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Interim Report

# MARINER MARS POWER SYSTEM OPTIMIZATION STUDY

Period Covered
4 March 1968 through 31 May 1968

TRW Report No. E-7443.3-024 JPL Contract 952151

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS7-100.

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# 1. INTRODUCTION

This is the interim report summarizing the activities performed by TRW Systems thus far and outlining the proposed effort for the remainder of the performance period under JPL Contract 952151 entitled, "Mariner-Mars Power System Optimization Study." This report summarizes the effort during the period 4 March 1968 to 31 May 1968.

The prime objective of the study is directed toward the development of an optimum Mariner-class spacecraft power system to provide improved utilization of solar array capacity and greater reliability than the present Mariner-Mars power system. The two missions identified for this study project are a Mars flyby and a Mars orbiter. In performance of this effort, the program is divided into the following tasks:

## 1.1 TASK I. ESTABLISHMENT OF MODEL SYSTEMS AND DETERMINATION OF OPTIMUM SYSTEM

### 1.1.1 Mission and Vehicle Requirements

Analyze the two specified missions to determine spacecraft configuration and power system interfaces, design tradeoff criteria and priorities, mission description and sequence of events, and reliability ground rules. Analyze load power requirements, including power profiles and power quality limits.

### 1.1.2 Subsystem Analysis

#### 1.1.2.1 Model Systems

Determine the model solar photovoltaic power system configurations considering the many possible systems which are compatible with the spacecraft requirements. Select several configurations (including the existing Mariner-Mars system) for further detailed analysis based on weight, reliability, array utilization, bus voltage characteristics, interface simplicity, flexibility, and demonstrated design.

#### 1.1.2.2 Analysis of Model Systems

Failure Modes and Effects. Perform component and system failure mode analyses to define areas where reliability improvements are required.

Methods to Increase Reliability. Analyze the failure mode to determine the methods to improve reliability through the use of redundancy, failure detection and switching, load grouping, ground commands, and element sizing.

Command and Control Circuitry. Provide isolation of the command inputs to the power system and determine methods of redundant control circuitry for fail-safe operation.

Transient Response. Provide improvement in the transient response characteristics of the power system for step load changes.

Weight-Reliability Optimization. Characterize the weight, efficiency, and reliability of the various system elements resulting from the aforementioned analysis of methods to improve performance and reliability. Utilize the modified TRW-developed computer program to optimize system weight and reliability.

#### 1.1.2.3 Subsystem Recommendation

Recommend the optimum system(s) for the flyby and orbiter, based on the results of the foregoing tasks and analysis indicating the major advantages, disadvantages, and weight-reliability tradeoffs.

## 1.2 TASK II. WEIGHT, SIZE, PARTS, AND RELIABILITY

Characterize the weight, size, component parts, and reliability of the recommended optimum system(s), and the system elements. Determine the system power and energy margins for the major mission modes, including the assumptions and design calculations.

## 1.3 TASK III. TELEMETRY MONITORING POINTS

Recommend the telemetry monitoring points for the recommended optimum system(s), including the required range and accuracy. Relate the criticality of the telemetry monitors to normal mission modes and likely failure conditions. Based on this analysis, rank the telemetry points in the order of importance.

## 1.4 TASK IV. BLOCK DIAGRAM AND CIRCUIT DESCRIPTION

Generate a detailed block diagram of the recommended system(s), including circuit types and redundancy, description of operation, and major performance characteristics such as voltage regulation, bus voltage variations, and heat dissipation. Delineate major electrical, thermal, or mechanical interfaces with the power user equipment or spacecraft. Identify critical power system characteristics or spacecraft interfaces which require special further detailed analysis or testing.

## 2. PRESENT STATUS OF THE STUDY

The completed effort for the reporting period 4 March to 31 May 1968 constitutes approximately 35 percent of the total engineering effort. Task 1.A and Task 1.B.A) are complete. The failure modes and effects analysis, Task 1.B.B) 1), is 90 percent complete and Tasks 1.B.B) 2) and 1.B.B) 5) are approximately 50 percent complete. The project schedule is shown in Figure 2-1.

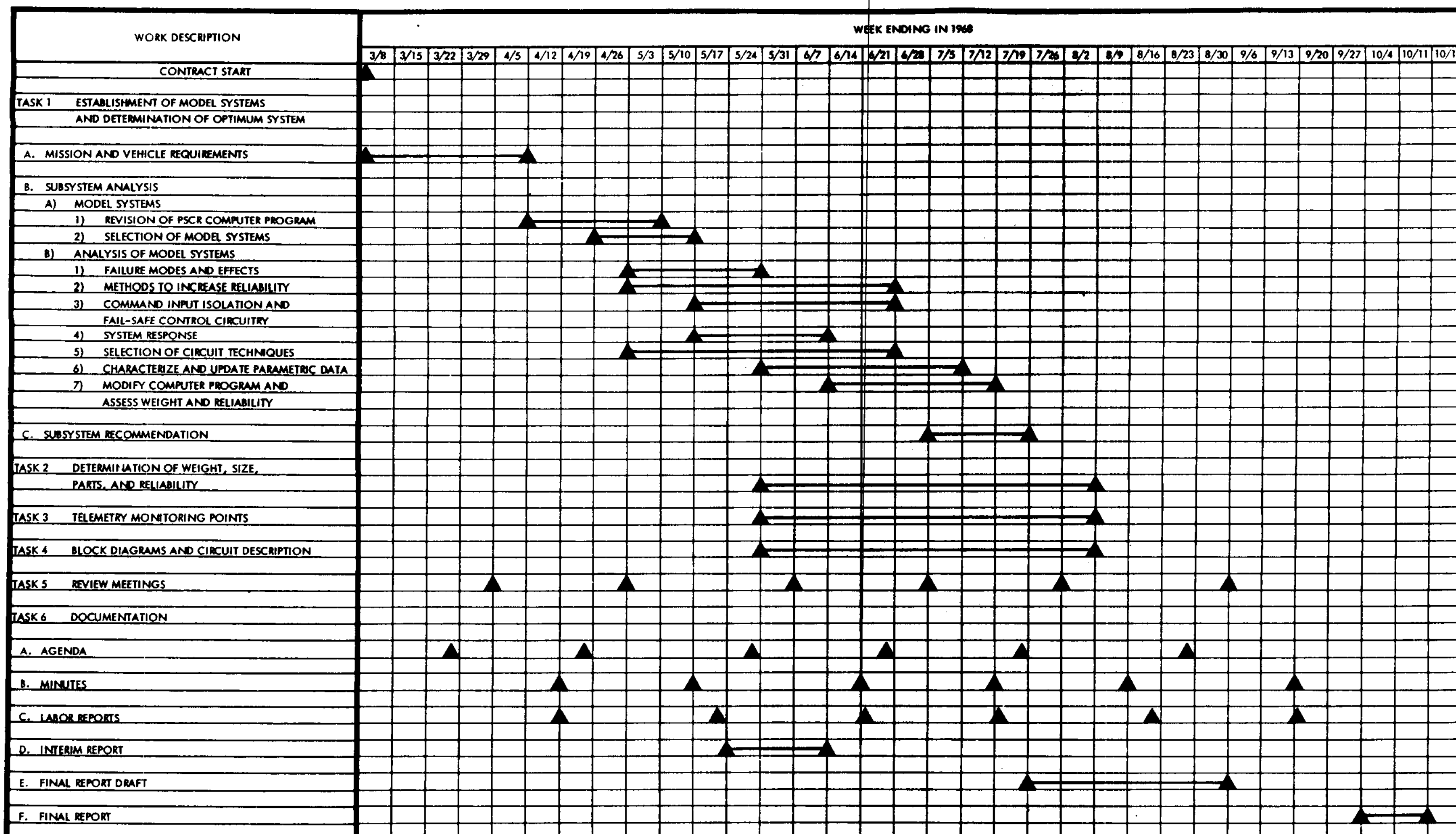


Figure 2-1. Project Schedule

# 3. STUDY RESULTS

## 3.1 MISSION AND SPACECRAFT ANALYSES

The initial effort involved the definition of the mission and spacecraft characteristics, the requirements imposed on the power system, and the establishment of design tradeoff criteria and guidelines to be applied towards the design and selection of the optimum power system.

Two missions have been identified for this study: Mars Flyby and Mars Orbiter. The orbiter will be based on 90 days in Mars orbit with no eclipse seasons. Specific launch dates have not been determined, but an early 1970 period is assumed. Launch dates and time will be considered in the comparative analysis as variables. Analyses performed in the course of TRW's Voyager studies show a range of Mars-sun distance (AU) dependent on the launch date. Typical values for arrival are 1.388 to 1.612 AU and 1.47 to 1.66 AU for arrival +90 days in orbit. Transit times can vary from 119 to 230 days. The spacecraft configuration will be the Mariner '69 which is fully attitude-stabilized in 3 axes and uses the Sun and Canopus as referenced objects. The spacecraft carries scientific instruments to obtain data on the Martian environment, atmosphere, surface properties, and biological life. The spacecraft body is octagonal in shape with four fixed solar panels comprising a total area of 83 $ft^2$. Louvers on the equipment bay provide thermal control. The spacecraft engineering equipment and experiments will be very similar to the Mariner Mars '69 except for valve and gimbal equipment for orbit insertion (orbiter mission).

### 3.1.1 Selection Criteria

The selection criteria to be applied to the various model power system configurations will include the following:

#### 3.1.1.1 Solar Array Power Utilization

Utilization of the maximum available power is highly desirable as it results in spacecraft load growth capability, increased allowance for array degradation, or successful operation in flight with higher than normal loads. The constraint on the power system design is to satisfy all power requirements with a 83 $ft^2$ array.

3.1.1.2 Reliability

Other than the minimum assessment requirement of $\geq 0.90$, the following aspects of reliability will be applicable:

a. Ability of system to detect failures and provide corrective action

b. Failure modes and effects

c. Testability

d. Utilization of proven components and derating of components

e. Complexity

3.1.1.3 Weight

Weight is a parameter to be traded off with system reliability. The weight allocations are as follows:

| | |
|---|---|
| Solar array (less structure) | 50.0 lb |
| Battery (less chassis and cover) plus power processing equipment | 71.7 lb |
| Total | 121.7 lb |

3.1.1.4 Demonstrated Design

Demonstrated design is highly desirable for it minimizes design risk and development time, and narrows the uncertainty in the performance calculations.

3.1.1.5 Interface Simplicity

Simplify the electrical, mechanical, and especially the thermal interface with the spacecraft configuration and power user equipment.

3.1.1.6 Flexibility

Minimize effects of launch/arrival dates, solar array temperature predictions, and solar array degradation. Minimize dependence on predicting battery charge/discharge voltage within narrow tolerances, provide capability of system to operate over wide limits of load, source voltages, environment, and abnormal mode operation.

3.1.1.7 Unregulated Bus Voltage

Minimization of the present 2:1 swing in unregulated bus voltage will provide advantages as follows:

a. Allow for ease in design (greater reliability) for users of unregulated bus voltage (TWT's, heaters, low-level circuitry).

b. Allow for increase in power utilization via reduction of TWT power (TWT converter efficiency decreases for wider input voltage range) and reduce the variability in power consumption of unregulated bus power users.

3.1.1.8 Transient Response

The ability of the power system to provide a low source impedance continuously will minimize load switching transients. Many loads (TWT, heaters, experiments, etc.) are switched on/off during the mission.

3.1.2 Design Guidelines

Several selected design guidelines to be applied to the model power system configurations are delineated below:

a. Backup redundancy techniques shall be employed to the extent that those events, functions, or sequences critical to the mission success may be initiated by two separate and independent means.

b. In order to assure increased reliability, the battery shall be required only for normal mission modes in which the array is not sun-oriented (e.g. launch, maneuvers, orbit insertion).

c. Eliminate the solar array zener diode voltage limiter.

d. Provide isolation of command inputs and provide fail-safe control circuitry.

e. Eliminate the two stable operating points which are characteristic of a solar array with pulsewidth modulated power conditioning equipment.

f. The electrical interface with the user equipment (e.g. 25-50 Vdc unregulated dc, 27.2 ± 5 percent Vrms, 1-$\phi$, 400-Hz power) is to be considered firm; however, internal power system characteristics are flexible.

## 3.2 SPACECRAFT POWER REQUIREMENTS

Tables 3-1 and 3-2 tabulate the load/power requirements for each subsystem and equipment categories as a function of major mission phases for the flyby and orbiter missions, respectively. These tables were based on JPL-furnished load information. Analysis of the load requirements for the flyby mission shows that the majority of the spacecraft engineering subsystems and all the experiments require regulated ac power from the 2.4 KHz inverter. A large portion of ac power (54 W) goes toward TCFM power and cruise heaters. Opportunities for reduction of required source power may be realized by regulated bus voltage systems supplying heater power directly, eliminating the losses in the conditioners (i. e. boost regulator and 2.4 KHz inverter). Requirements for 1$\phi$ and 3$\phi$ power are relatively low and are required only during certain mission phases. The primary user of unregulated dc power is the TWT power amplifier. It requires a dc/dc converter for conversion to high voltages required by the TWT. Other users of unregulated power include heaters and battery charging. The power requirements for the orbiter mission are similar to the flyby except for the gimbal and valve equipment that is required for Mars orbit insertion. Tentative requirements are 28 Vdc ±5 percent. This load requirement will be further investigated to determine acceptable voltage levels. Power utilization may be enhanced if, for example, this load could operate directly off the battery.

## 3.3 LOAD PROFILE ANALYSIS

Analyses were performed to compare the solar array load power capability and the total conditioned load power requirement as functions of mission time to define the critical design point (CDP). The CDP is defined as the condition of minimum power margin between load power and solar array capability. The CDP can be ascertained, knowing the solar array characteristics, by examination of the load requirements tabulated in Tables 3-1 and 3-2. For the flyby mission, the CDP occurs at near encounter with high level TWT's operating. The CDP for the orbiter mission occurs during the TV sequence near the end of mission life where the solar array power capability is minimum. For both CDP's, it is assumed that available battery power will not be credited towards sharing the load requirements with the solar array.

FOLDOUT FRAME 1

Table 3-1. Power Requirements (W) as a Function of Mission Phase -- Flyby Mission

FOLDOUT FRAME 2

| Item | Subsystem | Acronym | Equipment | Unreg DC | 2.4 KHz | 3φ 400 Hz | 1φ 400 Hz | Other | Mission Phase: 1 Launch | 2 Star Acq. | 3 Cruise Batt Chg | 4 Cruise | 5 Maneuver | 6 Enc Appr | 7 Far Enc | 8 Far Enc Hi Pwr TWT | 9 Far Enc Low Pwr TWT | 10 Near Enc | 11 Near Enc Hi Pwr TWT | 12 Near Enc Low Pwr TWT | 13 Playback |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Science | DAS | Data Automation Subsystem | | ▲ | | | | | | | | | | 20 | 20 | 20 | 20 | 20 | 20 | |
| 2 | | TV | Television | | ▲ | | | | | | | | | | 32 | 32 | 32 | 32 | 32 | 32 | |
| 3 | | IRR | Infrared Radiometer | | ▲ | | | | | | | | | | 3 | 3 | 3 | 3 | 3 | 3 | |
| 4 | | IRS | Infrared Spectrometer | | ▲ | | | | | | | | | | 4 | 4 | 4 | 4 | 4 | 4 | |
| 5 | | UVS | Ultraviolet Spectrometer | | ▲ | | | | | | | | | | 12 | 12 | 12 | 12 | 12 | 12 | |
| 6 | | IRSM | Infrared Spectrometer Motor | | | | ▲ | | | | | | | | | | | | 2 | 2 | |
| 7 | Attitude Control | A/C-1 | Attitude Control | | ▲ | | | | 13 | 25 | 4 | 4 | 23 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| 8 | | A/C-2 | Autopilot Control | | ▲ | | | | | | | | 29 | | | | | | | | |
| 9 | | GYRO 1 | Gyro Electronics | | ▲ | | | | 8 | 8 | | | 8 | | | | | | | | |
| 10 | | GYRO 2 | Gyro | | | ▲ | | | 9 | 9 | | | 9 | | | | | | | | |
| 11 | Scan Control | SCAN-1 | Scan Control Electronics | | ▲ | | | | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 26.5 | 28.5 | 28.5 | 26.5 | 16.5 | 16.5 | 5.3 |
| 12 | | SCAN-2 | Scan Control Motor | | | | ▲ | | | | | | | | 12 | 12 | 12 | 12 | 12 | 12 | |
| 13 | N/A | | | | | | | | | | | | | | | | | | | | |
| 14 | N/A | | | | | | | | | | | | | | | | | | | | |
| 15 | Radio Frequency | RFS | Radio Frequency Subsystem (except TWT) | | ▲ | | | | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 |
| 16 | | TWT | TWT (Power Amplifier) | ▲ | | | | | 60 | 60 | 60 | 60 | 60 | 60 | 60 | 99.0 | 60 | 60 | 99.0 | 60 | 99.0 |
| 17 | Central Computer and Sequencer | CC & S | Central Command and Sequencer | | ▲ | | | | 32.4 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 | 17.0 |
| 18 | Flight Telemetry | FTS | Flight Telemetry Subsystem | | ▲ | | | | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |
| 19 | Flight Command | FCS | Flight Command Subsystem | | ▲ | | | | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 |
| 20 | Data Storage | DSS | Data Storage Subsystem | | ▲ | | | | 21.0 | 21.0 | 17.7 | 17.7 | 17.7 | 17.7 | 18.0 | 18.0 | 18.0 | 23.0 | 23.0 | 23.0 | 21.0 |
| 21 | Pyrotechnic | PYRO | Pyrotechnic | | ▲ | | | | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 22 | Thermal Control | T/C-1 | TCFM Power and Cruise AC Heater | | ▲ | | | | 54.0 | 54.0 | 54.0 | 54.0 | 54.0 | 54.0 | | | | | | | 54.0 |
| 23 | | T/C-2 | DC Heater | ▲ | | | | | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | 26.0 | | |
| 24 | N/A | | | | | | | | | | | | | | | | | | | | |
| 25 | Power | PWR | Power Distribution | | ▲ | | | | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 |
| 26 | | BTCG | Battery Charger/Booster | ▲ | | | | | 0.5 | 0.5 | 25.0 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | | | | | | | Summary of Power Requirements | | | | | | | | | | | | | | |
| | | | | | | | Unreg DC | | 86.50 | 86.50 | 111.00 | 86.50 | 86.50 | 86.50 | 86.50 | 125.50 | 86.50 | 86.50 | 125.50 | 86.50 | 125.50 |
| | | | | | | | 2.4 KHz | | 186.35 | 183.95 | 151.65 | 151.65 | 207.65 | 151.65 | 190.15 | 192.15 | 192.15 | 195.15 | 185.15 | 185.15 | 154.95 |
| | | | | | | | 3φ 400 Hz | | 9.00 | 9.00 | 0 | 0 | 9.00 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | | | | | | | 1φ 400 Hz | | 0 | 0 | 0 | 0 | 0 | 0 | 12.0 | 12.0 | 12.0 | 12.0 | 14.0 | 14.0 | 0 |

Abnormal Gyro-On Loads

| | | | |
|---|---|---|---|
| GYRS 1 | 8.0 | 2.4 KHz | For All Phases Except 1, 2, 5 |
| GYRS 2 | 9.0 | 3φ, 400 Hz | |
| ACS 1 | 16.0 | 2.4 KHz | |
| TCS 2 | 9.8 | Unreg DC | |

Table 3-2. Power Requirements (W) as a Function of Mission Phase -- Orbiter Mission

FOLDOUT FRAME 1

FOLDOUT FRAME 2

| | | | | | | | | | MISSION PHASE | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Item | Subsystem | Acronym | Equipment | Unreg DC | 2.4 KHz | 3φ 400 Hz | 1φ 400 Hz | +28 VDC | 1 Launch | 2 Star Acq | 3 Cruise I Batt Chg | 4 Cruise Chg Off | 5 Maneuver | 6 Far Enc | 7 Orbit Insertion | 8 Far Enc Playback | 9 Orbit Trim | 10 Orbit Cruise | 11 TV Sequence | 12 Earth Occultation | 13 Playback ATR | 14 Playback DTR |
| 1 | Science | DAS | Data Automation Subsystem | | ▲ | | | | | | | | | 20.0 | | | | | 20.0 | | | |
| 2 | | TVS | Televisions | | ▲ | | | | | | | | | 32.0 | | | | | 32.0 | | | |
| 3 | | IRR | Infrared Radiometer | | ▲ | | | | | | | | | 3.0 | | | | | 3.0 | | | |
| 4 | | IRS | Infrared Spectrometer | | ▲ | | | | | | | | | 4.0 | | | | | 4.0 | | | |
| 5 | | UVS | Ultraviolet Spectrometer | | ▲ | | | | | | | | | 12.0 | | | | | 12.0 | | | |
| 6 | Science | IRSM | Infrared Spectrometer Motor | | | | ▲ | | | | | | | | | | | | 3.5 | | | |
| 7 | Attitude Control | A/C 1 | Attitude Control | | ▲ | | | | 13 | 25.0 | 4.0 | 4.0 | 23.0 | 4.0 | 23.0 | 4.0 | 23.0 | 4.0 | 4.0 | 4.0 | 4.0 | 4.0 |
| 8 | | A/C 2 | Attitude Control | | ▲ | | | | | | | | 10.5 | | 10.5 | | 10.5 | | | | | |
| 9 | | GYRE | Gyro Electronics | | ▲ | | | | 8.0 | 8.0 | | | 8.0 | | 8.0 | | 8.0 | | | | | |
| 10 | Attitude Control | GYRO | Gyro | | | ▲ | | | 9.0 | 9.0 | | | 9.0 | | 9.0 | | 9.0 | | | | | |
| 11 | Scan Control | SCNE | Scan Control Electronics | | ▲ | | | | 5.3 | 5.3 | 5.3 | 5.3 | 5.3 | 28.5 | 5.3 | 5.3 | 5.3 | 5.3 | 16.5 | 5.3 | 5.3 | 5.3 |
| 12 | Scan Control | SCNM | Scan Control Motor | | | | ▲ | | | | | | | 12.0 | | | | | 12.0 | | | |
| 13 | Propulsion | VALV | Valve | | | | | ▲ | | | | | 30.0 | | 30.0 | | 30.0 | | | | | |
| 14 | Propulsion | GIMB | Gimbal | | | | | ▲ | | | | | 35.0 | | 35.0 | | 35.0 | | | | | |
| 15 | Radio Frequency | RFS | Radio Frequency Subsystem (exc. TWT) | | ▲ | | | | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 | 32.2 |
| 16 | Radio Frequency | TWT | TWT (Power Amplifier) | ▲ | | | | | 55.0 | 55.0 | 55.0 | 55.0 | 55.0 | 89.0 | 55.0 | 89.0 | 55.0 | 55.0 | 89.0 | 55.0 | 89.0 | 55.0 |
| 17 | Central Comp and Sequencer | CC & S | Central Command and Sequencer | | ▲ | | | | 39.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 | 19.0 |
| 18 | Flight TLM | FTS | Flight Telemetry Subsystem | | ▲ | | | | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 | 15.0 |
| 19 | Flight Command | FCS | Flight Command Subsystem | | ▲ | | | | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 | 3.2 |
| 20 | Data Storage | DSS | Data Storage Subsystem | | ▲ | | | | 21.0 | 22.0 | 10.0 | 10.0 | 10.0 | 18.0 | 10.0 | 19.0 | 10.0 | 10.0 | 23.0 | 15.0 | 19.0 | 18.0 |
| 21 | Pyrotechnic | PYRO | Pyrotechnic | | ▲ | | | | | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| 22 | Thermal Control | T/C 1 | TCFM Power and Cruise ACHtr | | ▲ | | | | 50.0 | 50.0 | 50.0 | 50.0 | 50.0 | | 50.0 | 50.0 | 50.0 | 50.0 | | 50.0 | 50.0 | 50.0 |
| 23 | | T/C 2 | DC Heater | ▲ | | | | | 7.3 | 7.3 | 15.0 | 15.0 | 7.3 | 15.0 | 7.3 | 7.3 | 7.3 | 7.3 | 7.3 | 15.0 | 15.0 | 15.0 |
| 24 | Thermal Control | T/C 3 | DC Heater | ▲ | | | | | 4.9 | 4.9 | 10.0 | 10.0 | 4.9 | 10.0 | 4.9 | 4.9 | 4.9 | 4.9 | 4.9 | 10.0 | 10.0 | 10.0 |
| 25 | Power | BTCG | Battery Charge/Booster | ▲ | | | | | 0.5 | 0.5 | 25.0 | 0.5 | 0.5 | 0.5 | 0.5 | 25.0 | 0.5 | 25.0 | 0.5 | 0.5 | 0.5 | 0.5 |
| 26 | | BRFS | Battery Regulator Fail Sensor | ▲ | | | | | 1.5 | 1.5 | 1.5 | 1.50 | 1.5 | 1.50 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| 27 | Power | PWRD | Power Distribution | | ▲ | | | | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 | 2.25 |

| Summary of Power Requirements | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Unregulated DC | 69.20 | 69.20 | 106.50 | 82.00 | 69.20 | 116.00 | 69.20 | 127.70 | 69.20 | 93.70 | 103.20 | 82.00 | 116.00 | 82.00 |
| 2.4 KHz | 188.95 | 182.95 | 141.95 | 141.95 | 179.45 | 194.15 | 179.45 | 150.95 | 179.45 | 141.95 | 187.15 | 146.95 | 150.95 | 149.95 |
| 3φ 400 Hz | 9.00 | 9.00 | 0.00 | 0.00 | 9.00 | 0.00 | 9.00 | 0.00 | 9.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| 1φ 400 Hz | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 12.00 | 0.00 | 0.00 | 0.00 | 0.00 | 15.50 | 0.00 | 0.00 | 0.00 |
| +28 VDC | 0.00 | 0.00 | 0.00 | 0.00 | 65.00 | 0.00 | 65.00 | 0.00 | 65.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |

Abnormal Gyro-On Loads

| | | |
|---|---|---|
| ACS1 | 16.0 | 2.4 KHz |
| GYSE | 8.0 | 2.4 KHz |
| GYSO | 9.0 | 3φ 400 Hz |

Analysis of the battery requirements for the flyby mission shows that the battery is required only during launch and initial acquisition and mid-course maneuver and will be used only as a backup power source for the balance of the mission. Battery sizing is determined by midcourse maneuver load requirements. Preliminary estimates show that the sizing of the battery for the orbiter mission will be determined by the orbit insertion power requirements. Verification of this requires final determination of the duration of those mission modes requiring battery power.

## 3.4 SOLAR ARRAY CHARACTERISTICS

The electrical output of the solar panel has been determined based on the existing Mariner solar panel total area of 83 sq ft with 78 cells in series and 224 in parallel. The computations were made for distance and time periods shown in Table 3-3.

Table 3-3. Sun-Spacecraft—Distance and Array Operating Life

| Distance from Sun (AU) | Array Life (Days) |
|---|---|
| 1.00 | 0 |
| 1.388 | 150 |
| 1.612 | 150 |
| 1.586 | 240 |
| 1.67 | 240 |

The pertinent characteristics of the components are shown in Table 3-4.

Table 3-4. Component Characteristics

| | |
|---|---|
| **Solar Cells** | |
| Type | N-on-P silicon soldered covered |
| Size | 2 cm x 2 cm x 0.016 in. |
| Weight | 550 mg |
| Electrical characteristics at AMO, 28°C | $I_p$ = 0.125A |
| | $V_p$ = 0.480V |
| | $I_{sc}$ = 0.134A |
| | $V_{oc}$ = 0.598V |
| Resistivity | 1 ohm-cm |
| Series resistance | 0.4 ohm |
| Current temperature coefficient | $74 \times 10^{-6}$ A/°C |
| Voltage temperature coefficient | $2.2 \times 10^{-3}$ V/°C |
| Efficiency | 11.2 percent average |
| **Cover Slides** | |
| Type | Fused silica |
| Size | 2 cm x 2 cm x 0.020 in. |
| Cut-off wavelength | 0.410 μ |
| **Blocking Diode** | |
| Type | Silicon, glass |
| Peak inverse voltage | 100 V |
| Reverse leakage current | 3μA at PIV, 25°C |
| | 50μA at PIV, 100°C |
| Forward voltage drop | 0.87 V at 1A, 25°C |
| Current | 2A |

### 3.4.1 Electrical Output Characteristics

The electrical output, shown in Table 3-8 was calculated for the string-pair (consists of a pair of 78 series by 3 parallel cells) based upon orbital data given in Table 3-3, component characteristics shown in Table 3-4, nominal time independent power adjustment factors (50 percent probability) shown in Table 3-5, temperatures given in Table 3-6, and nominal time dependent loss factors shown in paragraph 3.4.1.2. Results of these calculations, including scaling to 224 parallel cells, are shown in Figure 3-1 for 1.0 AU and 1.45 AU distances (array life 150 days). Preliminary correlations between the calculated values and JPL-furnished test data on a pre-production solar panel are very good, e.g., within 2 percent at maximum power value (for same set of conditions).

Table 3-5. Time Independent Power Adjustment Factors

| | |
|---|---|
| $I_{sc}$ | |
| Cover Installation Losses (a) | 0.955 |
| Module Assembly Losses (b) | 0.960 |
| Cell Efficiency (c) | 1.00 |
| Uncertainty in Solar Constant (d) | 1.00 |
| Random Solar Intensity (e) | 1.00 |
| Product (abcde) | 0.9168 |
| $V_{oc}$ | |
| Measurement Error | 0 |

#### 3.4.1.1 Temperature

The temperatures corresponding to the various distances from the Sun are shown in Table 3-6 for an uninsulated array. The data was taken from TRW's Voyager studies.

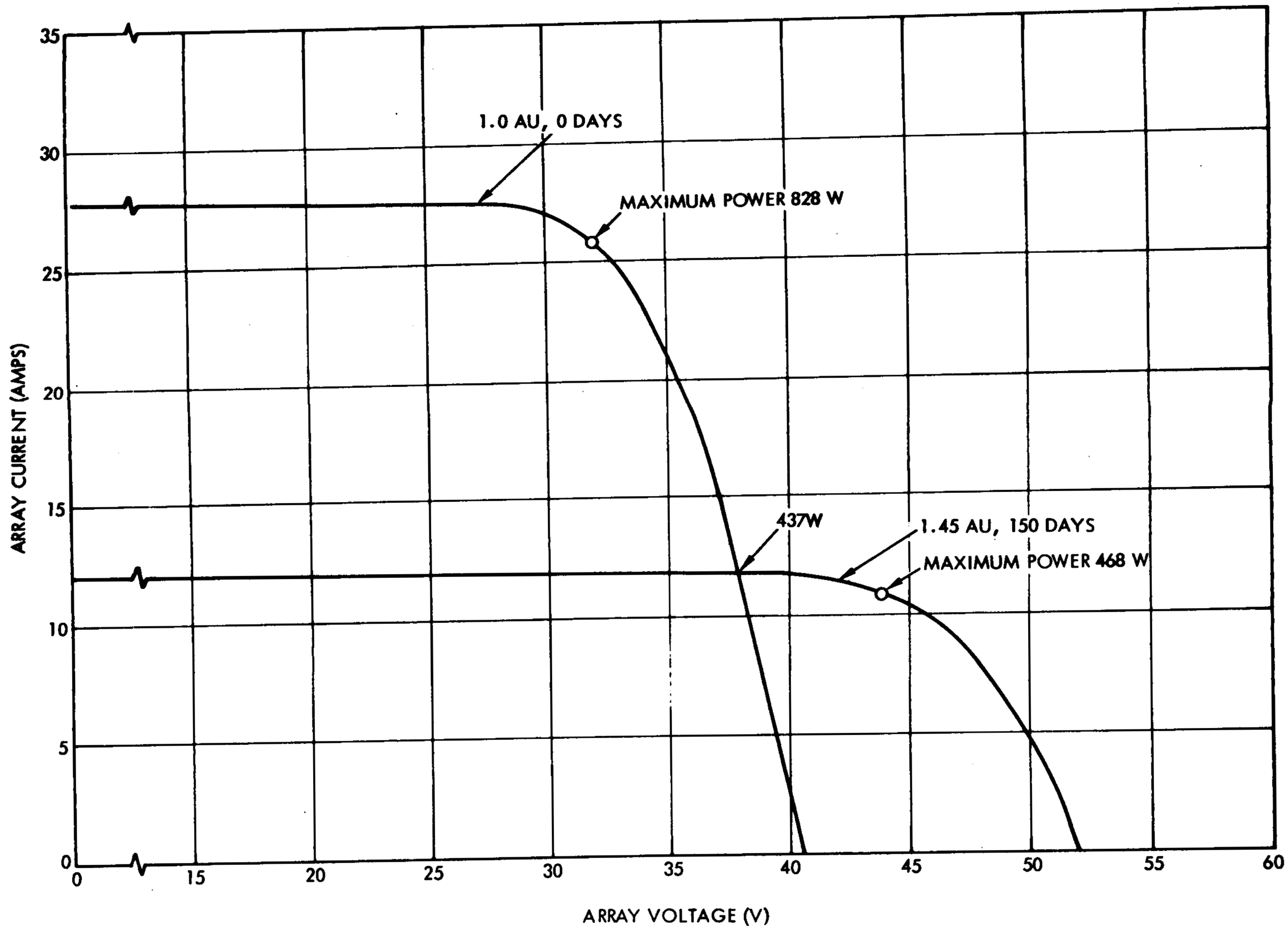


Figure 3-1. Solar Array Characteristics for Mariner Mars Solar Panel (Predicted)

Table 3-6. Temperatures Based on Distances from the Sun

| Distance from Sun (AU) | Solar Array Temperature (°C) |
|---|---|
| 1.00 | +54 |
| 1.388 | + 4 |
| 1.612 | -16 |
| 1.586 | -14 |
| 1.67 | -21 |

3.4.1.2 Time Dependent Loss Factors

Radiation. The nominal (50 percent confidence) yearly dosage based upon "Voyager Environmental Standards," dated 25 September 1967 from NASA, Voyager Project Office, is $5 \times 10^8$ 30 MeV protons/$cm^2$. This amounts to $3 \times 10^{13}$ 1 MeV equivalent electrons at the cell for 20 mils coverglass thickness. The nominal degradation factors (50 percent confidence) based on the above data are shown in Table 3-7.

Table 3-7. Nominal Voltage and Current Degradation for Yearly Dosages of $3 \times 10^{13}$ Equivalent 1 MeV Electrons per $cm^2$

| Time (Days) | Equivalent 1 MeV Electrons per $cm^2$ | Factor $V_{oc}$ Before | Factor $V_{oc}$ After | Factor $I_{sc}$ Before | Factor $I_{sc}$ After |
|---|---|---|---|---|---|
| 0 | 0 | 1.00 | 1.00 | 1.00 | 1.00 |
| 150 | $1.23 \times 10^{13}$ | 1.00 | 1.00 | 1.00 | 0.962 |
| 240 | $1.97 \times 10^{13}$ | 1.00 | 1.00 | 1.00 | 0.930 |

Cover Slide Transmittance Degradation due to Micrometeoroid Fluence

| Time (Days) | Factor |
|---|---|
| 0 | 1.00 |
| 150 | 0.995 |
| 240 | 0.992 |

Adhesive and Cover Slide Degradation due to Ultraviolet Radiation

| Time (Days) | Factor |
|---|---|
| 0 | 1.00 |
| 150 | 0.988 |
| 240 | 0.985 |

3.4.1.3 Wiring and Diode Voltage Drop

| | |
|---|---|
| Wiring | 0.38 V |
| Diode | 0.87 V |

Table 3-8. Electrical Characteristics of Solar Cell String-Pair for Various Orbital Conditions and Times Based on Nominal Time Dependent and Time Independent Factors (50 Percent Confidence)

| Time (Days) | AU | Temperature (°C) | Electrical Characteristics | | | |
|---|---|---|---|---|---|---|
| | | | $I_p$ (Amps) | $V_p$ (Volts) | $I_{sc}$ (Amps) | $V_{oc}$ (Volts) |
| 0 | 1.00 | +28°C | 0.683 | 36.5 | 0.737 | 45.1 |
| 0 | 1.00 | +54 | 0.695 | 32.1 | 0.749 | 40.7 |
| 0 | 1.388 | + 4 | 0.319 | 42.5 | 0.373 | 51.1 |
| 150 | 1.388 | + 4 | 0.302 | 42.5 | 0.353 | 51.1 |
| 0 | 1.612 | -16 | 0.210 | 46.4 | 0.264 | 55.0 |
| 150 | 1.612 | -16 | 0.199 | 46.4 | 0.250 | 55.0 |
| 0 | 1.586 | -14 | 0.220 | 46.0 | 0.274 | 54.6 |
| 240 | 1.586 | -14 | 0.200 | 46.0 | 0.249 | 54.6 |
| 0 | 1.67 | -21 | 0.188 | 47.4 | 0.242 | 56.0 |
| 240 | 1.67 | -21 | 0.171 | 47.4 | 0.220 | 56.0 |

3.4.1.4 Weight

The weight analysis for a module and the string pair are shown in Tables 3-9 and 3-10, respectively.

Table 3-9. Solar Cell Module Weight Analysis

| Unit | Quantity | Unit Weight (Lb x $10^{-3}$) | Total Weight (Lb x $10^{-3}$) |
|---|---|---|---|
| Solar cell | 18 | 1.21 | 21.78 |
| Cover slide | 18 | 0.99 | 17.82 |
| Cell interconnect | 20 | 0.026 | 0.52 |
| Module interconnect | 4 | 0.035 | 0.14 |
| Bus bar | 1 | -- | 1.27 |
| | | | 41.58 |

Table 3-10. String-Pair Weight Analysis

| Unit | Quantity | Unit Weight (Lb x $10^{-3}$) | Total Weight (Lb x $10^{-3}$) |
|---|---|---|---|
| Substrate | 1 | unknown | unknown |
| Module | 26 | 41.58 | 1081.1 |
| Diodes | 2 | 0.606 | 1.21 |
| Connector | 1 | unknown | unknown |
| Terminals | 6 | 0.14 | 0.84 |
| Terminal board | 1 | 1.6 | 1.6 |
| Module adhesive | As required | -- | 46.8 |
| Wire | -- | -- | 33.0 |
| Miscellaneous | -- | -- | 25.0 |
| | | | 1189.55 |

Based on the foregoing analysis, the total weight of the panel (less structure) for 224 strings is estimated to be 224/6 ($1189.55 \times 10^{-3}$) lb or 44.4 lb.

## 3.5 SELECTION OF MODEL SYSTEM CONFIGURATIONS

The selection of the model systems involved screening the various power system configuration possibilities to eliminate the less desirable ones. The final selection of the recommended optimum system will be made by subjecting the model systems to more detailed studies and analysis. The selection process progressed from the examination of 78 baseline power system configurations to the selected number of five. Table 3-11 is a matrix of power system configurations and Table 3-12 shows the justification for deletions of known system configurations. The synthesis of the configurations and the rationale are detailed in Final Report No. 07171-6001-R000, "Power System Configuration Study and Reliability Analysis" dated 18 September 1967. This work was performed by TRW for the Jet Propulsion Laboratory under Contract No. 951574.

The criteria for initial selection included primarily weight and reliability assessments (computer aided), maximization of solar array power margin (computer aided), complexity, flexibility, and demonstrated design. Table 3-13 summarizes the rationale in eliminating certain power system configurations. Figure 3-2 depicts the selected model power system configurations in simplified form; more detailed block diagrams of each system are shown in Figures 3-3 to 3-7. Figure 3-3 shows the existing Mariner '69 power system configuration. All relays are shown in the set position; also, telemetry current monitors are shown. Table 3-14 designates the cross-reference for the commands and some of the abbreviations utilized in the block diagrams. The more detailed block diagrams are intended to show required functions and not the final configuration. The various methods to perform the required functions will be the subject for further detailed analysis. For example, the active shunt limiter can be implemented by tapping the solar array and shunting current from the tapped portion through a power transistor or shunting current from the main bus via a series resistor and a power switch. Heat dissipation characteristics and solar array interface considerations are some factors which will be applied towards the final method selected. The implementation and arrangement of fault sensing, load switching and controls, automatic control versus ground control,

# Table 3-11. Summary of Selected Baseline Power System Configurations

Note

- Each configuration (combination of battery control, line regulator and array control) may be used with either AC or DC distribution.
- Applicable array controls indicated by uncircled numbers in each cell.
- Circled numbers in each cell designate reason for deleting certain configurations as listed in Table 3-12.

**ARRAY CONTROL LEGEND**

1. None
2. Zener
3. Active Shunt
4. PWM Buck Series
5. PWM Buck Series + $P_{max}$ Track
6. PWM Series Buck-Boost

| BATTERY CONTROLS | | LINE REGULATION 1 PWM Buck Line Reg | 2 Diss Line Reg | 3 Boost Line Reg | 4 Bk-Boost Line Reg | 5 No Reg |
|---|---|---|---|---|---|---|
| 1 | Switch + Resistor | 3 ⑦ ⑨ | NA ③ | 3, 4, 5 ⑦ ⑫ | 3 ⑦ ⑨ | NA ② |
| 2 | Same + Dischg Booster | 3 ⑦ ⑨ | NA ③ | 3, 4 ⑦ ⑪ ⑫ | 3 ⑦ ⑨ | NA ② |
| 3 | Dissipative Chg'r & Dischg. Sw. | 1, 2, 3 ⑨ | NA ③ | 2, 3, 4 ⑥ ⑩ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 4 | Same + Dischg. Booster | 1, 2, 3 ⑨ | NA ③ | 2, 3, 4 ⑥ ⑪ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 5 | PWM Buck Chg'r & Dischg. Sw. | 1, 2, 3 ⑨ | NA ③ | 2, 3, 4 ⑥ ⑩ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 6 | Same + Dischg. Booster | 1, 2, 3 ⑨ | NA ③ | 2, 3, 4 ⑥ ⑪ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 7 | PWM Boost Chg'r & Disch. Sw. | 1, 2, 3 ⑨ | 2, 3 ⑤ ⑨ | 2, 3, 4, 5 ⑥ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 8 | Same + Dischg. Booster | 1, 2, 3 ⑨ | NA ④ | 2, 3, 4 ⑥ ⑪ ⑫ | 1, 2, 3 ⑨ | NA ② |
| 9 | Diss. Chg. & Boost Dischg. Regulators | NA ① | NA ① | NA ① | NA ① | 3, 4, 5, 6 ⑧ |
| 10 | PWM Buck Chg. & Boost Dischg. Regulators | NA ① | NA ① | NA ① | NA ① | 3, 4, 5, 6 ⑧ |
| 11 | Same with Low Voltage Battery | NA ① | NA ① | NA ① | NA ① | 3, 4, 5, 6 ⑧ |

Table 3-12. Justifications for Deletions of Power System Configurations

| Circled Number (Table 3-11) | Reason for Deletion |
|---|---|
| 1 | Not applicable. Array and battery controls provide regulated bus. Additional line regulation not required. |
| 2 | Not applicable. Required bus voltage regulation cannot be provided by these battery controls. |
| 3 | Not applicable. Power loss in line regulator with maximum voltage at unregulated bus considered excessive. |
| 4 | Not applicable. Series dissipative regulator tends to produce constant current load and eliminate possibility of undesirable load sharing. |
| 5 | Array control 1 deleted. Unregulated bus voltage must be limited to minimize voltage drop across dissipative line regulator. |
| 6 | Array control 1 deleted. Must limit unregulated bus voltage to prevent overvoltage at regulated bus. |
| 7 | Array controls 1 and 2 deleted. Active regulator required by battery charge control to provide accurate voltage limit. |
| 8 | Array controls 1 and 2 deleted. Will not provide required ±1/2 percent bus voltage regulation. |
| 9 | Array controls 4, 5, and 6 deleted. Illogical to use two series bucking regulators in series. |
| 10 | Array control 5 deleted. Illogical to use line regulator if solar array output well regulated. With bucking charge control, array voltage must always exceed battery voltage. Boosting required only during battery discharge and should be included in battery controls. |
| 11 | Array control 5 deleted. Illogical to use discharge booster with maximum power tracking solar array control. Both prevent undesirable load sharing between array and battery. |
| 12 | Array control 6 deleted. Illogical to use two boost regulators in series. |

Table 3-13. Reasons for Eliminating Power System Configurations

| Systems | Reasons |
|---|---|
| 1. All system configurations with energy storage 1, 3, 5, and 7 | 1. These systems do not have the capability to prevent undesirable load sharing between the solar array and battery near the end of the mission. Solar array power availability constraints prohibit such a power system design. |
| 2. All systems with a dissipative line regulator | 2. The low efficiency of the dissipative regulator near the critical design point makes it undesirable. |
| 3. All systems with a PWM buck line regulator | 3. The boost line regulator offers weight advantages since it doesn't have to handle the full power. It also offers efficiency advantages especially at the critical design point. The PWM buck line regulator requires a higher voltage battery than a boost for the same regulated voltage. |
| 4. All systems with switch and resistor battery controls | 4. The dissipative charger systems offer more flexibility and control in terms of current limiting and charge voltage control. The switch and resistor approach is very highly dependent on charging source voltage and is thus not flexible. |
| 5. All systems with PWM buck charger | 5. The systems do not require highly efficient battery charging; therefore, the more simple and reliable dissipative charger is desirable. |
| 6. All systems with PWM buck charger and battery boost discharge regulator | 6. Same reason as in 5. |
| 7. All systems with PWM boost charger | 7. Selected configurations do not require a PWM boost charger. Reasons delineated in 5 also apply. |

Table 3-13. Reasons for Eliminating Power System Configurations (cont)

| Systems | Reasons |
|---|---|
| 8. All systems with low voltage battery (battery controls 11) | 8. For a nonredundant battery system, the low voltage battery system is not competitive from a weight standpoint (higher conversion losses with resulting increase in power conversion and battery weight). Low voltage systems are primarily applicable to long-life high reliability requirements or where partial success is acceptable with loss of a portion of the battery power. |
| 9. PWM buck array control with line regulator | 9. It is generally not desirable to have two series power-handling elements for reasons of lower reliability and increased losses. |
| 10. PWM buck series $+P_{max}$ tracker | 10. Maximum power trackers are generally applicable to low orbits where advantage can be taken of the transient (temperature) characteristics of the solar array. The boost regulator is more desirable since its efficiency is higher at the critical design point and is a simpler design. |
| 11. Buck-boost array control | 11. The active shunt limiter offers higher reliability and increased solar array power utilization. |
| 12. Zener limiter | 12. The active shunt limiter offers higher reliability, flexibility in adjusting the limiting voltage and provides narrow limiting voltage regulation. |

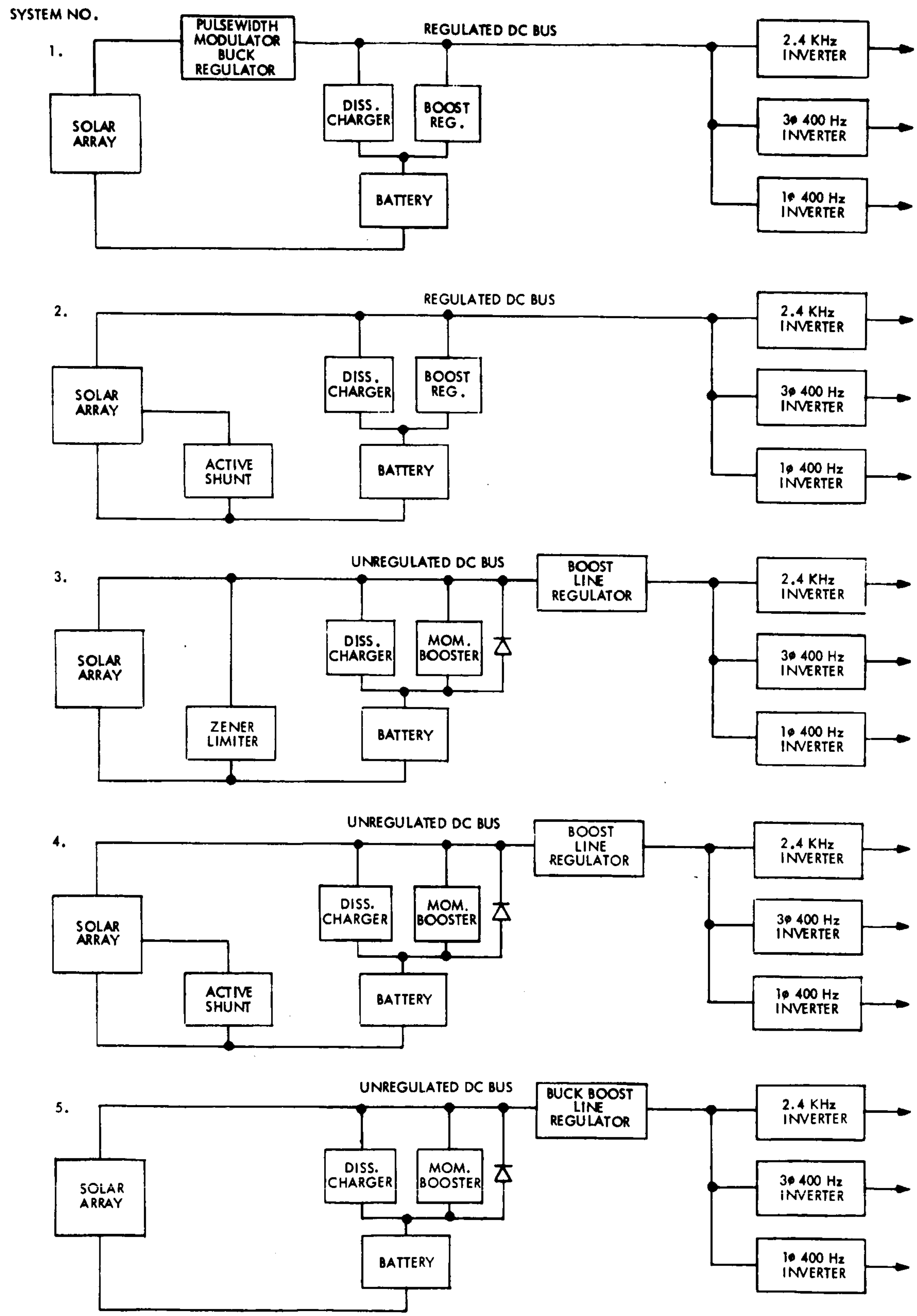


Figure 3-2. Selected Power System Configurations, Simplified Block Diagram

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

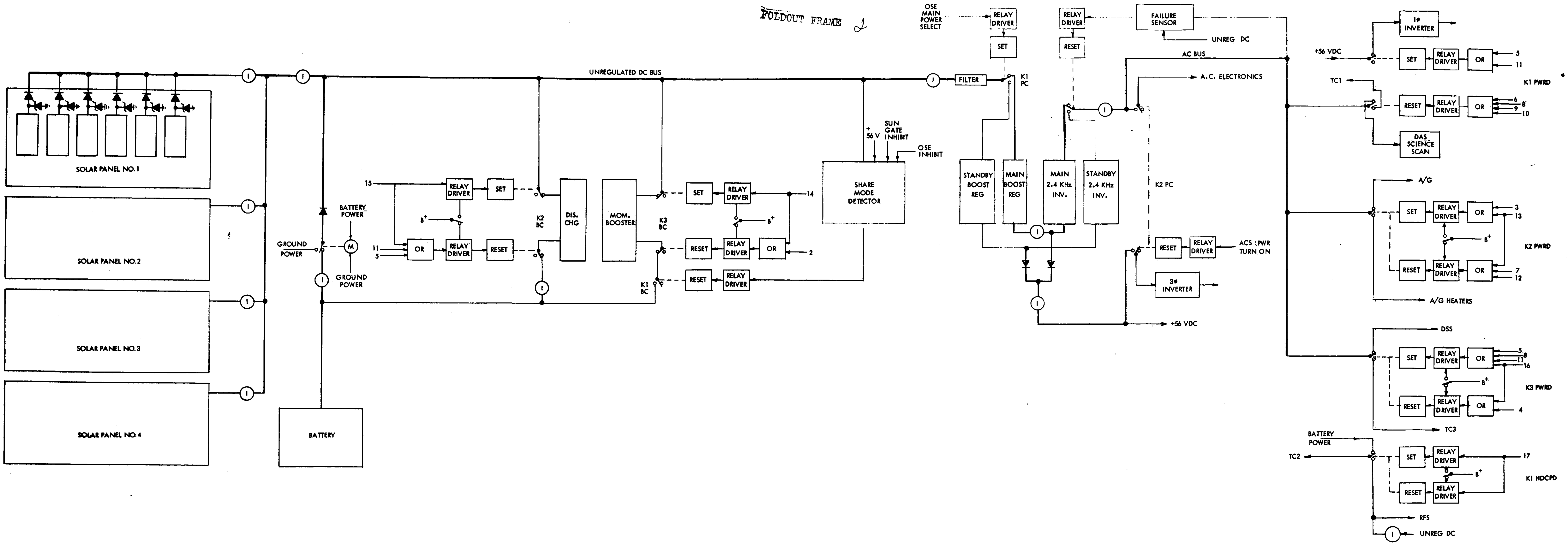


Figure 3-3. Unregulated DC Bus with Zener Limiter and Boost Line Regulator

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

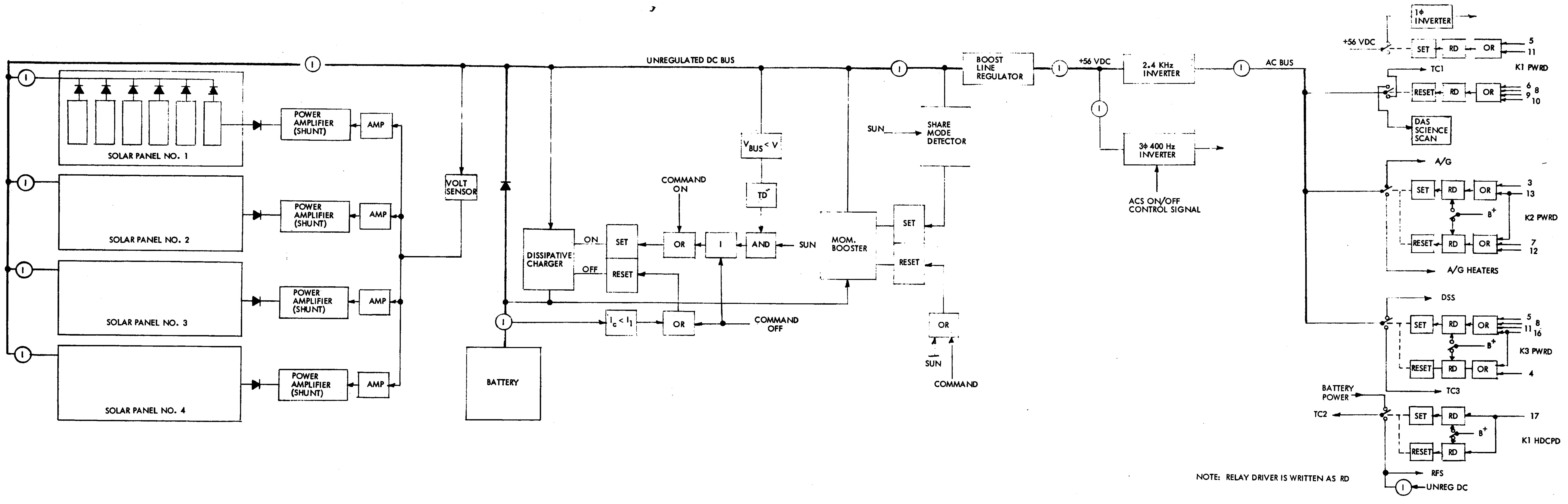


Figure 3-4. Unregulated DC Bus with Shunt Limiter and Boost Line Regulator

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

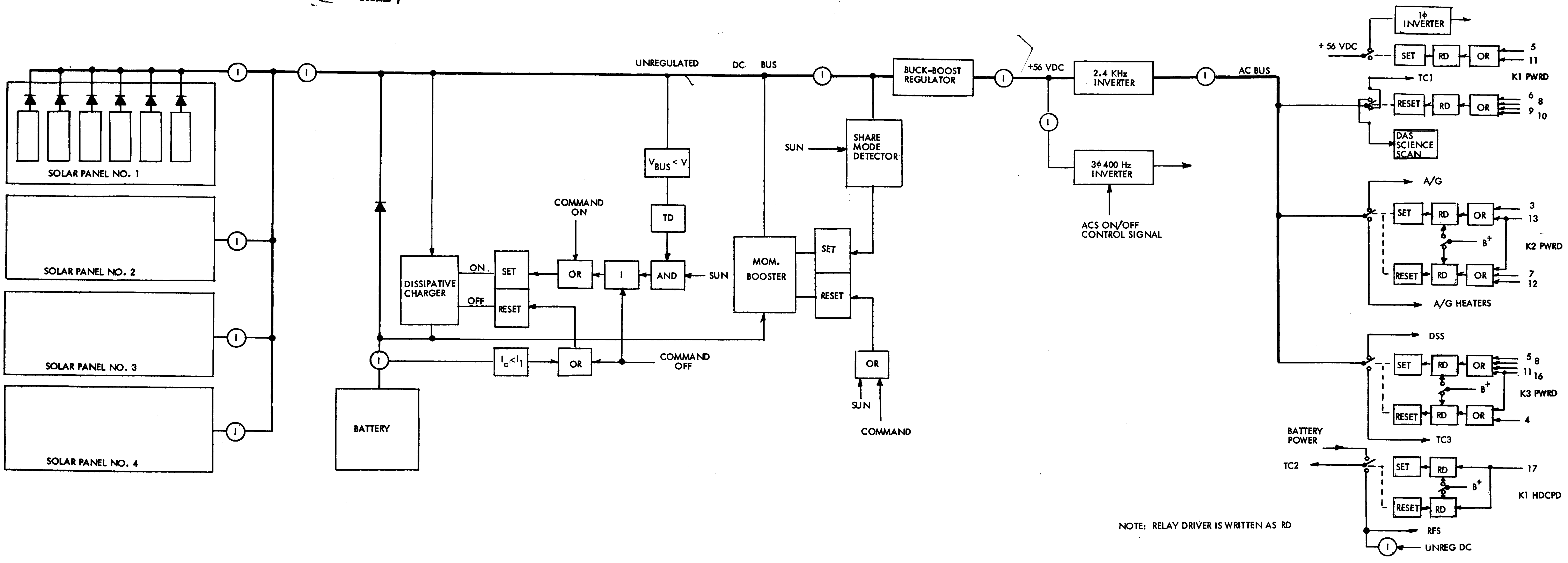


Figure 3-5. Unregulated DC Bus with No Array Control and Buck Boost Line Regulator

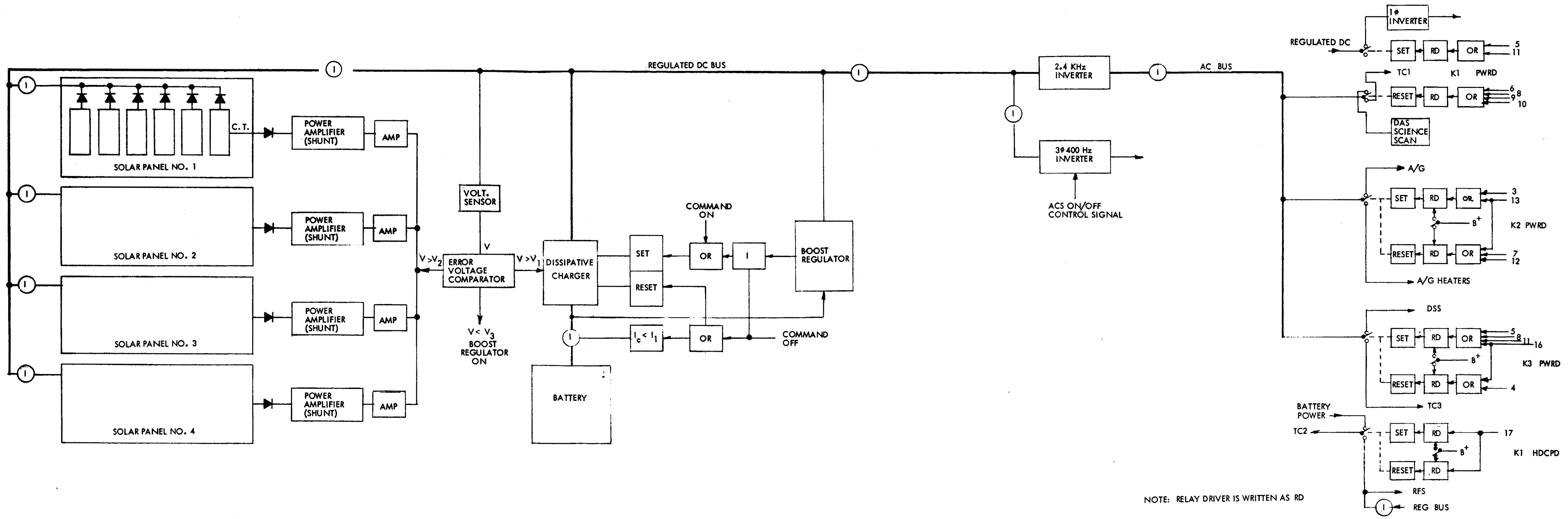


Figure 3-6. Regulated DC Bus with Shunt Limiter and Battery Boost Regulator

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

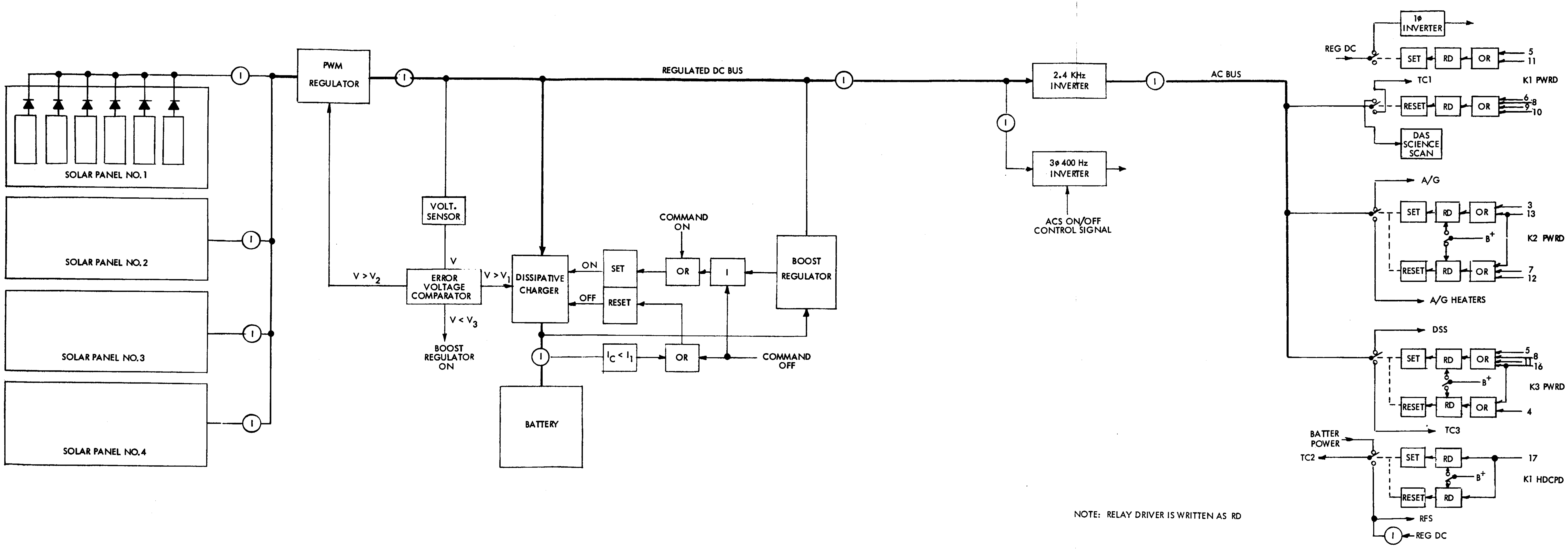


Figure 3-7. Regulated DC Bus with PWM Array Control and Battery Boost Regulator

## Table 3-14. Command Designation

| Command | Name | Source* | Type of Signal | Method of Actuation: (1) Relay | Set or Reset | Relay Location†: Pwr Dist. | BC | PC | HDCPD |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Gyros On | A/C | +28 V Referred to A/C Ground | K2* | R | | | ▲ | |
| 2 | Sun Gate Enable/Disable | A/C G1 | Isolated Circuit Closure | K3 | R | | ▲ | | |
| 3 | Approach Guidance (A/G) On | CC and S C4 | | K2 | S | ▲ | | | |
| 4 | Data Storage Subsystem (DSS) Off | CC and S L3 | | K3 | R | ▲ | | | |
| 5 | Encounter (ENC) Phase | CC and S N1 | | K1 | S | ▲ | | | |
| | | | | K3 | S | ▲ | | | |
| | | | | K2 | R | | ▲ | | |
| 6 | Near-Enc., Terminate | CC and S N5 | | K1 | R | ▲ | | | |
| 7 | Near-Enc. Sequence Enable | CC and S N6 | | K2 | R | ▲ | | | |
| 8 | Start Playback | CC and S P1 | | K1 | R | ▲ | | | |
| | | | | K3 | S | ▲ | | | |
| 9 | Cruise Mode | DC-1 | Isolated Circuit Closure (IS, IP, or Relay) | K1 | R | ▲ | | | |
| 10 | Playback Mode | DC-3 | Isolated Circuit Closure | K1 | R | ▲ | | | |
| 11 | Enc. Phase | DC-25 | | K1 | S | ▲ | | | |
| | | | | K2 | R | | ▲ | | |
| | | | | K3 | S | ▲ | | | |
| 12 | Near-Enc Sequence Enable | DC-26 | | K2 | R | ▲ | | | |
| 13 | A/G On/Off | DC-34 | | K2 | S | ▲ | | | |
| | | | | K2 | R | ▲ | | | |
| 14 | Boost Mode Enable/Disable | DC-37 | | K3 | S | | ▲ | | |
| | | | | K3 | R | | ▲ | | |
| 15 | Battery Charger On/Off | DC-38 | | K2 | S | | ▲ | | |
| | | | | K2 | R | | ▲ | | |
| 16 | DSS On/Off | DC-47 | | K3 | S | ▲ | | | |
| | | | | K3 | R | ▲ | | | |
| 17 | Battery/DC Bus DC Heater Toggle | DC-50 | | K1 | S | | | | ▲ |
| | | | | K1 | R | | | | ▲ |

(1) Relays magnetic latching except for K2 in PC

* Nonlatching

† 

| Nomenclature | Description |
|---|---|
| PWR DIST | Power Distribution Unit |
| BC | Battery Charger |
| PC | Power Control |
| HDCPD | Heater and DC Power Distribution (4A19) |

fail-safe control circuitry, type of redundancy, telemetry requirements, and the relative merits of each will constitute a major effort for the remainder of the performance period.

## 3.6 WEIGHT-RELIABILITY OPTIMIZATION

A computer program (modification of a program developed by TRW for JPL on Contract No. 951574) has been developed to provide an efficient instrument for quick evaluation of various power system configurations and the multitude of possible combinations of redundant elements for a given configuration. A brief description of the program and some typical printouts are delineated below. A detailed description will be presented in the final report.

A space power system consists of the following major components combined with a suitable solar array:

a. Power conditioning units
b. Line regulator
c. Array control
d. Energy storage

These units can be implemented in several distinct basic designs (types). Furthermore, each type could have several redundancy scheme alternates to improve reliability. The problem, then, is to evaluate each system design (case) to determine the optimum reliability alternates for each unit to achieve the highest reliability for prescribed subsystem weight constraints.

The TRW 940 Fortran 2 program is adaptable to this approach and operates in the following manner. The parameter information for each alternate of each type of each basic component is stored in a master data file. The program accesses this master file and reads a case specification from the input file. The alternate information for each type specified for each component is extracted from the master data file and the combinatorial search for that case is begun. Each possible combination of the alternatives is generated and the resulting subsystem weight and reliability is calculated by a subroutine. The weight and reliability of the system for this combination is stored along with alternate indicators. When all combinations have been evaluated, they are sorted by weight. An option in the program permits the output to be all the combinations or alternatively suppresses the output of dominated combinations. (A combination is dominated if a combination exists that has lower weight and an equal or greater reliability.) After the program finishes one case and the output is received, the program reads the input file for another case and repeats the above until all case specifications have been processed.

A subroutine computes the subsystem weight after a complete subsystem has been specified by the main program. Essentially, unit weights and efficiencies are given functions of the unit power. The computation proceeds backwards, from power conditioning equipment to solar array, and sizes each unit according to its power requirement as determined by previous unit power requirements and resultant efficiencies. Certain units are sized on peak requirements, others on average power requirements and inputs are provided accordingly.

The subsystem reliability is taken as the product of the unit reliabilities (any unit failure causes subsystem failure). The unit reliabilities as input are assumed independent of the unit power in that the unit is sized according to its power requirement and hence piece-part stress ratios are roughly invariant.

A typical example of the computer printout for one of the selected configurations is shown in Table 3-15. The system (flyby mission) consists of a shunt limiter array control (AC3), a boost line regulator (LR3), a dissipative charger and momentary booster and battery (ES2), and power conditioning units. The first column is the total weight of the power system including the solar array structure for 1.45 AU arrival. The second column is the system reliability. The third column (PSA) is the required solar array power at the critical design point. The fourth column (PBAT) is the required battery power during mid-course maneuver. The fifth column (WGT2) is the total system weight including solar panel substrate for 1.62 AU arrival. The sixth column (WGT3) is the total system weight less solar panel structure at 1.45 AU arrival. The last column (CONFIG.) designates the redundancy for each major element. The first digit in this column corresponds to the 2.4-KHz inverter. A zero or one indicates redundant or nonredundant inverter. Proceeding to the right, the digits indicate the 3$\phi$ inverter, 1$\phi$ inverter, array control, line regulator, and

Table 3-15. Typical Computer Printout for One Selected Power System for the Flyby Mission

MMPSØS "PØWER SUBSYSTEM ØPTIMIZATIØN STUDY" (DATA AS ØF 29MAY68)

| AC | LR | ES |
|---|---|---|
| 3 | 3 | 2 |

| WEIGHT | REL | PSA | PBAT | WGT2 | WGT3 | CØNFIG. |
|---|---|---|---|---|---|---|
| 137.37 | .8922182 | 370.15 | 339.46 | 149.95 | 97.20 | 000 0 0 00 |
| 138.37 | .9137268 | 370.15 | 339.46 | 150.96 | 98.21 | 000 0 0 01 |
| 142.28 | .9297178 | 374.04 | 343.51 | 154.99 | 101.69 | 000 0 1 01 |
| 146.32 | .9379195 | 374.04 | 343.77 | 159.04 | 105.74 | 010 0 1 01 |
| 150.41 | .9461935 | 374.39 | 343.77 | 163.14 | 109.79 | 011 0 1 01 |
| 151.56 | .9461935 | 379.29 | 349.34 | 164.46 | 110.41 | 110 0 1 01 |
| 155.65 | .9545406 | 379.64 | 349.34 | 168.56 | 114.46 | 111 0 1 01 |
| 162.41 | .9604525 | 385.51 | 349.34 | 175.52 | 120.58 | 111 1 1 01 |
| 173.06 | .9640567 | 374.04 | 343.51 | 185.77 | 132.47 | 000 0 1 10 |
| 174.99 | .9661254 | 374.04 | 343.51 | 187.70 | 134.40 | 000 0 1 11 |
| 177.12 | .9725613 | 374.04 | 343.77 | 189.84 | 136.54 | 010 0 1 10 |

-----

| | | | | | | |
|---|---|---|---|---|---|---|
| 179.05 | .9746483 | 374.04 | 343.77 | 191.77 | 138.47 | 010 0 1 11 |
| 179.08 | .9746483 | 374.39 | 343.51 | 191.81 | 138.46 | 001 0 1 11 |
| 181.21 | .9811409 | 374.39 | 343.77 | 193.94 | 140.59 | 011 0 1 10 |
| 183.14 | .9832463 | 374.39 | 343.77 | 195.87 | 142.52 | 011 0 1 11 |
| 184.77 | .9832463 | 379.29 | 349.34 | 197.67 | 143.62 | 110 0 1 11 |
| 186.93 | .9897963 | 379.64 | 349.34 | 199.84 | 145.74 | 111 0 1 10 |
| 188.86 | .9919202 | 379.64 | 349.34 | 201.77 | 147.67 | 111 0 1 11 |
| 193.65 | .9959266 | 385.51 | 349.34 | 206.76 | 151.82 | 111 1 1 10 |
| 195.62 | .9980637 | 385.51 | 349.34 | 208.73 | 153.79 | 111 1 1 11 |

the last two digits, the energy storage. The energy storage for this example has four combinations of redundant/nonredundant battery or charging control. For this particular case, 128 combinations were possible; however, the computer selectively prints out the nondominated combinations (20). A combination is dominated if a combination exists that has lower weight and an equal or greater reliability.

## 3.7 FAILURE MODES AND EFFECTS

Functional units that comprise the candidate systems include boost regulator, buck regulator, charge regulator, etc. Several approaches for implementing these functions have been selected. Primary failure modes have been identified for each functional unit. These failure modes have been related to specific systems to identify those which are catastrophic, produce degraded operation, or can be sustained with minimum effect. The seriousness of the failures, when compared with mission requirements, identifies problem areas requiring improvement. Future efforts will include:

1. Determination of the characteristics of the applicable redundancy methods (i.e., size, weight, power, reliability, failure modes)

2. Effect on power system and spacecraft performance.

Analyses of the failure modes, effects of the system elements, and typical components and circuitry required for the system elements have resulted in several guidelines for failure protection and reliability improvement. These aspects are discussed in the following paragraphs.

### 3.7.1 Magnetic Components

The failure rates of magnetic components (voltage and current transformers, inductors, mag-amps) can be reduced to extremely low values by judicious design and special manufacturing techniques. Increasing the spacing between turns and impregnating the coils with adequate compounds and epoxies reduces by a large amount the failure rates due to breakdowns of the magnet wire insulation (the least reliable characteristic of a magnetic component). The excellent success experienced by TRW with magnetic components in spacecraft applications suggests the feasibility of designing and manufacturing near fail-safe magnetic components.

This allows the circuit designer and the reliability analyst to eliminate redundancy provisions for magnetic components with a significant resultant weight savings.

3.7.2 Quad Redundancy

This technique may be considered a fail-safe scheme to the extent that at least two failures must occur before its redundant properties are destroyed. High-power losses generally make this technique unattractive for power circuits.

3.7.3 Majority Voting

This type of redundancy is rather similar to the special case of "parallel operating redundancy." The differences are that majority voting may accept shorted or open part failures and has an inherently higher parts count. Therefore, majority voting is best suited to circuits containing sensing or regulating functions where a relatively high parts count is justifiable.

3.7.4 Standby Redundancy

This scheme is commonly used in power circuit applications when efficiency considerations have great importance. It consists of two identical circuits; one is normally active and the other is deenergized but ready to be switched in place of the former in the event of a failure. This method requires the addition of a failure detector circuit in order to sense a malfunction. The failure detector circuit should be a fail-safe circuit since it has to recognize the malfunction, disconnect the damaged circuit, and then connect the standby unit. Its capability of failure recognition must be carefully assessed in terms of all the failure modes that may arise. Therefore, the testing considerations for this type of redundancy become a critical requirement.

3.7.5 Parallel Operating Redundancy

This type of redundancy requires that particular component failure modes will not impair the performance of the remaining portions of the circuit. Furthermore, the share of power or voltage handled by the remaining segments of the circuit, although higher after the failure has occurred, must still be within their rating. This type of redundancy is applicable to those particular high-power functions where efficiency considerations are of less importance. In addition to its poorer efficiency, this technique requires clearing circuitry (e.g., sensors and relays) or fusing and current sharing provisions (e.g., resistors or reactors).

### 3.7.6 Fail-Safe Redundancy

The fail-safe circuit is defined as one in which a failure of any component (shorted or open) would not impair the circuit performance. Several examples of such are quad redundancy and majority voting.

### 3.7.7 Methods of Failure Detection/Correction

#### 3.7.7.1 Fuses

This method is automatic in the sense that it does not require the support of any other special circuit. Its advantages are:

a. The detection function is attended by a protective one.

b. Its protective characteristics are particularly important when heavy fault currents (that could be damaging to relay contacts and semiconductor switches) are expected.

Its disadvantages are:

a. Relatively high failure rates

b. Testability limitations

c. Requirement of a low impedance source to be effectively cleared in the presence of a fault.

#### 3.7.7.2 Status Telemetry and Commands

The advantages of this approach are:

a. Replacement of complex automatic functions

b. Reliability improvement.

Its disadvantages are:

a. Additional telemetry requirements

b. Time involved in obtaining telemetry data and implementing commands.

3.7.7.3 Voltage, Current, or Frequency Detectors and Automatic Controls

The advantage of this method is its rapid detection and correction of malfunctions. Its disadvantage is the requirement of fail-safe design.