NI

TRW SYSTEMS

ONE SPACE PARK • REDONDO BEACH, CALIFORNIA

FACILITY FORM 602

N67-21173	
(ACCESSION NUMBER)	(THRU)
22	1
(PAGES)	(CODE)
CR-83120	03
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

SYSTEMS 82, REV. 10-65

E-7061.2-299

SECOND QUARTERLY PROGRESS REPORT

JPL Contract No. 951574

POWER SYSTEM CONFIGURATION STUDY AND RELIABILITY ANALYSIS

Period Covered:

7 October 1966 through 6 January 1967

This work was performed for the Jet Propulsion Laboratory, California Institute of Technology, sponsored by the National Aeronautics and Space Administration under Contract NAS 7-100.

by

W. G. Binckley

TRW SYSTEMS

ABSTRACT

Study efforts during the second project quarter are reported. Investigations leading to the development of photovoltaic power system design optimization data and procedures for five interplanetary missions are described. Candidate baseline power system configurations are summarized. System reliability analyses and procedures for selecting optimum configurations are discussed.

DISCLAIMER CLAUSE

NOTICE

This report was prepared as an account of Government-sponsored work. Neither the United States, nor the National Aeronautics and Space Administration (NASA), nor any person acting on behalf of NASA:

a. Makes warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or

b. Assumes any liabilities with respect to the use of, or for damages resulting from, the use of any information, apparatus, method, or process disclosed in this report.

As used above, "person acting on behalf of NASA" includes any employee or contractor of NASA, or employee of such contractor, to the extent that such employees or contractor of NASA, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment with such contractor.

Requests for copies of this report should be referred to:

National Aeronautics and Space Administration
Office of Scientific and Technical Information
Washington 25, D.C.

CONTENTS

ILLUSTRATIONS

TABLES

1. INTRODUCTION

This is the second quarterly progress report covering work performed by TRW Systems under JPL Contract 951574, "Power System Configuration Study and Reliability Analysis." This report summarizes the study effort during the period 7 October 1966 through 6 January 1967.

The principal objective of this study project is the development of photovoltaic electric power system design optimization data and procedures for five interplanetary missions: 0.3 AU and 5.2 AU probes, and Venus, Mars, and Jupiter orbiters. The project is divided into the following tasks:

Task I: Model Spacecraft Requirements

(a) Mission Analysis. Analyze the five specified missions to determine spacecraft configurations for each, based on booster capabilities, mission objectives, and subsystem requirements.

(b) Power Requirements. Analyze model spacecraft configurations to establish load power requirements including power profiles and characteristic voltage levels and regulation limits.

Task II: Baseline Power System Configurations

(a) Solar Array Analysis. Determine current-voltage characteristics of solar array as functions of mission time for each model spacecraft.

(b) Analysis of Baseline Systems. Define alternative baseline (nonredundant) power system configurations which are compatible with each of the spacecraft models. Determine advantages and disadvantages of each with respect to reliability, weight, spacecraft integration, efficiency, complexity, and flexibility.

Task III: Power Systems of Improved Reliability

(a) Methods of Reliability Improvement. Perform component and system failure mode analyses for each baseline configuration and establish methods of improving component reliability.

(b) Effects of Reliability Improvement. Investigate and describe effects of reliability improvements on component reliability, weight and efficiency, and system weight and reliability. Establish procedures and input data for reliability-weight optimization.

Task IV: System Recommendations

Compare alternative system configurations from Task III to select those providing maximum reliability as a function of weight. Recommend an optimum configuration for each model spacecraft.

Task V: Telemetry Criteria

Investigate telemetry monitoring points, parameter ranges, and priorities for various system configurations from Task III. Investigate utilization of telemetry data during both normal and abnormal system operation. Develop generalized criteria for power system telemetry requirements.

In addition to a final report which will fully document all study efforts, a "Spacecraft Power System Configuration Reference Manual" will be prepared to provide a design reference for use in the determination of optimum power system configurations for various interplanetary missions.

2. PRESENT STATUS OF THE STUDY

The study efforts completed during the first and second quarters represent approximately 40 percent of the total planned engineering effort. Task I, the determination of model requirements, is complete. Task II, the analysis of baseline power systems for each model requirement, is approximately 80 percent complete. Task II, the analysis of methods of reliability improvement is 30 percent complete. Tasks II and III have been delayed as a result of additional efforts required in developing the procedure for reliability-weight optimization of the large number of candidate power system configurations. Discussion of this problem area and its solution is contained in Section 3, Study Results.

The revised project schedule is shown in Figure 1.

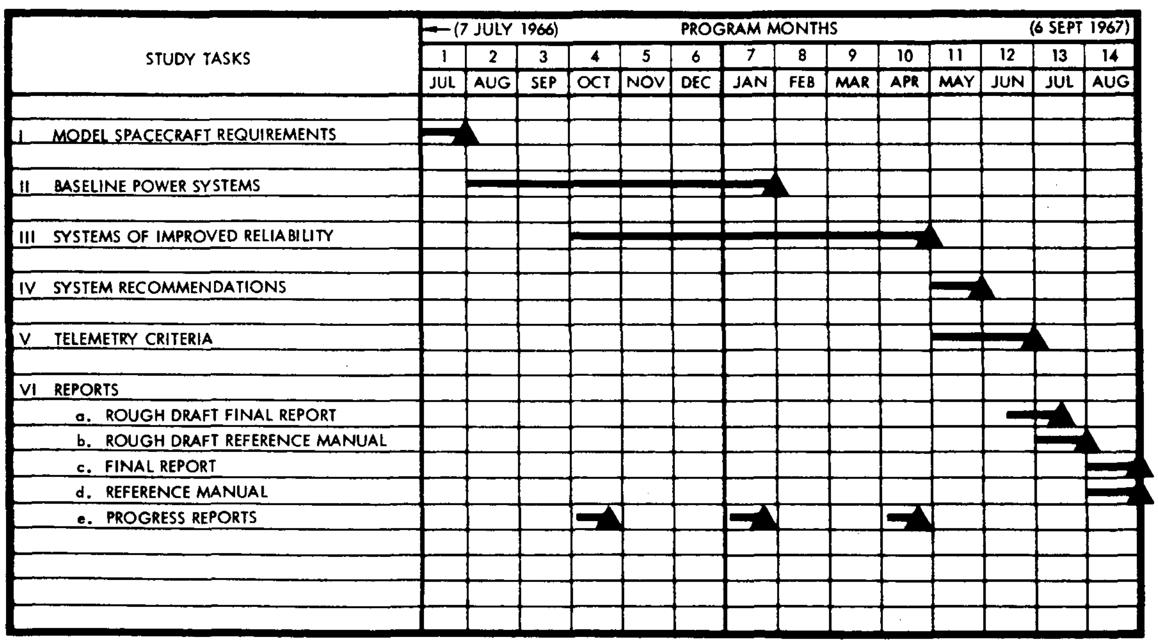

Figure 1. PSC Study and Reliability Analysis Project Schedule

3. STUDY RESULTS

3.1 BASELINE SYSTEM ANALYSIS

The analysis of alternative baseline power system configurations continued during the second project quarter. This effort was divided into three areas of investigation: determination of candidate power supplies; determination of candidate power conditioning equipment; and determination of system control logic requirements. The power supplies include the photovoltaic source, energy storage, control, and regulation functions as described in the first quarterly progress report. The power supply output, in all cases, is a regulated dc bus. The power conditioning equipment consists of those functions necessary to convert the regulated dc bus power to the various regulated dc and ac outputs required by the load equipment. The system control logic includes sensing, logic, and switching functions to effect proper operation of the power supply. These functions are associated primarily with the battery charge and discharge controls.

3.1.1 Power Supply Configurations

As described in the first quarterly progress report, the investigation of candidate power supply configurations was based on selecting specific implementations for five basic functional power supply configurations.

These selections were based in part on the following general considerations:

a) Solar Array Controls. Solar array regulators of the series type may employ either switching (pulse-width-modulated) or dissipative techniques. Although less complex than the switching type, the dissipative regulator severely penalizes system efficiency since its losses are directly proportional to the difference between solar array voltage and the regulated output voltage. For the relatively large range of solar array voltages typical of the interplanetary missions under consideration, the dissipative approach has been rejected in favor of the more efficient switching type.

Similarly, shunt regulators may employ either switching or dissipative techniques. However, in the shunt configuration, power dissipation is a direct function of the excess solar array power capability relative to the load demand. The dissipative shunt regulator, therefore, tends to maximize system efficiency at the critical design point when excess solar array capability is a minimum and the added complexity of a switching type shunt regulator is not warranted from the standpoint of system efficiency. The potentially large variations in heat dissipation in the nonswitching shunt regulators tend to complicate the thermal interface with the spacecraft; however, thermal control techniques have been successfully implemented by TRW to accommodate this approach on a variety of spacecraft applications.

b) Battery Charge Controls. Investigations of battery control techniques were based on the use of either silver-zinc or silver-cadmium batteries. Nickel-cadmium batteries were not considered because of their magnetic field properties and associated interactions with the magnetic field measuring experiments which are common to all of the mission/spacecraft models under consideration. Both constant current and constant potential charge control approaches were investigated. The selected approach employs battery voltage limiting and decreasing charge current as an inverse function of battery terminal voltage. Charging is terminated when the battery current falls to a predetermined low level indicative of a fully charged state. For those cases where the bus voltage can be limited to maximum battery charging voltage, a simple current-limiting resistor and series switch can be used.

Bucking type chargers of both dissipative and switching types are considered for those cases where the solar array operating voltage exceeds the maximum battery charging voltage. For those cases where this voltage differential is relatively small and since required battery charging rates are low, the efficiency penalty associated with the use of dissipative regulators may be offset by the reliability advantages of this simpler approach. For those cases where the battery charging voltage exceeds the solar array voltage, a voltage boosting charger is used.

Finally, for those power supply configurations employing a regulated main dc bus, the charger may include bus-voltage feedback to further limit battery charging current in those cases of marginal solar array capability where normal battery current could produce a main bus under-voltage condition.

c) Battery Discharge Controls. For those power supplies in which the main bus voltage varies with the battery charge-discharge status, a switching function has been incorporated to provide a direct lossless discharge path from battery to bus. The alternative approach of relying on a diode to provide a unidirectional discharge path is considered undesirable because of the voltage drop and power loss associated with this approach. The added control complexity to implement this approach is considered a lesser penalty than the added battery weight to accommodate series diode losses, particularly in view of the probable need for series redundant power diodes to insure adequate reliability.

The discharge booster, as employed in those power supplies containing an unregulated main bus, serves to overcome unnecessary battery load sharing at the lower end of the bus voltage range when the solar array could support the system load at a higher operating voltage as shown in Figure 2. With a pulse-width-modulated line regulator, the load on the

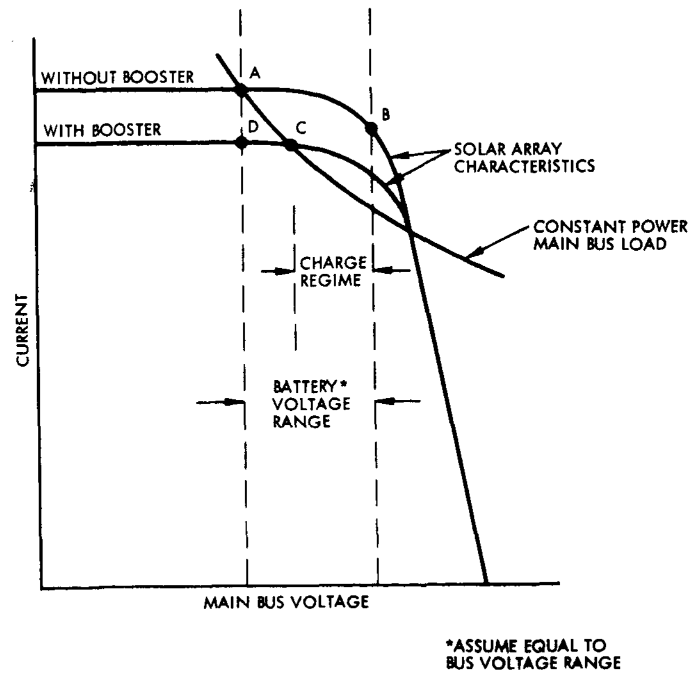

Figure 2. Comparison of Solar Array Operating Conditions With and Without Battery Discharge Booster

main bus approaches a constant power characteristic as a function of bus voltage. Therefore, at lower voltages, the current demand is high. In a simple case, emergence from a solar eclipse, the battery is discharging to support the total load and the bus voltage is at the lower end of its range. As the solar array is illuminated, it will deliver current to the load and must be sized to supply the total load current at the lower operating voltage (Point A). When the array current capability builds to the point at which battery discharge is no longer required, the bus voltage will rise, the load current will reduce, and the battery will begin accepting charge from the solar array. Since battery-charging current requirements are low, the array will tend to have a significant excess power capability at the higher voltages during battery charging (Point B). This inability to make use of the maximum solar array power capability at normal voltages clearly penalizes the power system from the standpoint of solar array weight. The magnitude of this penalty is dependent on the relationship between the battery voltage range and the solar array maximum power point voltage.

To improve the utilization of array power, a battery discharge booster may be employed to force the bus voltage to a higher level when an unnecessary load-sharing condition exists. With this approach, the solar array may be designed to provide required load current only at voltages corresponding to battery charging conditions (Point C). The booster power capability need be adequate only to supply the difference in power between the load requirement at battery discharge voltage (Point A) and the solar array capability at that same voltage (Point D).

Power sources which generate a regulated dc bus directly by regulating both battery and solar array outputs independently require a continuous boosting regulator for battery discharge. This approach of course eliminates the need for a separate line regulator. The selection of a boosting regulator for this application is based on minimizing the voltage difference between the regulated bus and the battery during charging conditions. The reduction in battery voltage during discharge, therefore, requires boosting back to the regulated bus level.

d) Line Regulators. Bucking line regulators may be either of the dissipative or switching type. As in the case of array controls, the former has been rejected for the majority of the power supply configurations because of its poor efficiency with significant variations in input voltage (unregulated bus voltage). It has been considered, however, for certain configurations wherein the array and battery controls limit the unregulated bus voltage variations to approximately one half of the normal battery voltage excursion. Line boost and buck-boost regulating functions are implemented using conventional pulse-width-modulation techniques.

3.1.2 Power Conditioning Equipment

The investigation of alternative power conditioning approaches has been based on two general approaches to supplying multiple regulated dc and ac outputs from the central regulated dc bus of the selected power supply configurations. The first of these employs centralized converters and dc power distribution to perform the major portion of the power-conditioning functions. The second approach employs centralized inverters with ac power distribution to transformer rectifiers located with the load equipment. A major consideration in evaluating various configurations to implement these approaches was the fact that centralized regulation and conditioning equipment tends to improve system reliability and reduce system weight. The reliability improvement is based on minimizing the number of electronic parts required. The weight reduction is based on the fact that packaging weight becomes a smaller fraction of component weight as the power handling capability of any unit is increased.

a) DC Distribution. The selected power conditioning configuration for dc distribution is illustrated in Figure 3. Analysis of the load input

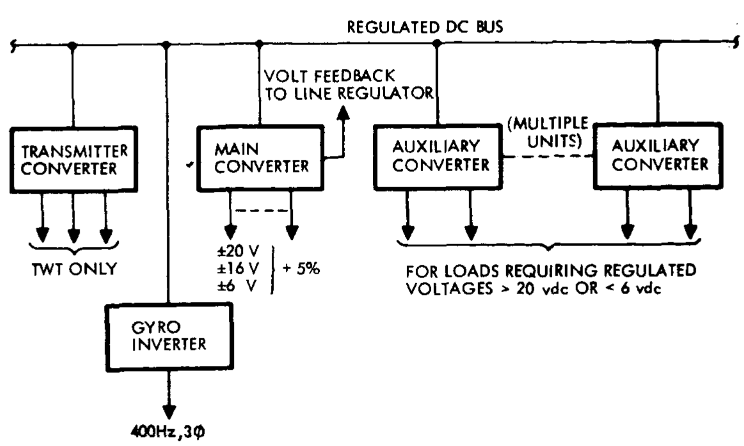

Figure 3. Selected Power Conditioning Configuration for AC Distribution

power characteristics established during the first quarter of the project disclosed extensive usage of ±20, ±16, and ±6 volts dc at varying degrees of regulation. These were selected, therefore, as standard secondary voltages for distribution to the loads. The regulation, ripple and transient voltage tolerances of the loads typically require supplementary active filtering at their inputs when supplied from a common source. An unregulated main converter was selected, therefore, to provide ±5% outputs with additional regulation functions provided within the load equipment as required. Voltage feedback from the converter output stage is used to control the line regulator (not shown) which supplies the converter input. Requirements for high voltages, close regulation, and matching between the power supply and TWT transmitters dictated the use of a separate converter for this requirement. Additional regulated auxiliary converters are used to supply those loads requiring input voltages greater than 20 volts or less than 6 volts which are excluded from the centralized distribution system. AC power for gyros is derived from a separate inverter.

b) AC Distribution. The selected power conditioning configuration for ac distribution is illustrated in Figure 4. An unregulated main inverter is used to supply the ac bus. This ac voltage is sensed to control the dc line regulator included within the power supply. The ac power is distributed to multiple unregulated transformer rectifier units which provide ±5 percent dc voltages to the loads. As in the case of dc distribution, additional regulation requirements are satisfied within the load equipment and a separate inverter is provided for gyro requirements.

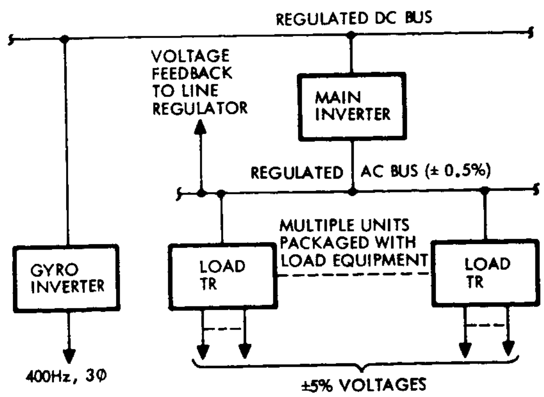

Figure 4. Selected Power Conditioning Configuration for DC Distribution

Analysis of power conditioning requirements and definition of components for each model spacecraft were completed during the reporting period. In the case of dc distribution, power requirements of less than one watt at nonstandard voltages were assumed to be generated within the load equipment. For the ac distribution approach, separate transformer-rectifiers were assumed for each item of load equipment identified during previous phases of the study.

3.1.3 System Control Logic

System control and logic requirements were investigated to establish those functions necessary for proper operation of the integrated power systems. These were determined to consist chiefly of battery charge and discharge control functions. Specifically, means of terminating battery charge, controlling the battery discharge switch used in many of the systems, detecting unnecessary battery load sharing and controlling the discharge booster to terminate this undesirable operating mode where applicable were analyzed.

An example of the selected logic which incorporates each of these requirements is illustrated in Figure 5. In this case battery charging is

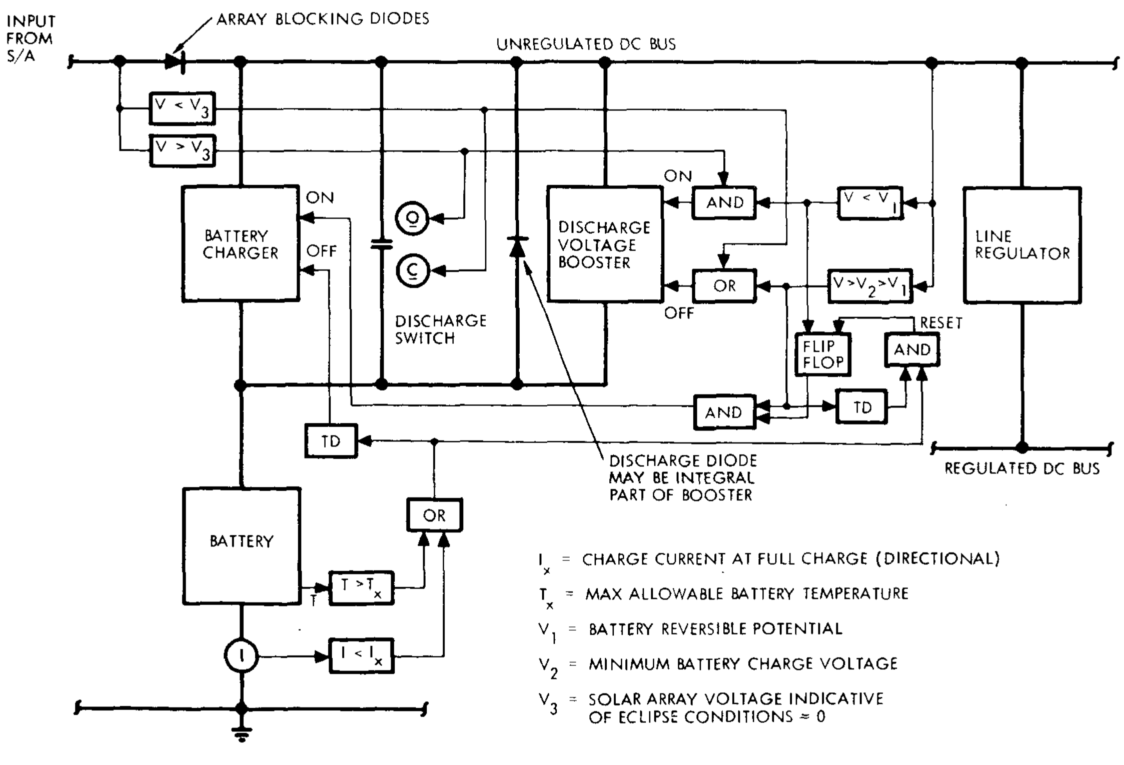

Figure 5. Example of Selected System Control Logic

terminated when the charging current falls to a predetermined level. The normally open discharge switch is closed when solar array voltage indicates loss of solar array orientation or entry into eclipse conditions. The discharge voltage booster is energized when the unregulated dc bus voltage decreases to a level indicative of battery discharge and the solar array voltage is indicative of non-eclipse conditions. When the battery is discharging, the charger is de-energized to minimize power losses in the system. If the action of the discharge booster restores the system to normal operating voltage, the booster is de-energized and battery charging initiated. If the discharge booster is not capable of transferring the entire load to the solar array, battery load sharing continues through the discharge diode. Similar logic and control configurations have been defined for each candidate power system configuration to complete the baseline system definitions.

3.1.4 Configuration Summary

A matrix defining 148 selected candidate power system configurations resulting from this study task is shown in Table I. Each vertical column represents one combination of line regulation and power conditioning equipment. Each horizontal row represents one combination of battery charge and discharge controls. Numerals within the matrix represent the appropriate solar array controls for each configuration. Circled numerals reference justifications for deletion of possible combinations as listed in Table II.

3.2 SYSTEM RELIABILITY ANALYSES

System reliability analyses have included the analysis of methods of improving system reliability and the analysis of methods of selecting optimum power system configurations based on maximum reliability and minimum weight. To date, the investigation of reliability improvement methods has been concentrated on the determination of preferred techniques for implementing redundancy at the component level. In the development of a method for system reliability-weight optimization, emphasis has been placed on adapting an existing TRW computer program to the specific needs of this study and preparing the necessary input data for this program.

Table I. Summary of Selected Baseline Power System Configurations

ARRAY CONTROLS SHOWN IN MATRIX

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/POWER CONDITIONING									
	PWM Buck Line Reg DC Distr	PWM Buck Line Reg AC Distr	Diss Line Reg DC Distr	Diss Line Reg AC Distr	Boost Line Reg DC Distr	Boost Line Reg AC Distr	Bk-Boost Line Reg DC Distr	Bk-Boost Line Reg AC Distr	No Reg DC Distr	No Reg AC Distr
Switch + Resistor	3 7 9	3 7 9	NA 3	NA 3	3, 4, 5 7 12	3, 4, 5 7 12	3 7 9	3 7 9	NA 2	NA 2
Same + Dischg Booster	3 7 9	3 7 9	NA 3	NA 3	3, 4 7 11 12	3, 4 7 11 12	3 7 9	3 7 9	NA 2	NA 2
Dissipative Chg'r & Dischg. Sw.	1, 2, 3 9	1, 2, 3 9	NA 3	NA 3	2, 3, 4 6 10 12	2, 3, 4 6 10 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
Same + Dischg. Booster	1, 2, 3 9	1, 2, 3 9	NA 3	NA 3	2, 3, 4 6 11 12	2, 3, 4 6 11 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
PWM Buck Chg'r & Dischg. Sw.	1, 2, 3 9	1, 2, 3 9	NA 3	NA 3	2, 3, 4 6 10 12	2, 3, 4 6 10 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
Same + Dischg. Booster	1, 2, 3 9	1, 2, 3 9	NA 3	NA 3	2, 3, 4 6 11 12	2, 3, 4 6 11 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
PWM Boost Chg'r & Disch. Sw.	1, 2, 3 9	1, 2, 3 9	2, 3 5 9	2, 3 5 9	2, 3, 4, 5 6 12	2, 3, 4, 5 6 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
Same + Dischg. Booster	1, 2, 3 9	1, 2, 3 9	NA 4	NA 4	2, 3, 4 6 11 12	2, 3, 4 6 11 12	1, 2, 3 9	1, 2, 3 9	NA 2	NA 2
Diss. Chg. & Boost Dischg. Regulators	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	3, 4, 5, 6 8	3, 4, 5, 6 8
PWM Buck Chg. & Boost Dischg. Regulators	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	NA 1	3, 4, 5, 6 8	3, 4, 5, 6 8

NOTE: Circled numbers designate applicable justification for deletions (Table II).

TABLE II. JUSTIFICATIONS FOR DELETIONS OF POWER SYSTEM CONFIGURATIONS

1. Not applicable. Array and battery controls provide regulated bus. Additional line regulation not required.

2. Not applicable. Required bus 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% 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.

3.2.1 Methods of Reliability Improvement

With the establishment of a variety of alternative power system configurations, subsequent study efforts have been directed toward analysis of the components of each to establish methods of improving their reliability. To achieve this end, proper parts application, electrical and thermal derating, and the use of redundancy are the conventional approaches. The first two of these have been assumed in establishing part failure rates for use in assessing the reliability of the various components.

Component design approaches under investigation include parallel and standby component level redundancy as well as quad and majority voting approaches to circuit level redundancy. Results of these investigations, thus far, have favored the use of standby techniques for power conditioning and series regulating components, majority voting for the system control and logic circuits and for the control circuits of shunt regulators, quad elements for the shunt power handling circuits and parallel redundancy of the batteries. Redundancy is normally implemented in solar array designs by multiple parallel interconnections between adjacent series strings of cells. This approach minimizes array power losses in event of single cell open circuit failures which represent the predominant failure mode.

3.2.2 Reliability-Weight Optimization

Evaluations of the reliability and weight of each candidate power system configuration for varying degrees of redundancy in each of the system components will be performed with the use of existing TRW computer programs. The principal one of these calculates the weight and reliability of all possible combinations of series elements in a system where each element has two or more alternative configurations and selects the combination which yields maximum reliability for a given weight constraint. As applied to the power system optimization, the program will evaluate all combinations of redundant and nonredundant components for a given system configuration and select a series of combinations of minimum weight for a series of given reliability values. Thus, for each of the baseline system configurations, the program will establish optimum component redundancy levels yielding minimum system weight as a function of system reliability.

This program has been modified to calculate system weight taking into account component efficiency as a function of redundancy and power output. Thus, the weight of a component, such as the line regulator, is determined from its required output power as well as the type of redundancy employed in the line regulator itself. The required power output of this particular component, of course, is determined by the efficiency and required outputs of the power conditioning equipment. Parametric data relating component efficiency to output power has been prepared for nonredundant configurations. Additional data is being prepared to reflect the effect of selected methods of implementing redundancy on the efficiency of each component.

System reliability calculations are based on the assumption that any part failure in a nonredundant configuration constitutes a system failure. Thus, all power system components are considered in-line elements of the system reliability models. A typical system configuration consists of eleven components. With three levels of redundancy in each component as originally planned, the computer must evaluate an average of 3^{11} combinations for each system configuration. The machine time required for this number of calculations was determined to be excessive relative to the scope of the study contract.

Several approaches to reducing the amount of computation required were investigated. Included among these were analyses of mathematical approaches to evaluating system functions involving reliability, efficiency and weight to determine optimum system configurations directly. The discontinuous nature of these relationships, however, was determined to be inconsistent with this approach. The more promising of the approaches investigated appear to be a reduction in the number of redundant configurations evaluated for each component and the establishment of a minimum allowable reliability for the power systems. The first of these has been initiated through analyses to define a single preferred technique for implementing redundancy in any given component. Preliminary results have effected a significant reduction in the number of combinations required. The second approach is being investigated to establish a realistic minimum reliability allocation for the power system and will eliminate a significant number of nonredundant and partially redundant system configurations. Although a delay in the planned study program has resulted from these added investigations, their results have indicated that the planned study efforts will be completed successfully.