charge Effect	0.0000

Note: TCP = Thermal Control Plate

TABLE B-9

PMAD PDCA-L3 BASELINE SYSTEM OUTPUT STATES

Plant State	Output State Probability	Output Capability	Days/ Year	Power (MW) Output
1	99.9813%	33.33%	364.93	0.0250
2	0.0187%	0.00%	0.07	0.0000

TABLE B-10

PMAD PDCA-L3 COMPONENT CRITICALITY RANKING

Subsystem	Component	Definition	Ranking Factor
SS-PDCUL3A	PDCUL3A	Power Distribution Control Unit	.0049
SS-PDCUL3B	PDCUL3B	Power Distribution Control Unit	.0049
SS-NSU1A	NSU1A	Node Switching Unit	.0002
SS-NSU1B	NSU1B	Node Switching Unit	.0002
SS-MBSU1	MBSU1	Main Bus Switching Unit	.0002
SS-MBSU2	MBSU2	Main Bus Switching Unit	.0002
SS-PDCUL5A	PDCUL5A	Power Distribution Control Unit	.0002
SS-PDCUL5B	PDCUL5B	Power Distribution Control Unit	.0002
SS-NSU4A	NSU4A	Node Switching Unit	.0002
SS-MBSU4	MBSU4	Main Bus Switching Unit	.0002
SS-PDCU1A	PDCU1A	Power Distribution Control Unit	.0002
SS-PDCU1B	PDCU1B	Power Distribution Control Unit	.0002
SS-PDCU3B	PDCU3B	Power Distribution Control Unit	.0002
SS-PDCUL1B	PDCUL1B	Power Distribution Control Unit	.0002
SS-PDCUL2B	PDCUL2B	Power Distribution Control Unit	.0002
SS-PDCUL4A	PDCUL4A	Power Distribution Control Unit	.0002
SS-PDCUL4B	PDCUL4B	Power Distribution Control Unit	.0002
SS-NSU3A	NSU3A	Node Switching Unit	.0002
SS-NSU3B	NSU3B	Node Switching Unit	.0002
SS-MBSU3	MBSU3	Main Bus Switching Unit	.0002
SS-PDCU3A	PDCU3A	Power Distribution Control Unit	.0002
SS-PDCUL1A	PDCUL1A	Power Distribution Control Unit	.0002
SS-PDCUL2A	PDCUL2A	Power Distribution Control Unit	.0002
SS-XFMR1A	XFMR1A	Node Transformer	.0001
SS-XFMR1B	XFMR1B	Node Transformer	.0001
SS-XFMR4	XFRM4	Node Transformer	.0001
SS-MBSU1	MBSU1-TCP	Main Bus Switching Unit-TCP	.0001
SS-MBSU2	MBSU2-TCP	Main Bus Switching Unit-TCP	.0001
SS-MBSU4	MBSU4-TCP	Main Bus Switching Unit-TCP	.0001
SS-XFMR3	XFMR3	Node Transformer	.0001
SS-MBSU3	MBSU3-TCP	Main Bus Switching Unit	.0001
SS-RADPNL	RADPNL	Radiator Panel Assembly	.0001
TCS	ACCUM	Thermal Control System Accumulator	.0000
TCS	Pipeset	Thermal Control System	.0000
TCS	TC Pump1	Thermal Control System Pump	.0000
TCS	TC Pump2	Thermal Control System Pump	.0000
SS-LOAD	LOAD	Perfectly Available 25 Kw Load	.0000

Note: TCP = Thermal Control Plate

TABLE B-11

INSOLAR COMPONENT DATA CHANGE RESULTS MTTR CHANGE FROM 1,080 TO 6 HRS

	Component	Single Component				Multiple Component			
		A %	EA %	FOR %	EFOR %	A %	EA %	FOR %	EFOR %
	Baseline	99.9217	89.3472	0.0783	10.6528	99.9217	89.3472	0.0783	10.6528
1	ALPHA PDT	99.9416	90.4425	0.0584	9.5575	99.9416	90.4425	0.0584	9.5575
2	BETA PDT	99.9218	90.4300	0.0782	9.5700	99.9416	91.5386	0.0584	8.4614
3	SAElec	99.9217	90.4300	0.0783	9.5700	99.9416	92.6476	0.0584	7.3524
4	SSU	99.9218	90.4300	0.0782	9.5700	99.9416	93.7698	0.0584	6.2302
5	DCSU	99.9218	90.4300	0.0782	9.5700	99.9416	94.9054	0.0584	5.0946
6	TCPs	99.9232	91.6020	0.0768	8.3980	99.9418	97.2982	0.0582	2.7018
7	RPVB & LPVB	99.9218	90.7967	0.0782	9.2033	99.9418	98.8744	0.0582	1.1256
8	A-GmCntrlr	99.9217	89.6813	0.0783	10.3187	99.9418	99.3081	0.0582	0.6919
9	A-GimBrng	99.9217	89.5700	0.0783	10.4300	99.9418	99.6008	0.0582	0.3992
10	Radpnl	99.9246	89.4931	0.0754	10.5069	99.9421	99.7638	0.0579	0.2362
11	PMC	99.9795	89.3989	0.0205	10.6011	99.9999	99.8216	0.0001	0.1784
12	OMBSU	99.9227	89.3777	0.0773	10.6223	99.9999	99.8365	0.0001	0.1635
13	PDCU	99.9227	89.3777	0.0773	10.6223	99.9999	99.8514	0.0001	0.1486
14	INVERTER	99.9217	89.3773	0.0783	10.6227	99.9999	99.8663	0.0001	0.1337
15	B-GmCntrlr	99.9216	89.3690	0.0784	10.6310	99.9999	99.8911	0.0001	0.1089
16	ACCUM	99.9220	89.3649	0.0780	10.6351	99.9999	99.9110	0.0001	0.0890
17	B-GmBrng	99.9217	89.3618	0.0783	10.6382	99.9999	99.9277	0.0001	0.0723
18	Pipeset	99.9219	89.3582	0.0781	10.6418	99.9999	99.9302	0.0001	0.0698
19	A-GimMtrl & 2	99.9217	89.3512	0.0783	10.6488	99.9999	99.9356	0.0001	0.0644
20	PVSC	99.9217	89.3485	0.0783	10.6515	99.9999	99.9366	0.0001	0.0634
21	B-GimMtrl & 2	99.9216	89.3474	0.0784	10.6526	99.9999	99.9368	0.0001	0.0632
22	TCPumpl & 2	99.9217	89.3473	0.0783	10.6527	99.9999	99.9368	0.0001	0.0632

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR: Equivalent Forced Outage Rate

TABLE B-12

ECLIPSE COMPONENT DATA CHANGE RESULTS MTTR CHANGE FROM 1,080 TO 6 HOURS WITHOUT CHARGE EFFECTS

Component	Single Component				Multiple Component			
	A %	EA %	FOR %	EFOR %	A %	EA %	FOR %	EFOR %
Baseline	99.9218	89.5751	0.0782	10.4249	99.9218	89.5751	0.0782	10.4249
1 Battery	99.9218	90.9478	0.0782	9.0522	99.9218	90.9478	0.0782	9.0522
2 Alpha-PDT	99.9416	90.6733	0.0584	9.3267	99.9416	92.0627	0.0584	7.9373
3 DCSU	99.9219	90.6732	0.0781	9.3268	99.9416	93.1914	0.0584	6.8086
4 Fault Isolator	99.9219	90.6732	0.0781	9.3268	99.9416	94.3338	0.0584	5.6662
5 CDU	99.9219	90.6732	0.0781	9.3268	99.9417	95.4903	0.0583	4.5097
6 TCPs	99.9233	93.4101	0.0767	6.5899	99.9418	99.5786	0.0582	0.4214
7 Radpnl	99.9248	89.7218	0.0752	10.2782	99.9421	99.7416	0.0579	0.2584
8 PVSC	99.9219	89.6604	0.0781	10.3396	99.9421	99.7991	0.0579	0.2009
9 PMC	99.9797	89.6270	0.0203	10.3730	99.9999	99.8570	0.0001	0.1430
10 PDCU	99.9228	89.6058	0.0772	10.3942	99.9999	99.8719	0.0001	0.1281
11 OMBSU	99.9228	89.6058	0.0772	10.3942	99.9999	99.8868	0.0001	0.1132
12 Inverter	99.9218	89.6058	0.0782	10.3942	99.9999	99.9017	0.0001	0.0983
13 Accum	99.9222	89.5929	0.0778	10.4071	99.9999	99.9215	0.0001	0.0785
14 DC RBI 1&2	99.9219	89.5884	0.0781	10.4116	99.9999	99.9364	0.0001	0.0636
15 Pipeset	99.9221	89.5862	0.0779	10.4138	99.9999	99.9390	0.0001	0.0610
16 TCPump 1&2	99.9219	89.5752	0.0781	10.4248	99.9999	99.9390	0.0001	0.0610

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-13

ECLIPSE COMPONENT DATA CHANGE RESULTS MTTR CHANGE FROM 1080 TO 6 HRS WITH CHARGE EFFECTS

Component	Single Component				Multiple Component			
	A %	EA %	FOR %	EFOR %	A %	EA %	FOR %	EFOR %
Baseline	99.9210	75.9550	0.0790	24.0450	99.9210	75.9550	0.0790	24.0450
1 Battery	99.9211	78.3040	0.0789	21.6960	99.9211	78.3040	0.0789	21.6960
2 Alpha-PDT	99.9415	76.8862	0.0585	23.1138	99.9415	79.2639	0.0585	20.7361
3 Beta-PDT*	99.9213	76.8848	0.0787	23.1152	99.9416	80.2343	0.0584	19.7657
4 SSU*	99.9213	76.8848	0.0787	23.1152	99.9416	81.2222	0.0584	18.7778
5 DCSU	99.9214	77.8273	0.0786	22.1727	99.9416	83.2232	0.0584	16.7768
6 SAElec*	99.9213	76.8848	0.0787	23.1152	99.9416	84.2465	0.0584	15.7535
7 Fault Isolator	99.9211	77.8285	0.0789	22.1715	99.9416	86.3239	0.0584	13.6761
8 CDU	99.9211	77.8285	0.0789	22.1715	99.9416	88.4543	0.0584	11.5457
9 RPVB & LPVB*	99.9213	77.2018	0.0787	22.7982	99.9416	89.9066	0.0584	10.0934
10 TCPs	99.9230	83.8871	0.0770	16.1129	99.9418	99.2927	0.0582	0.7073
11 Radpnl	99.9242	76.1625	0.0758	23.8375	99.9421	99.5638	0.0579	0.4362
12 PVSC	99.9212	76.1001	0.0788	23.8999	99.9421	99.6792	0.0579	0.3208
13 PMC	99.9789	75.9990	0.0211	24.0010	99.9999	99.7370	0.0001	0.2630
14 OMBSU	99.9220	75.9809	0.0780	24.0191	99.9999	99.7519	0.0001	0.2481
15 PDCU	99.9220	75.9809	0.0780	24.0191	99.9999	99.7668	0.0001	0.2332
16 Inverter	99.9211	75.9809	0.0789	24.0191	99.9999	99.7817	0.0001	0.2183
17 Accum	99.9214	75.9802	0.0786	24.0198	99.9999	99.8145	0.0001	0.1855
18 DC-RBI 1&2	99.9210	75.9779	0.0790	24.0221	99.9999	99.8430	0.0001	0.1570
19 Pipeset	99.9213	75.9706	0.0787	24.0294	99.9999	99.8474	0.0001	0.1526
20 TCPump 1&2	99.9211	75.9550	0.0789	24.0450	99.9999	99.8474	0.0001	0.1526

A : Availability*
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

Note : Charge Effect component that is only in Inslr System and not in Eclipse System.

TABLE B-14

PMAD PDCA-L3 COMPONENT DATA CHANGE RESULTS (MTTR CHANGE FROM 1,080 TO 6 HOURS)

Component	Single Component				Multiple Component			
	A %	EA %	FOR %	EFOR %	A %	EA %	FOR %	EFOR %
Baseline	99.9813	33.3271	0.0187	66.6729	99.9813	33.3271	0.0187	66.6729
1 PDCUs	99.9994	33.3331	0.0006	66.6669	99.9994	33.3331	0.0006	66.6669
2 NSUs	99.9833	33.3278	0.0167	66.6722	99.9997	33.3332	0.0003	66.6668
3 MBSUs	99.9830	33.3277	0.0170	66.6723	99.9997	33.3332	0.0003	66.6668
4 XFMRs	99.9825	33.3275	0.0175	66.6725	99.9997	33.3332	0.0003	66.6668

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-15

VARIATION OF INSOLAR RELIABILITY WITH MTBF SCALE FACTOR

	Scaling All Components		Scaling Spared Scenario Components	
MTBF Scale Factor	EA (%)	A (%)	EA (%)	A (%)
0.7	85.1047	99.8401	86.4993	99.8440
0.8	86.8454	99.8776	87.6737	99.8795
0.9	88.2222	99.9033	88.5956	99.9040
1.0	89.3472	99.9217	89.3472	99.9217
1.1	90.2616	99.9353	89.9498	99.9348
1.2	91.0376	99.9456	90.4616	99.9449
1.3	91.6993	99.9536	90.8964	99.9527
1.4	92.2700	99.9600	91.2704	99.9590
1.5	92.7672	99.9652	91.5953	99.9640
1.6	93.2044	99.9694	91.8804	99.9682
1.7	93.5918	99.9728	92.1325	99.9717
1.8	93.9374	99.9758	92.3570	99.9745
1.9	94.2746	99.9782	92.5582	99.9770
2.0	94.5276	99.9804	92.7396	99.9792
3.0	96.3195	99.9913	93.8943	99.9902
4.0	97.2274	99.9951	94.4756	99.9942
5.0	97.7761	99.9969	94.8256	99.9961

A : Availability
EA: Equivalent Availability

TABLE B-16

INSOLAR COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	Alpha PDT			Beta PDT	
0.70	61320	88.8833	0.70	61320	88.8885
0.80	70080	89.0760	0.80	70080	89.0790
0.90	78840	89.2264	0.90	78840	89.2278
1.00	87600	89.3472	1.00	87600	89.3472
1.10	96360	89.4462	1.10	96360	89.4451
1.20	105120	89.5289	1.20	105120	89.5268
1.30	113880	89.5990	1.30	113880	89.5961
1.40	122640	89.6592	1.40	122640	89.6556
1.50	131400	89.7114	1.50	131400	89.7072
1.60	140160	89.7571	1.60	140160	89.7524
1.70	148920	89.7975	1.70	148920	89.7924
1.80	157680	89.8334	1.80	157680	89.8279
1.90	166440	89.8656	1.90	166440	89.8597
2.00	175200	89.8946	2.00	175200	89.8883
3.00	262800	90.0785	3.00	262800	90.0702
4.00	350400	90.1708	4.00	350400	90.1614
5.00	438000	90.2262	5.00	438000	90.2162
	DSCU			SAElect	
0.70	61320	88.8885	0.70	61320	88.8885
0.80	70080	89.0790	0.80	70080	89.0790
0.90	78840	89.2278	0.90	78840	89.2278
1.00	87600	89.3472	1.00	87600	89.3472
1.10	96360	89.4451	1.10	96360	89.4451
1.20	105120	89.5268	1.20	105120	89.5268
1.30	113880	89.5961	1.30	113880	89.5961
1.40	122640	89.6556	1.40	122640	89.6556
1.50	131400	89.7072	1.50	131400	89.7072
1.60	140160	89.7524	1.60	140160	89.7524
1.70	148920	89.7924	1.70	148920	89.7924
1.80	157680	89.8279	1.80	157680	89.8279
1.90	166440	89.8597	1.90	166440	89.8597
2.00	175200	89.8883	2.00	175200	89.8883
3.00	262800	90.0702	3.00	262800	90.0702
4.00	350400	90.1614	4.00	350400	90.1614
5.00	438000	90.2162	5.00	438000	90.2162

(Continued)

TABLE B-16 (Continued)

INSOLAR COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	PMC			Inverter	
0.70	30660	89.2955	0.70	30660	89.3265
0.80	35040	89.3191	0.80	35040	89.3357
0.90	39420	89.3354	0.90	39420	89.3423
1.00	43800	89.3472	1.00	43800	89.3472
1.10	48180	89.3560	1.10	48180	89.3510
1.20	52560	89.3627	1.20	52560	89.3540
1.30	56940	89.3680	1.30	56940	89.3565
1.40	61320	89.3722	1.40	61320	89.3585
1.50	65700	89.3756	1.50	65700	89.3602
1.60	70080	89.3784	1.60	70080	89.3616
1.70	74460	89.3807	1.70	74460	89.3629
1.80	78840	89.3826	1.80	78840	89.3639
1.90	83220	89.3843	1.90	83220	89.3648
2.00	87600	89.3857	2.00	87600	89.3657
3.00	131400	89.3930	3.00	131400	89.3704
4.00	175200	89.3956	4.00	175200	89.3726
5.00	219000	89.3968	5.00	219000	89.3737
	OMBSU			PDCU	
0.70	61320	89.3265	0.70	91980	89.3265
0.80	70080	89.3357	0.80	105120	89.3357
0.90	78840	89.3423	0.90	118260	89.3423
1.00	87600	89.3472	1.00	131400	89.3472
1.10	96360	89.3510	1.10	144540	89.3510
1.20	105120	89.3540	1.20	157680	89.3540
1.30	113880	89.3565	1.30	170820	89.3565
1.40	122640	89.3585	1.40	183960	89.3585
1.50	131400	89.3602	1.50	197100	89.3602
1.60	140160	89.3616	1.60	210240	89.3616
1.70	148920	89.3629	1.70	223380	89.3629
1.80	157680	89.3639	1.80	236520	89.3639
1.90	166440	89.3648	1.90	249660	89.3648
2.00	175200	89.3657	2.00	262800	89.3657
3.00	262800	89.3704	3.00	394200	89.3704
4.00	350400	89.3726	4.00	525600	89.3726
5.00	438000	89.3737	5.00	657000	89.3737

(Continued)

TABLE B-16 (Continued)

INSOLAR COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	SSU			TCPs	
0.70	61320	88.8885	0.70	91980	88.3876
0.80	70080	89.0790	0.80	105120	88.7865
0.90	78840	89.2278	0.90	118260	89.0977
1.00	87600	89.3472	1.00	131400	89.3472
1.10	96360	89.4451	1.10	144540	89.5517
1.20	105120	89.5268	1.20	157680	89.7223
1.30	113880	89.5961	1.30	170820	89.8669
1.40	122640	89.6556	1.40	183960	89.9910
1.50	131400	89.7072	1.50	197100	90.0986
1.60	140160	89.7524	1.60	210240	90.1928
1.70	148920	89.7924	1.70	223380	90.2761
1.80	157680	89.8279	1.80	236520	90.3500
1.90	166440	89.8597	1.90	249660	90.4163
2.00	175200	89.8883	2.00	262800	90.4760
3.00	262800	90.0702	3.00	394200	90.8544
4.00	350400	90.1614	4.00	525600	91.0441
5.00	438000	90.2162	5.00	657000	91.1580
	A-GimCntrlr			A-GimBrng	
0.70	61320	89.2057	0.70	91980	89.2523
0.80	70080	89.2645	0.80	105120	89.2918
0.90	78840	89.3104	0.90	118260	89.3225
1.00	87600	89.3472	1.00	131400	89.3472
1.10	96360	89.3774	1.10	144540	89.3674
1.20	105120	89.4027	1.20	157680	89.3843
1.30	113880	89.4240	1.30	170820	89.3986
1.40	122640	89.4424	1.40	183960	89.4108
1.50	131400	89.4583	1.50	197100	89.4214
1.60	140160	89.4722	1.60	210240	89.4308
1.70	148920	89.4846	1.70	223380	89.4390
1.80	157680	89.4955	1.80	236520	89.4463
1.90	166440	89.5054	1.90	249660	89.4529
2.00	175200	89.5142	2.00	262800	89.4588
3.00	262800	89.5703	3.00	394200	89.4962
4.00	350400	89.5984	4.00	525600	89.5149
5.00	438000	89.6153	5.00	657000	89.5262

TABLE B-17

VARIATION OF ECLIPSE RELIABILITY WITH MTBF SCALE FACTOR WITHOUT CHARGE EFFECTS

	Scaling All Components		Scaling Spared Scenario Components	
MTBF Scale Factor	EA (%)	A (%)	EA (%)	A (%)
0.7	85.3182	99.8410	86.5302	99.8447
0.8	87.0755	99.8781	87.7886	99.8799
0.9	88.4584	99.9036	88.7773	99.9043
1.0	89.5751	99.9218	89.5751	99.9218
1.1	90.4943	99.9354	90.2310	99.9350
1.2	91.2652	99.9457	90.7809	99.9449
1.3	91.9207	99.9537	91.2483	99.9528
1.4	92.4847	99.9600	91.6504	99.9590
1.5	92.9752	99.9652	91.9999	99.9641
1.6	93.4057	99.9694	92.3066	99.9682
1.7	93.7866	99.9729	92.5779	99.9717
1.8	94.1258	99.9758	92.8195	99.9746
1.9	94.4299	99.9783	93.0361	99.9771
2.0	94.7041	99.9804	93.2314	99.9792
3.0	96.4515	99.9913	94.4753	99.9902
4.0	97.3319	99.9951	95.1020	99.9942
5.0	97.8624	99.9969	95.4795	99.9960

A : Availability
EA: Equivalent Availability

TABLE B-18

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080) WITHOUT CHARGE EFFECTS

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	Alpha PDT			CDU-Fault Isolator	
0.70	61,320	89.1100	0.70	61,320	88.6473
0.80	70,080	89.3032	0.80	70,080	89.0321
0.90	78,840	89.4541	0.90	78,840	89.3332
1.00	87,600	89.5751	1.00	87,600	89.5751
1.10	96,360	89.6744	1.10	96,360	89.7738
1.20	105,120	89.7573	1.20	105,120	89.9399
1.30	113,880	89.8276	1.30	113,880	90.0808
1.40	122,640	89.8879	1.40	122,640	90.2018
1.50	131,400	89.9402	1.50	131,400	90.3068
1.60	140,160	9.9861	1.60	140,160	90.3989
1.70	148,920	90.0266	1.70	148,920	90.4803
1.80	157,680	90.0626	1.80	157,680	90.5527
1.90	166,440	90.0949	1.90	166,440	90.6176
2.00	175,200	90.1239	2.00	175,200	90.6760
3.00	262,800	90.3083	3.00	262,800	91.0476
4.00	350,400	90.4008	4.00	350,400	91.2342
5.00	438,000	90.4564	5.00	438,000	91.3464
	DCSU			PVSC	
0.70	61,320	89.1100	0.70	30,660	89.5101
0.80	70,080	89.3032	0.80	35,040	89.5391
0.90	78,840	89.4541	0.90	39,420	89.5598
1.00	87,600	89.5751	1.00	43,800	89.5751
1.10	96,360	89.6744	1.10	48,180	89.5868
1.20	105,120	89.7573	1.20	52,560	89.5960
1.30	113,880	89.8276	1.30	56,940	89.6033
1.40	122,640	89.8879	1.40	61,320	89.6093
1.50	131,400	89.9402	1.50	65,700	89.6143
1.60	140,160	89.9861	1.60	70,080	89.6185
1.70	148,920	90.0266	1.70	74,460	89.6220
1.80	157,680	90.0626	1.80	78,840	89.6251
1.90	166,440	90.0949	1.90	83,220	89.6277
2.00	175,200	90.1239	2.00	87,600	89.6300
3.00	262,800	90.3083	3.00	131,400	89.6429
4.00	350,400	90.4008	4.00	175,200	89.6484
5.00	438,000	90.4564	5.00	219,000	89.6541

(Continued)

TABLE B-18 (Continued)

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)
WITHOUT CHARGE EFFECTS

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	Inverter			TCPs	
0.70	61,320	89.5544	0.70	91,980	87.9671
0.80	70,080	89.5635	0.80	105,120	88.6339
0.90	78,840	89.5702	0.90	118,260	89.1556
1.00	87,600	89.5751	1.00	131,400	89.5751
1.10	96,360	89.5790	1.10	144,540	89.9197
1.20	105,120	89.5820	1.20	157,680	90.2077
1.30	113,880	89.5845	1.30	170,820	90.4520
1.40	122,640	89.5865	1.40	183,960	90.6620
1.50	131,400	89.5882	1.50	197,100	90.8443
1.60	140,160	89.5896	1.60	210,240	91.0041
1.70	148,920	89.5909	1.70	223,380	91.1453
1.80	157,680	89.5919	1.80	236,520	91.2710
1.90	166,440	89.5928	1.90	249,660	91.3836
2.00	175,200	89.5937	2.00	262,800	91.4851
3.00	262,800	89.5985	3.00	394,200	92.1299
4.00	350,400	89.6006	4.00	525,600	92.4539
5.00	438,000	89.6017	5.00	657,000	92.6487
	OMBSU			PDCU	
0.70	61,320	89.5544	0.70	61,320	89.5544
0.80	70,080	89.5635	0.80	70,080	89.5635
0.90	78,840	89.5702	0.90	78,840	89.5702
1.00	87,600	89.5751	1.00	87,600	89.5751
1.10	96,360	89.5790	1.10	96,360	89.5790
1.20	105,120	89.5820	1.20	105,120	89.5820
1.30	113,880	89.5845	1.30	113,880	89.5845
1.40	122,640	89.5865	1.40	122,640	89.5865
1.50	131,400	89.5882	1.50	131,400	89.5882
1.60	140,160	89.5896	1.60	140,160	89.5896
1.70	148,920	89.5909	1.70	148,920	89.5909
1.80	157,680	89.5919	1.80	157,680	89.5919
1.90	166,440	89.5928	1.90	166,440	89.5928
2.00	175,200	89.5937	2.00	175,200	89.5937
3.00	262,800	89.5985	3.00	262,800	89.5985
4.00	350,400	89.6006	4.00	350,400	89.6006
5.00	438,000	89.6017	5.00	438,000	89.6017

(Continued)

TABLE B-18 (Continued)

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)
WITHOUT CHARGE EFFECTS

Scale Factor	MTBF (Hours)	System EA (%)
	PMC	
0.70	30,660	89.5233
0.80	35,040	89.5469
0.90	39,420	89.5633
1.00	43,800	89.5751
1.10	48,180	89.5839
1.20	52,560	89.5907
1.30	56,940	89.5960
1.40	61,320	89.6002
1.50	65,700	89.6036
1.60	70,080	89.6064
1.70	74,460	89.6087
1.80	78,840	89.6107
1.90	83,220	89.6123
2.00	87,600	89.6137
3.00	131,400	89.6211
4.00	175,200	89.6237
5.00	219,000	89.6249

TABLE B-19

VARIATION OF ECLIPSE RELIABILITY WITH MTBF SCALE FACTOR (With Charge Effects)

	Scaling All Components		Scaling Spared Scenario Components	
MTBF Scale Factor	EA (%)	A (%)	EA (%)	A (%)
0.7	67.3951	99.8363	69.7498	99.8420
0.8	70.8905	99.8757	72.2724	99.8782
0.9	73.6448	99.9022	74.2968	99.9032
1.0	75.9550	99.9210	75.9550	99.9210
1.1	77.8984	99.9348	77.3422	99.9343
1.2	79.5514	99.9453	78.5159	99.9445
1.3	80.9756	99.9535	79.5228	99.9524
1.4	82.2150	99.9599	80.3961	99.9587
1.5	83.3033	99.9651	81.1605	99.9638
1.6	84.2661	99.9693	81.8353	99.9680
1.7	85.1246	99.9728	82.4354	99.9715
1.8	85.8947	99.9758	82.9724	99.9744
1.9	86.5888	99.9782	83.4558	99.9769
2.0	87.2181	99.9803	83.8933	99.9790
3.0	91.3017	99.9912	86.7171	99.9901
4.0	93.4086	99.9951	88.1641	99.9942
5.0	94.6943	99.9968	89.0435	99.9960

A : Availability
EA: Equivalent Availability

TABLE B-20

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080) WITH CHARGE EFFECTS

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	Alpha PDCU			PDCU/Fault Isolator	
0.70	61320	75.5606	0.70	61320	74.3885
0.80	70080	75.7244	0.80	70080	75.0362
0.90	78840	75.8523	0.90	78840	75.5466
1.00	87600	75.9550	1.00	87600	75.9550
1.10	96360	76.0392	1.10	96360	76.2916
1.20	105120	76.1095	1.20	105120	76.5745
1.30	113880	76.1691	1.30	113880	76.8156
1.40	122640	76.2202	1.40	122640	77.0233
1.50	131400	76.2646	1.50	131400	77.2002
1.60	140160	76.3034	1.60	140160	77.3595
1.70	148920	76.3378	1.70	148920	77.4969
1.80	157680	76.3683	1.80	157680	77.6232
1.90	166440	76.3957	1.90	166440	77.7327
2.00	175200	76.4203	2.00	175200	77.8357
3.00	262800	76.5767	3.00	262800	78.4730
4.00	350400	76.6551	4.00	350400	78.7938
5.00	438000	76.7023	5.00	438000	78.9887
	DCSU			PVSC	
0.70	61320	75.1707	0.70	30660	75.8442
0.80	70080	75.4974	0.80	35040	75.8939
0.90	78840	75.7537	0.90	39420	75.9290
1.00	87600	75.9550	1.00	43800	75.9550
1.10	96360	76.1262	1.10	48180	75.9748
1.20	105120	76.2644	1.20	52560	75.9904
1.30	113880	76.3872	1.30	56940	76.0032
1.40	122640	76.4878	1.40	61320	76.0133
1.50	131400	76.5754	1.50	65700	76.0218
1.60	140160	76.6571	1.60	70080	76.0288
1.70	148920	76.7249	1.70	74460	76.0349
1.80	157680	76.7851	1.80	78840	76.0400
1.90	166440	76.8389	1.90	53220	76.0445
2.00	175200	76.8879	2.00	87600	76.0484
3.00	262800	77.2073	3.00	131400	76.0704
4.00	350400	77.3622	4.00	175200	76.0797
5.00	438000	77.4609	5.00	219000	76.0849

(Continued)

TABLE B-20 (Continued)

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080) WITH CHARGE EFFECTS

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	PMC			Beta PDT - INSLR Component in CEs	
0.70	30660	75.9110	0.70	61320	75.5630
0.80	35040	75.9310	0.80	70080	75.7273
0.90	39420	75.9449	0.90	78840	75.8562
1.00	43800	75.9550	1.00	87600	75.9550
1.10	48180	75.9625	1.10	96360	76.0419
1.20	52560	75.9682	1.20	105120	76.1096
1.30	56940	75.9727	1.30	113880	76.1725
1.40	61320	75.9762	1.40	122640	76.2216
1.50	65700	75.9791	1.50	131400	76.2625
1.60	70080	75.9815	1.60	140160	76.3070
1.70	74460	75.9835	1.70	148920	76.3401
1.80	78840	75.9851	1.80	157680	76.3695
1.90	83220	75.9865	1.90	166440	76.3956
2.00	87600	75.9877	2.00	175200	76.4197
3.00	131400	75.9939	3.00	262800	76.5805
4.00	175200	75.9961	4.00	350400	76.6556
5.00	219000	75.9972	5.00	438000	76.7062
	SAElect - INSLR Component in CEs			SSU - INSLR Component in CEs	
0.70	61320	75.5630	0.70	61320	75.5630
0.80	70080	75.7273	0.80	70080	75.7273
0.90	78840	75.8562	0.90	78840	75.8562
1.00	87600	75.9550	1.00	87600	75.9550
1.10	96360	76.0419	1.10	96360	76.0419
1.20	105120	76.1096	1.20	105120	76.1096
1.30	113880	76.1725	1.30	113880	76.1725
1.40	122640	76.2216	1.40	122640	76.2216
1.50	131400	76.2625	1.50	131400	76.2625
1.60	140160	76.3070	1.60	140160	76.3070
1.70	148920	76.3401	1.70	148920	76.3401
1.80	157680	76.3695	1.80	157680	76.3695
1.90	166440	76.3965	1.90	166440	76.3956
2.00	175200	76.4197	2.00	175200	76.4197
3.00	262800	76.5805	3.00	262800	76.5805
4.00	350400	76.6556	4.00	350400	76.6556
5.00	438000	76.7062	5.00	438000	76.7062

(Continued)

TABLE B-20 (Continued)

ECLIPSE COMPONENT MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)

Scale Factor	MTBF (Hours)	System EA (%)	Scale Factor	MTBF (Hours)	System EA (%)
	Inverter			TCPs	
0.70	61320	75.9374	0.70	91980	72.7811
0.80	70080	75.9452	0.80	105120	74.0870
0.90	78840	75.9508	0.90	118260	75.1198
1.00	87600	75.9550	1.00	131400	75.9550
1.10	96360	75.9582	1.10	144540	76.6480
1.20	105120	75.9608	1.20	157680	77.2279
1.30	113880	75.9629	1.30	170820	77.7236
1.40	122640	75.9646	1.40	183960	78.1569
1.50	131400	75.9661	1.50	197100	78.5273
1.60	140160	75.9673	1.60	210240	78.8523
1.70	148920	75.9683	1.70	223380	79.1461
1.80	157680	75.9692	1.80	236520	79.4041
1.90	166440	75.9700	1.90	249660	79.6369
2.00	175200	75.9707	2.00	262800	79.8464
3.00	262800	75.9747	3.00	394200	81.1916
4.00	350400	75.9765	4.00	525600	81.8656
5.00	438000	75.9775	5.00	657000	82.2765
	OMBSU			PDCU	
0.70	61320	75.9374	0.70	61320	75.9374
0.80	70080	75.9452	0.80	70080	75.9452
0.90	78840	75.9508	0.90	78840	75.9508
1.00	87600	75.9550	1.00	87600	75.9550
1.10	96360	75.9582	1.10	96360	75.9582
1.20	105120	75.9608	1.20	105120	75.9608
1.30	113880	75.9629	1.30	113880	75.9629
1.40	122640	75.9646	1.40	122640	75.9646
1.50	131400	75.9661	1.50	131400	75.9661
1.60	140160	75.9673	1.60	140160	75.9673
1.70	148920	75.9683	1.70	148920	75.9683
1.80	157680	75.9692	1.80	157680	75.9692
1.90	166440	75.9700	1.90	166440	75.9700
2.00	175200	75.9707	2.00	175200	75.9707
3.00	262800	75.9747	3.00	262800	75.9747
4.00	350400	75.9765	4.00	350400	75.9765
5.00	438000	75.9775	5.00	438000	75.9775

TABLE B-21

VARIATION OF PMAD PDCA-L3 RELIABILITY WITH MTBF SCALE FACTOR

	Scaling All Components		Scaling Spared Scenario Components	
MTBF Scale Factor	EA (%)	A (%)	EA (%)	A (%)
0.7	33.3186	99.9558	33.3209	99.9627
0.8	33.3228	99.9683	33.3238	99.9713
0.9	33.3254	99.9761	33.3257	99.9771
1.0	33.3271	99.9813	33.3271	99.9813
1.1	33.3283	99.9850	33.3281	99.9844
1.2	33.3292	99.9877	33.3289	99.9867
1.3	33.3299	99.9897	33.3295	99.9886
1.4	33.3304	99.9912	33.3300	99.9900
1.5	33.3308	99.9924	33.3304	99.9912
1.6	33.3311	99.9934	33.3307	99.9921
1.7	33.3314	99.9942	33.3310	99.9930
1.8	33.3316	99.9949	33.3312	99.9936
1.9	33.3318	99.9954	33.3314	99.9942
2.0	33.3320	99.9959	33.3316	99.9947
3.0	33.3327	99.9982	33.3324	99.9972
4.0	33.3330	99.9989	33.3327	99.9981
5.0	33.3331	99.9993	33.3328	99.9985

A : Availability
EA: Equivalent Availability

TABLE B-22

PMAD PDCU MTBF SENSITIVITY ANALYSIS (MTTR = 1,080)

Scale Factor	MTBF (Hours)	System EA (%)	Power
PMC			
0.70	61320	33.3209	24.990675
0.80	70080	33.3238	24.99285
0.90	78840	33.3257	24.994275
1.00	87600	33.3271	24.995325
1.10	96360	33.3281	24.996075
1.20	105120	33.3289	24.996675
1.30	113880	33.3295	24.997125
1.40	122640	33.3300	24.9975
1.50	131400	33.3304	24.9978
1.60	140160	33.3307	24.998025
1.70	148920	33.3310	24.99825
1.80	157680	33.3312	24.9984
1.90	166440	33.3314	24.99855
2.00	175200	33.3316	24.9987
3.00	262800	33.3324	24.9993
4.00	350400	33.3327	24.999525
5.00	438000	33.3328	24.9996

TABLE B-23

INSOLAR SYSTEM DESIGN AND OPERATIONAL COMPARISON

System Variation	A (%)	EA (%)	FOR (%)	EFOR (%)
Baseline: MTTR=1080	99.9217	89.3472	0.0783	10.6528
Baseline: MTTR=6	99.9998	99.7735	0.0002	0.2265
Sparing Scenario	99.9998	96.2047	0.0002	3.7953
Baseline with All Component MTBFs Doubled	99.9804	94.5276	0.0196	5.4724
Sparing Scenario with All Component MTBFs Doubled	99.9999	98.0785	0.0001	1.9215
Baseline with Sparing Scenario Component MTBFs Doubled	99.9792	92.7396	0.0208	7.2604

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-24

ECLIPSE SYSTEM DESIGN AND OPERATIONAL COMPARISON WITHOUT CHARGE EFFECTS

System Variation	A (%)	EA (%)	FOR (%)	EFOR (%)
Baseline: MTTR=1080	99.9218	89.5751	0.0782	10.4249
Baseline: MTTR=6	99.9999	99.9390	0.0001	0.0610
Sparing Scenario	99.9998	96.9585	0.0002	3.0415
Baseline with All Component MTBFs Doubled	99.9804	94.7041	0.0196	5.2959
Sparing Scenario with All Component MTBFs Doubled	99.9999	98.4926	0.0001	1.5074
Baseline with Sparing Scenario Component MTBFs Doubled	99.9792	93.2314	0.0208	6.7686

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-25

ECLIPSE SYSTEM DESIGN AND OPERATIONAL COMPARISON WITH CHARGE EFFECTS

System Variation	A (%)	EA (%)	FOR (%)	EFOR (%)
Baseline: MTTR=1080	99.9210	75.9550	0.0790	24.0450
Baseline: MTTR=6	99.9999	99.8474	0.0001	0.1526
Sparing Scenario	99.9998	92.5490	0.0002	7.4510
Baseline with All Component MTBFs Doubled	99.9803	87.2181	0.0197	12.7819
Sparing Scenario with All Component MTBFs Doubled	99.9999	96.2409	0.0001	3.7591
Baseline with Sparing Scenario Component MTBFs Doubled	99.9790	83.8933	0.0210	16.1067

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-26

PMAD PDCA-L3 SYSTEM DESIGN AND OPERATIONAL COMPARISON

System Variation	A (%)	EA (%)	FOR (%)	EFOR (%)
Baseline: MTTR=1080	99.9813	33.3271	0.0187	66.6729
Baseline: MTTR=6	99.9999	33.3333	0.0001	66.6667
Sparing Scenario	99.9994	33.3331	0.0006	66.6669
Baseline with All Component MTBFs Doubled	99.9959	33.3320	0.0041	66.6680
Sparing Scenario with All Component MTBFs Doubled	99.9998	33.3333	0.0002	66.6667
Baseline with Sparing Scenario Component MTBFs Doubled	99.9947	33.3316	0.0053	66.6684

A : Availability
EA : Equivalent Availability
FOR : Forced Outage Rate
EFOR : Equivalent Forced Outage Rate

TABLE B-27

PMAD MODEL CONFIGURATION COMPARISON

Model Configuration	MTTR=1080		MTTR=6	
	EA (%)	A (%)	EA (%)	A (%)
Ring (PDCA-L3)	33.3271	99.9813	33.3333	99.9999
Radial	33.3281	99.9842	33.3333	99.9999
Outside PDCU	32.6324	97.8973	33.3295	99.9886

EA : Equivalent Availability
A : Availability

TABLE B-28

EPS INSOLAR PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-1.3

MTTR = 1080

Output State	Output State Capability (%)	State Probability	Output Power Level (kw)
1	33.33	0.997308	24.9975
2	31.83	0.000550	23.8725
3	25.00	0.001061	18.7500
4	24.69	0.000036	18.5175
5	24.38	0.000001	18.2850
6	12.50	0.000073	9.3750
7	12.19	0.000001	9.1425
8	0.00	0.000970	0.0000

Equivalent Availability - 33.29%
Average Power Output Capability = 24.9646 kw

MTTR = 6

1	33.33	0.999995	24.9975
2	31.83	0.000000	23.8725
3	25.00	0.000003	18.7500
4	24.69	0.000000	18.5175
5	24.38	0.000000	18.2850
6	12.50	0.000000	9.3750
7	12.19	0.000000	9.1425
8	0.00	0.000003	0.0000

Equivalent Availability - 33.33%
Average Power Output Capability = 24.9974 kw

Sparing Eight Critical ORUs

1	33.33	0.999911	24.9975
2	31.83	0.000060	23.8725
3	25.00	0.000017	18.7500
4	24.69	0.000001	18.5175
5	24.38	0.000000	18.2850
6	12.50	0.000001	9.3750
7	12.19	0.000000	9.1425
8	0.00	0.000008	0.0000

Equivalent Availability = 33.33%
Average Power Output Capability = 24.9971 kw

TABLE B-29

EPS ECLIPSE PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-L3 WITHOUT CHARGE EFFECTS

MTTR-1080

Output State	Output State Capability (%)	State Probability	Output Power Level (kw)
1	33.33	0.998222	24.9975
2	30.00	0.000524	22.5000
3	25.00	0.000209	18.7500
4	20.00	0.000061	15.0000
5	15.00	0.000012	11.2500
6	10.00	0.000004	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000969	0.0000

Equivalent Availability = 33.29%

Average Power Output Capability = 24.9698 kw

MTTR-6

1	33.33	0.999998	24.9975
2	30.00	0.000000	22.5000
3	25.00	0.000000	18.7500
4	20.00	0.000000	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000001	0.0000

Equivalent Availability = 33.33%

Average Power Output Capability = 24.9975 kw

Sparing Eight Critical ORUs

1	33.33	0.999973	24.9975
2	30.00	0.000008	22.5000
3	25.00	0.000009	18.7500
4	20.00	0.000001	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000008	0.0000

Equivalent Availability = 33.33%

Average Power Output Capability 24.9972 kw

TABLE B-30

EPS ECLIPSE PERIOD STATE PROBABILITIES OF POWER OUTPUT FROM PDCA-L3 WITH CHARGE EFFECTS

MTTR= 1080

Output State	Output State Capability (%)	State Probability	Output Power Level (kw)
1	33.33	0.991804	24.9975
2	30.00	0.003766	22.5000
3	25.00	0.002011	18.7500
4	20.00	0.000945	15.0000
5	15.00	0.000337	11.2500
6	10.00	0.000133	7.5000
7	5.00	0.000027	3.7500
8	0.00	0.000977	0.0000

Equivalent Availability = 33.25%
Average Power Output Capability = 24.9341 kw

MTTR- 6

1	33.33	0.999996	24.9975
2	30.00	0.000000	22.5000
3	25.00	0.000003	18.7500
4	20.00	0.000000	15.0000
5	15.00	0.000000	11.2500
6	10.00	0.000000	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000003	0.0000

Equivalent Availability - 33.33 %
Average Power Output Capability = 24.9975 kw

Sparing Eight Critical ORUs

1	33.33	0.999894	24.9975
2	30.00	0.000050	22.5000
3	25.00	0.000035	18.7500
4	20.00	0.000009	15.0000
5	15.00	0.000002	11.2500
6	10.00	0.000001	7.5000
7	5.00	0.000000	3.7500
8	0.00	0.000008	0.0000

Equivalent Availability - 33.33%
Average Power Output Capability = 24.9968 kw

TABLE B-31

BASELINE SPACE STATION EPS EXPECTED AVERAGE ANNUAL ORU FAILURE RATE

ORU	Quantity	Average Annual ORU Failure Rate
*SAElec	8	0.8000
*SSU	8	0.8000
*Beta PDT	8	0.8000
B-GimBrng	8	0.5333
G-GimCntrlr	8	0.8000
B-GimMtr 1&2	16	1.6000
*DCSU	8	0.8000
Inverter	8	0.8000
PVSC	8	1.6000
Pipeset	12	0.4000
Accum	12	0.8000
TCPump1&2	24	0.7500
OMBSU	4	0.4000
*Alpha-PDT	2	0.2000
A-GimBrng	2	0.1333
A-GmCntrlr	2	0.2000
A-GimMtr 1&2	4	0.4000
*PDCU-		
Outboard A-Jnt	4	0.4000
PMAD Inside	28	2.8000
PMAD Outside	4	0.4000
*PMC	2	0.4000
XFMR	8	0.5333
NSU	10	1.0000
MBSU	4	0.4000
Fault Isolator	20	2.0000
CDU	20	2.0000
DC-RBI 1&2	40	4.0000
Subtotal	282	25.7499
*TCPs	136	9.0667
TOTAL	418	34.8166

Failure Rate When Only Critical ORU MTBFs are Doubled is 16.0833

*Critical ORU

APPENDIX C

REFERENCES

REFERENCES

1. User's Guide for the UNIRAM Availability Assessment Methodology: Version 2.0. ARINC Research Corporation, April 1988.
2. MIL-HDBK-217E, Reliability Prediction of Electronic Equipment. October 27, 1986.
3. Space Station Power System Description Document. Preliminary Report, NASA Lewis Research Center, July 16, 1987.
4. Guide for the Assessment of the Reliability of Gasification - Combined Cycle Power Plants. Interim Report, ARINC Research Corporation, November 1980.

APPENDIX D

DEFINITIONS OF TERMS AND CONCEPTS USED IN THIS REPORT

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APPENDIX D

DEFINITIONS OF TERMS AND CONCEPTS USED IN THIS REPORT

Availability (A) - The percentage of time that a system is capable of producing power (Ref. 1).

Equivalent Availability (EA) - The percentage of the gross maximum energy production of the system is available during a given period (Ref. 1). Figure D-1 provides a visual representation of equivalent availability. Figure D-1a is a graph of the power output states listed in Table D-1. The area under the curve in Figure D-1a represents the amount of energy produced by the system. Figure D-1b is an equivalent representation of the energy in Figure D-1a. Both boxes in Figure D-1b represent the equivalent availability of the system, which is 67.5 percent. Box 1 shows 100-percent power generated for 67.5 percent of the period. Box 2 shows 67.5-percent power generated for 100 percent of the period. The key is that in either case, 67.5 percent of the gross maximum energy production is available during the period.

Equivalent Forced Outage Rate (EFOR) - the percentage of the gross maximum energy production of the system that is desired within a certain period but is unavailable (Ref. 1). Since the Space Station EPS is modeled with zero reserve shutdown hours (Section 1.2.9) and zero scheduled outage hours (Section 1.2.10), EFOR = 1 - EA.

Failure Rate (λ) - The average number of failures that occur per unit of time in a specified time interval (Ref. 2).

Forced Outage Hours (FOH) - The number of hours for which the system is unavailable as a result of full (100 percent) forced outages.

Forced Outage Rate (FOR) - The percentage of time service in a system is desired but is unavailable as a result of full (100 percent) forced outages (Ref. 1).

Maintainability (M) - The probability that a failed system is restored to operable condition in a specified amount of downtime (Ref. 3).

Mean Time Between Failures (MTBF) - The average time that a component operates before it fails.

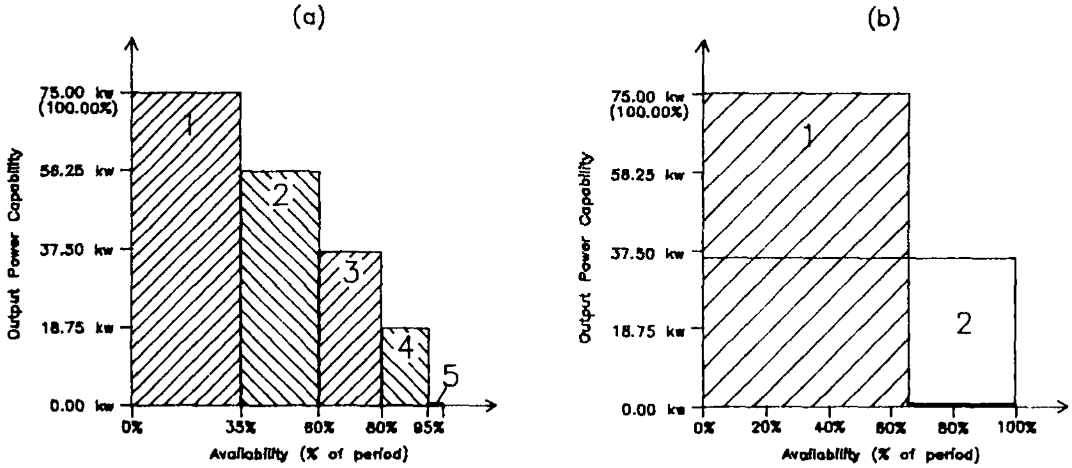

FIGURE D-1

ILLUSTRATION OF EQUIVALENT AVAILABILITY

TABLE D-1

SAMPLE SYSTEM POWER OUTPUT STATES

Output State	State Output Capability %	State Probability	State Output Power Level kW
1	100.00	0.3500	75.00
2	75.00	0.2500	56.25
3	50.00	0.2000	37.50
4	25.00	0.1500	18.75
5	0.00	0.0500	0.00

Mean Time To Restore (MTTR) - The average amount of time that a component will be in a system in a failed state.

Reliability (R) - The probability that a system used under stated conditions will perform satisfactorily for at least a given period (Ref. 3).

Reserve Shutdown Hours (RSH) - The number of hours that a system is available but is not generating power because of economic or other reasons. For example when power is not needed, the system is not operated.

Scheduled Outage Hours (SOH) - The number of hours that a system is unavailable as a result of planned outages or scheduled maintenance outages. Both a scheduled maintenance outage and a planned outage are periods during which a system is shut down. Maintenance is performed during a scheduled maintenance outage but it is not performed during a planned outage.

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Report Documentation Page

1. Report No.
NASA CR-182198

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Space Station Electrical Power System Availability Study

5. Report Date
November 1988

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
5149-11-01-4744

10. Work Unit No.
483-32-12
483-31-02

9. Performing Organization Name and Address
ARINC Research Corporation
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Annapolis, Maryland 21401

11. Contract or Grant No
C-31003-J

13 Type of Report and Period Covered
Contractor Report
Final

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135-3191

14 Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract

ARINC Research Corporation performed a preliminary reliability, availability, and maintanability (RAM) analysis of the NASA Space Station Electric Power System (EPS). The analysis was performed using the ARINC Research-developed UNIRAM RAM assessment methodology and software program. The analysis was performed in two phases: EPS modeling and EPS RAM assessment. The EPS was modeled in four parts: the insolar power generation system, the eclipse power generation system, the power management and distribution system, (both ring and radial power distribution control unit [PDCU] architectures), and the power distribution to the inner keel PDCU's. The EPS RAM assessment was conducted in five steps: (1) the use of UNIRAM to perform baseline EPS model analyses and to determine orbital replacement unit (ORU) criticialities; (2) the determination of EPS sensitivity to on-orbit spared of ORU's and the provision of an indication of which ORU's may need to be spared on-orbit; (3) the determination of EPS sensititivity to changes in ORU reliability; (4) the determination of the expected annual number of ORU failures; and (5) the integration of the power generation system model results with the distribution system model results to assess the full EPS. Conclusions were drawn and recommendations were made.

17. Key Words (Suggested by Author(s))
Availability; Space station; Electrical power systems; Reliability; Maintainability

18 Distribution Statement
Unclassified – Unlimited
Subject Category 18

19. Security Classif. (of this report)
Unclassified

20 Security Classif. (of this page)
Unclassified

21 No of pages
181

22. Price*
A09

NASA FORM 1626 OCT 86

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