NASA CR-179587

Space Station WP-04 Power System Final Study Report DR-15

Volume 1 Executive Summary

G.J. Hallinan
Rockwell International
Rocketdyne Division

January 19, 1987

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Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract NAS3-24666

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RI/RD86-306

SPACE STATION WP-04
POWER SYSTEM

CONTRACT NUMBER NAS 3-24666

FINAL STUDY REPORT
DR-15
VOLUME 1 OF 2-EXECUTIVE SUMMARY

19 JANUARY 1987

Rocketdyne Division
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Canoga Park, California 91304

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NASA LEWIS RESEARCH CENTER

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ENGINEERING AND INTEGRATION

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TYPE 2

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FOREWORD

During the 21-month Phase B Space Station Electric Power System study contract, Rocketdyne submitted some 56 data requirement documents in addition to regular monthly status reports. This complete set of documentation comprises the Rocketdyne-generated knowledge base for the Electric Power System.

The intent of this final report is to summarize the major study activities and results, and to provide the reader with an overview of Rocketdyne's Phase B study contract. Although the final report contains a significant amount of data to support the study conclusions, it is suggested that the reader refer to the DR in which an analysis or study was initially reported, for complete details and documentation. A complete list and schedule of all contract data requirement submittals is provided in Section 1.0, Figure 1-2.

1.0 INTRODUCTION

This is Volume I: Executive Summary of the two volume Final Study Report for contract number NAS 3-24666, Definition and Preliminary Design of Electric Power System for the Space Station and platforms (WP-04). Period of performance for the contract was from 19 April 1985 through 19 January 1987.

The contract was performed by Rocketdyne with contributions from the following team members:

- Ford - batteries and PV system
- Garrett - CBC receiver/power conversion unit
- General Dynamics - 20 kHz converters
- Harris - SD concentrator
- Sundstrand - ORC receiver/power conversion unit

In addition LTV Corporation provided thermal heat rejection designs and Lockheed provided PV array information.

The study reported upon herein reflects the program requirements for the Space Station and platforms as they existed prior to the recommendations of the Critical Evaluation Task Force (CETF); i.e. 75 kw station with 25 kw PV and 50 kw SD. Per NASA-LeRC direction the post-CETF change to an 87.5 kw station with 37.5 kw PV was reflected in the final DR-09 cost submittal but was not incorporated into the Phase B preliminary design.

This volume contains a summary of activities and significant achievements of the study effort (Section 1.0), a summary of results (Sections 2.0), a summary of trade studies (Section 3.0), and a summary of costing activities (Section 4.0).

Volume II summarizes the study results in additional detail and includes backup information and supporting data. Volume II follows the format and order of the contract SOW and includes sections covering systems analysis and trades (Section 2.0) preliminary design (Section 3.0), advanced development (Section 4.0), customer accommodations (Section 5.0), operations planning (Section 6.0), product assurance (Section 7.0), and design and development phase planning (Section 8.0).

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1.1 STUDY ACTIVITIES

The activities associated with Rocketdyne's Phase B Study Contract were performed in accordance with the objectives outlined in the contract SOW. All technical and schedule milestones were met. Figure 1-1 is an overview of the complete Phase B program showing the period of performance for each activity and the dates of key milestones and DR submittals.

Following is a brief overview of Rocketdyne's Phase B study activities:

- System Engineering and Integration - defined and conducted all SE&I activities including analysis of missions, systems, and operations requirements; conceptual system design and analysis; design- to-cost activities; system analysis and trade studies; information system analysis; man-tended option studies; automation and robotics planning; and evolutionary growth studies.

- Preliminary Design Tasks - performed the preliminary design of the baselined hybrid electric power system (EPS) including analysis of interfaces; subsystem optimization; definition of test and verification requirements; and preparation of preliminary drawings, descriptions, data sheets, ICD's, and CEI specifications at the EPS assembly level.

- Advanced Development - identified technological issues and appropriate advanced development activities; prepared an advanced development plan (DR-05) for work to be performed under the scope of the Phase B contract; implemented the advanced development plan with the completion of activities applicable to the CBC and ORC solar dynamic heat receivers. The concentrator reflective surface, and concentrator deployment/latchup mechanism; performed and reported complimentary IR&D activities related to the Phase B study effort.

- Customer Accommodations - identified customer accommodation features of the EPS and reported results in DR's as required.

V1-10/2

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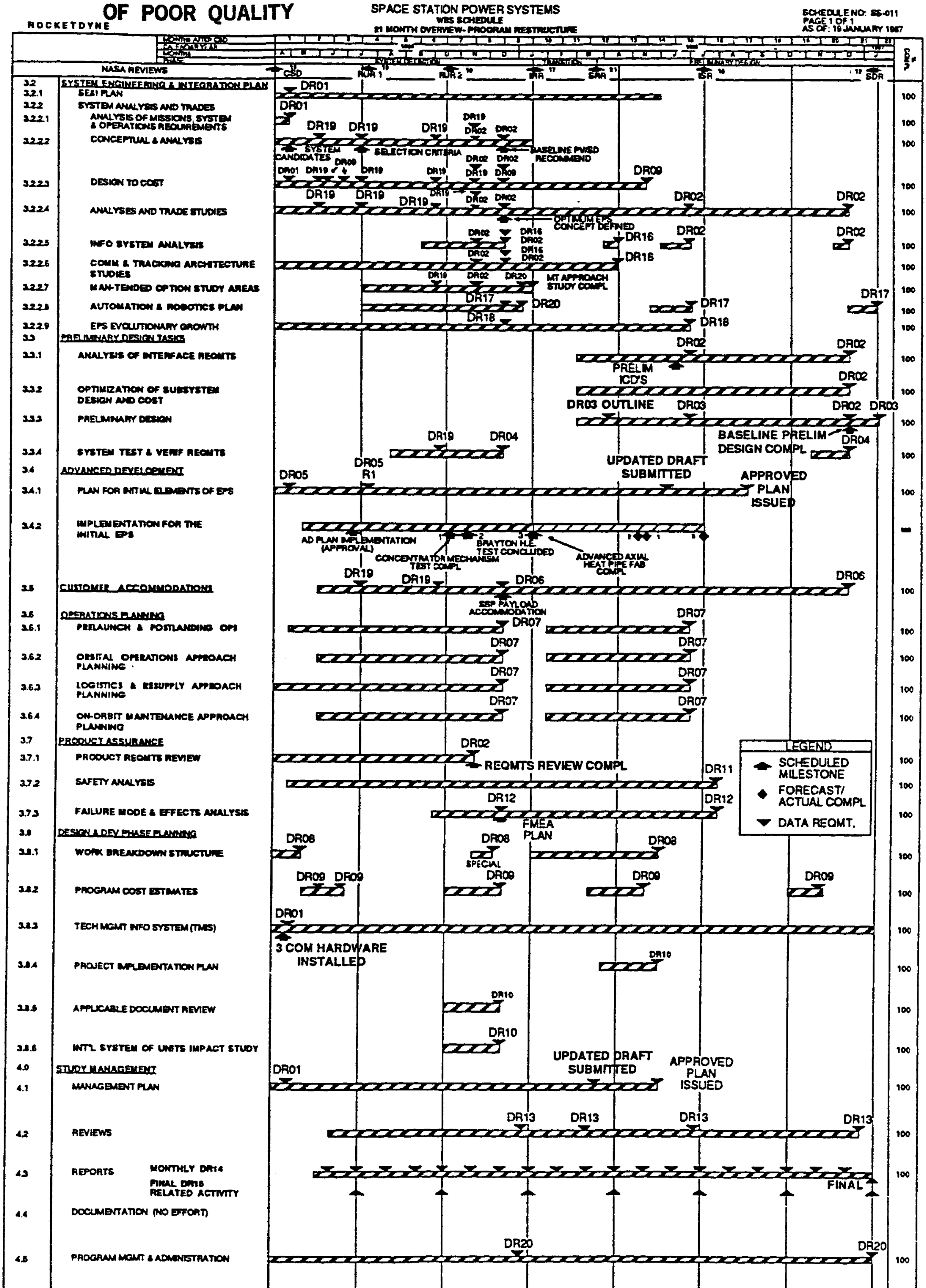

Figure 1-1 Program Overview

- o Operations Planning - performed operations studies for the EPS in the areas of pre-launch and post-landing operations, orbital operations, logistics and resupply, and on-orbit maintenance.

- o Product Assurance - performed product assurance evaluations for the EPS in the areas of safety, reliability, maintainability, and quality; prepared a preliminary safety analysis and preliminary failure mode and effects analysis for the EPS.

- o Design and Development Phase Planning - performed design and development phase planning including work breakdown structure, program cost estimates, project implementation plan (risk assessment), applicable document review, and international system of units (SI) impact study.

1.2 SIGNIFICANT ACHIEVEMENTS

Along with the successful completion of Rocketdyne's Phase B Study Contract and accomplishment of all contract objectives there were several significant achievements which merit special attention and are highlighted in the following paragraphs.

- o Conceptual Design and Reference Configuration Selection - The Phase B conceptual design effort was a major undertaking which included the definition of multiple station and platform electric power system concepts, the performance of numerous trade studies and analyses, and the incorporation of significant hardware test results. This effort led to the selection of the recommended hybrid configuration. This effort culminated in the recommendation of:

  - A hybrid station EPS with a savings of approximately $3 billion in life cycle cost compared to an all PV station,
  - Batteries for station energy storage with slightly lower costs than regenerative fuel cells and featuring commonality with the platform, and

V1-10/3

- Either ORC or CBC-based SD power, with a choice between these two technically feasible options being delayed while development activities continue.

o Preliminary Design - A comprehensive preliminary design effort was completed for the baselined hybrid EPS. This effort was accomplished at the assembly level and included the preparation of preliminary drawings, descriptions, data sheets, ICDs, CEI specifications, and test and verification requirements.

o Trade Studies - In order to provide backup data and support for the conceptual and preliminary design efforts, Rocketdyne identified and performed some 103 trade studies at the system and subsystem levels. These trade are summarized in Section 3.0 and divided into categories as follows:

System	24
PV Subsystem	17
SD Subsystem	45
PMAD Subsystem	17
Total	103

o Design to Cost - Rocketdyne's active design-to-cost effort during the Phase B Study Contract resulted in excellent consistency of WP-04 cost estimates during the EPS preliminary design. As shown below, the December 1985 cost estimate (beginning of preliminary design) and the November 1986 cost estimate (end of preliminary design), adjusted for program changes, agreed within $25 million (~2%).

	87 $ IN MILLIONS NO PRIME FEE	
DEC 85 DR-09 HYBRID CONFIGURATION		1,115
37 1/2 kw PV, 37 1/2 kw SD 400 hz		
WITH PROGRAM CHANGES		
20 khz distribution vs 400 hz Power level increase (75 to 87 1/2 kw) FSE from "OR" to "C/D" FEL delay from 4-92 to 1-93	105	1,220

V1-10/4

NOV 86 DR-09 ESTIMATE	1,195
37 1/2 kw PV, 50 kw SD 20 khz	
DIFFERENCE IN ESTIMATES	-25

- o Data Requirement Submittals - During the Phase B Study Contract Rocketdyne maintained a perfect record of on-schedule data requirement submittals. In addition to monthly status reports (DR-14), a total of 55 DRs were submitted to NASA-LeRC, plus an unscheduled man-tended approach report. Figure 1-2 illustrates the Rocketdyne data requirement submittal schedule.

- o Advanced Development - The following advanced development activities were performed by Rocketdyne team members during the Phase B Study Contract, leading to increased understanding and resolution of several SD technology issues. These activities were performed in accordance with our Advanced Development Plan (DR-05).

<u>Garrett</u>

- Characterization of $LiF-MgF_2$ and $LiF-CaF_2$ eutectic phase change materials
- High temperature vacuum sublimination tests of candidate receiver materials
- Thermal cycling of a LiF - filled thermal energy storage device

<u>Sundstrand</u>

- Generation of a specification for an axial heat pipe compatible with thermal energy storage and the organic working fluid requirements
- Design and analysis to meet these requirements
- Fabrication and assembly of the heat pipe

<u>Harris</u>

- Characterization of the kinematics of the concentrator concept
- Evaluation of substrates, reflective coatings, and protective coatings for possible use on the concentrator

V1-10/5

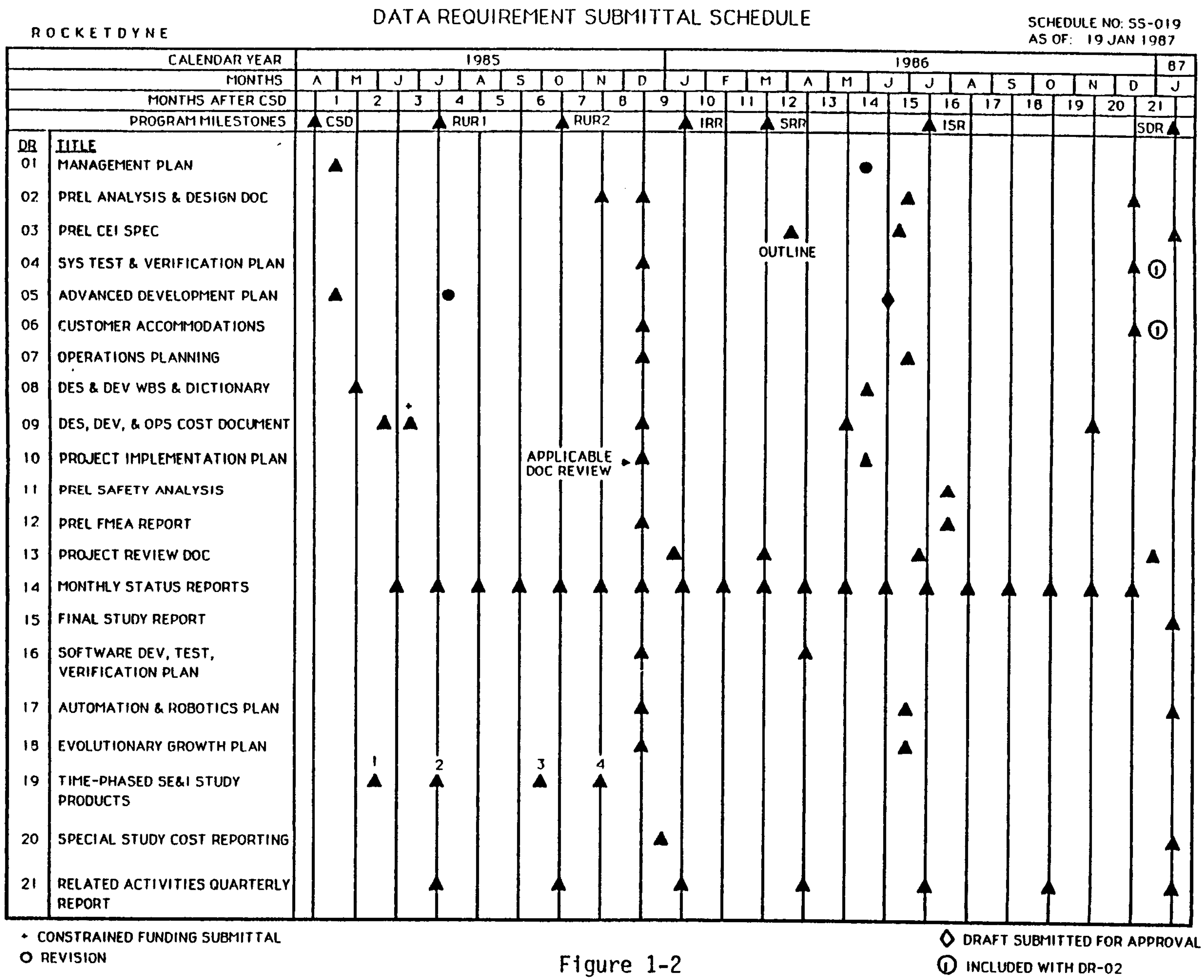
ROCKETDYNE
DATA REQUIREMENT SUBMITTAL SCHEDULE
SCHEDULE NO: SS-019
AS OF: 19 JAN 1987
CALENDAR YEAR
1985
1986
87
MONTHS
A M J J A S O N D J F M A M J J A S O N D J
MONTHS AFTER CSD
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21
PROGRAM MILESTONES
CSD
RUR1
RUR2
IRR
SRR
ISR
SDR
DR
TITLE
01 MANAGEMENT PLAN
02 PREL ANALYSIS & DESIGN DOC
03 PREL CEI SPEC
04 SYS TEST & VERIFICATION PLAN
05 ADVANCED DEVELOPMENT PLAN
06 CUSTOMER ACCOMMODATIONS
07 OPERATIONS PLANNING
08 DES & DEV WBS & DICTIONARY
09 DES, DEV, & OPS COST DOCUMENT
10 PROJECT IMPLEMENTATION PLAN
11 PREL SAFETY ANALYSIS
12 PREL FMEA REPORT
13 PROJECT REVIEW DOC
14 MONTHLY STATUS REPORTS
15 FINAL STUDY REPORT
16 SOFTWARE DEV, TEST, VERIFICATION PLAN
17 AUTOMATION & ROBOTICS PLAN
18 EVOLUTIONARY GROWTH PLAN
19 TIME-PHASED SE&I STUDY PRODUCTS
20 SPECIAL STUDY COST REPORTING
21 RELATED ACTIVITIES QUARTERLY REPORT
OUTLINE
APPLICABLE DOC REVIEW
1
2
3
4
* CONSTRAINED FUNDING SUBMITTAL
O REVISION
◇ DRAFT SUBMITTED FOR APPROVAL
(I) INCLUDED WITH DR-02

Figure 1-2

Complementary independent research and development (IR&D) activities in the SD, PMAD and PV areas were performed outside the scope of the Phase B study contract. These were reported quarterly in the related activity report.

All team members performed IR&D effort that complimented the Phase B activity. The areas addressed were as follows:

Ford

- Kapton substitute studies
- Solar array evaluations
- DC PMAD component studies
- NiH_2 batteries
- NaS batteries

Garrett

- CBC Receiver/Thermal Storage Design Fabrication and Test

General Dynamics

- AC PMAD component evaluations

Harris

- Concentrator Studies

Sundstrand

- ORC receiver/storage thermal storage test
- ORC fluid evaluation
- ORC two phase fluid management
- AC PMAD studies

Rocketdyne

- ORC and CBC thermal storage media studies
- Liquid metal cooled receiver/thermal storage system for CBC and ORC
- Thermal control modeling
- Dynamic modeling of SD subsystem
- PMAD architecture studies
- Health monitoring
- Higher order language evaluation
- PMAD test bed implementation

2.0 SUMMARY OF RESULTS

The following sections describe the Phase B results for preliminary design, man-tended option, automation and robotics, evolutionary growth, software development environment, advanced development, customer accommodations, operations planning, product assurance and design and development phase planning.

2.1 ELECTRIC POWER SYSTEM (EPS) PRELIMINARY DESIGN

The Electric Power System (EPS) for the Space Station program consists of a combination photovoltaic (PV) and solar dynamic (SD) power generation subsystem and a power management and distribution (PMAD) subsystem.

The solar power generation module concept for the EPS consists of two 12.5 kWe rated PV modules and two solar dynamic power modules. Each PV module consists of two solar arrays. Table 2.1-1 summarizes how the solar dynamic modules combine with the photovoltaic modules to provide IOC and growth station power requirements of 75 and 300 kWe net, respectively.

Table 2.1-1
SUMMARY OF SOLAR DYNAMIC/PV POWER MODULE CAPABILITIES

	IOC	GROWTH
SD nominal module design power (kWe)	25	25
SD minimum power/module (kWe)	26	26
SD maximum power/module (kWe)	30	30
Number of SD modules	2	12
SD minumum power (kWe)	52	312
PV minimum power (kWe)	23.5	23.5
Station minimum power (kWe)	75.5	335.5
SD maximum power (kWe)	60.0	360.0
PV maximum power (kWe)	42.5	42.5
Station maximum power (kWe)	102.5	402.5

The PMAD subsystem (Figure 2.1-1) consists of that hardware and software necessary to control power generation from all sources and distribute it to the variable load centers throughout the Space Station structure and manned modules (Figure 2.1-2).

The preliminary EPS design meets all system requirements and power module requirements. The following are key requirements for the Space Station EPS.

a) The Space Station EPS shall be a PV-SD hybrid system consisting of two PV power generation modules, two SD power generation modules and the PMAD subsystem.

b) The PV power modules shall be located on each side of the main keels, inboard of the solar dynamic module.

c) The PV power modules shall utilize solar array wings and batteries that are common to those used on the platform EPS.

d) The two PV power modules shall provide nominally a total of 25 kW net to the load converter inputs.

e) the SD power modules shall provide nominally a total of 50 kW net to the load converter inputs.

f) The total system power delivered to the loads by the PV and SD modules shall be 75 kW at completion of IOC.

The gimbal joints provide single-axis pointing for the station and platform PV solar arrays and SD modules to maximize solar insolation interception. They also feather the arrays and modules when required, to minimize drag resistance, and position the arrays and modules for maintenance.

Each PV solar array or SD module requires one beta joint. A total of four PV beta joints and two SD module beta joints are required for the IOC station. when the SD growth is complete there will be twelve SD beta joints total. The platform has two alpha joints, one for each PV solar array.

Preliminary designs for the station beta joints and platform alpha joints were completed. The station beta joint design for the PV array and SD modules are identical, with the exception of software instructions, which are unique to each application. The platform alpha joint contains many of the same components as the station beta joint. The station beta/platform alpha joint is

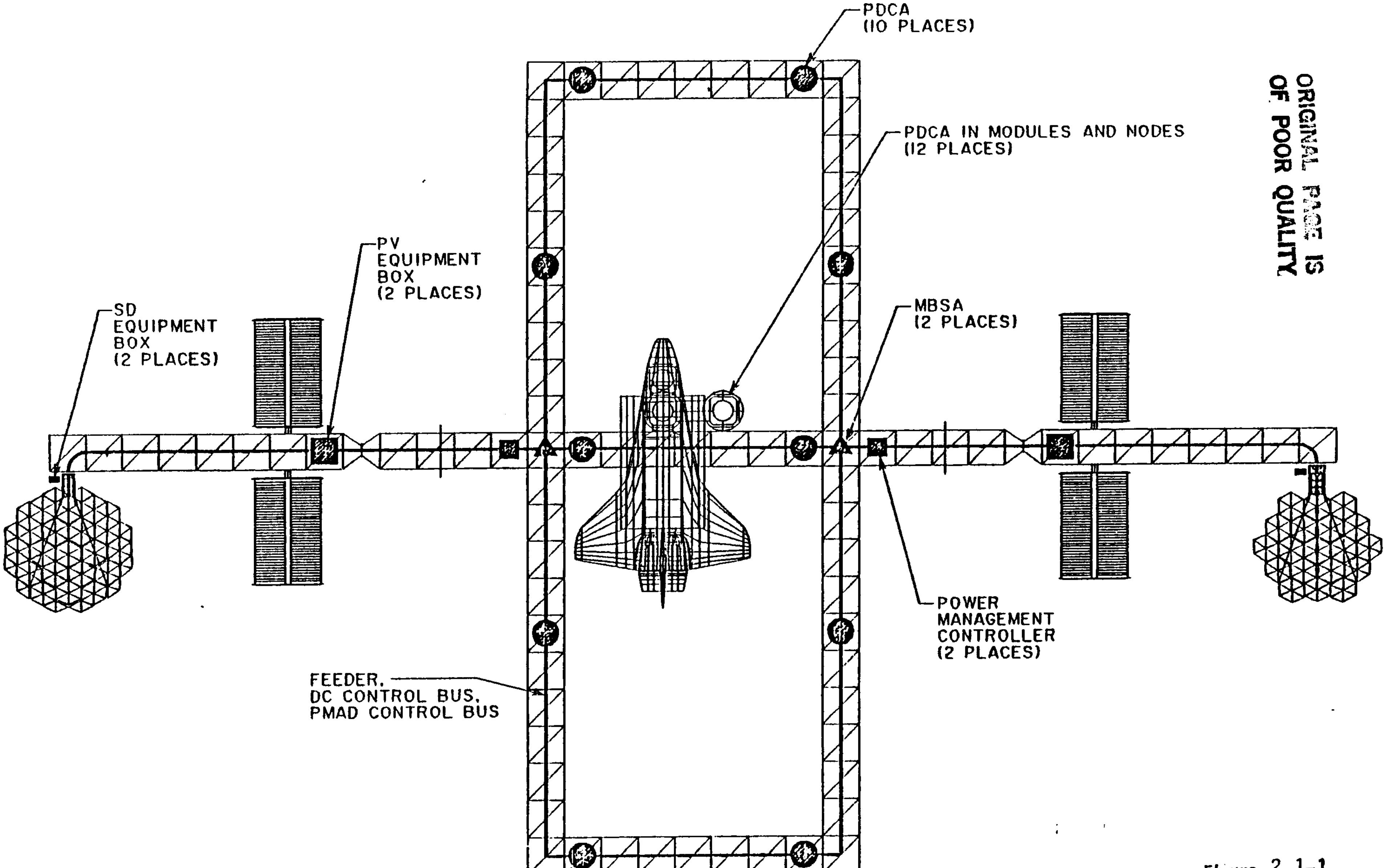

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Figure 2.1-1

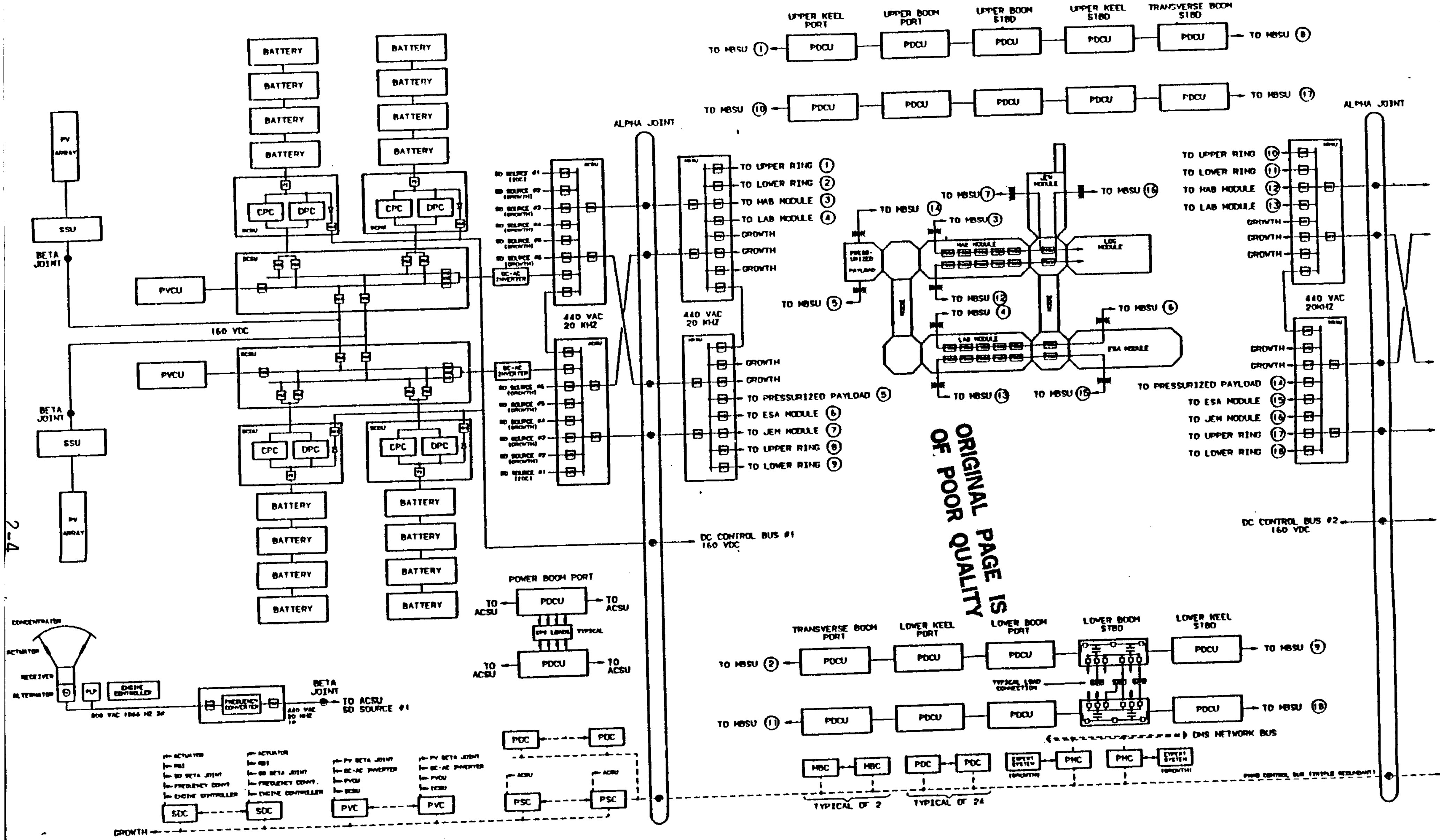
Rockwell International Corporation
Rocketdyne Division
Canoga Park, California

SPACE STATION EPS COMPONENT LOCATIONS

SIZE	FSCM NO.	DWG NO.
C	02602	7R070021
SCALE NONE	DO NOT SCALE PRINT	SHEET

2-477

EPS SYSTEM DIAGRAM



LEGEND

AC - ALTERNATING CURRENT
ACSU - AC SWITCHING UNIT
BCDU - BATTERY CHARGE/DISCHARGE UNIT
CPC - CHARGE POWER CONVERTER
DC - DIRECT CURRENT
DCSU - DC SWITCHING UNIT
DMS - DATA MANAGEMENT SYSTEM
DPC - DISCHARGE POWER CONVERTER
EPS - ELECTRICAL POWER SYSTEM
ESA - EUROPEAN SPACE AGENCY
FI - FAULT ISOLATOR
HAB - HABITAT MODULE
JEM - JAPANESE ENGINEERING MODULE
KHZ - KILO HERTZ
LAB - LAB[illegible]ORY MODULE
LOG - LO[illegible] MODULES
MBC - [illegible]ONTROLLER

MBSU - MAIN BUS SWITCHING UNIT
PVCU - PHOTOVOLTAIC CONTROL UNIT
PDC - POWER DISTRIBUTION CONTROLLER
PDCU - POWER DISTRIBUTION AND CONTROL UNIT
PLR - PARASITIC LOAD RESISTOR
PMAD - POWER MANAGEMENT AND DISTRIBUTION
PMC - POWER MANAGEMENT CONTROLLER
PSC - POWER SOURCE CONTROLLER
PV - PHOTOVOLTAIC
PVC - PV CONTROLLER
RBI - REMOTE BUS ISOLATOR
SD - SOLAR DYNAMIC
SDC - SD CONTROLLER
SSU - SEQUENTIAL SHUNT UNIT
VAC - VOLTS ALTERNATING CURRENT
VDC - VOLTS DIRECT CURRENT

2. VOLTAGE INSIDE ALL PRESSURIZED MODULES AND TO ALL LOADS IS 208 VAC 20 KHZ 1Ø.
1. COMPONENTS OUTBOARD OF THE STBD ALPHA JOINT ARE THE SAME AS COMPONENTS OUTBOARD OF THE PORT ALPHA JOINT.

NOTE: UNLESS OTHERWISE SPECIFIED

Figure 2.1-2

EPS SYSTEM DIAGRAM

E 02602 7R070009

comprised of five subassemblies: bearing, transition structure, drive, roll ring, and controls and instruments.

The EPS also includes government furnished equipment (GFE) such as truss sections used for the PV and SD modules and utility trays used by the PMAD subsystem. These will be supplied by WP-02.

Each of the two platforms (polar and co-orbiting) have two PV array wings that are similar to those used on the station and PV PMAD ORUs that are identical to those on the station.

2.1.1 PV Subsystem

The PV subsystem will supply power to the Space Station and platforms. The station PV power subsystem contains two PV power modules, each located just outboard of the alpha joint on the transverse boom. Each module consists of two light-weight photovoltaic array wings, a PV equipment box containing: four NiH_2 storage batteries, PV source PMAD, thermal control and heat rejection for every storage and PMAD losses; required truss structure (GPE) and two beta joints with roll rings for power/data transfer.

The platform PV power system consists of two light-weight photovoltaic array wings, four NiH_2 storage batteries.

The PV power source activities encompassed conceptual design, trade studies, and preliminary design in the following areas:

- o Photovoltaic (PV) Arrays
- o Battery Energy Storage
- o DC Power Management and Distribution (PMAD)
- o Integrated Thermal Control (ITC)

In support of system configuration studies, and the evaluation of design alternatives and their impacts on system performance, Rocketdyne performed numerous sizing studies on batteries, solar arrays, and the entire photovoltaic (PV) power subsystem. These studies provided part of the basis for the PV versus solar dynamic (SD) power trades and the recommendation of the hybrid power system approach.
V1-2/3

Under the PV array tasks, a range of trade studies were performed to define the optimal design for the station and platform arrays, with assistance from Lockheed Missiles and Space Corporation (LMSC) on an as-required basis. Options examined included concentrator and planar arrays, deployable and erectable construction, and solar cells of different construction, thickness and area. The design finally selected supports the station and platform with a common solar array wing design. It is a flexible planar array with dual blankets, using 8 x 8 cm gridded-back silicon solar cells at a nominal voltage of 160 V.

The energy storage effort conducted by Ford Aerospace Communication Corp (FACC) included conceptual design of several battery concepts for the Station and Platforms, based on nickel-cadmium (Ni-Cd) and nickel-hydrogen (Ni-H_2) technologies, as well as alternative advanced systems. These were traded to arrive at a preferred battery technology selection, which was Ni-H_2 for both Station and Platform. Following the NASA selection of Ni-H_2 batteries over regenerative fuel cells, and the PV/SD hybrid power system over all-PV and all-SD, the designs were refined to yield a common battery hardware design for the station and platforms. This design includes eight 62-Ah batteries on the station and four on the platform.

The integrated thermal control (ITC) assembly is designed with capability to acquire and transport excess heat from the batteries and PMAD to dedicated electrical power system radiators. A mechanically pumped two phase (MPTP) system using ammonia as the working fluid was selected as the baseline design. An alternative design is the capillary pumped loop (CPL) system. The primary difference is that the MPTP design incorporated a motor driven pump, while capillary action provides the pumping power in the CPL system. The ITC is a redundant system, with alternate, independent cold plates manifolded to separate, independent flow loops. The performance of both MPTP and CPL systems has been demonstrated in ground tests.

The conceptual design of the PV source PMAD was modeled after proven space power systems, adjusted for a nominal operating voltage of 160 V, and alternative concepts were examined and traded. The selected approach uses sequential shunt regulation of array power and individual charge and discharge power converters for battery management. A switching center was baselined which provides all the dc power switching and fault isolation functions. Two options for dc power distribution at 160 V and 440 V were sized and evaluated for use by Rocketdyne and NASA in distribution power frequency and voltage trades, which finally resulted in selection of the 440 V 20 kHz baseline.

In addition to these architecture and design oriented efforts, support was provided in such areas as operations planning, growth, automation and robotics, test and verification, and risk analysis.

2.1.1.1 Baseline Design Requirements

The baseline design is a result of requirements and design iterations. The final requirements are as follows for the Station:

- o Nominal constant power operation
  - 23.5 kWe to the user load input
  - 1.0 kWe share of the PMAD processor load
- o Peaking operation
  - 23.5 kWe average power to user load input
  - 1.0 kWe continuous share of PMAD processor load
  - 42.5 kWe peak power to user load input
  - 7.5 minute peak in eclipse and/or sunlight

and for the Platform:

- o Nominal constant power operation
  - 8.0 kWe to the user load input
  - 0.5 kWe PMAD processor load
- o Peaking operation
  - 8 kW average power to user load input
  - 0.5 kW continuous PMAD processor load
  - 16.0 kW peak power to user load input
  - 5.0 minute peak in eclipse and/or sunlight

V1-2/5

In addition, the preliminary design of the PV subsystem has been guided by the principal of commonality between the hardware designs for the Station and the Platforms and the requirement to minimize the platform first launch weight. This approach is appropriate since the station PV power elements are sized to provide a nominal output of 24.5 kWe and are not expected to grow, while the platform power level, served by PV exclusively, starts at 8 kW and grows to 24 kW. The similarity between the power levels suggests that commonality should be practical and beneficial in reduced development cost.

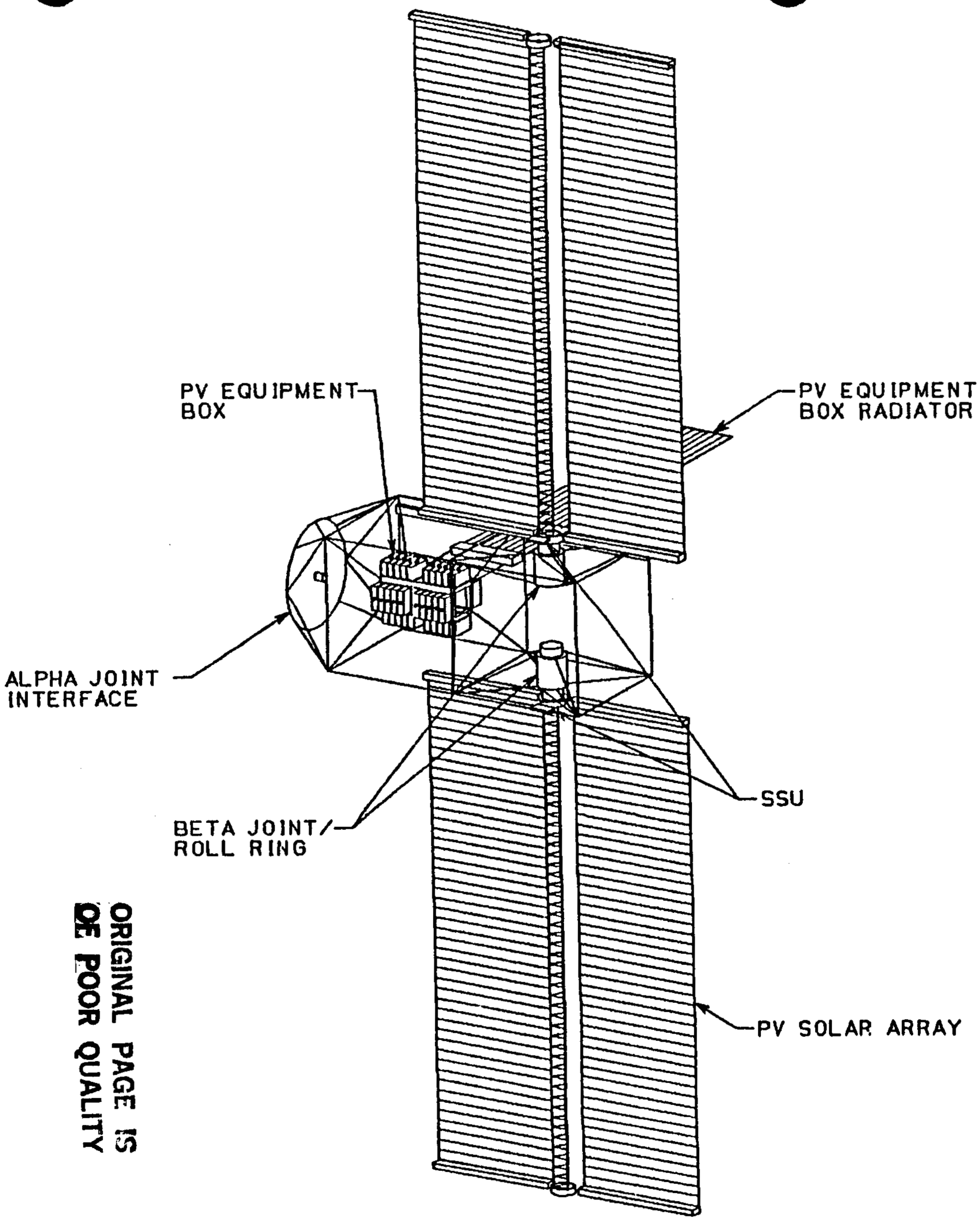
2.1.1.2 Design Overview

The station PV subsystem consists of two PV power modules, located on the port and starboard side of the station transverse boom. Each module consists of two solar array wings, a PV equipment box containing: four $Ni\text{-}H_2$ storage batteries, PV electronics, thermal control and heat rejection for energy storage and PMAD losses; required truss structure (GFE), roll rings, and beta joints. The platform PV subsystem consists of the same equipment except the equipment box and thermal control, and is distributed over the structure as determined by overall Platform layout and growth considerations.

The subsystem within one module contains two common source power buses, each served by two solar array wings, two switching sequential shunt units (SSU), one PV power control unit (PVCU), four nickel-hydrogen ($Ni\text{-}H_2$) batteries with associated battery charge/discharge units (BCDU) including charge power (buck) converters (CPC) and discharge power (boost) converters (DPC), and a dc switching unit (DCSU), containing switchgear and cabling. Resonant inverters convert source power to 20 kHz, 440 V single phase AC distribution power.

Photovoltaic Arrays - The photovoltaic array system for the station is based on Lockheed's design of a large area, deployable/retractable planar, flexible panel substrate array (Figure 2.1.1-1). The design is similar to the array technology demonstrated in the OAST-1 flight experiment on STS-41D in September 1984. The solar array system is composed of four wings on the Station and two on the IOC Platforms. Each wing has two identical blanket assemblies, each stowable in a container/cover assembly. The wings are supported by a deployable coilable/longeron mast.

V1-2/6



Station Photovoltaic Array Design Summary

Active panels per blanket	46	
Circuits per panel	0.5	
Circuits per blanket	23	
Blankets per wing	2	
Wings per station	4	
Cells per panel	196	
Cells per circuit	392	
Cells per blanket	9016	
Cells per wing	18032	
Cells per station	72128	
Operating Voltage	160 V	
Solar Cell		
- Type	Silicon, N on P, shallow junction	
- Size	8 cm x 8 cm, cropped corners	
	200 um thick	
- Active Area	6600..1144 sq cm	
- Base Resistivity	2 ohm-cm	
- Coverglass	150 um thick CMX	
- Coatings	Dual system, TiO/Al203	
- Contact Pattern	Wrap through	
Electrical Configuration		
- each panel	1 parallel x 196 series cells	
- each circuit	1 parallel x 392 series cells	
- each blanket	46 parallel x 392 series cells	
Number of blankets per wing	2	
Number of panels per wing	96	(48 per blanket; 46 celled)
Number of cells per wing	18032	(196 per panel)
Number of bypass diodes per wing	2392	(26 per panel)
Wing power - kW	14.2	(3 years on orbit)
Wing mass - kg	485	
Wing lenght - m	20.3	
width - m	9.57	
area - sq m	194	(Outline)
	152	(Blanket)
Natural Frequency - Hz	0.16	(Torsion)
Allowable acceleration - g	0.090	(Maximum ultimate; Wing perpendicular)
Stowed volume - cu m	2.96	(2 blanket boxes Plus mast canister)

Figure 2.1.1-1

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Canoga Park, California

SPACE STATION EPS
PV MODULE

SIZE C | FSCM NO. 02602 | DWG NO. 7R070048
SCALE NONE | DO NOT SCALE PRINT | SHEET

DWG NO. 7R070048 SH

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Energy Storage - Batteries - The space station and platform use nickel-hydrogen ($Ni-H_2$) batteries for energy storage associated with the PV subsystem. In order to achieve commonality between the station and platform application, a moderate capacity of 62 Ah was selected. This capacity provides a close fit to station battery capacity and symmetry (even number of batteries) requirements, and accommodates the platform capacity needs with minimal mass.

Each battery consists of 92 $Ni-H_2$ cells in series and is divided into four assemblies with 23 cells each. A single assembly can serve as a complete battery on systems within the space station program that may use a 30 V bus, such as the MSC, and associated vehicles such as the OMV and OTV.

On the station eight batteries are used in the PV power subsystem, four per PV module. The Polar Platform uses three in the first-launch and one in the second launch for a total of four in the IOC configurations.

Integrated Thermal Control - The integrated thermal control (ITC) assembly is designed with capability to acquire and transport excess heat from the batteries and PMAD to dedicated electrical power system radiators. It maintains a temperature of $5 \pm 5^{\circ}C$ at the batteries under all but contingency or failure conditions. A mechanically pumped two phase (MPTP) system using ammonia as the working fluid was selected as the baseline design. The 1.3 cm diameter liquid line is approximately 5.0 meters long, and the 2.5 cm diameter vapor line is also 5.0 meters long. An alternative design is the capillary pumped loop (CPL) system. The primary difference is that the MPTP design incorporated a motor driven pump, while capillary action provides the pumping power in the CPL system. The ITC is a redundant system, with alternate, independent cold plates manifolded to separate, independent flow loops. The performance of both MPTP and CPL systems has been demonstrated in ground tests. In addition, two CPL systems have flown in the payload bay of the shuttle. These units verified that the performance of the CPL design in space is the same as on the ground.

Source PMAD - The source PMAD equipment provides source bus voltage regulation to a nominal 160 V through the photovoltaic charge units (PVCUs) and sequential shunt units (SSUs). The PVCU senses bus voltage across a capacitor bank and drives a pulse-width modulation (PWM) circuit based on the error signal, the difference between bus voltage and a reference voltage. The SSUs contain switching circuits that shunt individual solar cell strings in the array response to the PWM signal, to maintain bus regulation while matching power delivery to demand.

The charge power converter (CPC) provides charge power to a battery by buck regulation of source bus power to the voltage required by the battery as a function of state of charge and charge rate. The current provided to the batteries is determined by a coulometry algorithm implemented in the PV source processor. Charge current level and end-of-charge taper profile and timing are based on measured discharge capacity on the previous eclipse discharge.

During eclipse the batteries provide power in accordance with the demand. Discharge power from individual batteries is regulated with individual discharge power converters (DPCs) to provide balanced battery operation in case of health status differences. The regulators boost voltage to the nominal source bus voltage of 160 V. The switching functions and fault isolation within the source PMAD system is provided by the DC switch units (DCSUs), which contain all high-power switchgear.

2.1.2 SD Subsystem

SD modules are designed for 25 kWe nominal power. The range of conditions under which this power must be delivered include variation in solar insolation (1.323 to 1.419 kW/m2), variation in sunlight and eclipse duration consistent with operation over a range of orbits (28.5 deg. inclination, 180 to 250 nautical miles altitude), and variation in reflectivity of the concentrator (0.93 to 0.90). The actual power generated by the SD modules under these conditions varies from 26 kWe net to 30 kWe net.

Two concepts were studied extensively for the SD subsystem: closed brayton cycle and organic rankine cycle. One concept will be selected as part of the Phase C/D proposal process.

The SD subsystem consists of the assemblies shown in Figure 2.1.2-1 or 2.1.2-2. Design drawings and descriptions for these assemblies are presented in the Preliminary Analysis and Design Document DR02. The major assemblies are

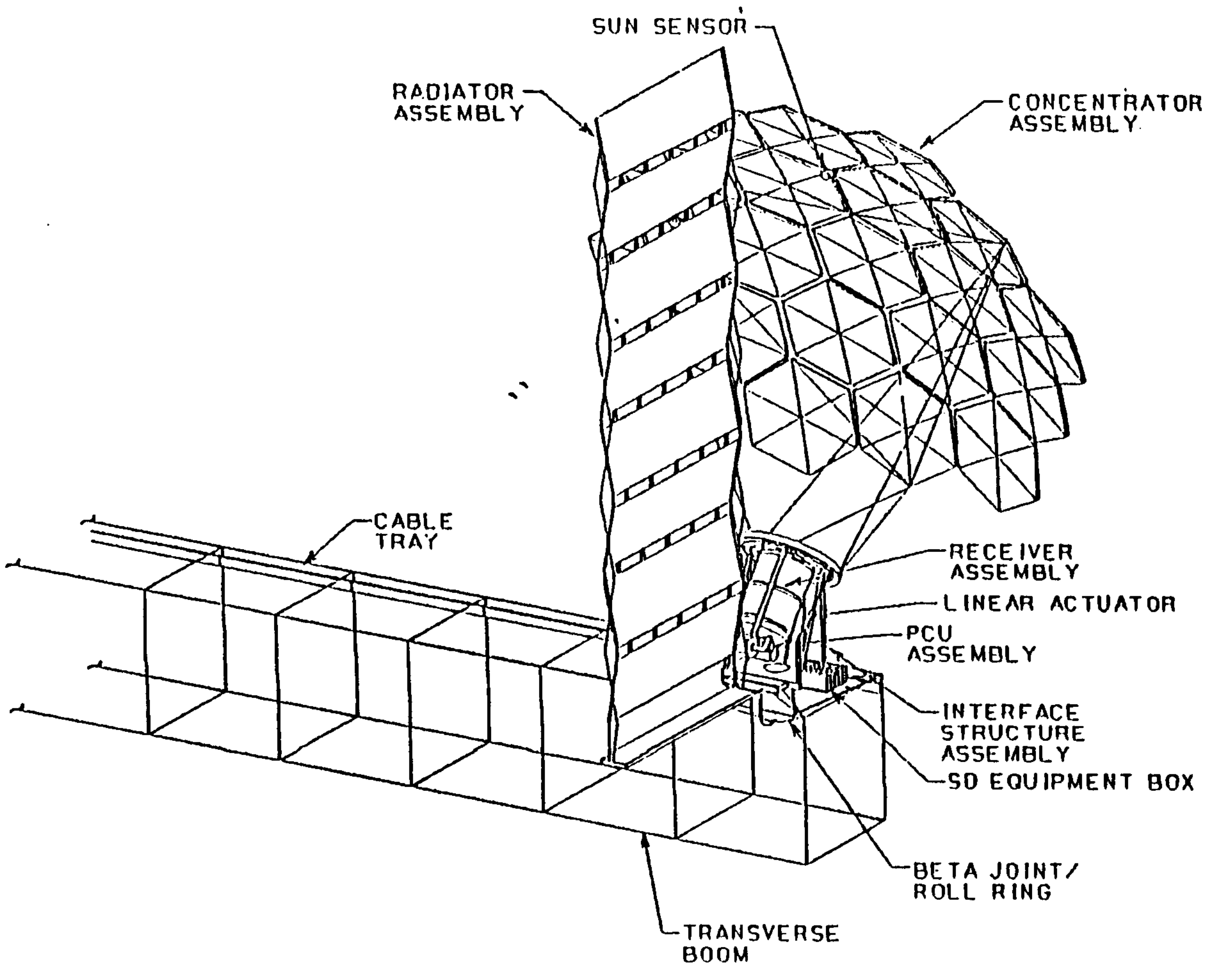

Figure 2.1.2-1

Rockwell International Corporation Rocketdyne Division	
SPACE STATION EPS	
SD POWER MODULE (CBC)	
C 02602	7R070063
NONE	

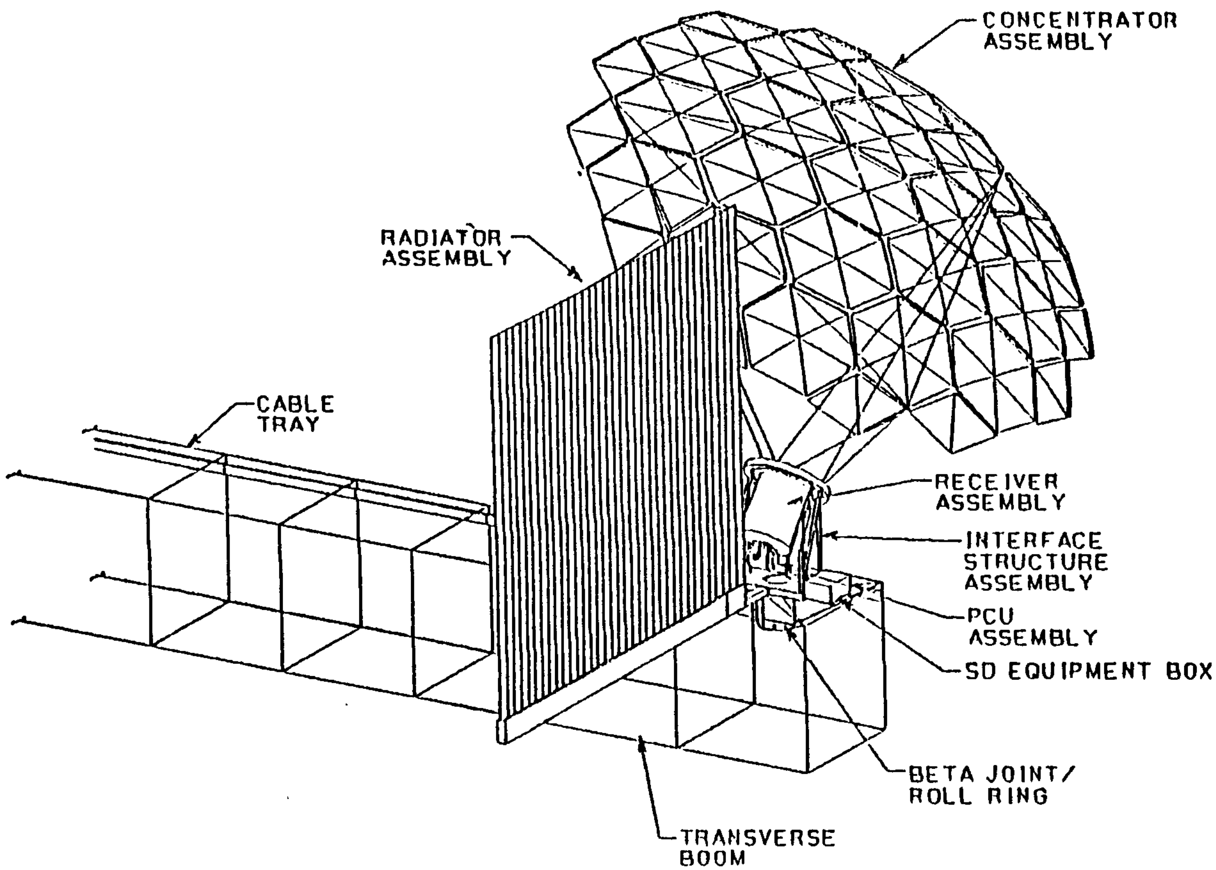

Figure 2.1.2-2

Rockwell International Corporation
Rocketdyne Division

SPACE STATION EPS
SD POWER MODULE (ORC)
C 02602 7R070064
NONE

the concentrator, the receiver, the power conversion unit (PCU), the radiator, and the interface assembly.

The concentrator captures and focuses incoming solar flux with a reflective concave surface and sends it through the receiver aperture. It includes pointing equipment to maintain proper solar orientation. The receiver accepts and absorbs the incoming concentrated solar flux in a cavity. Some of the power is transferred to the PCU be heating a working fluid, and the balance is stored as thermal energy in a phase change salt where it can be retrieved later for use during eclipse. The PCU takes energy from the receiver in the form of heated working fluid, converts some of the energy to electrical power in a heat engine, and sends the rest of the energy to the radiator as waste heat. The heat engine works by extracting useful work from the difference in the shaft power supplied by pressurized heated working fluid expanding through a turbine and the shaft power required to drive a pump or compressor operating on the cooled low pressure working fluid with a similar flowrate and pressure ratio. The radiator receives waste heat from the PCU via mass transport and heat exchange. It then dissipates the waste heat to space by thermal radiation. The interface assembly consists of an interface structure and a solar dynamic equipment box. The interface structure provides load carrying capability between the various assemblies and the solar dynamic beta joint which connects the SD subsystem to the balance of the station. The equipment box provides a protected mounting point for the majority of the solar dynamic subsystem electronics and serves as a central point for cabling interconnections.

2.1.2.1 Concentrator Preliminary Design

A preliminary design of solar dynamic concentrators suitable for application with ORC or CBC power conversion units and receivers was completed. A common conceptual design was used for both concepts in order to minimize development costs. The primary differences between the two concepts is in the reflective surface slope errors and pointing accuracy as well as the total reflective surface area requirements.

The concentrator configuration is the offset Newtonian reflector, gimbaled about the receiver aperture center. Fine pointing is provided by two linear actuators located between a two-axis fine pointing mechanism and the interface structure. This configuration is known as the Parabolic Offset Linear Actuated Reflector, or POLAR concept. The concentrator assembly consists of four subassemblies including: reflective surface, structure, mechanisms, and controls and instruments. The ORC concentrator requires 19 full size hex truss and 12 edge wedge panels to provide the required receiver power to the ORC receiver during all projected operating environments and modes. The CBC concentrator requires 19 full size hex trusses to provide the required receiver power to the CBC receiver during all projected operating environments and modes.

2.1.2.2 Receiver / Power Conversion Unit

2.1.2.2.1 CBC Receiver / Power Conversion Unit

The CBC receiver and power conversion unit (PCU) assembly (see Figure 2.1.2.2.1-1) consists of three major elements. These are the receiver, the power conversion equipment, and the engine electric control loop equipment. Table 2.1.2.2.1-1 summarizes the CBC option.

The receiver integrates the functions of solar absorbing surface, thermal energy storage (TES) for eclipse power, and heat source heat exchanger (HSHX) for the PCU. It consists of a cylindrical absorbing cavity whose walls are lined with a series of 82 heat absorbing tubes each of which is encased in a series of small canisters containing TES salt. The tubes are connected to manifolds at each end and form the HSHX. The salt in the canisters form the TES. The outer surface of the canisters forms the solar absorbing surface. The receiver interfaces optically with the concentrator by accepting the concentrated solar flux. It interfaces with the PCU by heating cycle gas circulated through interconnecting ducts. It interfaces structurally with the PCU and the interface structure.

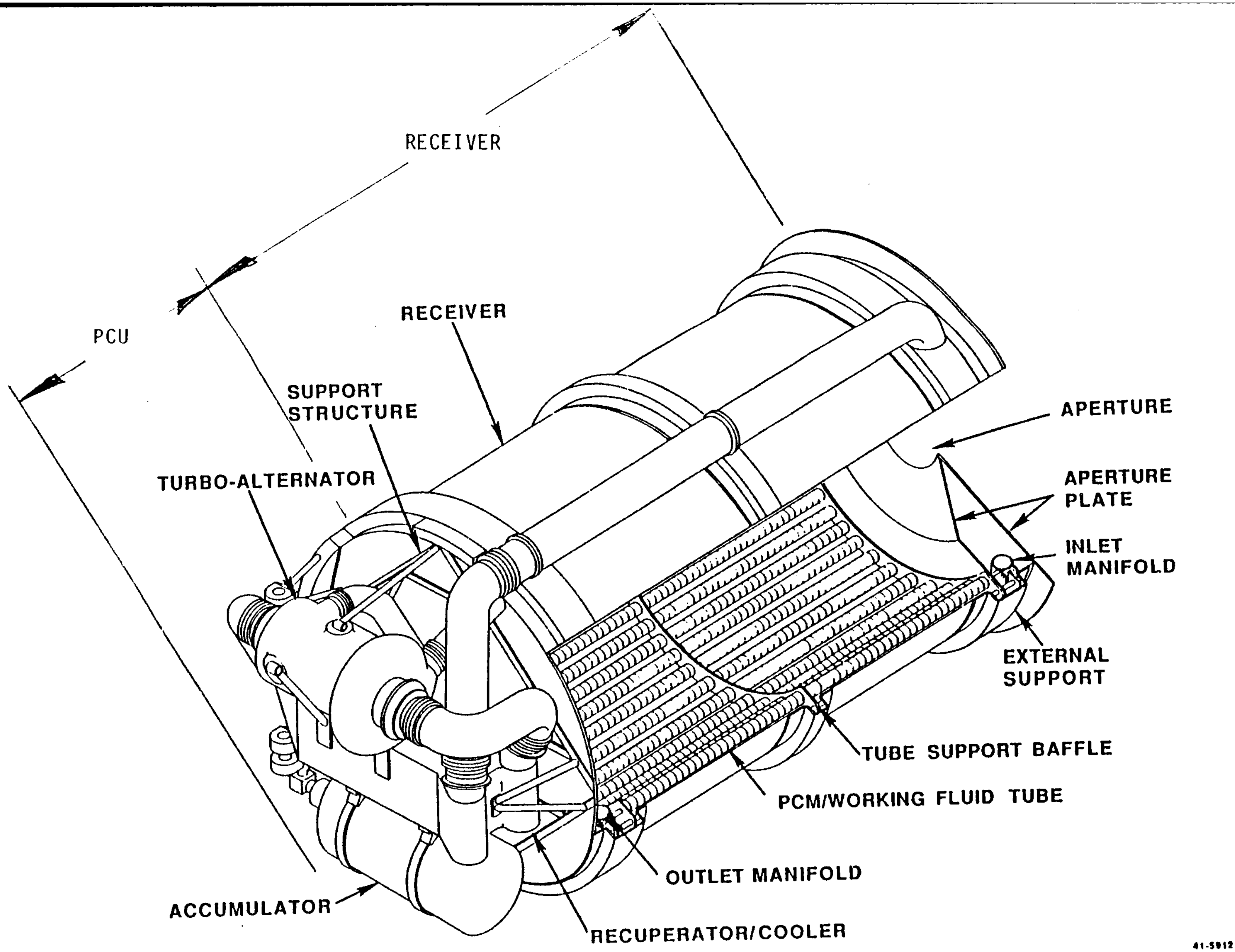

FIGURE 2. 2.1-1
CLOSED BRAYTON CYCLE R IVER / POWER CONVERSION UNIT

TABLE 2.1.2.2.1-1
SUMMARY OF SOLAR DYNAMIC
CLOSED BRAYTON CYCLE OPTION

Key Characteristics	
Working Fluid	Helium/Xenon mixture @ MW = 40
Maximum Fluid Temperature	1034 K (1402 F)
Heat Rejection Temperature Range	447 K (346 F) to 265 K (18 F)
Primary Thermal Storage Medium	Lithium fluoride/calcium difluoride
Receiver Cavity Temperature Range	967 K (1280 F) to 1083 K (1490 F)
Receiver Heat Transport	Cavity Reradiation & conduction
Radiator Heat Transport	Coolant transport, space radiation
Radiator Surface	Z93 White Paint
Reflective Surface	Magnesium Fluoride/Alumina/Silver

System Design Performance		Efficiency (%)
PMAD (effective) (0.882 eff & 1 kWe)		85.0
SD Controls & Parasitic		96.2
Alternator	93.4	
Thermal Cycle	36.4	
Power conversion unit (Subtotal)		34.0
Cavity (optical & thermal)	92.0	
Receiver surface loss effects	92.8	
Receiver (Subtotal)		85.4
Interception	97.0	
Reflectivity	90.0	
Concentrator (Subtotal)		87.3
Sun-to-Bus (Minimum Insolation Orbit) (@ PLR load = 0)		20.8

Around the <u>entire</u> min insolation orbit

*Expected value at BOL + 3 years without replacing failed radiator panels.

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The function of the power conversion equipment is to accept heat from the receiver and convert some of it into electric power while passing the rest of the thermal power to a compact heat sink heat exchanger for eventual radiation to space. It consists of a brayton heat engine including compressor, turbine, alternator, recuperator, gas coolers, ducting, and a gas accumulator with valves. The brayton cycle works by extracting useful (electric) work from the difference in the shaft power supplied by heated high pressure gas expanding through a turbine and the shaft power required to drive a compressor operating on the cooled low pressure gas with similar flowrate and pressure ratio. The PCU interfaces with the receiver via gas ducts as a heat source, and with the radiator via coolant lines as a heat sink. It also interfaces with the engine controller via power and instrumentation cables for control and as a link to PMAD, and with the receiver and interface structure via structural ties for support.

The function of the electric loop control equipment is to manage the operation of the CBC receiver / PCU consistent with the twin goals of performance in supplying power to PMAD in the amount and quality required, and limiting cycle conditions to those which assure long component life. The control equipment consists of dual redundant controllers each having power, logic, signal conditioning and communication circuitry, a parasitic load radiator (PLR), an accumulator valve actuator, and interconnect cables. The controller adjusts rotor speed, and hence alternator frequency by modulating PLR voltage, adjusts supply voltage by modulating field coil current, and controls cycle thermal condition by modulating accumulator pressurization through use of the valve actuators. The controller interfaces with the PCU via cables, a cold plate, and structural ties for support and cooling and to supply control while accepting alternator power. It interfaces with the PMAD to accept control signals and to supply power.

2.1.2.2.2 <u>ORC Receiver/Power Conversion Unit</u>

The reference concept for the SD-ORC consists of two ORC modules each designed for 25 kWe nominal power. Because these modules are designed to operate with varying insolation (1.323 kW/m^2 to 1.419 kW/m^2) and with orbital/eclipse ranges corresponding to 180 to 250 nm orbital parameters, the actual power generation capability is expected to be 26.1 to 29.7 kWe at the

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three year design point. Table 2.1.2.2.2-1 shows key characteristics and design efficiencies for the ORC module.

The SD-ORC module consists of the assemblies shown in Figure 2.1.2-2. Detailed design drawings and descriptions for these assemblies are presented in DR-02, the Preliminary Analysis and Design Document. The major assemblies are the concentrator, which focuses incoming solar energy, the receiver which converts the solar energy to heat energy by vaporizing the working fluid and stores solar energy for vaporization during eclipse periods, the power conversion unit (PCU) which converts the heat energy to electrical energy, and the radiator which rejects heat from the thermodynamic cycle to space. Minor assemblies are the parasitic load resistor (PLR) which matches PCU electrical output to user requirements, the interface structure which connects the major components to the station beta joint and the electronics enclosure which contains the electronic controls.

The ORC receiver/PCU (Figure 2.1.2.2.2-1) consists of the receiver and power conversion unit (PCU). The ORC receiver absorbs solar energy reflected by the concentrator and thermally transfers it to the engine working fluid. Excess energy is collected during the insolation period and stored in integral thermal energy storage canisters as latent heat of fusion. This latent heat is given up during the eclipse period to provide continuous power to the engine working fluid. In addition, the receiver must accommodate peak power requirements and must maintain the peak toluene temperature within an acceptable limit. The PCU utilizes a regenerated organic Rankine cycle turbine/alternator to convert the thermal energy from the receiver into electrical energy. The receiver/PCU has a mechanical, electrical, and fluid interfaces with the interface structure. The electrical interfaces provide connection to the SD equipment box and the fluid interfaces connect with the condenser.

2.1.2.3 <u>SD Radiator Assembly</u>

Separate design concepts were generated for the ORC and CBC radiator assemblies. A constructible, heat pipe radiator using a flat contact interface was selected for the ORC preliminary design. For this concept, commonality was

TABLE 2.1.2.2.2-1
SUMMARY OF SOLAR DYNAMIC
ORGANIC RANKINE CYCLE OPTION

Key Characteristics	
Working Fluid	Toluene
Maximum Operating Temperature	399°C (750°F)
Effective Heat Rejection Temperature	60.4°C (140.7°F)
Thermal Storage Medium	LiOH
Receiver Operating Temperature	482°C (900°F)
Receiver Heat Transport	Potassium Heat Pipes
Radiator Heat Pipes	Aluminum/Ammonia
Radiator Surface	Z93 White Paint
Reflective Surface	Magnesium Fluoride over $Al_2O_3/Ag/Al_2O_3$

System Design Performance	Efficiency (%)	
PMAD (effective) (88.2% less 1 kWe)		85.1
Controls		96.8
PCU		
Alternator	91.7	
Thermal Cycle	29.9	
Subtotal		27.4
Receiver		
Absorptivity	95.8	
Reradiation	94.7	
Subtotal		90.7
Concentrator		
Reflectivity	90.0	
Interception	99.7	
Subtotal		89.7
Sun-to-Bus (Nominal case, PLR load = 0)		18.3

*Expected value at BOL + 3 years without replacing failed radiator panels.

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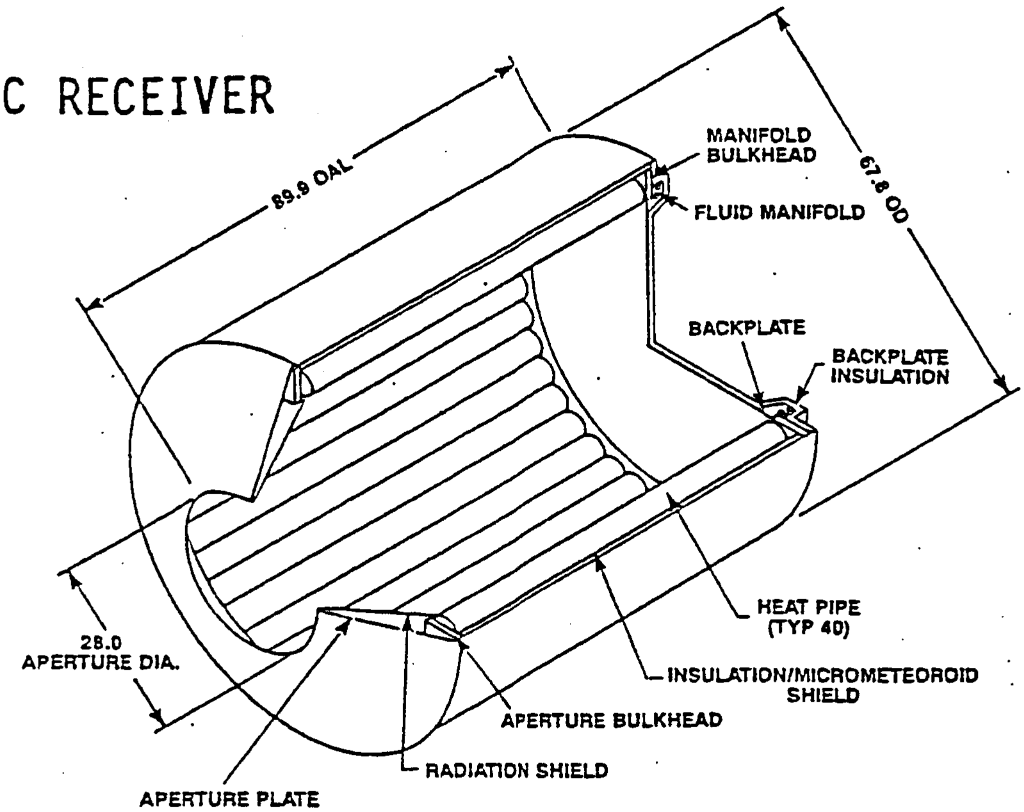
ORC RECEIVER



ORC PCU

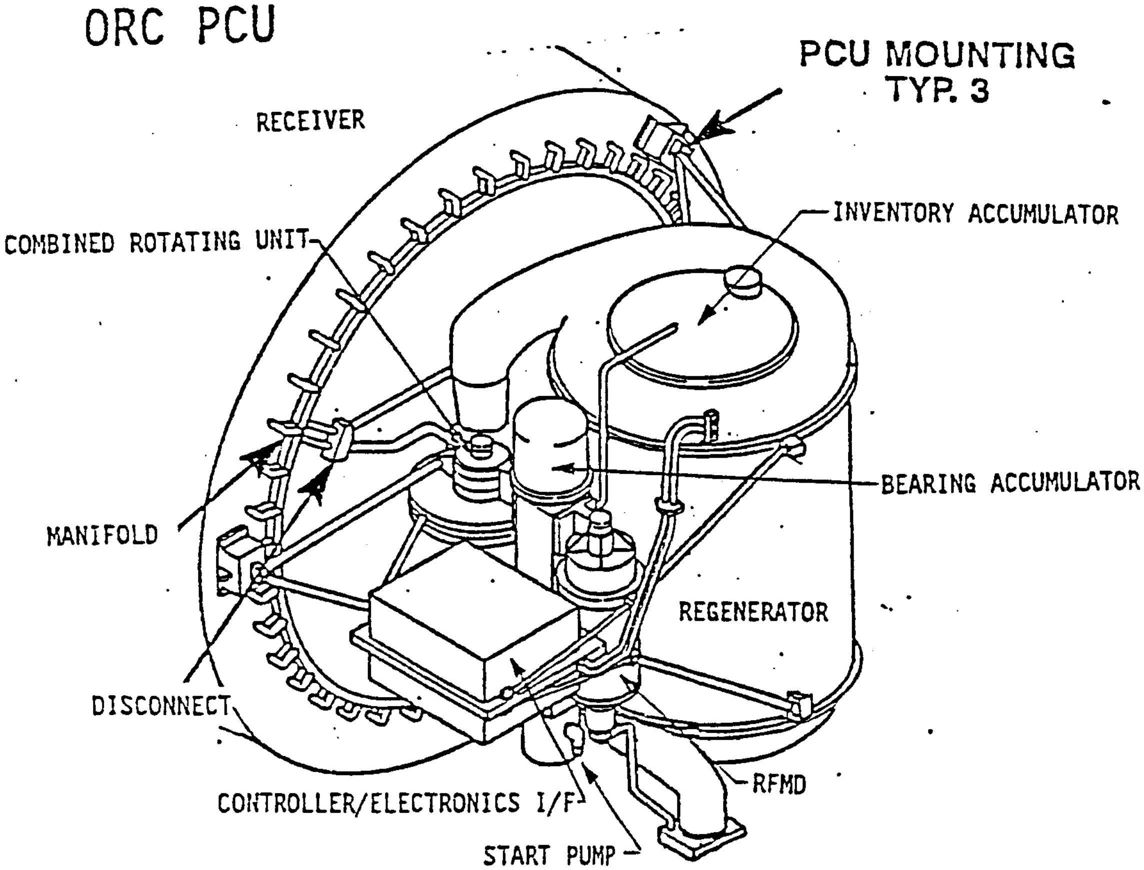


Figure 2.1.2.2.2-1

maintained, to the maximum extent practical, with hardware being developed for other thermal control systems on the Space Station. A deployable, pumped fluid loop radiator was chosen for the CBC preliminary design. This concept provides a minimum weight and cost design to interface with the relatively high temperature, single phase CBC working fluid.

2.1.2.3.1 CBC Radiator Preliminary Design Description

The CBC radiator preliminary design consists of redundant, pumped fluid loops that interface with the PCU at the gas cooler heat exchanger and with eight separate radiator panels. The honeycomb panels contain tube extrusions and provide flow passages to accommodate separately the primary and redundant fluid loops. Each panel is 2.3 m (7.5 ft) long and 8.0 m (26.4 ft) wide and contains bonded facesheets (fins) for radiant heat transfer. Meteroid and debris penetration protection is provided through use of bumpered tube construction techniques.

The panel assembly is deployed on-orbit using a scissors-type deployment mechanism. Deployment and retraction are possible either automatically by incorporating deployment motors, or by using a crank. The later can be activated using MRMS with an adapter or manually by EVA through a hand operated crank. The radiator panel design is similar in construction to the STS Orbiter design and the deployment mechanism is an adaption of the mechanism used to successfully deploy the Skylab Apollo Telescope Mount solar arrays.

2.1.2.3.2 ORC Radiator Preliminary Design Description

The ORC radiator preliminary design consists of 31 heat pipe panels, each of which are 12.7 m (41.6 ft) long and 40.6 cm (16 in) wide. The panels utilize Lockheed tapered artery heat pipes made of aluminum material containing ammonia working fluid.

All panels incorporate two separate heat pipes, each having one condenser leg and three evaporator legs. The heat pipes are assembled into an aluminum honeycomb matrix structure. The later is then bonded to aluminum facesheets which form the radiator fins. This type of panel construction was successfully employed in the fabrication of the Orbiter radiators.

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The panels separately interface with the ORC condenser by means of a flat, pressurized contact surface which allows on-orbit assembly and replacement of each panel. This interface design is currently being developed under a NASA-JSC ADP program.

2.1.2.4 Interface Assembly

The interface assembly is comprised, in the case of the CBC concept, of two subassemblies. One is the interface structure subassembly and the other is the SD equipment box subassembly. For the ORC, the interface assembly consists of three subassemblies: The interface structure, the SD equipment box, and the capillary pumped loop heat rejection subassembly. The interface structure subassembly, in turn, consists of two components: the adaptor and the superstructure. The SD equipment box subassembly, for the CBC concept, consists of six components: the utility plate, an SD control box, a redundant SD control box, an AC-to-AC frequency converter, a pump accumulator package, and a redundant accumulator package. The SD equipment box subassembly for the ORC concept consists of the same components except that the pump accumulator packages, in the CBC case, are replaced by capillary pumped loop packages. The SD equipment box contains the electronic components necessary (1) to control the SD subsystem and (2) to convert the AC alternator power to 20 kHz AC for distribution, in addition to components that handle the heat load created by the first two items. Each SD equipment box contains six ORUs of which one is the utility plate. The box has been attached to the adaptor plate providing good access for maintenance purposes.

2.1.3 PMAD Subsystem

The Phase B PMAD subsystem included performance of conceptual design analyses, trade studies, and preliminary design for a power management and distribution subsystem that will maximize electric power availability to all space station users. This is tempered by selection of system components and arrangements that maximize system efficiency while minimizing weight so that the most cost effective system results. User interfaces must also be kept simple yet provide reliable utility-grade electric power during all phases of the space station life. All requirements of the Space Station Program Definition Requirements Documents (JSC 30000) must also be satisfied.

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The completion of each PMAD task has been documented in the various Data Requirements (DR) Documents that have been submitted to support each phase of the contract. Seventeen PMAD trade studies and analyses were completed that resulted in a baseline PMAD subsystem definition. The PMAD subsystem definition met all space station requirements, and was baselined as a dual, 20 kHz, 440 Volt, single phase, power distribution network in a ring configuration. The system accepts power from hybrid sources (DC and low frequency AC), converted power to 20 kHz, and delivers utility-grade, 20 kHz, 208 volt, single phase power to user interfaces conveniently located at all load center locations on the space station. The control system selected uses a hiearchy of controllers that communicate over a dedicated PMAD control bus. ADA was selected as the space station software language.

The preliminary design phase carried forward the baseline PMAD subsystem. Components and equipment were selected that had proven space flight experience or were similar to proven items. Where new technology was being used such as 20 kHz inverters, completed NASA advanced development work and in-house IR&D results were used to define PMAD equipment. Thirty-one types of components and equipment were then combined in logical and functional assemblies, and orbital replacement units (ORU's) were defined (Table 2.1.3-1). Interfaces for each ORU were defined, and parametric data such as mass, efficiency, and thermal requirements were defined for all ORU's. The entire PMAD subsystem is comprised of ORU's that when properly connected and provided with appropriate interfaces, results in a functional PMAD subsystem.

The controls required for the overall EPS were integrated into the PMAD subsystem, and included startup, shutdown, pointing and tracking, power generation control, load management, fault protection, configuration control, and health monitoring. Preliminary software requirements were defined, and software code estimates were completed. Hardware to support the necessary control functions were integrated into appropriate ORU's.

Table 2.1.3-1 Summary of PMAD ORUs

IOC QUANTITY

ORU	STATION	EACH PLATFORM
Sequential Shunt Unit (SSU)	4	2
Photovoltaic Control Unit (PVCU)	4	2
Battery Charge/Discharge Unit (BCDU)	12	4
DC-AC Inverter	4	3
Photovoltaic Controller	4	2
DC Switching Unit (DCSU)	4	2
AC Switching Unit (ACSU)	4	2
Power Source Controller	4	-
Frequency Converter	2	-
Solar Dynamic Controller	4	-
Main Bus Switching Unit (MBSU)	4	-
Power Distribution & Control Unit (PDCU) Truss	24	4
Power Distribution & Control Unit (PDCU, Module	24	-
Power Management Controller (PMC)	2	2
Transformer	10	-
Node Bus Switching Unit (NBSU)	2	2
NSTS Power Converter	2	2

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Table 2.1.3-2 contains a summary of the estimates for lines of Ada source code, along with the corresponding memory allocations. The equivalent lines of source code are computed using share factors based on commonality among the various controllers. For those functions used on more than one controller, a share factor is calculated from the number of using types. Also, to account for integration and test costs, 20% is added for each controller over one.

IOC POWER SYSTEM SOFTWARE SIZING ESTIMATES

	Software	
Processor	Ada	Equiv Src
Power Management Controller	19925	19925
Power Distribution & Control Unit	10200	4635
Main Bus Switching Unit	10175	4300
Power Source Controller	11625	5770
Photovoltaic Controller	12325	6470
Solar Dynamic Controller	13125	7470
Total	77375	48570

Table 2.1.3-2 Summary of Software Sizing Estimates

The resulting output of the preliminary design is a cost-effective PMAD subsystem design that meets the requirements and goals of the Space Station Phase B program.

The overall PMAD subsystem functions as a dual power bus system with independent sources for each bus. The two Main Bus Switching Assemblies (MBSA) function as the independent sources, each feeding its own network of ring feeders. The MBSA is also the paralleling and synchronization point for all sources of power connected to that MBSA.

Electrical loads are served from power distribution and control assemblies (PDCA) located throughout the station. The PCDAs contain remote power controllers (RPC) that serve as the electrical interface with each load. The RPCs function to protect the Electrical Power System (EPS) from load faults. RPCs are also used for load shedding operations during system overload situations.

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The PMAD control system is designed for automatic and autonomous operation with minimum routine operator interactions. Operators may, however, interact with the PMAD control system through the data management system (DMS) interface with the power management processor whenever necessary or desired. The PMAD control system is designed to control all power sources and distribution equipment to ensure maximum power availability to subsystem and payloads in accordance with mission priorities. This control includes source paralleling and synchronization, real and reactive load sharing between sources, voltage and frequency regulation, harmonic distortion monitoring, load shedding, fault detection and isolation, and system health monitoring. Loads are monitored and RPCs are designed to protect the system from load faults. The control of the distribution network is designed to detect faults and isolate the smallest segment of the system necessary to clear the fault thus maintaining power availability to the maximum number of loads.

2.1.4 Interface Control Document (ICD)

A preliminary ICD for the interfaces between work package 04 (WP-04) element systems, and work packages 01, 02 and 03 elements and systems was developed. The document addresses the electric power system (EPS) on the station, the polar platform (POP), and the co-orbiting platform (COP). Because of commonality the POP and COP interfaces are, at this stage, handled together. The interfaces dealt with are functional and physical. Interfaces with the natural environment are considered as design requirements and therefore are not part of the ICD. Interfaces with the national space transportation system (NSTS) and with extra-vehicular activity (EVA), intra-vehicular activity (IVA), and robotics shall be developed more fully.

The architrctural control document (ACD) and baseline control document (BCD) in conjunction with the various design, development, test and evaluation (DDT&E) documentation, establish the interface requirement documents (IRD) and the interface control documents (ICD). The number of ICD's is under development.

The ICD identifies the interface, describes its nature, and establishes the responsibilities and scope of the work packages associated with it. The nature of the interfaces identified could be one or a combination of the following:

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- Mechanical
- Envelope
- Man-made environment, and
- Electrical, control, and data

During the process of identifying the interfaces it was concluded that they should be between orbital replacement units (ORUs) and not at lower assembly level. This establishes clear responsibility for performance, and simplifies design, development, and verification. All of which should have a positive affect on cost.

The ICD also identifies ORUs and/or components within the interfacing ORUs which are government furnished equipment (GFE). GFE which are used by other WP's yet are provided by WP04 are so indicated.

The ICD, in addition to its description of the individual interfacing ORUs, also addresses, for the station, the overall EPS electrical characteristics as required to support the station electrical power users requirements.

The dynamic interaction between the EPS and the station is dealt with on a conceptual level in the ICD. Inertial loads are imposed on the EPS by the station, e.g. reboost, docking, alpha joint, etc. On the other hand the rotation of the beta joints will affect the station. Vibration input to the outboard transverse truss may affect the controllability of the pointing and tracking of the SD concentrator and PV solar array. The requirements are now under development.

ICD development in many cases preceeded the preliminary design; Also, in some cases the interfacing WP's designs were not available. Assumptions were made in order to provide a base for further ICD development. Therefore the present ICD main value is in identifying the interfaces and establishment of responsibilities. Detail description of the interfaces shall evolve as the design progresses.

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2.1.5 Contract End Item Specifications

During the Phase B contract, Rocketdyne has prepared and submitted two sets of preliminary part I CEI specifications. The initial submittal, dated 24 June 1986, was directed by NASA-LeRC to consist of five contract end item specifications, as follows:

1) Station PV Module
2) Station SD Module
3) Station PMAD Subsystem
4) Platform PV Subsystem
5) Platform PMAD Subsystem

The second submittal, dated 19 January 1987 represented an updated set of CEI specifications reflecting the final pre-CETF baseline configurations for the EPS. The complete preliminary part I CEI specifications are included in DR-03.

2.1.6 System Test and Verification

The Phase B test and verification effort included analyses of CEI and inter-work package level activities necessary to support Space Station program requirements as identified in the EPS CEI specifications (DR-03) and the PDRD (JSC 30000). An overview of the Phase C/D program relationships and participation in the NASA Verification Working Group permit a structuring of the T&V program to form the basis for an efficient, integrated system of allocating requirements, coordinating across WP/SSPP boundaries, and providing results to NASA on the status of the Rocketdyne activities.

Specific reporting on test and verification requirements is presented in DR-02. Section 5 of that report encompased results of analyses and trades performed to establish the test and verification of inter-WP interfaces at the subsystem level. It contains detailed requirements for satisfying each on-orbit operations external interface "verificatiaon by simulation, analysis, inspection, demonstration or test, during the various phases of the Phase C/D program; development, qualification, acceptance integrated systems, pre-launch and on-orbit.

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2.1.7 External Thermal Environment Data Base

The External Thermal Environment Data Base (ETEDB) consists of a geometric mathematical model and a passive thermal mathematical model of the Space Station Electrical Power System. The development of these models was performed under an add-on to the WP-04 Phase B contract. The TRASYS computer program was used for the geometric math model, and the SINDA computer program was used for the thermal math model. The baseline IOC configuration and the man tended configuration (25 kw of photovoltaic power only) were analyzed. Models were developed for beta angles of 0, 52, and -52 degrees. The geometry reflected in the models is that which was current in May of 1986 when the modeling was started.

The geometric math models were used to calculate the thermal radiation environment of all Space Station power system components as a function of both orbital position and beta angle. This included reflected energy from the earth and other components, as well as the incident solar energy. The results of these analyses were heat fluxes that were then used as inputs to the thermal math models. The temperatures of the components were also calculated as a function of orbital position and beta angle. The size of these models was limited, because they were later integrated into the geometric and thermal math models of the entire Space Station. Details of the analyses and results are contained in the final report, External Thermal Environment Data Base", RI/RD86-234, 29 July 1986.

2.2 MAN-TENDED OPTION

The electric power sytem (EPS) for a man-tended approach (MTA) Space Station was studied by Rocketdyne as a potential phase in the development and buildup of a permanently manned capability (PMC) station. This study concluded that there could be a man-tended phase in the station buildup at a small penalty in overall cost. These results were documented in a Man-Tended Approach Study submitted to NASA-LeRC on 17 January 1986.

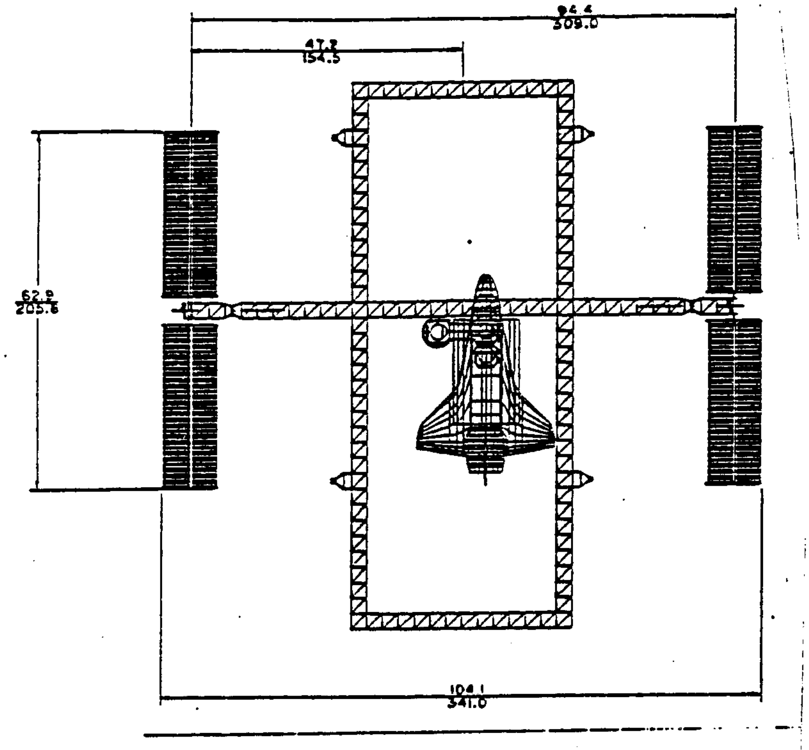
The study focused on a hybrid EPS which had already been recommended by Rocketdyne at that time, RFC's or batteries for energy storage, and CBC or ORC for SD Power. The hybrid configuration begins as a MTA station with 37.5 kW of PV and RFCs or batteries for energy storage. Growth to PMC is accomplished with the addition of two 25-kW SD modules (CBC or ORC) to 87.5 kW total. Additional batteries or RFC reactant tankage would be added to the ESS for peaking and contingency requirements, and only minor additions are required by the PMAD subsystem since most of the components are already present on the MTA station. Two launch packages are sufficient to complete the EPS for the MTA station, with one additional launch required to add the elements needed for growth to a hybrid PMC station. Figure 2.2-1 shows the reference MTA and PMC station configurations.

The cost savings that could be realized with an MTA station was evaluated in detail for the specific operating scenarios of three years MTA operation (1992-1994) followed by two years PMC operation (1995-1996), compared with five years PMC operation (1992-1996). The average cumulative cost savings for the MTA increases steadily through 1992, the year of initial station operation. At this point, cumulative savings average $193M, due to DDT&E and production cost savings, as well as operations and additional savings during the first year of operation. However, beginning in 1993, DDT&E and production costs for the MTA growth to the PMC are charged and the savings begin to evaporate. By the end of 1995, first year of PMC station operation (for the MTA scenario), all savings are gone and the MTA in fact, has cost some $33M more than the initial PMC scenario. This is explained by noting that the savings in operations and operational costs obtained by operating an MTA station for three years, is smaller than the added cost of building a PMC station in two phases instead of one. Results of this analysis are shown in Table 2.2-1, which represents an average of four cases analyzed.

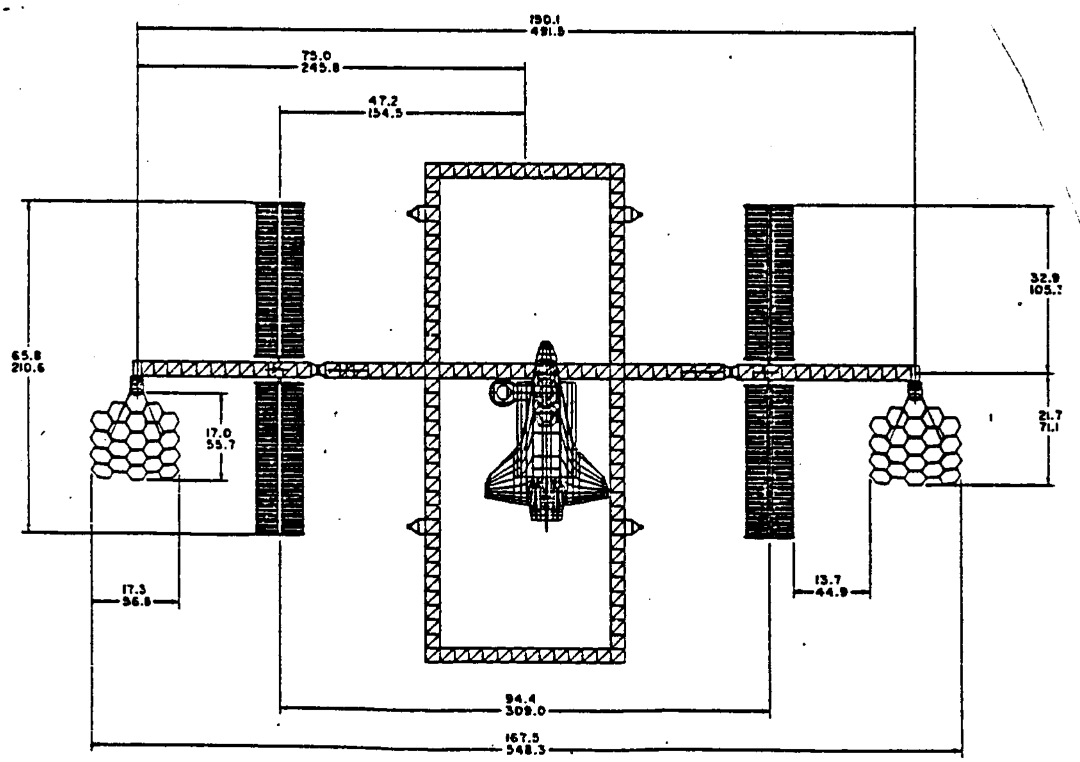
2.3 AUTOMATION AND ROBOTICS

During the Phase B conceptual and preliminary design work, our efforts in automation and robotics were based on guidance provided in the ATAC Report.

Automation is an integral part of the Space Station Electric Power System. The IOC station power system will be designed for flexibility so that increasingly sophisticated software and its associated hardware can be added in orbit. The goal at IOC is for the system to automatically operate, reconfigure



Man-Tended Station



PMC Station

Figure 2.2-1
Reference MTA & PMC Station Configurations

Table 2.2-1 Cumulative Cost Comparison of MTA and PMC Stations ($M)*

YEAR	MTA	PMC
1987	10	12
1988	106	127
1989	318	379
1990	743	875
1991	915	1056
1992	1213	1406
1993	1368	1476
1994	1436	1544
1995	1638	1604
1996	1693	1660

*Average of four cases analyzed

itself in case of failure, adequately monitor health, and provide a diagnostic expert system to assist with maintenance, failure isolation and ORU replacement. The evolutionary approach to automation will encourage the development and implementation of advanced technology to reduce human intervention and thus increase man's productivity. Beyond IOC, increasing expert system capability, health monitoring, artificial intelligence, and advanced sensors will be a vital extension of our current technology, their possible application to the Space Station will provide a clear focus for automation research and advanced development.

The development of the Rocketdyne and NASA LeRc power tests beds and their associated control software and hardware provides an excellent testing capability for advanced control, health monitoring, failure detection, isolation, and reconfiguration as well as expert systems and artificial intelligence. Such development resources will provide valuable data prior to IOC and beyond.

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For the assembly and early operation of the Space Station, teleoperation and EVA are expected to be available. Based on the expected national effort in robotic development, it is anticipated that this technology will be increasingly utilized during the growth and subsequent timeframes. Potential robotic applications and interim plan for automation and robotics have been submitted in DR17. To implement realistic goals for both the IOC and beyond,to establish basic level of automated control and diagnostic for the initial station and detail plans for expanding capabilities, we have developed a strategy that calls for three phases of automation development.

1. IOC - Initial hardware and software for diagnostics and controls.

2. Growth - Increase software sophistication and autonomy including increased use of expert systems for diagnostics, maintenance and control.

3. Advanced - Addition of the new diagnostic and computational hardware, with expanded use of artificial intelligence for all software applications.

An important aspect of this automation strategy is that research and development must be pursued to improve cost effective implementation of advances in available technology/analysis methods such as, Computer Capability, Artificial Intelligence, Diagnostic Sensors, Failure Mode Analysis, State Estimation, Control Theory. This research will be supported by Rocketdyne and NASA LeRC power system test beds to test new ideas and to improve design concepts.

By working from this solid base of applications research, it will be possible to continuously upgrade the station and platform power systems, as advancements in automation become affordable and practical. In this matter the station power system will become increasingly autonomous, and consequently will steadily improve the productivity of man in space.

2.4 EVOLUTIONARY GROWTH

The evolutionary growth study examined the planned growth configuration for the hybrid EPS including capabilities, limitations and constraints. Specifically examined were the system flexibility to grow beyond the base growth configurations and the feasibility for incorporation of advanced technologies. Early results indicated that costs for resizing the power generation modules for growth were not offset by any savings, and it was most cost-effective to grow by increasing the solar dynamic power. Therefore EPS growth is accomplished by replication of SD modules in blocks of 50 kWe, consisting of two 25 kWe modules. Growth of the platform power EPS will take place by replication of PV arrays and addition of batteries. The PMAD growth will be accomodated by extension of the DC and AC power buses and addition of PDCA's. Growth scenarios from man tended to 175 kWe, from 75 kWe to 332 kWe, and from 75 kWe to 487 kWe were studied.

The study considered the various technical factors in analyzing add-on power generation capability. Total estimated costs, incremental production costs and annual costs for the growth configurations were provided. Several growth path scenarios were evaluated and growth schedules were presented.

The growth scenario costs (reported in DR-19, DP4.4) illustrated that while IOC costs for the four principal concepts are roughly comparable, there is a wide disparity in life-cycle costs. For all growth scenarios considered, the SD option has a significant life-cycle cost advantage over PV. This advantage increases as the amount of PV on the IOC station increases. The difference is primarily attributable to the much higher replacement cost of PV hardware.

Technical constraints and limitations that affect the growth station were considered. They included shuttle constraints, module size, power losses, drag, shadowing, boom size, conductor mass, weight, structural factors, and scar factors. The schedule limitation for growth scenarios over 10 years placed a limit on the technological advancement that can be employed for EPS growth. Therefore, the study used existing technology and advanced technologies that could be ready by the end of preliminary design. As a result, nuclear and Stirling growth options were eliminated.

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The selected concept has the flexibility to accommodate new or modified SD modules, or possibly larger modules. The initial silicon PV arrays could be replaced with more advanced and higher capacity GaAs arrays and the Ni-H_2 batteries by Na-S batteries. This would be applicable on both the station and platform. Advanced PV growth is addressed in DR-19, DP4.3. The station flexibility also permits the use of other apportionments of PV and SD power.

2.5 SOFTWARE DEVELOPMENT ENVIRONMENT

The Software Development Environment (SDE) is the collection of software tools (programs) used for the specification, development, testing, configuration control, and documentation of computer programs.

2.5.1 Program Specification Tools

Program specification tools fall into two categories: word processors and Program Design Languages (PDLs). The use of commercial PDLs as well as Ada for writing algorithmic descriptions of requirements was examined and found to be feasible.

2.5.2 Program Development Tools

The program development tools selected for use are as follows:

a) Language: Ada (Certified cross compiler on the host computer)
b) a host computer such as the VAX 11/780 running under VMS
c) a micro-processor development system
d) a test support computer for controling, monitoring, and recording the results of test runs

2.5.3 Program Test Tools

The tools to be used provide the capability to test programs with pre-defined test sequences. To support this capability, the following programs were selected:

a) Test specification language compiler- This program compiles test sequences into transactions that can be loaded in real time to a system under test.

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b) Test driver- This program accepts test transactions and passes them to a system under test in real time.

c) Test monitor- This program acquires, time stamps, and records the results of a real time test.

d) Test reporter- This program reduces the results of a real time test to reports of interest.

2.5.4 Program Configuration Tools

These tools allow a complete system to be built from its source modules by testers or configuration control personnel. The system can then be tested or delivered to the customer. Part of the output of these programs is a list of the programs used to build the system, along with the version identifier of each program.

2.5.5 Documentation Tools

These tools are word processors used to document program specifications, test plans, test procedures, configuration control procedures, etc. In addition, they provide the capability necessary to annotate test results with the date the test was run and the controller(s) that were tested. This will ensure proper identification for review and cataloging purposes.

2.6 ADVANCED DEVELOPMENT

Numerous advanced development activities have been carried out that support the Phase B program. Some were implemented within the Phase B program; others were implemented with external funding.

The Phase B advanced development plan (DR-05) was formulated to address selected, key issues in providing for efficient capture, storage and transfer of heat energy from concentrated sunlight to a dynamic heat engine. The DR-05 advanced development plan was implemented. All activities described therein were completed.

The Garrett Corporation undertook to characterize LiF-MgF_2 Phase Change Material (PCM) for the CBC; conduct high temperature vacuum sublimation tests of candidate receiver materials; and thermally cycle a CBC thermal energy storage device. All tasks were completed, resulting in the following conclusions/recommendations pertaining to the CBC receiver design.

a. $LiF-MgF_2$ eutectic was characterized in detail and found to be unacceptable as a thermall energy storage PCM. The reason for this was that the release of the test of fusion occurred over a 300°F temperature range rather than at the theoretical eutectic temperature. Complimentary IR&D activities identified $LiF-CaF_2$ as a substitute PCM. The latter eutectic was characterized using differential thermal analysis techniques and found to be acceptable as the thermal energy storage medium.

b. Three candidate receiver materials (Inconel 600, 625 and MA754) were tested to ascertain rates of chromium sublimation. The measured material losses were projected for a 30 year CBC receiver life. All three alloys were found to have acceptable lives. Complimentary IR&D activities identified Haynes 188 as the preferred CBC receiver material. Since the Haynes 188 chromium content is similar to the contents tested in the Inconel materials, the 30-year projected material sublimation is expected to be acceptable for the Haynes 188 receiver.

c. A 2-inch diameter inernally finned concentric tube TES canister was cycle tested in a radiant heating furnace. The heat transfer performance was as predicted; however, a braze joint failure occurred after 33 melt/freeze cycles. A detailed examination of the hardware was performed. It was found that braze joints are not appropriate to this design. Future fabrication will utilize all welded construction.

The Sundstrand Corporation undertook to develop a specification for design and fabrication of an advanced ORC heat pipe with thermal energy storage. These tasks were successfully completed utilizing LiOH as the phase change material, potassium as the heat transport medium and nickel as the TES containment material, as reflected in the baseline ORC design.

The Harris Corporation completed two tasks as part of their advanced development activities; 1) characterization of concentrator hardware kinematics, and 2) evaluation of candidate substrates, reflective coatings, and protective coatings for ability to withstand atomic oxygen attack in LEO. Both tasks were completed successfully; the former leading to selection of an all-latch, constructible concentrator option, and the latter supporting the selection of silver reflective surface and $SiOx/MgF_2$ protective surface over a graphite/epoxy substrate as the baseline design configuration for the Space Station concentrator surface segments.

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Numerous other advanced development activities were carried out (and are continuing). These activities are complimentary in nature. Many of these activities are being funded with Rocketdyne team member IR&D funds. Others are being funded by the U.S. government. These activities are related to the Phase B contract effort but not a direct part of it. Rocketdyne has provided a summary status report quarterly to NASA and has also supported NASA's Advanced Development Program Reviews with detailed briefings to NASA program personnel. A complete list of the related activities is contained in Figure 2.6-1. The listing is organized by major system element (power generation, energy storage, PMAD, system technology) and includes both IR&D and contracted activities.

2.7 CUSTOMER ACCOMMODATIONS

Work Package 04 has the responsibility of providing utility power to all customers (housekeeping loads and payloads). To define an electrical power system that effectively accommodates customer needs the latest version of the "Langley data base" currently resident at NASA/JSC was utilized for a reference. Comparisons of various approaches and their ability to accommodate different load configurations were studied. A concept using a moderate number of power distribution centers and a family of standard load converters tailored to user equipment needs was selected.

2.7.1 Design Approach

All electrical loads are served from 22 power distribution and control assemblies (PDCA) which are located throughout the station. Each PDCA contains remote power controllers (RPC) that function as the electrical interface with each load. Three RPC sizes were found to accommodate the users, (75 amp, 25 amp, 5 amp). Connection to more than one RPC is required for fault tolerant operation. The user can choose to be a critical load which connects to three RPCs, an essential load which connects to two RPCs or a non-essential load connecting to a single RPC. The EPS will supply power to Work Package 02 utility ports and Work Package 01 equipment racks as well as Work Package 03 utility ports. Utility ports and locations will be determined by other work packages.

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1.0 POWER GENERATION SUBSYSTEM

1.1 PV SOLAR ARRAY TECHNOLOGY

1.1.1 KAPTON SUBSTRATE SUBSTITUTE (FORD)

1.1.1.1 MANUFACTURING EVALUATION OF CANDIDATE SUBSTITUTE

1.1.1.2 TASK RESTRUCTURED (SEE 1.1.4)

1.1.2 SOLAR ARRAY DESIGN/COST OPTIMIZATION (FORD)

1.1.3 ATOMIC OXYGEN TEST DEVELOPMENT (SPACE TRANSPORTATION SYSTEMS DIVISION, ROCKWELL)

1.1.4 SOLAR ARRAY THERMAL CYCLING LIFE (FORD)

1.1.5 SEMI-PARABOLIC, LOW APERTURE THROUGH SOLAR CONCENTRATOR (GENERAL DYNAMICS)

1.2 SD ORC RECEIVER/STORAGE (SUNDSTRAND)

1.2.1 THERMAL ENERGY STORAGE

1.2.2 ADVANCED CIRCUMFERENTIAL HEAT PIPE

1.2.3 ADVANCED HEAT PIPE TEST

1.2.4 RECEIVER MATH MODEL

1.2.5 DEMONSTRATION HEAT PIPES

1.2.6 TOLUENE DEGRADATION

1.2.7 WORKING FLUID STABILITY

1.2.8 TWO-PHASE THERMAL MANAGEMENT SYSTEM

1.2.9 RC-1 DEGRADATION

1.2.10 ORC DEMONSTRATION ENGINE

1.3 SD BRAYTON CYCLE RECEIVER/THERMAL STORAGE (GARRETT)

1.3.1 RECEIVER SECTION

1.3.2 CHROMIUM SUBLIMATION

1.3.3 PHASE CHANGE MATERIALS

1.4 SD GENERIC RECEIVER (ROCKETDYNE)

1.4.1 ALTERNATE PHASE CHANGE MATERIAL INVESTIGATION

1.4.2 LIQUID METAL LOOP THERMAL STORAGE

1.4.3 GENERIC RECEIVER/STORAGE DEVELOPMENT AND ENGINE DEMONSTRATION

1.5 SD CONCENTRATOR TECHNOLOGY (HARRIS)

1.5.1 DEPLOYABLE TRUSS STRUCTURE

1.5.2 LARGE SPACE STRUCTURES TECHNOLOGY

1.5.3 DESIGN AND TECHNOLOGY STUDY FOR EXTREME PRECISION ANTENNA STRUCTURES

1.5.4 ADVANCED MATERIALS

1.5.5 THIN FILM SOLAR CONCENTRATOR DEVELOPMENT

1.5.6 MAST FLIGHT EXPERIMENT

1.2.9 RC-1 DEGRADATION

1.2.10 ORC DEMONSTRATION ENGINE

1.3 SD BRAYTON CYCLE RECEIVER/THERMAL STORAGE (GARRETT)

1.3.1 RECEIVER SECTION

1.3.2 CHROMIUM SUBLIMATION

1.3.3 PHASE CHANGE MATERIALS

1.4 SD GENERIC RECEIVER (ROCKETDYNE)

1.4.1 ALTERNATE PHASE CHANGE MATERIAL INVESTIGATION

1.4.2 LIQUID METAL LOOP THERMAL STORAGE

1.4.3 GENERIC RECEIVER/STORAGE DEVELOPMENT AND ENGINE DEMONSTRATION

1.5 SD CONCENTRATOR TECHNOLOGY (HARRIS)

1.5.1 DEPLOYABLE TRUSS STRUCTURE

1.5.2 LARGE SPACE STRUCTURES TECHNOLOGY

1.5.3 DESIGN AND TECHNOLOGY STUDY FOR EXTREME PRECISION ANTENNA STRUCTURES

1.5.4 ADVANCED MATERIALS

1.5.5 THIN FILM SOLAR CONCENTRATOR DEVELOPMENT

1.5.6 MAST FLIGHT EXPERIMENT

1.5.7 NAVY REMOTE OCEANOGRAPHIC SATELLITE SYSTEM

1.5.8 SOLAR CONCENTRATOR ADVANCED DEVELOPMENT

1.5.9 NASA SCATTEROMETER ANTENNA SUBSYSTEM

1.5.10 KINEMATICS RESEARCH MODEL

1.6 TRANSIENT MODEL AND ANALYSIS (ROCKETDYNE)

1.7 SOLAR POWER ELECTRIC ENERGY DEMONSTRATION SYSTEM (ROCKETDYNE)

1.8 POWER GENERATION THERMAL CONTROL MODELING (ROCKETDYNE)

1.9 SOLAR DYNAMIC POWER SYSTEM DEFINITION STUDY (ROCKETDYNE)

1.10 PV/ESS ON-ORBIT PERFORMANCE MODELING (ROCKETDYNE)

2.0 ELECTRICAL ENERGY STORAGE SUBSYSTEM

2.1 NICKEL-HYDROGEN BATTERY LIFE TESTS (FORD)

2.2 HIGH CAPACITY IPV $Ni-H_2$ CELLS AND BATTERIES (FORD)

2.2.1 CELL DESIGN AND DEVELOPMENT

2.2.2 BATTERY DESIGN AND DEVELOPMENT

2.2.3 THERMAL DESIGN

2.2.4 ENGINEERING MODEL CELLS

2.3 SODIUM-SULFUR BATTERIES (FORD)

2.3.1 RELIABILITY AND COST TRADES

2.3.2 LARGE BATTERY DESIGNS

2.3.3 IMPROVED CELL DESIGNS

2.3.4 THERMAL DESIGN AND CONTROL

2.3.5 TASK RESTRUCTURED (SEE 2.3.6)

2.3.6 CELL DEVELOPMENT

2.3.7 BATTERY DEVELOPMENT

2.4 ADVANCED (BIPOLAR) $Ni-H_2$ BATTERY DEVELOPMENT

2.5 REGENERATIVE FUEL CELL ENERGY STORAGE SYSTEM STUDY (SPACE STATION SYSTEMS DIVISION, ROCKWELL)

3.0 POWER MANAGEMENT AND DISTRIBUTION SUBSYSTEM

3.1 DC POWER SYSTEM MODEL UPGRADE (FORD)

3.2 HIGH POWER, HIGH VOLTAGE REGULATORS (FORD)

3.2.1 SOLAR ARRAY SHUNT REGULATOR

3.2.2 HIGH POWER VOLTAGE REGULATOR

3.3 AC ACOUSTIC NOISE STUDY (SUNDSTRAND)

3.4 AC REMOTE POWER CONTROLLER (SUNDSTRAND)

3.5 AC RESONANT CONVERTER (SUNDSTRAND)

3.6 AC POWER SYSTEM MODEL STUDY (SUNDSTRAND)

3.7 AC RESONANT POWER CIRCUIT TECHNOLOGY (SUNDSTRAND)

3.8 PMAD TEST BED (ROCKETDYNE)

3.9 HIGHER ORDER LANGUAGE (ROCKETDYNE)

3.10 PMAD ADAPTIVE CONTROL SYSTEM (ROCKETDYNE)

3.11 SPACE POWER SYSTEM COMPONENT CHARACTERIZATION (ROCKETDYNE)

3.12 AC POWER SYSTEM TEST BED (25 KW) (GENERAL DYNAMICS)

3.13 AC POWER SYSTEM BREADBOARD (5 KW) (GENERAL DYNAMICS)

4.0 SYSTEM TECHNOLOGY

4.1 COST MODEL DEVELOPMENT AND VERIFICATION (FORD)

4.2 GEOSTATIONARY PLATFORM BUS STUDY (FORD)

4.3 COMMUNICATIONS SATELLITE SYSTEMS OPERATIONS WITH THE SPACE STATION (FORD)

4.4 ADAPTIVE RIGID BODY CONTROL FOR AN EVOLVING SPACE STATION (FORD)

4.5 CONTROL SYSTEM ARCHITECTURE (ROCKETDYNE)

4.6 SPACE POWER SYSTEM HEALTH MONITORING (ROCKETDYNE)

4.7 SPACE MODELING AND SIMULATION (ROCKETDYNE)

4.8 SPACE STATION FLIGHT EXPERIMENTS (ROCKETDYNE)

4.9 SPACE STATION EXPERIMENT DEFINITION: ADVANCED POWER SYSTEM TEST BED (FORD)

4.10 ADVANCED THERMAL DISCONNECT (GENERAL DYNAMICS)

Figure 2.6-1 Advanced Research and Development Activities

2.7.2 Resources

All PDCAs on the Space Station and Platform deliver utility power of the same voltage and frequency. This allows payloads to be moved from one station or platform location to another without modification. There are 22 PDCAs located on the Space Station. A total of ten PDCAs are located throughout the truss structure at regular intervals to support truss mounted loads. Loads within manned modules are serviced by 12 PDCAs. The power management and distribution system of the platform is nearly identical to that of the station. Because of the platforms' smaller size, only two PDCAs (one housekeeping and one payload) are used. Electrically and mechanically, the platform's user interfaces maintain a high degree of commonality with that of the station. Payloads are attached to the PMAD subsystem the same way as on the station.

2.7.3 Load Converters

Work Package 04 will design, qualify, and produce a family of load converters to satisfy customer needs. For commonality and ease of integration, all Space Station customers can use this family of load converters thus lowering payload development costs. Preliminary study results indicate that the following ten configurations should be developed.

Load Converter	Voltage	Freq. (Hz)	Phase	Power (watts)	Reg (%)	Mass (lbs)	Length (in)	Width (in)	Height (in)	Thermal (watts)	EFF (%)	Load Description
#1	120	400	3	200	5	12	10	4	4	20	90	lights, small motors
#2	208	400	3	500	5	25	10	5	5	45	91	pumps, motors
#3	TBD	var	1	1000	10	40	15	6	6	80	92	induction heating devices
#4	TBD	var	1	500	10	25	10	6	6	45	91	heating devices
#5	5	DC	-	200	2	5	5	3	3	40	80	electrical processor and controls
#6	+/-15	DC	-	1000	2	40	15	5	5	150	85	electrical/instrumentation devices
#7	50	DC	-	500	5	20	10	5	5	85	83	controls, devices
#8	28	DC	-	1000	10	40	15	5	5	150	85	critical devices
#9	150	DC	-	200	2	10	6	3	3	30	85	battery processes
#10	400	DC	-	500	5	5	10	5	5	70	86	transmitters

2.8 OPERATIONS PLANNING

Rocketdyne Phase B operations planning efforts concentrated on interfacing with Work Package participants and other NASA centers to cover all aspects of Space Station processing, assembly, and operation. This knowledge was brought back to designers working on the various EPS concepts to assure that an operable design that considered all life cycle cost aspects would result.

Pre-launch/post-landing processing, launch packaging/manifest, assembly sequence & methods, operations, on-orbit maintenance, test & verification requirements/procedures, safety, reliability, and life cycle cost, were discussed and reviewed in working group meetings at LeRC, JSC, KSC, MSFC, and GSFC.

Identification of commonality opportunities in the power generation, energy storage and the PMAD subsystem, and other general opportunities were made (reported in DR19, DP4.1).

Preliminary assessments of on-orbit assembly of both ORC and CBC SD power systems, including mass, volume and EVA timelines were made. Also included were annual costs for ORU's, consummables, on-orbit operations and maintenance, and ground based equipment for all eight Space Station reference configurations. Operations & logistics comparison ratings were also submitted for each reference EPS concept trade study. These results were reported in DR-19, DP4.2.

Launch packaging, on-orbit assembly, preliminary ILS resource requirements to support maintenance, and additional operations & logistics ratings of each reference EPS concept were summarized in DR-19, DP4.3.

The annual cost of maintenance and maintenance support, resource requirements to support maintenance, EPS logistics requirements, and launch packaging for space station reference concepts was developed and reported in DR-19, DP4.1.

Other Activities included:

1) Development of the EPS Operations Plan, and submittal of this data report including the body of the ILS plan (DR-07) in December 1985.

2) Recommended that the Space Station Pre-launch Post-landing PDRD & Plan be changed to identify a specific ground processing option as it will affect Phase C/D planning.

3) Provided comments on the following data to NASA/LeRC:

- on-orbit assembly of WP-04 hardware
- the LSA planning team's standardized LSA process.
- updated ORU lists periodically based on latest EPS configuration.
- Restructured JSC 30000 with new data separation, i.e. (1) Functional Requirements, (2) Processing Requirements, and (3) Design-to-Requirements.
- The proposed EPS maintainability Requirements document.
- Boeing Aerospace Space Station Planning & Analysis Study. During this review and meeting, Rocketdyne provided up-to-date EPS data so that the Boeing system will produce more realistic failure rates and criticality category codes.

4) Provided WP-02 contractors with (1) EPS hardware attachment details and assembly timelines for their use in determining station assembly sequence and (2) correct battery package and cable weights for their use in manifest analyses.

5) Assisted in preparation of Packaging, Handling, & Transportation requirements document. Submitted a strawman plan to NASA/LeRC.

2.9 PRODUCT ASSURANCE

The primary Product Assurance functions in Phase B were to:

a) aid in the selection of the most suitable electrical power system concept for the Space Station,

b) conduct a formal Failure Modes and Effects Analysis and a Preliminary Safety Analysis of the selected concept, and

c) absorb and promulgate NASA's product assurance objectives and requirements for providing a safe, productive, economically viable work environment in an Earth orbiting vehicle.

In support of the concept selection, analyses were conducted to identify and quantify (where applicable) the reliability and safety features of each system which have the most, or the least, impact on Space Station design and operation. Maintainability/ maintenance considerations were addressed to the extent that they contributed to the determination of anticipated failure frequencies and replacement times.

Simplified block diagrams of the candidate concepts were prepared based upon the orbital replacement units (ORUs) which comprise the respective systems. By using consistent reliability predictions for comparable ORUs, relative probabilities of successful system performance were computed and system availabilities were assessed. Extrapolations of data acquired for similar equipment exposed to less severe environments were combined with conservative engineering judgments to quantify the relative reliabilities of the candidate concepts. The hybrid concept was found to offer a favorable combination of reliability/availability.

Comparisons between the inherent safety aspects of the candidates were also conducted. Evaluations were performed of the absolute safety of the systems' fluids, the potential for adverse incidents occurring as a result of the type of system being considered (i.e., Solar Dynamic or Photovoltaic), and the opportunities for encountering personnel and equipment hazards.

A matrix was developed which presents the various hazards associated with the respective systems and their major elements. Each existing hazardous condition or opportunity for a hazardous condition to develop was tabulated in relation to the most prominent phases of the Space Station's operational life: launch, deployment/erection, on-orbit operation, and maintenance. Further, an overview tabulation of the most significant hazards and their relative severity as a function of operational life was prepared. The hybrid concept was judged to satisfy safety requirements.

In compliance with contract requirements, a Preliminary Safety Analysis (DR 11) and a Failure Modes and Effects Analysis (DR12) were prepared and submitted in July 1986.

A critical review of the original product assurance requirements document (J840001, Product Assurance Requirements for the Space Station) was performed and reported in DR 02 (November 1985). Subsequently, a series of NASA and Space Station work package contractor meetings were conducted to develop a coordinated product assurance requirements document that would satisfy program perceived needs. These efforts culminated in the issuance of Section 9 to JSC 30000, Space Station Program Definition and Requirements Document and its baselining in October 1985. These data have been distributed throughout Rocketdyne and provided to the major team members as the documents have evolved for use in the concept definition and preliminary design process.

2.10 DESIGN AND DEVELOPMENT PHASE PLANNING

The design and development phase planning task embodied planning for the C/D phase of the Space Station Power program. It included development of a work breakdown structure (WBS) and WBS Dictionary (DR-08) defining every element of the structure. Each version of the WBS and dictionary submitted to NASA-LeRC for review and approval provided the basis for estimating in each subsequent submittal of the Design, Development, and Operations Cost Document (DR-09), another requirement of this task. The cost document submittals were comprised of cost estimates based on various design scenarios and groundrules. Also included as a part of Phase C/D planning was development of a technical management information system (TMIS). Rocketdyne has implemented a personal computer local area network providing resources for programming, modeling, financial planning, scheduling, database management, word processing, and electronic mail with access to its subcontractors and NASA-LeRC. The various TMIS capabilities have been demonstrated and widely used during Phase B, providing the essential base for the expanded system planned for Phase C/D.
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In addition, other design and development phase planning for the Space Station Power Program Phase C/D are as follows:

a) the Project Implementation Risk Assessment Plan of the EPS. The technical risk is the risk of obtaining poorer than expected operational performance due to problems encountered during design, development, test, verification, and production. When the technical performance becomes unacceptable and requires additional resources, the risk factor contributes to costs and schedule risks.

b) The reviewing of the "J" series documents to focus on enhancing the cost effectiveness of the Space Station Program (SSP) and the applicability to Phase C/D of the Electric Power System (EPS).

c) International Systems of Units Input Study where Rocketdyne as part of the Project Implementation Plan conducted a study (reported in DR10) to assess and evaluate the impact of adapting the SI Standard to Work Package 04 of the Space Station. The study, which encompassed both literature and subcontractor survey, ascertained that some subsystems can be specified in metric terms without undo problems, while others will have significant cost impact.

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3.0 SUMMARY OF TRADE STUDIES

The objectives of Rocketdyne's trade study and analysis effort prior to IRR were to (1) provide sufficient data on competing concept designs, including costs, to allow NASA-LeRC to select the electrical power system (EPS) concept(s) that best support the station and platforms and (2) develop extensive supporting data and parametric analysis results for use by NASA in higher level system trades.

The major system trade studies in support of the EPS design were reported in DR19, DP's 4.2, 4.3 and 4.4. These studies developed reference concepts, decision criteria, and evaluated data from which recommendations were made.

Rocketdyne's overall trade study plan is illustrated in Figure 3.1-1. Three trade study iterations were made prior to IRR. The trade study schedule including subsystem trades and analysis is shown in Figure 3.1-2. The first two iterations (reported in DPs 1 & 2) were completed prior to RUR's 1 and 2. The last iteration (reported in DP 4.4) was completed two months prior to IRR. Rocketdyne's trade study convergence plan is represented in Figure 3.1-3. The circles on the left-hand side of this figure represent the point-of-departure designs and alternatives selected prior to contract study. As the trade studies progressed through the iterations, the subsystem options were progressively reduced and the reference concepts refined.

3.1 SYSTEM TRADES

Twelve reference concepts were selected for evaluation and comparison for the most recent (DP.4.4) systems study iteration. These reference concepts are shown in Table 3.1-1 and described in detail in Section 3.0 of DP.4.4. All 12 concepts included PV platforms.

The reference concepts were designed to satisfy a common set of requirements to provide a fair basis for comparison. These common requirements included (1) average, peak, and contingency power requirements and failure tolerance criteria; (2) PMAD efficiency assumptions; and (3) station buildup power levels.

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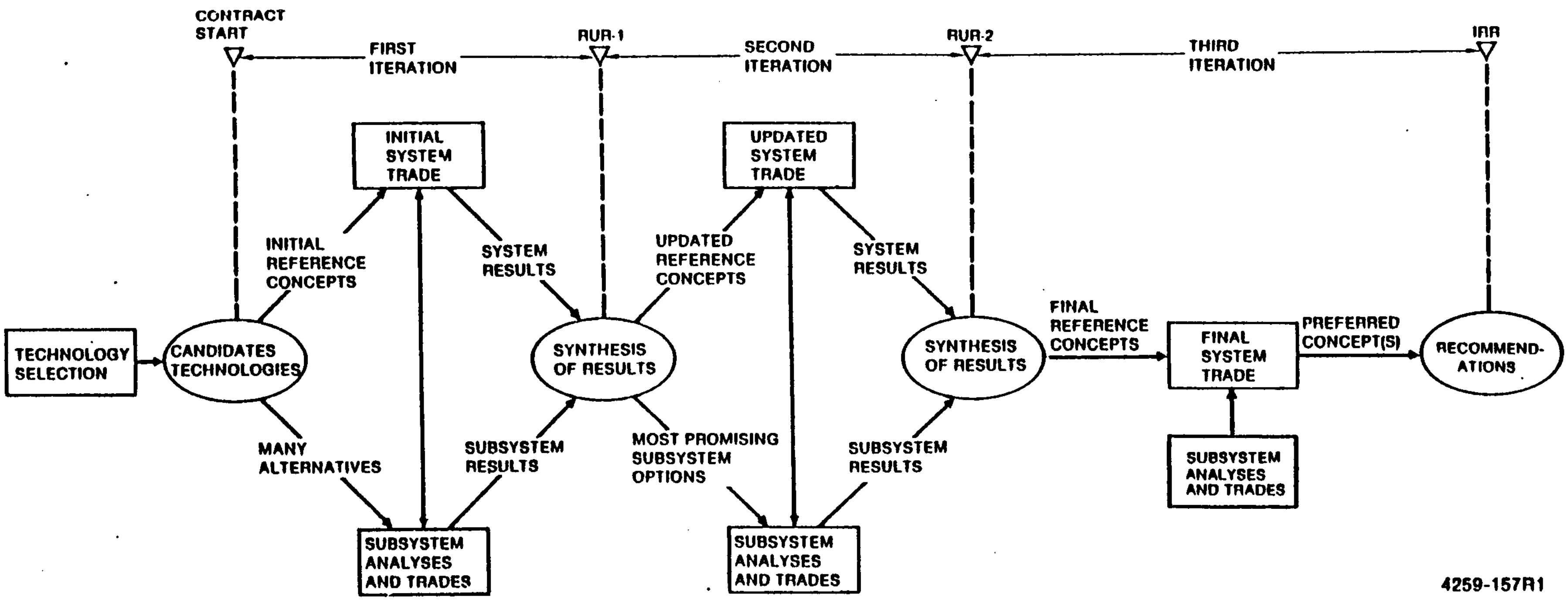

Figure 3.1-1 Overall Trade Study Plan

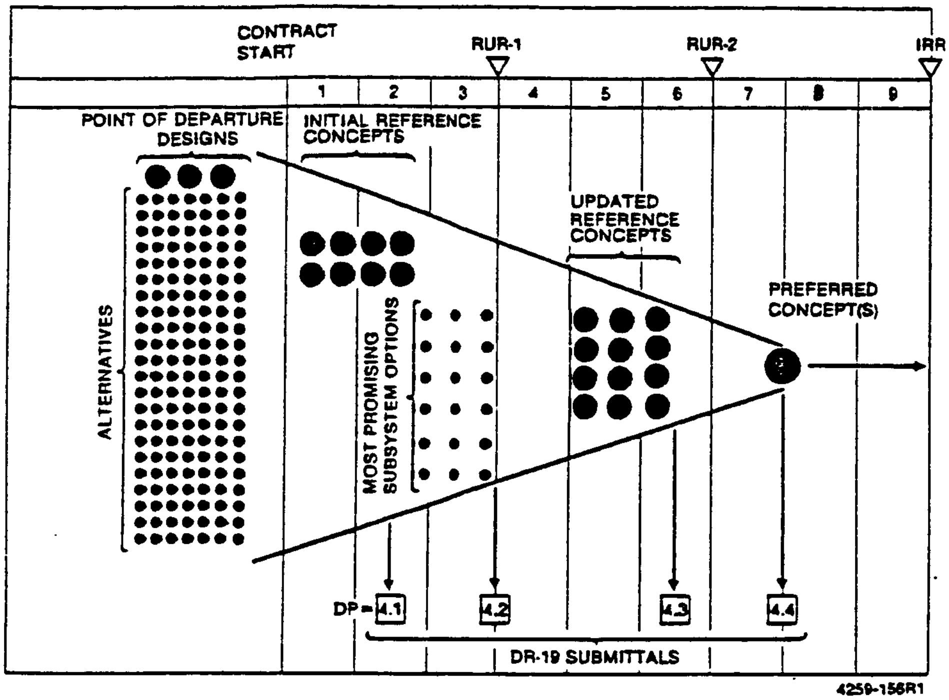

Figure 3.1-3 Trade Study Convergence Plan

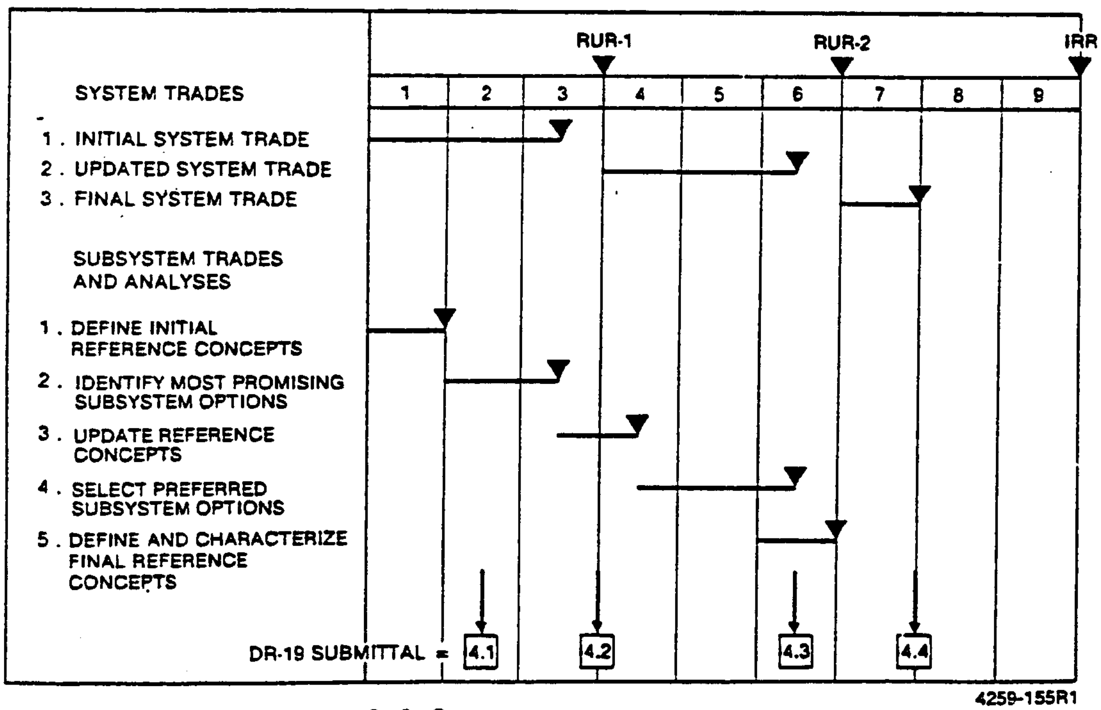

Figure 3.1-2 Trade Study Schedule

TABLE 3.1-1

REFERENCE CONCEPTS (DP 4.4)

Concept			Station Man-Tended (37.5 kW)	IOC (75 kW)	Growth (300 kW)	Platform Initial (8 kW)	Platform Growth (24 kW)
PV	RFC		PV	PV	PV	PV	PV
	B		PV	PV	PV	PV	PV
SD	CBC		CBC	CBC	CBC	PV	PV
	ORC		ORC	ORC	ORC	PV	PV
Hybrid	RFC	CBC	PV	PV/CBC	PV/CBC	PV	PV
		ORC	PV	PV/ORC	PV/ORC	PV	PV
	B	CBC	PV	PV/CBC	PV/CBC	PV	PV
		ORC	PV	PV/ORC	PV/ORC	PV	PV
PV/SD GROWTH	RFC	CBC	PV	PV	PV/CBC	PV	PV
		ORC	PV	PV	PV/ORC	PV	PV
	B	CBC	PV	PV	PV/CBC	PV	PV
		ORC	PV	PV	PV/ORC	PV	PV

PV = photovoltaic
RFC = regenerative fuel cell
B = batteries
SD = solar dynamic
CBC = closed Brayton cycle
ORC = organic Rankine cycle

Methodology of Evaluation

The decision criteria used in the system trade study consisted of three elements: (1) go/no-go constraints, (2) objective measures, and (3) supplemental (subjective) ratings. The go/no-go constraints were fundamental limits so important that it would not be worth considering concepts that do not satisfy them. The go/no-go constraints used in out trade studies included (1) STS compatibility and (2) IOC schedule. All of the reference concepts satisfied these go/no-go constraints.

The objective measures were the primary means for ranking the reference concepts. The objective measures in our decision criteria included: (1) initial cost, (2) growth cost, (3) operations cost (including maintenance and logistics), and (4) life-cycle cost (LCC).

The supplemental (subjective) ratings provided an additional means, other than cost, for rating the concepts. These subjective ratings supplemented the objective (cost) measures and affected decisions when the objective rankings were about equal. The supplemental rating criteria included (1) technology readiness (schedule/cost risk), (2) reliability and availability of power, (3) safety, (4) growth potential, (5) flexibility to accommodate lower IOC power requirements, (6) capability for larger peaks/contingency, (7) flexibility to allow lower orbit altitudes, and (8) tolerance to pointing errors.

Sections 4.2 of DP-4.4 details the objective and subjective criteria.

Associated Costs and Sensitivity

Table 3.1-2 shows our base cost estimates for each of the 12 reference EPS concepts, broken down into five major cost elements.

Figure 3.1-4 compares LCCs for the four major EPS options. The costs shown in this figure are the average of those for the subsystem options in Table 3.1-2. Figure 3.1-4 clearly indicates that operations cost is a major part of LCC. Figure 3.1-5 breaks operations cost into its constituent elements for the PV and SD concepts This figure shows the major operations cost

TABLE 3.1-2

SUMMARY OF STATION EPS COSTS (1987 $M)*

					HYBRID				PV/SD GROWTH			
	PV		SD		RFC		B		RFC		B	
COST ELEMENT	RFC	B	CBC	ORC	CBC	ORC	CBC	ORC	CBC	ORC	CBC	ORC
Phase C/D cost (75 kW)	946	923	984	990	1053	1031	1028	1006	1119	1103	1088	1072
Other IOC cost **	170	176	234	256	230	235	222	227	170	170	176	176
Growth cost (75-300 kW)	1303	1283	871	863	953	951	953	951	953	951	953	951
Operating Cost (30 years)	3635	3719	1912	1813	2082	2006	2089	2014	2299	2240	2318	2258
Total (life-cycle cost)	6075	6101	4001	3922	4318	4223	4292	4198	4541	4464	4535	4457

* DP 4.4

** Includes hardware launch, initial spares and impact on other station system costs

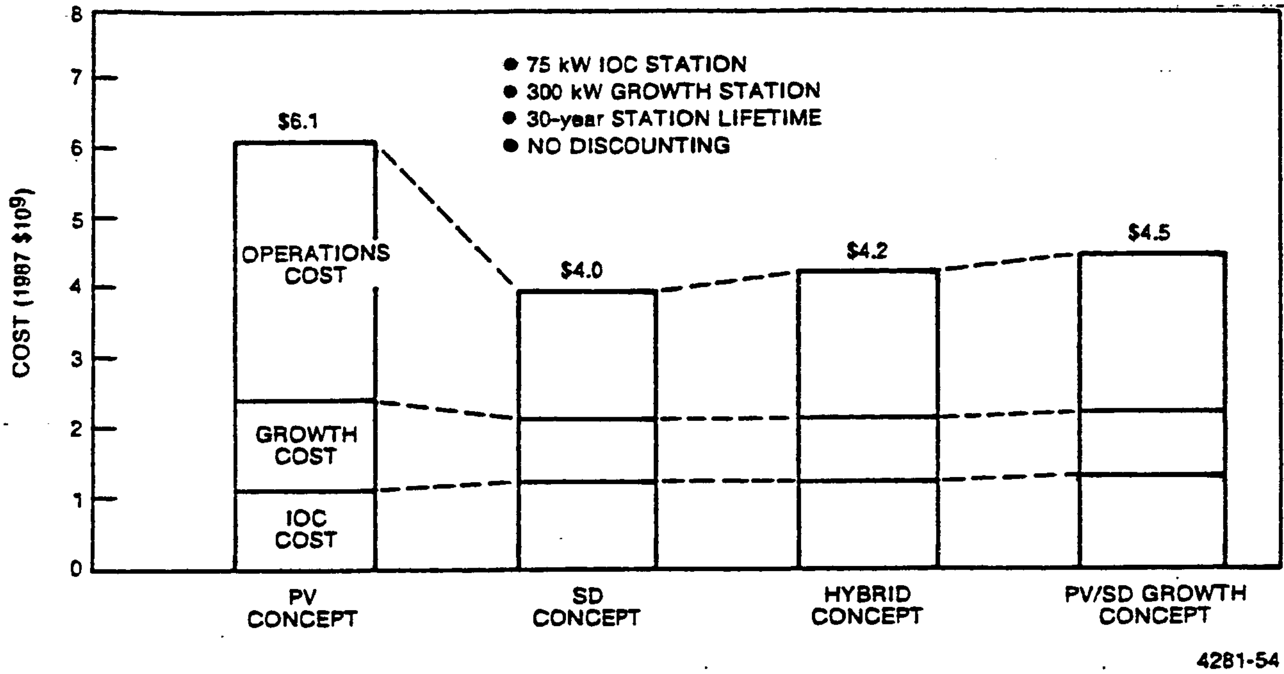

Figure 3.1-4 Station EPS Life-Cycle Cost Comparison(DP 4.4)

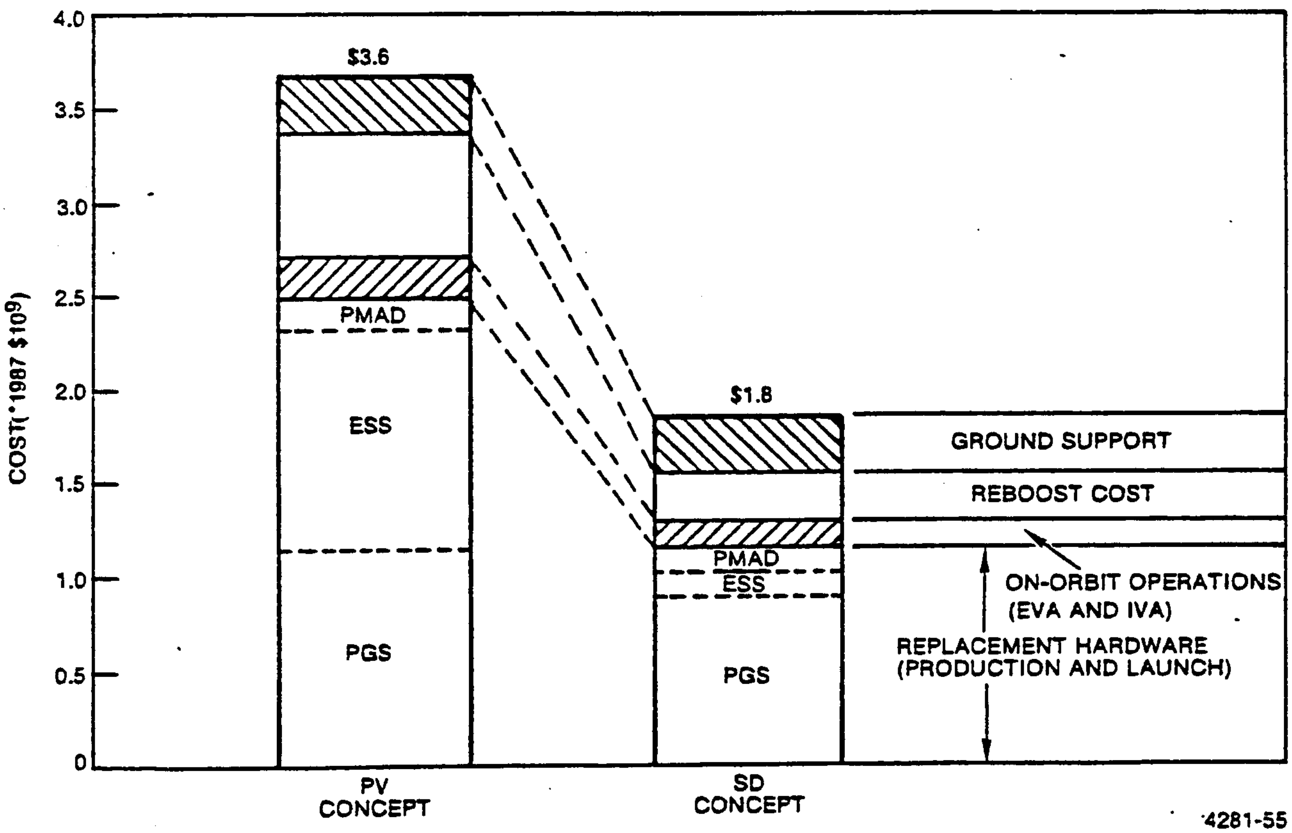

Figure 3.1-5 PV versus SD Operations Cost Comparison (DP 4.4)

elements for the PV concept to be (1) PGS and ESS replacement hardware and (2) reboost. The PGS replacement costs are large for the PV concept, even though a low PV array replacement frequency of once every 25 years was used; this is so because PV arrays have large production costs. The ESS replacement costs are large because batteries and RFCs are postulated to have (high) replacement frequencies of once every 5 and 6 years, respectively. The major operations cost element for the SD concept is replacement hardware. The major contributors to this cost are the concentrators and receivers, which are assumed to have replacement frequencies of approximately once every 25 years. The details of the cost analysis are presented in Section 4.3 of DP-4.4. Figure 3.1-6 shows the sensitivity of station EPS LCC to several key assumptions in the cost assessment. For all cases examined, the PV concept has significantly higher LCC than the other system options.

Supplemental (Subjective) Analysis

Subjective ratings are used in the system trade to supplement the objective (cost) measures and thereby provide a better basis for decision making. The subjective ratings for the final reference concepts and the bases for them are presented in Section 4.4 of DP-4.4.

Table 3.1-3 summarizes the supplemental (subjective) ratings given in the 12 reference concepts. These ratings reflected best judgement concerning the eight supplemental criteria categories. Highlights of this table include:

- The principal strengths of the PV concept are their technology readiness (low schedule and cost risks), tolerance of pointing errors, flexibility to accommodate lower IOC power requirements, and inherent capability to handle large peak loads. Current indications are that station control and dynamics considerations may prevent growth beyond about 225 kW (net) with PV concepts, but this should be confirmed by WP-02.

- The major strengths of the SD concepts are their growth potential and flexibility for lower orbit altitudes (due to their small drag

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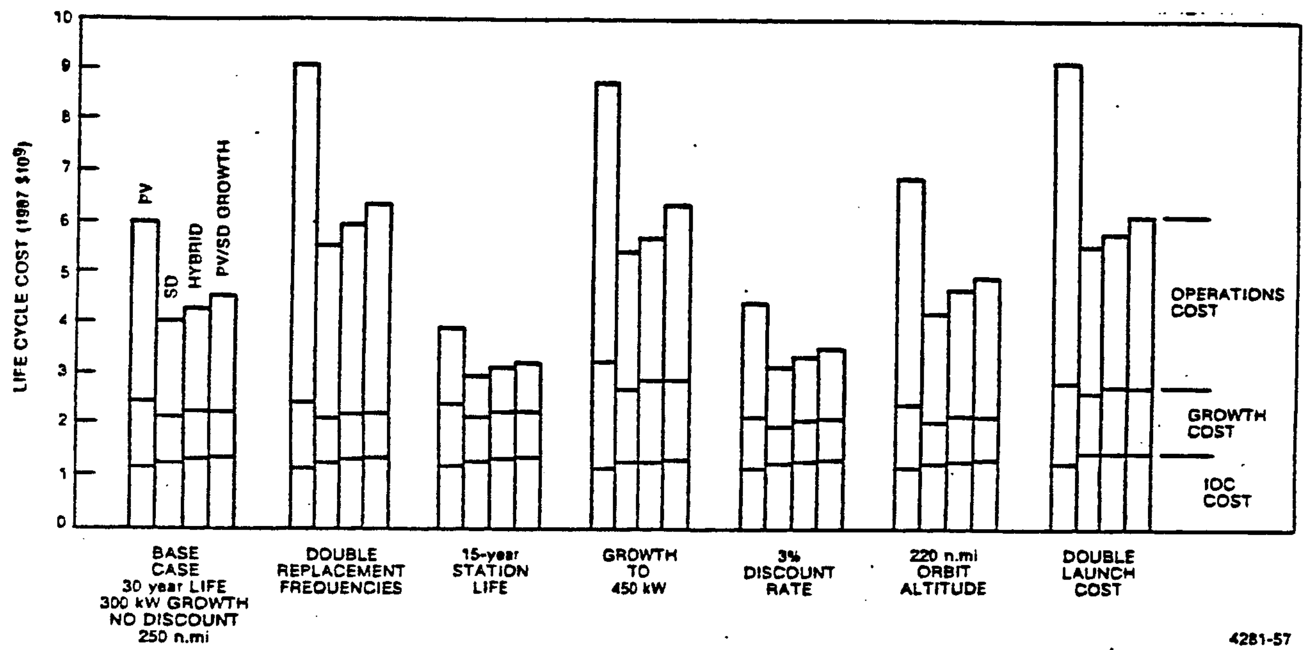

Figure 3.1-6 Sensitivity of Station EPS Life-Cycle Cost to Variations in Key Assumptions (DP 4.4)

TABLE 3.1-3

SUBJECTIVE RATINGS

Criteria	PV		SD		Hybrid				PV/SD Growth			
					RFC		B		RFC		B	
	RFC	B	CBC	ORC	CBC	ORC	CBC	ORC	CBC	ORC	CBC	ORC
Technology development risk	B^-	B^+	C	C^+	C^+	B^-	B^-	B	B^-	B^-	B^+	B^+
Reliability and availability of power	B^-	B	C	C	B^-	B^-	B	B	B^-	B^-	B	B
Safety	B^-	B	C	C^-	C	C^-	C^+	C	C^+	C	B^-	C^+
Growth potential	C	D	A^-	A^-	A^-	A^-	B	B	C^+	C^+	C	C
Flexibility for lower IOC power requirements	A^-	A	B^-	B^-	A^-	A^-	A	A	A^-	A^-	A	A
Capability for larger peaks/ contingency	A	B^+	C^-	C	B	B^+	C^+	B^-	B^+	A^-	B^-	B
Flexibility for lower orbit altitudes	D^+	D^+	A	B^+	B^+	B^-	B^+	B^-	B	B^-	B	B^-
Tolerance of pointing errors	A	A	C	C^+	B^-	B	B^-	B	B	B^+	B	B^+

areas). In addition to these advantages, SD offers significantly lower LCC than PV.

- The subjective ratings for the hybrid concepts are generally between those of the PV and SD concepts. Hybrid advantages include good programmatic flexibility (e.g., ability to readily adapt to lower IOC power requirements and larger growth requirements), capability for larger peaks and contingency, and good growth path with low schedule/cost risk.

- The PV/SD growth concepts are similar to the hybrids, but they provide less programmatic flexibility and have more problematic growth paths since SD is not included on the IOC station.

- Batteries are rated higher than RFCs in the areas of technology readiness (schedule/cost risk) and reliability, but poorer in growth potential and the capability to accommodate larger peaks and/or contingency requirements.

- The CBC and ORC concepts are rated approximately equal.

Design Trade Off and Recommendations

The competing options for the latest major system trade studies have been identified and analyzed in detail in Section 4.0 of DP-4.4. Discussion of the alternatives considered, the significant cost drivers and the rationale for selection was also presented. A summary of the conclusions and recommendations reported in DP 4.4 follows.

The RFC versus battery trade study concluded that the selection depend greatly on stored energy requirements (e.g., for contingency, peak power, load matching, safe haven) and commonality considerations that extend beyond WP-04. It was, therefore, recommended that requirements should be firmed up and commonality opportunities discussed with other work package centers before a selection is made. Following DP 4.4 submittal, the battery option was selected because of requirement changes and to provide commonality with the platform ESS. Elimination of the safe haven requirement and a reduction of contingency power requirements reduced the stored energy requirements and the advantage of RFC growth potential.

The CBC versus ORC trade study concluded that both concepts have roughly equivalent cost and technical performance. No overwhelming discriminators have been identified to date. However, tests that were currently under way to demonstrate the key design features of each could have uncovered potential discriminators. It was, therefore, recommended that the decision on CBC versus ORC be delayed until the results of these tests are available. Since DP 4.4, preliminary ORC test results have been completed and CBC tests have just been started.

The key conclusions of the PV versus SD trade are:

- PV is desirable for initial station buildup and offers advantages of the lower development cost and risk. It has good inherent peaking an contingency capability, and tolerance of pointing errors However, it has a LCC that is about 50% higher than SD.

- SD provides good growth potential and significantly lower LCC. Large module sizes are best for growth and low LCC.

- Hybrid concepts combine strengths of PV and SD.

- PV panels and either RFCs or batteries support early station buildup and satisfy peaking, contingency, and safe haven requirements.

- SD modules (either CBC or ORC) provide a low-cost means to achieve full IOC power level and growth.

- The PV/SD growth concept offers potential advantages similar to those of the hybrid concept, but requires SD development in parallel with construction of a full PV station if current growth schedules are to be achieved. Also, programmatic pressure may delay SD development indefinitely, resulting in limited station growth potential and high power costs.

Based on these conclusions, the hybrid concept (SD augmented with PV) was recommended as the reference for the Space Station.

In addition to the major system trade studies, a peaking power split (hybrid concept) and a gimbal joint trade study were completed and reported in the June 1986 submittal of DR-02.

The peaking power study evaluated proportional and inherent peaking power splits and recommended the inherent peaking power split option.

The gimbal joint study evaluated three gimbal joint design approaches to meet the PV, SD and platform requirements. Combination of unique designs for each application to a common design for all three applications were evaluated. The common design approach selected.

3.2 PV SUBSYSTEM TRADES

A number of trade studies were performed to arrive at the baseline design. (Tables 3.2-1 and 3.2-2). The general approach with these studies was to characterize options in terms of cost and performance parameters translated into cost, followed by quantitative comparisons of the options.

3.2.1 Solar Array

In the area of photovoltaic arrays a key cost driver was the drag-reboost fuel supply requirement. Other factors were technology maturity, production cost considerations, and on-orbit installation costs. The main studies were:

- Array Voltage (selected 160 v)
- Cell Size (selected 8x8 cm)
- Cell Material (selected Si over Ga As)
- Cell Configuration (IR transparency, Thickness, Contacts)
- Planar versus Concentrator Array (selected planar)
- Deployable versus Erectable Array (selected deployable)

Table 3.2-1 MAJOR COMPLETED PV MODULE SYSTEMS TRADE STUDIES

TRADE STUDY	OPTIONS CONSIDERED	APPROACH SELECTED	RATIONALE
PV Array Voltage	• 160 V • Other Voltage	• 160V	• Conservative selection to prevent unacceptable plasma losses and arcing.
Array Cell Size	• 6 x 6 cm • 8 x 8 cm • 10 x 10 cm	• 8x 8 cm	• Cost and packing density favors largest practical size. • Technological and cost uncertainties eliminated 10 x 10 cm size.
Array Cell Material	• Silicon • GaAs	• Silicon	• Cost and weight favors Si cells.
Array Cell Configuration	• Transparent • Full Contact • 100 to 600-μm stack thickness	• Transparent • 350-μm stack thickness	• Transparent cell provides higher efficiency. • Lowest cost approach.
Planar vs Concentrating PV Array	• Concentrating • Planar	• Planar	• Concentrating arrays require finer pointing and have higher mass and unresolved technical issues in the LEO environment.
Deployable vs Erectable PV Array	• Deployable • Erectable	• Deployable	• Minimizes EVA time and provides retractability.
Energy Storage	• Regenerative Fuel Cell • NiCd Batteries • IPV NiH_2 Batteries • Bipolar NiH_2 Batteries	• IPV NiH_2 Batteries	• Batteries offer lower cost with current requirements and have lower technology risk. • IPV NiH_2 batteries selected based on cost, efficiency, and development risk.

Table 3.2-2 MAJOR ON-GOING AND PLANNED PV MODULE SYSTEMS TRADE STUDIES

TRADE STUDY	OPTIONS TO BE CONSIDERED	CURRENT REFERENCE APPROACH	SCHEDULED COMPLETION (Months after contract start)	KEY DECISION CRITERIA
Type of Thermal Control	• Mechanically pumped loop • Capillary pumped loop • Passive Cooling	• Mechanically pumped loop	8	• Cost • Commonality • Reliability • Technology Readiness • Capability to meet requirements
PV Array Power Regulation and Control	• Sequential Shunt Unit (SSU) • Zero-cycle Bidirectional Inverter	• SSU	10	• System Simplicity • Efficiency • Reliability • Cost • Technology Readiness • Operational Constraints

The selected configuration provides a combination of low cost, high maturity and low risk.

3.2.2 Energy Storage

In the battery energy storage area the major battery alternatives were traded based on fairly detailed conceptual design studies to define mass, size and cost parameters. These conceptual designs were then traded based on an assessment of development cost, production cost, technology maturity, and development risk. Commonality was also included as a major determinant of the final selected configuration. The three main options and areas studied were:

- o Nickel-Hydrogen Batteries (IPV - Individual Pressure Valve)
- o Nickel-Hydrogen Batteries (Bipolar)
- o Nickel-Cadmium Batteries

The IPV nickel-hydrogen battery was selected through these studies, and then traded against the regenerative fuel cell option, resulting in final selection of the nickel-hydrogen system based on cost, efficiency, and development risk.

3.2.3 PV Thermal Control

In the integrated thermal control area the major alternatives were traded based on Rocketdyne's understanding of WP-02 ITC common hardware and on conceptual design studies to define mass, size, and efficiency parameters. The major thermal control alternatives traded were capillary pumped loop (CPL) and mechanically pumped two phase (MPTP) system.

In the source PMAD area the conceptual design of a sequential shunt regulated system was traded against alternative regulation approaches and unregulated systems. The current baseline selection of the shunt regulated approach was based on the maturity and flight experience of this system, since other factors, such as cost, did not provide significant discrimination between options.

3.3 SD SUBSYSTEM TRADES

SD subsystem tradestudies were conducted for the concentrator, CBC and ORC receiver/power conversion units, and radiators. The single engine, 25 kw SD module configuration was selected after studying sizes ranging from 18.75 kw to 37.5 kw with single and dual engines.

3.3.1 Concentrator Trade Studies

A preliminary structural dynamics design analysis and trade study in support of the Solar Dynamic (SD) concentrator, interface structure and fine pointing controls trades was completed. The objective of the analysis was to evaluate novel concentrator fine pointing mechanisms and interface structure concepts in terms of structural dynamic performance and system mass characteristics. It was concluded from the results of this study that the dual axis fine pointing mechanism/interface structure configuration, adopted as part of the preliminary design reference concept,is both low in mass and sufficiently rigid to effectively avoid modal frequencies below one Hertz.

A fine-pointing concentrator control option evaluation was completed in support of the concentrator preliminary design. The objective of the study was to evaluate several fine-pointing control concepts in terms of control loop logic and suitability for this application. The optical performance of four of these concepts was also evaluated. It was concluded, as a result of this study, that viable control loops for concentrator fine-pointing control can be of a simple variety and that the optical performance of the reference configuration is acceptable, based on the data obtained to date.

Five alternate concepts were considered for the on-orbit assembly of the reflector subassembly. They included: a fully automatic, motorized, hinged/latched concept requiring no EVA for assembly; a fully deployable, non-motorized, hinge/latch concept requiring no EVA; a hinge/latch concept which is part EVA, part IVA assembly wherein all the panels are connected with hinges; a hinge/latch concept which is part EVA, part IVA assembly where the assembly of three groups of hex-trusses is required; and a latch only, all-EVA assembly concept. The all latch concept appears to be clearly superior to the other alternatives considered. In addition to its high quantitative ranking, it is the most flexible with respect to assembly location and method, and has a reasonable assembly timeline. The all latch design is the recommended approach and has been included in the reference preliminary design concept.

3.3.2.1 CBC Receiver/PCU Trade Studies

Table 3.3.2.1-1 summarizes the trade studies carried out within the scope of the CBC PCU design effort.

Major analysis and advanced development work was also directed toward the CBC receiver. Phase change material investigation activities settled on lithium fluoride-calcium fluoride eutectic as the thermal energy storage material. Detailed thermal-stress modeling using creep damage integration techniques provided analytical confirmation of CBC receiver life margin.

Control loop trade studies were also pursued. These identified that the preferred control concept for thermal energy management and peaking operation was a working fluid inventory control scheme using a gas accumulator and valves. In addition, the parasitic load radiator concept and implementation were determined by trades involving PLR control scheme options and redundancy considerations.

3.3.2.2 SD-ORC Subsystem Trades

Numerous analyses and trade studies were undertaken during preliminary design of the organic rankine cycle solar dynamic power generation subsystem. Completion of these studies resulted in an optimized, cost effective design concept for the Organic Rankine Cycle. These studies are summarized in Table 3.3.2.2-1.

3.3.3 SD Radiator Trade Studies

A series of trade studies were carried out to examine various potential options in order to select a recommended approach for both the ORC and CBC preliminary radiator designs. The results of these trade studies are summmarized in Table 3.3.3-1.

Table 3.3.2.1-1

MAJOR TRADE STUDIES - CBC

Study	Options Considered	Approach Selected	Trade Rationale
TES Salt Selection	LiF, LiF-MgF, LiF-CaF_2, Li_2CO3, others	LiF-CaF_2	Compatibility Good Receiver Life Good efficiency
Salt Containment Design	Large vs small scale evaporation	Small Canisters	Lower stresses Better life Mass Production Economics
Containment Material	Inco 600, Inco 625, MA754 Hast. B2, Haynes 188	Haynes 188	Superior creep Strength Good fabricability Good pedigre
Receiver Aperture Size	Range 14 - 22 inches	17 inches	Low mass, low cost for reasonable optics & reasonable pointing
Alternative Selection	Rice, PMG	Rice	Experience in BRU, Dips Better rotor dynamics Better voltage control
Alternator Cooling	Working fluid only, Working fluid & coolant	WF & Coolant	Compact Better cycle eff.
Gas Cooler .Type	Tube-fin, Plate-fin	Plate-fin	Minimum mass
.Coolant passes	2 - 8	8 passes	Minimum Mass
.Fin density	12 - 16 Hot, 16 - 20 cold	12/in hot 16/in cold	Minimum Mass
.Aspect ratio	0.1 - 2.0	0.235	Minimum Mass
Receiver Temperature Control Selection	Recuperator Bypass Inventory Control Rotor Speed Control	Inventory control	Better efficiency Good reliability Less GN&C impact
PLR Radiator Design	Switched resistance back Unswitched resistance back	Unswitched resistance back	Low EMI Good reliability Loo thermal stress
Thermodynamic State Point Trades Parameter			
Parameter			
Recuperator effectiveness	0.84 - 0.97	0.94	Minimum Mass
Gas Cooler effectiveness	0.84 - 0.97	0.94	Minimum Mass
Compressor inlet temperature	48IOR - 580R	520R	Minimum Mass
Compressor pressure ratio	1.6 - 2.2	1.9	Compromise mass/accum. size
Compressor specific speed	0.07 - 0.10	0.093	Compromise efficiency/pressure
Rotor speed	20 - 40 (1000 rpm)	32,000	Compriomise alternator/aero
Pressure drop ratio	0.90 - 0.95	0.93	Compromise mass/duct size
Bleed gas	0.02 - 0.05	0.025	Minimum for cooling

TABLE 3.3.2.2-1

MAJOR TRADE STUDIES - ORC

TRADE STUDY	OPTIONS CONSIDERED	APPROACH SELECTED	RATIONALE
State Point Effects	.Operate with back pressure relief valve (BPRV) .Operate without BPRV	Operate without BPRV	Improves system efficiency and reliability with reduced mass and complexity
Maximize Efficiency	.Turbine Inlet Temperature .Turbine Inlet Pressure .RFMD Pressure	.Turbine Inlet: 750°F/610psia .RFMD Pressure: 5psia	.Selected turbine inlet temperature to minimize toluene degradation .Pressure maximize efficiency .Supercritical inlet pressure avoids 2-phase vaporizer conditions .RFMD pressure minimized system weight
RFMD	.Unique Design .Design similar to WPO2	Similar to WPO2 TPTMS	.WPO2 RFMD will be modified by deleting control feature
Effects of Pointing Error	.Active aperture plate cooling .Passive Aperture plate cooling	Passive Cooling	Flux densities on aperture are within the capability of passive cooling
Aperture Sizing	.Aperture Diameter	28 in Diameter	Finite difference computer model indicated that this diameter minimized losses and maximized tolerance to tracking errors
Type of Absorber	.Direct Insolation .Heat Pipes	Heat Pipes	Lightweight, simple, and accommodates axial flux distribution
Heat Pipe Heat Pipe Selection	.Direct Insolation untailored, tailored, or radiation coupled .Heat pipe multiple, single, or parallel flow	Multiple axial heat pipes, each including TES canisters and vaporizer	.Lightweight .Low Risk .Best flux distribution .Solar heated startup possible .Circumferential heat pipes can be added if needed .Adaptable to alternate TES material
Type of Heat	.Single .Multiple	.Multiple Heat Pipes	.Simpler Fabrication .Redundant .Ground Testable
Circumferential flux maldistribution	.Circumferential heat pipes .No circumferential heat pipes	No circumferential heat pipes	.Results of receiver math model indicated that expected circumferential flux distribution is acceptable
Type of Thermal Energy Storage	.Sensible .Phase Change	.Phase Change	.Lighter Mass .LiOH is well characterized and meets requirements
Salt selection	.Over 100 Alternatives	LiOH	.High heat of fusion, density, and melt-temperature .Low volume change & corposion RATE .Experience
*vaporizer	.Bayonet/Return Flow .Through Flow	Bayonet/Return Flow	.Simple Interface .Free for Thermal Growth
Alternator	9 different types	Rice	.Good efficiency/weight trade .Regulated voltage to source converter
Radiator/ Condenser Interface	.Annular .Flat Plate	Flat Plate	.Minimum fluid joints .Replaceable pressurization system .Common with Wp-02
PLR Design	.Direct Load .Electric Load	Electric Load	.Low losses and EMI .Acceptable speed resolution .Simple circuits .Power quality requirements achieved .Fast response
Level of Redundant	.No component redundancy .Controller redundant .PLV & Controller redundant .PLV, Controller and Tracking redundant .Complete redundancy	Controller redundant	.Best compromise of reliability versus complexity and mass
Working Fluid	.Toluene .RC-1	Toluene	.100,000 + hrs toluene experience .No comparable RC-1 data .Toluene is more readily available .RC-1 thermal stability not well documented
Number of ORC Engines	.2 PGS modules with 2 PCV's per receiver .2 PGS modules with 2 PCU per receiver .4 PGS modules with 1 PCU per receiver	2 PGS modules with 1 PCU per receiver	.IOC power requirement and failure tolerance set module size and redundancy .Minimum life cycle cost

Table 3.3.3-1. Results of SD Radiator Trades

Trade Study	Recommended Approach: ORC	Recommended Approach: CBC
Radiator location	Collocated, same side of beta joint as PCU, mounts to SD interface structure	
Raditor/PCU transport loop	Direct-connected system loop with dry contact interface	Single-phase heat transfer loop
Radiator/PCU Thermal Interface	Mechanical contact using pressurized system with flat interface	Gas cooler heat exchanger interfaces with single-phase pumped loop
Radiator Coatings	Zinc oxide (Z93) white paint recommended as the baseline coating, silver teflon is a backup option	
Radiator method of heat rejection	Constructible with flat interface	Deployable pumped loop
ORC constructible radiator trades	Aluminum/benzene in combination with aluminum/ ammonia high capacity heat pipes	
CBC pumped loop vs. heat pipe radiator		Pumped loop radiator
ORC pumped loop vs. heat pipe radiator	Heat pipe radiator	
ORC constructible radiator trades	Lockheed tapered artery, aluminum/ ammonia heat pipes	
ORC radiator commonality	Recommended SD radiator panel design use common technology but optimized for higher heat capacity and temperature. Use identical contact interface.	

3.4 PMAD SUBSYSTEM TRADES

The PMAD subsystem level trades, hardware trades, and software trades are summarized in Tables 3.4-1 a and b, 3.4-2 and 3.4-3, respectively.

TRADE STUDY	PURPOSE	OPTIONS CONSIDERED	RECOMMENDATION
PMAD Man-Tended Option Study	Evaluate effect on man-tended option of distribution architecture changes on manned option	Man-tended option has reduced power source & loads. Man-tended option would use only PV as a source	Designed for Manned option
Evolutionary Growth Study	Ensure that design at IOC has maximum growth potential	Incorporation of advanced technology components. Quantitative incr- ease in modular growth elements.	Growth considera- tion should be in- cluded in design decisions
PMAD Health Maintenance	Evaluate status monitoring and control of power system health isolation	Built-in provisions for monitoring basic current,volts temperature. Additional measure- ment of pressure, flow rate, vibra- tion, acceleration, strain	IOC is primarily diagnostic: ident- fy faults as they occur
PMAD Load Analysis	Determine sizing of distribution equipment (PDCA) capacity for external station areas	PDCA 50kW needed for external loads. Maximun demand loading for lower/ upper ring feeder network. Maximun demand loading is 50kW.	Each PDCU, ring feeder capacity and PDCU bus should be sized at 50 kW

Table 3.4-1a. PMAD Subsystem Level Trades Summary

TRADE STUDY	PURPOSE	OPTIONS CONSIDERED	RECOMMENDATION
PMAD Primary Power Quality	Consider use of bulk load conversion to make standard power voltages available to the loads	20 kHz primary power useable only for some heating & lighting loads. All other loads require rectification and/or conversion that reflects distortion and EMI into 20kHz waveform	Standard power voltages of 120V, 400Hz, single phase and 28Vdc and 50Vdc can be supplied from bulk conversion. Distortion due to rectification can be minimized with inductive input filters and low RF filters for EMI reduction
PMAD Primary Distribution Power Type	Consider use of 20kHz primary distribution power	NASA selected primary power distribution of 440Vac, single phase,20kHz. Prior studies considered dc, 400Hz and 20kHz.	A distinct advantage of 20kHz power is the use of 20kHz resonant power converters with controlled fault current shut down and rapid current limiting to prevent catastrophic fault currents

Table 3.4-1b. PMAD Subsystem Level Trades Summary (concluded)

TRADE STUDY	PURPOSE	OPTIONS CONSIDERED	RECOMMENDATION
PMAD Distribution Architecture Trade Study	Select a suitable distribution configuration for PMAD	Architecture considered included ring radial, Star, and Network configuration	The ring configuration has the best moss, good efficiency, low switch gear count and flexibility
PMAD Feeder Study	Identify and evaluate distribution cable parameters affecting distribution characteristics and losses	Power distribution characteristics consider charactistics impedance shunt current losses, power losses, and EMI emissions	Cables for both primary and secondary distribution of 20KHz power require high surface area configuration such as "Litz" wire
PMAD Computer Fault Tolerance & Redundancy Study	Establish basic feature of a suitable processor for PMAD	Standby vs active redundant configuration. Potential restart mechanism after restored failure. Error detection and correction for single event upsets. Selfchecking pairs and triple redundancy	The basic processor should have redundant configuration with automatic, autonomous secondary switching and manual interaction capability, and provide for on-orbit repair
PMAD Bus Alternative Study	Select a communication means between PMAD controller and their controlled devices	CSMA/CD type bus MIL-STD-1553B - I EEE 802 - dedicated net controller - common vs separate net with DMS	1. Use MIL-STD-1553B as a LAN for RBI and RPC and between controllers. 2. A dedicated net controller to unload system controller
PMAD Subsystem/ Component Optimization Study	To determine use if a DC or AC connection to source power	ESS Connection to Source Power: DC versus AC Connection	DC Connected

Table 3.4-2. PMAD Hardware Trades Summary

TRADE STUDY	PURPOSE	OPTIONS CONSIDERED	RECOMMENDATION
PMAD HOL Selection	To select the programming language in the Space Station project	Ada, C, Fortran, Pascal, PL/M	Ada Selected. C is acceptable. HAL/S, Jovial not considered since Ada replaces them
Software Development Environment	To determine the degree of cent-lization for the software develop-ment environment	Fully centralized S/W on 1 T/S cpu. Centralized Cntl, same H/W & S/W at all sites. Decentralized H/W with specific S/W. Fully decentral-ized H/W & S/W.	Time varying degree of centralization with muchlatitude during early devel-opment, to strict centralized control at integration.
SSIS/DMS Interface with PMAD	To determine the type of interface to use between PMAD and the DMS	Independent PMAD Network. Shared DMS Network Distributed PMAD configuration with central Power Mgt Controller.	Independent PMAD Network
PMAD Control - Central vs Distributed Processing	To determine the type of network structure to use for PMAD	Centralized. Federated. Hierarchical.	EPS: Hierarchical DMS: Federated
PMAD Data Trans-mission: Optical versus Wire	To determine the type of trans-mission medium to use between PMAD controllers	Fiber optics vs wire	Wire
PMAD Local Power Control	To determine when to use software or hardware for PMAD local power control	Hardware vs Software control	Software, except where response time can only be met by hardware

Table 3.4-3. PMAD Software Trades Summary

4.0 COSTING ACTIVITIES

During Phase B, estimates were made of IOC cost and life-cycle cost (LCC) for the station and platforms. The estimates were continuously updated as design requirements and configurations matured. Cost drivers were identified to show where cost reduction efforts would be most productive. These cost analyses played a significant role during the numerous trade studies since a primary goal of each study was to minimize both IOC cost and LCC.

Cost documentation included: IOC costs in DR-09 (3 June 1985, 26 June 1985, 6 December 1985, 19 December 1985, 15 May 1986, and 15 November 1986), cost drivers in DR-02 (June 1986 and December 1986) and trade studies LCC in DR-19,DP 4.2 (July 1985), DP 4.3 (October 1986) and DP4.4 (November 1985).

4.1 COSTING METHODOLOGY

The first cost estimates were prepared for the Phase B proposal. The RCA PRICE cost model was used to estimate IOC and growth station costs. Sufficient information about PV, SD, and PMAD components was available to input weights, complexity factors, and quantities into PRICE.

During Phase B, the PRICE inputs were updated as the design requirements and component configurations matured. The FAST cost model was compared to PRICE. When no significant differences were identified between the results obtained from the two models, use of the PRICE model was continued. An independent cost model was developed using cost estimating relationships (CERs). Again, the results substantiated the PRICE model. PRICE was more versatile and easier to use with numerous changes to input data, so it was used for all the Phase B trade studies.

Since it was desired to minimize EPS LCC as well as IOC cost, Rocketdyne developed an LCC model that was used extensively during the trade studies. The model incorporates the PRICE estimates for IOC cost, growth hardware cost and replacement hardware cost. It calculates the cost of launch, reboost, and on-orbit operations. It uses masses, drag coefficients, mean time between replacements (MTBR), EVA & IVA times,atmospheric density and orbital altitudes. Outputs include LCC breakdowns for station and platforms by PV, SD, and PMAD subsystem and by DDT&E, IOC production, initial spares, growth production, and annual operation. Figure 4-1 shows the cost assessment logic and information flow.

As designs matured, the Rocketdyne team members submitted cost estimates for their hardware. Since these estimates were generally within 15% of the PRICE estimates, they were incorporated in subsequent cost analyses. PRICE was still used for PMAD. Finally, for the last submittal of DR-09 (November 1985986) team member and vendor cost estimates were obtained for the PMAD components.

Level of effort (LOE) costs for the EPS were estimated using either the model PRICE, as a factor on hardware costs, "bottoms up" estimates or combinations of these. LOE included work package management, SE&I, GSE, IACO, test, FSE, customer integration, international integration, product assurance, operations planning, logistics, maintainability and automation and robotics. The Rocketdyne LCC model used a factor based on past experience. Early DR-09 submittals included a combination of PRICE estimates and "bottoms up" estimates. The final DR-09 used "bottoms up" estimates.

4.2 COST OPTIMIZATION

The Rocketdyne LCC model described in Section 4.1 was used extensively in the numerous trade studies to minimize both IOC cost and LCC. Five different LCC scenarios were examined during each trade study, namely:

1) Concurrent platforms and station (base case)
2) Delayed platforms
3) Man-tended station
4) High-power station and platforms
5) No platforms

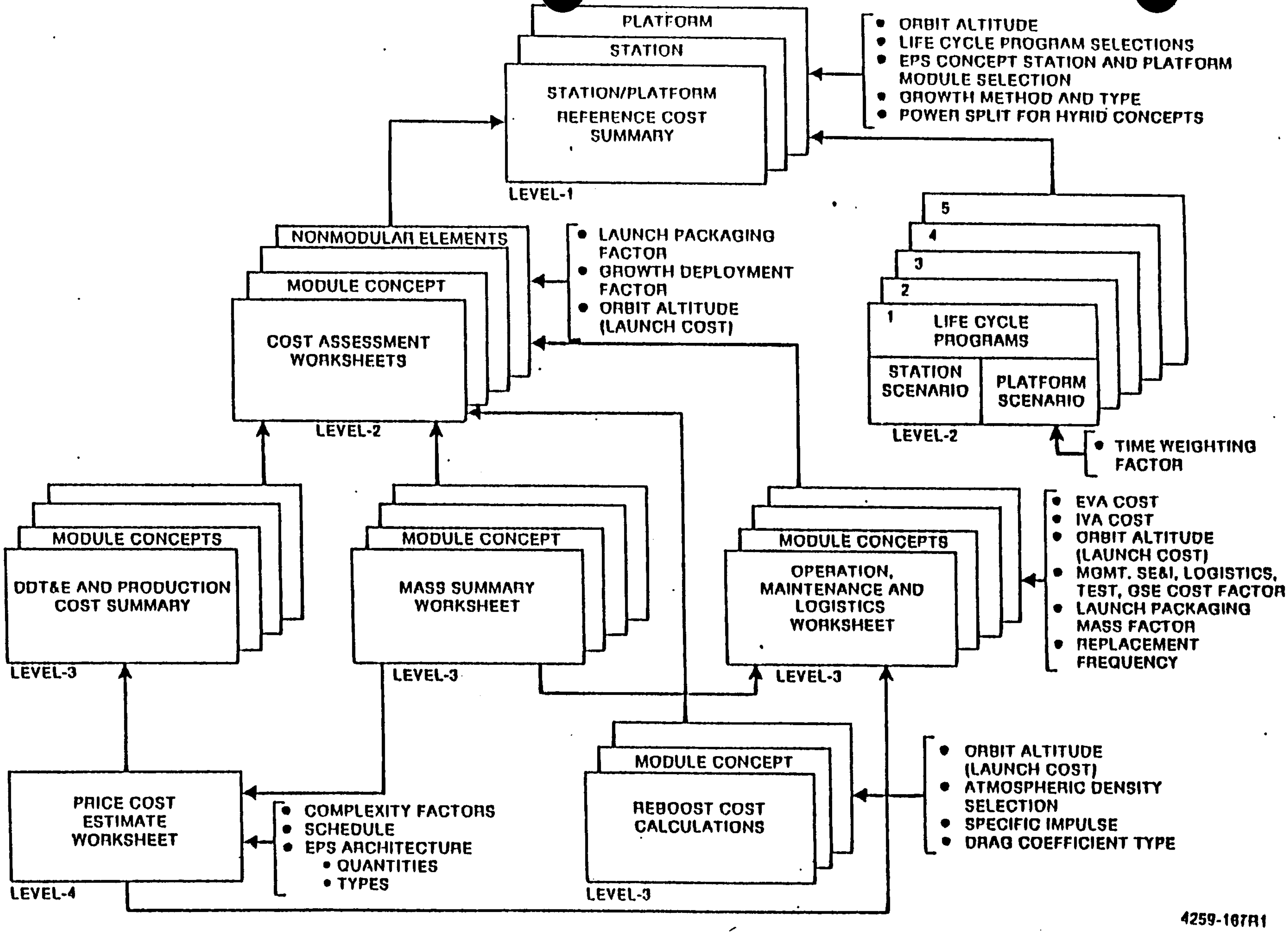

Figure 4-1 Cost Assessment Logic and Information Flow in Rocketdyne LCC Estimating Code

The most extensive trade study was that of PV vs. SD. This study actually looked at types of options: PV, SD, hybrid and PV/SD growth (PV at IOC with growth by SD). The results showed that IOC costs for PV, SD, and hybrid were approximately equivalent (and lower than PV/SD growth), but SD and hybrid had large LCC savings compared to PV (~$3B). The LCC results are shown in Figure 4-2. The hybrid concept was recommended due to its greater technical flexibility and lower programmatic risk.

The Rocketdyne LCC model was used to examine the cost sensitivity of the PV vs SD study to of a wide range of variables. These included cost growth, station growth power, station lifetime, double replacement frequencies, discount rate, orbit altitude, and double launch costs. All sensitivity cases examined showed the same relationships as in Figure 4-2.

Cost optimization studies included the effects of hardware commonality, primarily between station and platforms. The studies showed that significant cost savings are possible by using identical solar array panels, common Ni-H_2 batteries, and a PMAD subsystem with the same distribution frequency. Cost savings arise from lower IOC costs for DDT&E, flight hardware and initial spares. Also, with fewer kinds of hardware, operations costs are reduced for training and replacement spares provisioning.

The design trade studies resulted in many other cost effective selections including:

1) Linear-actuated offset concentrators -- much lower cost than numerous other evaluated concepts.

2) SD state points -- selected to maximize lifetime and minimize weight, both of which minimize costs.

3) SD pumped-loop radiator -- lower cost than heat pipe radiator.

4) PV cell size -- more power per unit cost results in lower total cost.

5) PV lightweight, flexible, deployable array -- cost savings in weight and EVA time.

The Phase B studies were very successful in selecting a design that cost-effectively satisfies all NASA and user requirements.

STATION LIFE CYCLE COST COMPARISON
FOR 30 year STATION LIFE

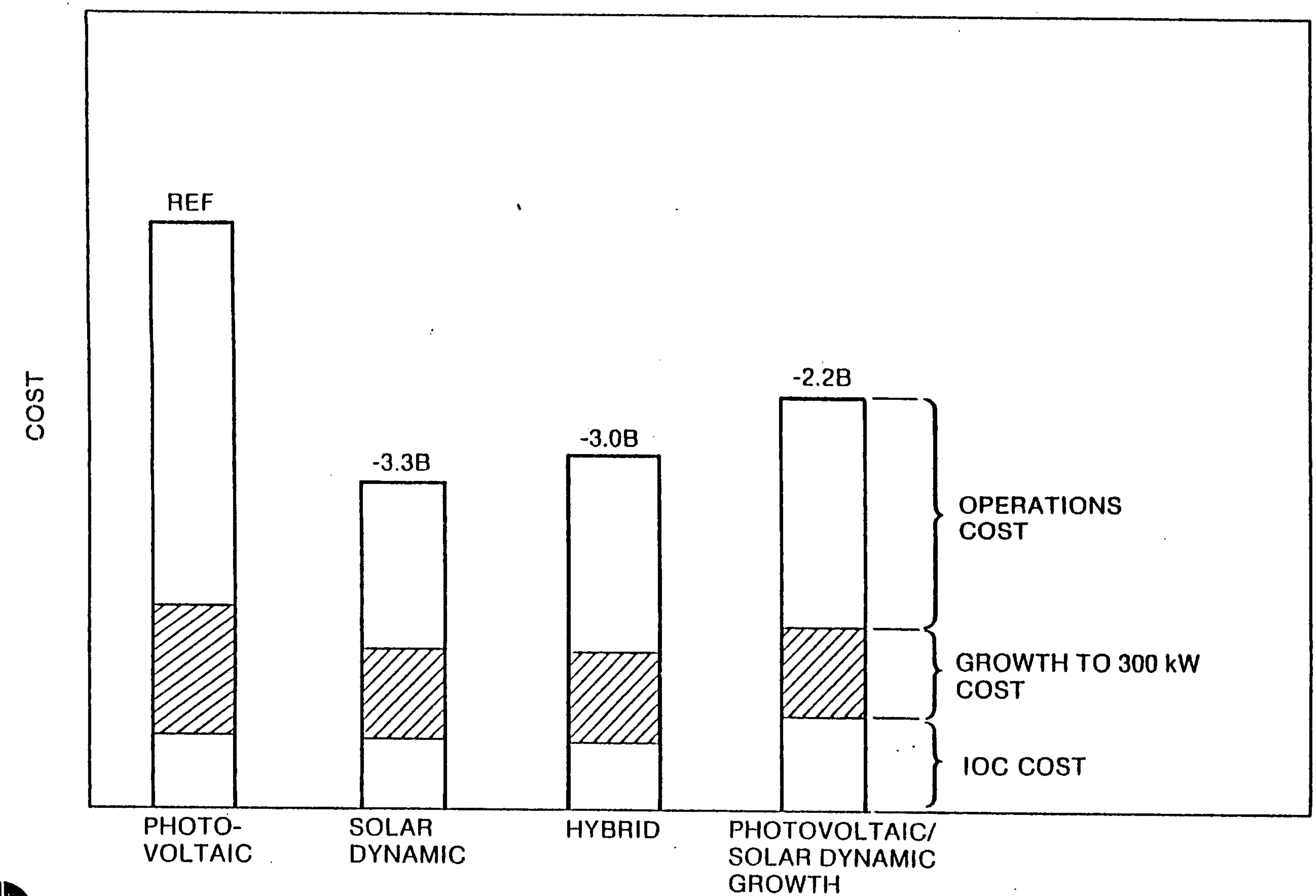

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Figure 4-2