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THIRD QUARTERLY PROGRESS REPORT

JPL Contract No. 951574

POWER SYSTEM CONFIGURATION STUDY AND RELIABILITY ANALYSIS

Period Covered:

7 January through 6 April 1967

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by

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TRW SYSTEMS

ABSTRACT

Study efforts during the third project quarter are reported. Methods of implementing component redundancy are described. Component parts counts, efficiency and weight data are included. A method for power system reliability-weight optimization and the results of initial optimization computer runs are described. Power system EMC considerations are summarized.

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ILLUSTRATIONS

ILLUSTRATIONS (Continued)

TABLES

1. INTRODUCTION

This is the third 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 January 1967 through 6 April 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 three quarters represent approximately 70 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 complete. Task III, the analysis of methods of reliability improvement is 80 percent complete.

Parametric weight and efficiency data for the various power system components have been prepared and are included in this report. Computer inputs, including reliability assessments of each component have been prepared. Initial results of the reliability-weight optimization computations for one power system configuration have been obtained and are included in this report.

The project schedule is shown in Figure 1.

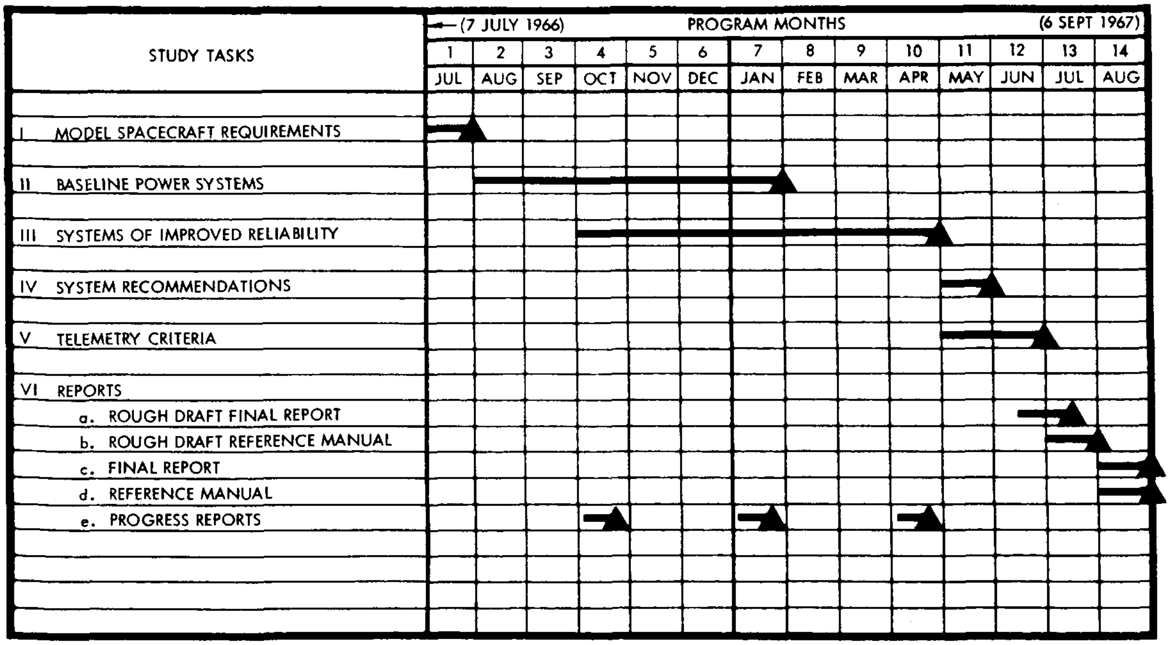


Figure 1. PSC Study and Reliability Analysis Project Schedule

3. STUDY RESULTS

3.1 RELIABILITY ANALYSES

To date, the power system reliability analyses have concentrated on quantitative comparisons of the reliabilities and weights of the alternative system configurations, taking into account the possibility of adding redundancy at the component level in each system. A broad spectrum of baseline system configurations has been selected for these analyses. The computer program described in Section 3.3 of this report selects redundancy levels in the components of each system configuration to yield maximum system reliability as a function of overall system weight. Direct comparisons can then be made of the various optimized system configurations to determine those which provide the highest reliability for any given weight constraint for each of the seven missions specified for this study program.

The reliability calculations have been based on the assumption that any single part failure in a nonredundant component constitutes a power system failure. This simplification has permitted the analysis of a relatively large number of power system configurations leading to the determination of one or more "best" candidates for each mission. The reliability of each component in the various systems has been established on the basis of its parts count and the part failure rates listed in Table I. These failure rates have been based primarily on TRW OGO, Vela, and Pioneer spacecraft flight experience. Demonstrated orbital operating times and numbers of parts by type are shown in Tables II and III, respectively. Battery cell failure rates represent estimated values based on the very limited data available for the silver-zinc and silver-cadmium types in space applications. The failure rate used is twice that used for nickel-cadmium cells by TRW.

3.1.1 Component Redundancy

As reported previously, specific methods of implementing redundancy in the components of the various systems have been selected for the system optimization analyses. The investigations leading to these selections

Table I. Recommended Failure Rates for Power System Configuration Study

Part Type	Principal Electrical and Other Stress	Spacecraft Equipment Failures/10^9 Hr at Case Temperature 30°C
	Rated Power, Percent	
Diode:		
Silicon (< 1 w)	25	5
Silicon power (> 1 w)	25	14
Zener	25	55
Transistor:		
Silicon (< 1 w)	25	28
Silicon power (> 1 w)	25	56
Resistor:		
Carbon composition	25	12
Metal film	25	3
Wirewound, power	25	65
	Rated Voltage, Percent	
Capacitor:		
Ceramic	25	25
Mica, dipped	25	3
Paper, Mylar	25	40
Tantalum:		
Foil	25	21
Solid (series resistance ≥ 3 ohms/v)	25	21
Transformer:		
Low voltage, class H or T insulation	Hot spot ≤ 125°C	30 + 30/winding
Inductor:		
Low voltage, class H or T insulation	Hot spot ≤ 125°C	30
Relay:		
Base rate, class H or T coil insulation, magnetic latching (2 coils)	Hot spot ≤ 125°C	15 (failures/10^9 cycles)
Connector:		
Per active pin (soldered)		10
Connector:		
Per active pin (crimped)		5

Table I. Recommended Failure Rates for Power System Configuration Study (Continued)

Part Type	Principal Electrical and Other Stress	Spacecraft Equipment Failures/10^9 Hr at Case Temperature 30°C
Connection: Soldered	Orbital conditions	0.5
Connection: Welded		0.5
Solar Cell:		1
Battery Cell: Silver cadmium		150
Battery Cell: Silver zinc		150

Table II. Part Type Demonstrated Orbital Operating Hours (Vela and OGO)

Part Type	Number of Failures	Operating Hours Vela and OGO
<u>Transistors:</u>		
Silicon	2	106,073,965
<u>Diodes:</u>		
Silicon	1	385,629,667
Zener		7,508,145
<u>Resistors:</u>		
Carbon composition		74,482,179
Metal film		292,450,010
Wirewound		4,374,113
<u>Capacitors:</u>		
Ceramic	1	63,428,620
Dipped mica		2,926,213
Tantalum foil		1,030,847
Tantalum solid		42,916,870
Plastic		233,919
Mylar paper		387,862
<u>Magnetics:</u>		
Transformer		25,782,120
Inductor		1,397,461
Filter		3,281,707
<u>Relays:</u>		
Latching		5,630,944

Table III. Part Group Total Number of Orbital Parts (Vela and OGO)

Part Group	Number of Parts
Transistors	13,989
Diodes	45,855
Capacitors	15,505
Resistors	44,541
Magnetics	3,531
Relays	408

have included consideration of the failure modes of each type of component, the effects of component failures on system operation and the effects of implementing redundancy on component weight and performance.

Four basic approaches to implementing redundancy were considered for each type of component: parallel, standby, quad, and majority voting. The reliability equations and basic configuration for each are described in the following paragraphs.

Since each part of a nonredundant component has its own failure rate, the general equation for the probability of survival is:

$$P_S = e^{-\lambda t}$$

where

P_S = probability of survival or reliability

λ = the summation of the failure rates for all parts

t = total operating time required.

Figure 2 shows a basic system configuration of "N" elements connected in series. The equation for the probability of survival of the system is

$$P_S = P_1 \times P_2 \times ---- \times P_n$$

where

$P_1 \longrightarrow P_n$ are the reliabilities of each element.

Figure 3 shows a parallel redundant system comprised of two groups of 1 through "N" series elements. Each of the two parallel groups is completely independent and either one can perform the required function.

The probability of survival is:

$$P_S = 1 - [(1 - P_A)(1 - P_B)]$$

where

P_A and P_B are the survival probabilities of the independent strings.

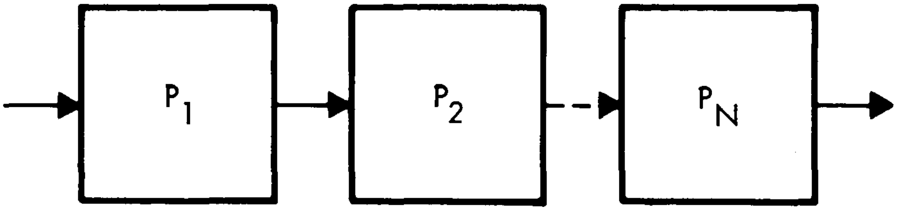


Figure 2. Basic System Reliability Model

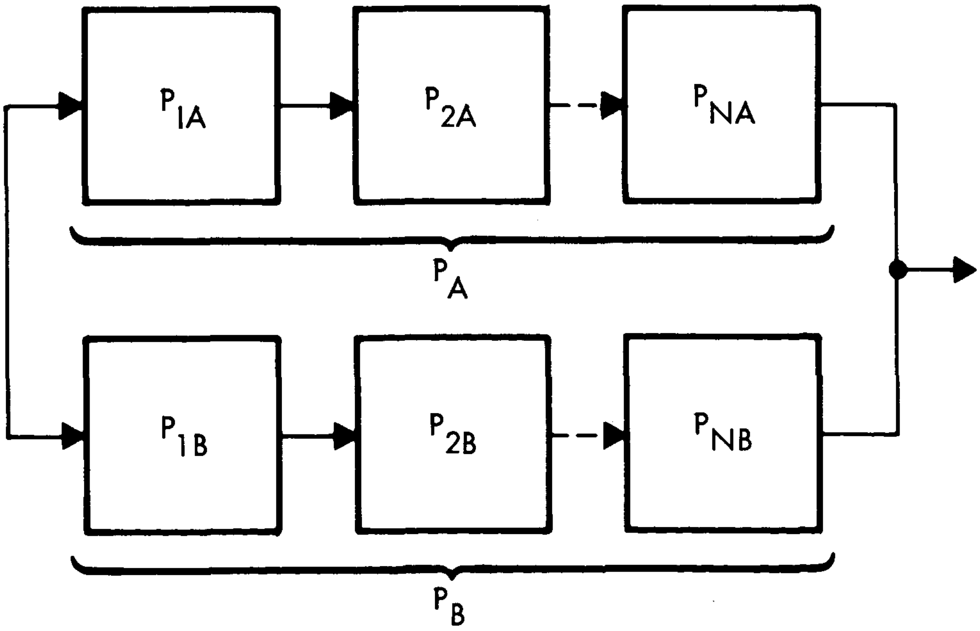


Figure 3. Parallel Redundant System Reliability Model

Parallel operating channels have limited usage because there are some failure mode conditions which they cannot correct. For example, one of the two parallel channels could fail in a manner which causes their common output voltage to go above limits.

In the standby redundant configuration of Figure 4, there are two parallel channels, but only one is operating at any time. This configuration requires additional circuitry to sense a failure in the operating channel and a switching element to transfer to the standby elements in case of a primary element failure.

The equation for probability of survival is:

$$P_S = 1 - \left[(1 - P_1 P_{SW})(1 - P_2 P_{SW})\right]$$

where

P_1 and P_2 are the reliabilities of the independent channels, and

P_{SW} = the reliability of the failure sensing and switching elements.

Standby redundancy is generally used for power circuits since it does not cause a significant loss in efficiency.

Quad redundancy is normally implemented at the part level and is illustrated in Figure 5. Either string can perform the required function. The reliability of this configuration is:

$$P_S = 1 - (1 - P_1^2)^2$$

where

P_1 = the reliability of a single part.

The quad configuration is normally not used for series power handling circuits because of its poor efficiency.

Figure 6 shows a block diagram of a majority voting configuration. Two out of the three circuits must be operative in order to perform the required function. The probability of survival is:

$$P_S = 1 - \left[(1 - P_1 P_2)(1 - P_2 P_3)(1 - P_1 P_3)\right]$$

where

P_1, P_2, and P_3 are the reliabilities of each element.

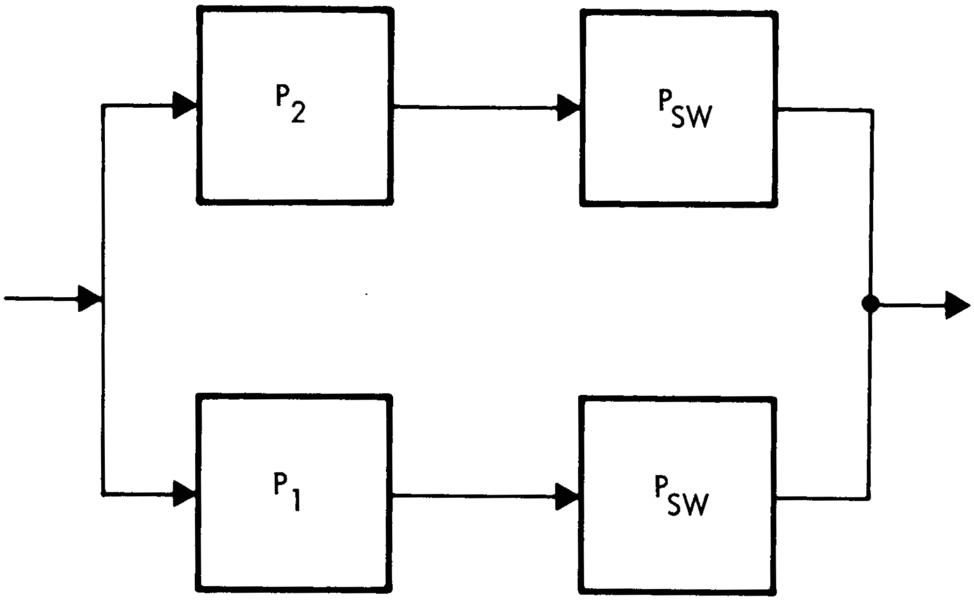


Figure 4. Standby Redundant System Reliability Model

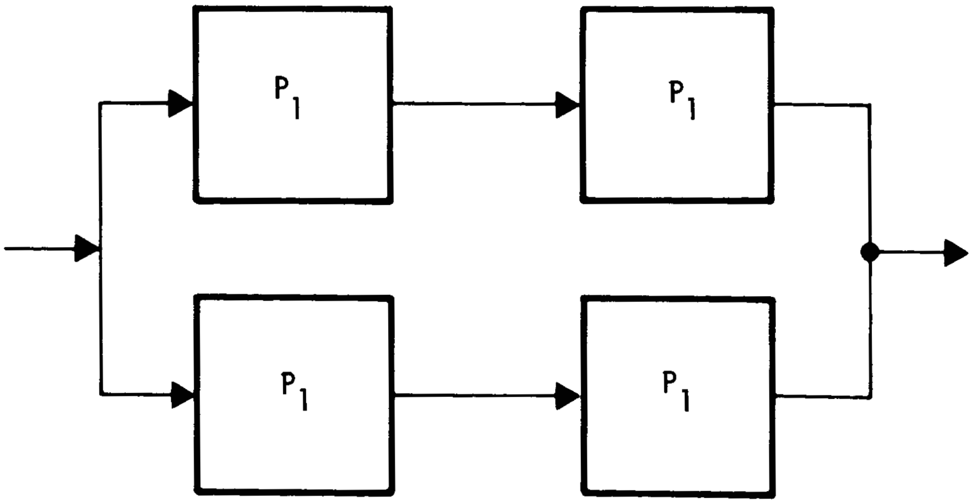


Figure 5. Quad Redundant System Reliability Model

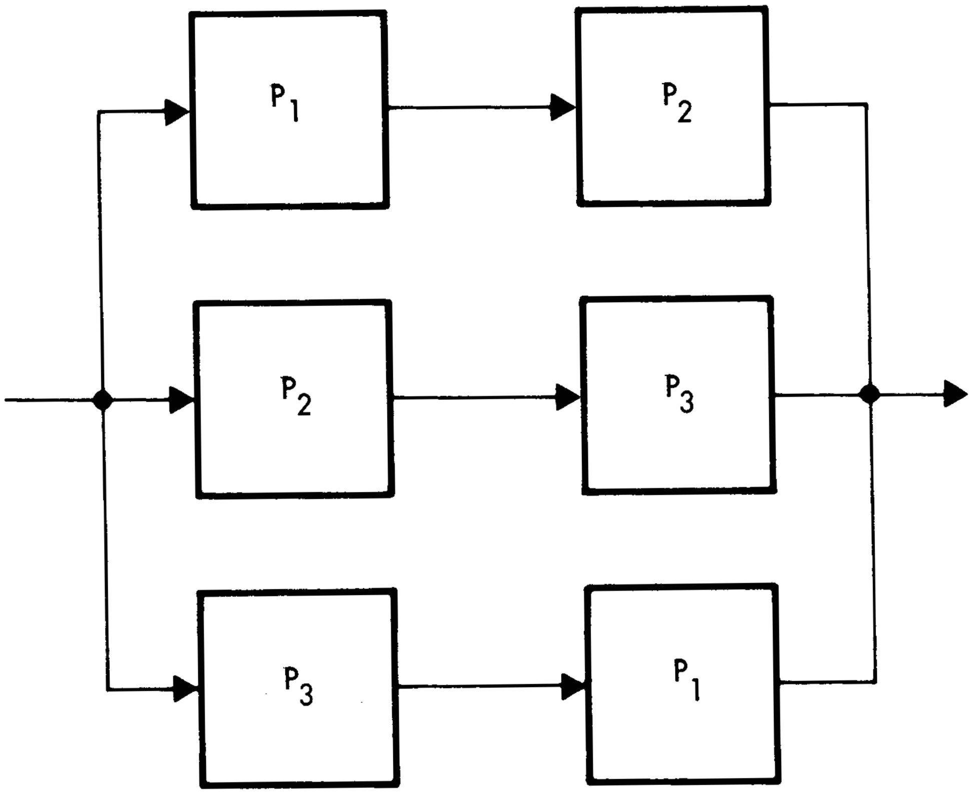


Figure 6. Majority Voting System Reliability Model

In most cases $P_1 = P_2 = P_3$, therefore

$$P_S = 1 - (1 - P_1^2)^3$$

Majority voting redundancy is generally applied to low-power sensing circuits.

3.1.2 Selected Redundant Configurations and Parts Counts

The power systems have been divided into the following sections, each of which may have many design configurations:

- Solar array
- Array control
- Battery control
- Battery
- Line regulator
- Power conditioning equipment
  (ac or dc distribution)

3.1.2.1 Solar Array

The solar array configuration is the same for either a baseline system or a redundant system and includes multiple parallel interconnections of series strings of cells to minimize the effects of cell or connection open circuit failures on the output power of the array.

3.1.2.2 Array Controls

Five specific array control designs have been considered:

- Zener diode shunt
- Active dissipative shunt
- Pulse width modulated series bucking regulator
- Pulse width modulated series bucking regulator
  with maximum power tracking
- Buck-boost pulse width modulated regulator.

The zener diode voltage limiter design is the same for the baseline and redundant configurations and uses multiple parallel shunt circuits, each controlling a parallel section of the array. If a diode shorts, the solar power will be degraded by 1/N where N is the number of parallel zener diodes. Series diodes between the zener diode connection and the common solar array bus prevent current flow through a shorted zener diode from the other parallel array sections. If a zener diode opens, the remaining diodes will limit total array voltage.

The active shunt redundant design uses the majority voting configuration for the voltage sensing and error amplifying stages as illustrated in Figure 7, and uses the quad part configuration for the power transistors and output filter. Figure 7a shows that the nonredundant configuration of the voltage sensing and error amplifier is composed of a voltage divider that reduces the magnitude of the sensed voltage to a level comparable to the reference, a precision voltage reference, a summing point, and an error amplifier stage. The redundant majority voting block diagram is illustrated in Figure 7b. It has three nonredundant parallel circuits plus three AND gates and an OR gate. Each AND gate receives two amplified signals and if they are correct the signal is obtained.

The problem in design with this approach is that the total gain of the circuit varies by a factor of 3 to 1 depending on the failure modes and it has to be considered to ensure that the regulation or stability is not affected. The quad part configuration is permissible in this case for the shunt power elements because they become active only when there is excessive solar array power in relation to the load demand and do not, therefore, degrade system efficiency.

The pulse width modulated series bucking regulator uses a switching series transistor that controls the power from the solar array to the spacecraft loads. The quad component configuration is not used for this series switch since it would cause a signficant decrease in system efficiency. Parallel operating regulators cannot be used because if a switching transistor shorts, the full solar array voltage will appear on the output and the other parallel regulator could not control for this condition. Therefore the standby redundant configuration is used and if a failure occurs, the failed regulator is switched out and the standby regulator is energized to control the array output. This approach will produce an output transient during the switching interval; however, all of the systems include a battery and line filters which will tend to minimize the effects

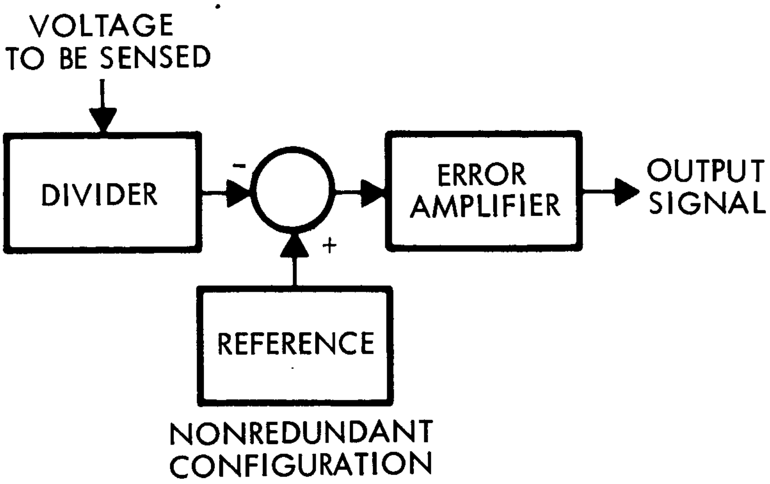


Figure 7a. Voltage Sensing and Error Amplifier Block Diagram

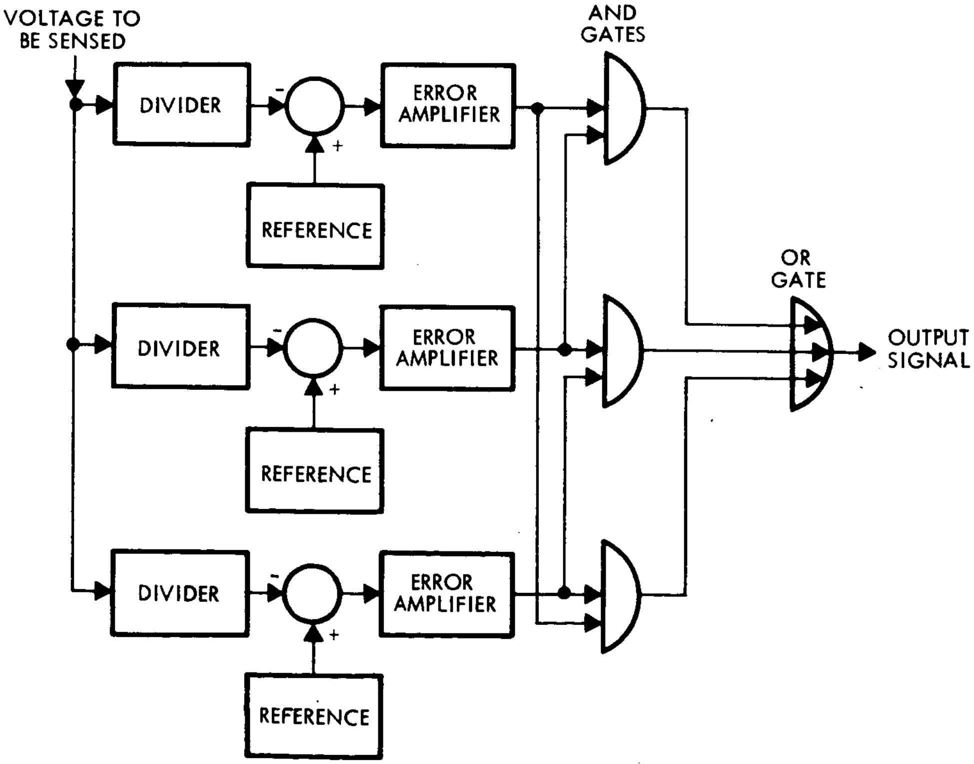


Figure 7b. Redundant Configuration

of this momentary power interruption. The failure sensing circuits monitor the output voltage and generate the transfer signal if the output voltage is not within tolerance. A sufficient time delay is designed into the circuitry so that erroneous transfer is not allowed during start-up or load-switching transients. The maximum power tracking regulator and the buck-boost regulator also use the standby redundancy configuration. The parts count for baseline and redundant configurations of each array control are shown in Tables IV and V.

3.1.2.3 Battery Controls

The four basic battery control block diagrams are illustrated in Figures 8 through 11 for those systems which combine the array and battery at an unregulated bus.

The basic designs shown are:

- Bucking charger and discharge switch
- Bucking charger, discharge switch and line booster
- Boost charger and discharge switch
- Boost charger, discharge switch and line booster

Standby redundancy cannot be used for these controls because of the extreme difficulty in sensing a failure or out-of-tolerance condition over the wide range of charge and discharge operating conditions. Instead the majority voting redundancy is used for the low level signals and logic and part redundancy is used for the power circuits. The selected methods of implementing part redundancy are shown in Figure 12.

The redundant transformer (Figure 12a) consists of two series transformers with parallel primary and secondary windings which are interconnected. The parallel windings protect against open circuit failures and the series transformers are used to protect against turn-to-turn shorts in one winding. The disadvantages of this approach are that each winding must be capable of full load current rating and also full input voltage rating. Each transformer is twice as large as a simple non-redundant transformer and the total VA rating of the magnetics is four times normal. The same technique is used for a choke but in this case, the effect of an inductance change to 50 percent of normal, should a winding develop a turn-to-turn short, must be considered in the design.

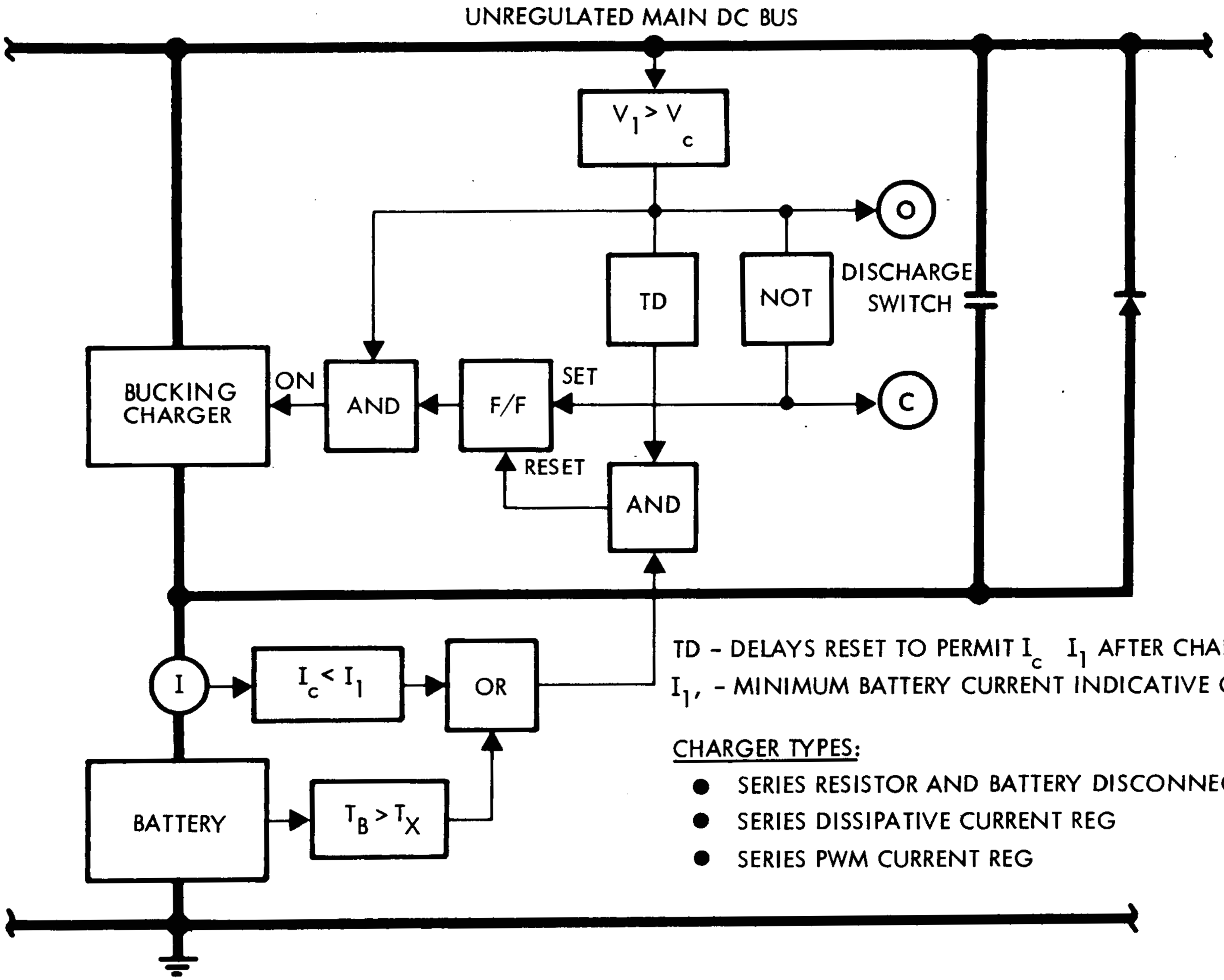
Table IV. Array Control Baseline Parts Count
Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Transistor		Magnetics			Relays		Other/ Comments
	Carbon Composition	Metal Film	Wire Power	General-Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	< 1 W	> 1 W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	
Zener						15											
Active Shunt		13	4			1	1	3		4	3						
PWM Buck		21	4	13	1	2	2	3		6	2	3	2	1			
PWM Buck and Pmax Tracker		40	4	16	1	4	3	3	4	16	2	6	2	1			
PWM Buck-Boost		21	3	13	1	2	1	3		6	2	4	1	1			

Table V. Array Control Redundant Parts Count
Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Transistor		Magnetics			Relays		Other/ Comments
	Carbon Composition	Metal Film	Wire Power	General-Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	< 1 W	> 1 W	Transformers	Chokes	Mag-Amps	General	Latching 2 Coil	
Zener						15											
Active Shunt (A)			4		3			3			3						Quad parts
Active Shunt (B)		15				1	2			6							Majority voting
PWM Buck		47	4	17	1	4	2	3	2	16	2	3	2	1		1	Standby
PWM Buck and Pmax Tracker		66	4	20	1	6	3	3	6	26	2	6	2	1		1	Standby
PWM Buck Boost		47	3	17	1	4	1	3	2	16	2	4	1	1		1	Standby

NOTE: Quantities shown are for each element of the applicable redundant configuration (i. e., for quad parts, total quantity per component = number shown x 4).



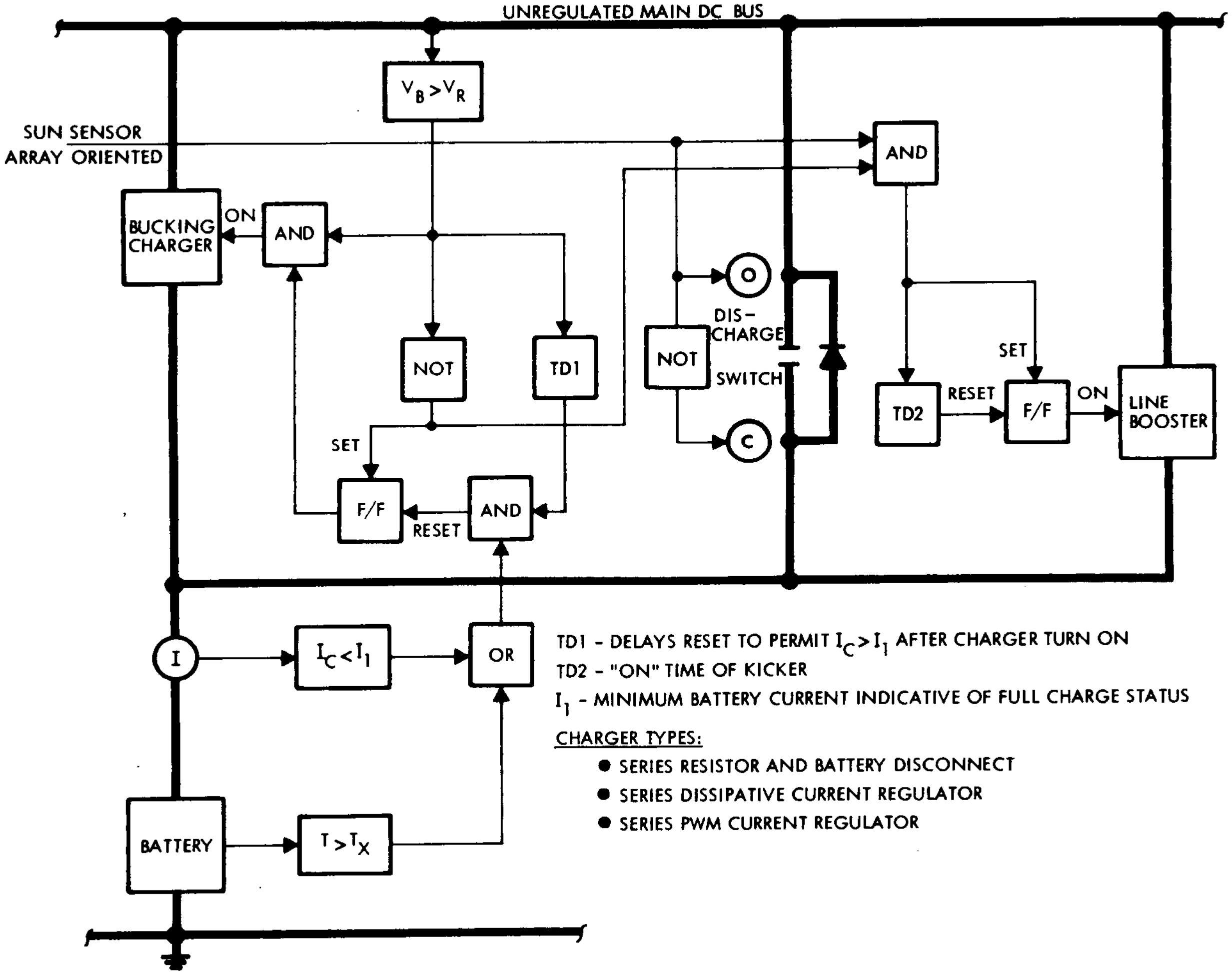
TD - DELAYS RESET TO PERMIT I_c I_1 AFTER CHARGER TURN ON

I_1, - MINIMUM BATTERY CURRENT INDICATIVE OF FULL CHARGE STATUS

CHARGER TYPES:

- SERIES RESISTOR AND BATTERY DISCONNECT
- SERIES DISSIPATIVE CURRENT REG
- SERIES PWM CURRENT REG

Figure 8. Battery Controls Block Diagram Bucking Charger and Discharge Switch

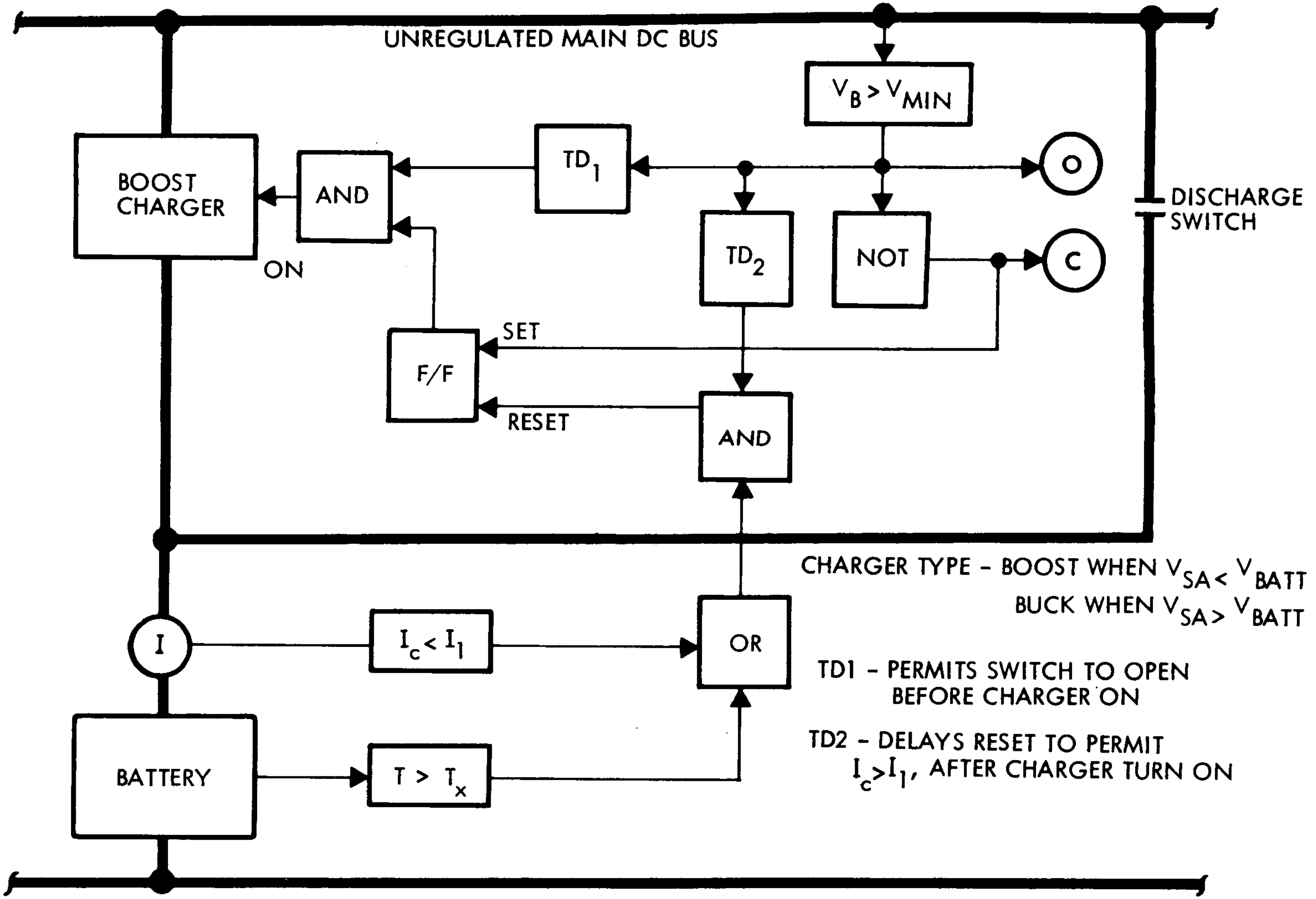


TD1 - DELAYS RESET TO PERMIT $I_C > I_1$ AFTER CHARGER TURN ON
TD2 - "ON" TIME OF KICKER
I_1 - MINIMUM BATTERY CURRENT INDICATIVE OF FULL CHARGE STATUS

CHARGER TYPES:

- SERIES RESISTOR AND BATTERY DISCONNECT
- SERIES DISSIPATIVE CURRENT REGULATOR
- SERIES PWM CURRENT REGULATOR

Figure 9. Battery Controls Block Diagram Bucking Charger, Discharge Switch, and Line Booster

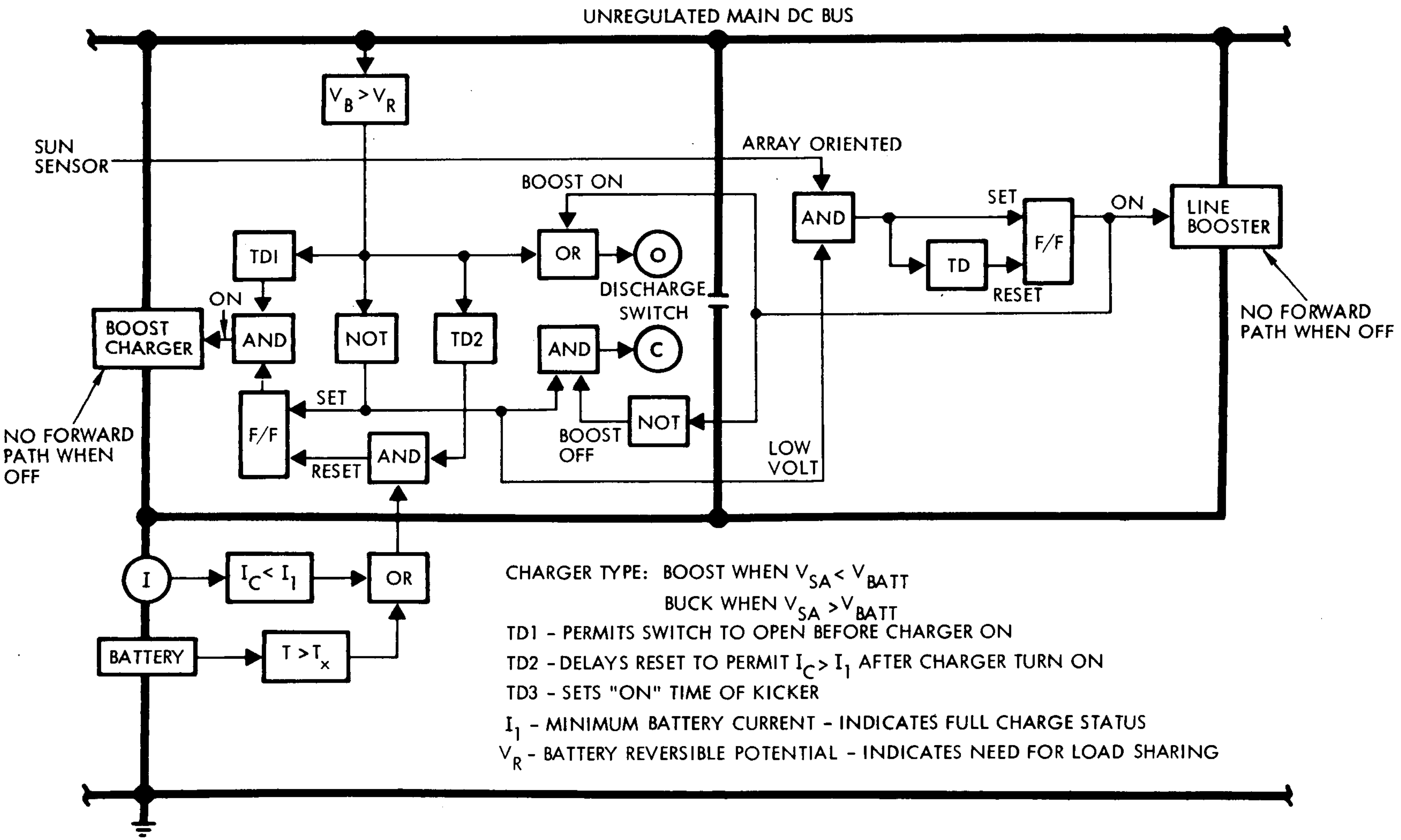


CHARGER TYPE - BOOST WHEN $V_{SA} < V_{BATT}$
BUCK WHEN $V_{SA} > V_{BATT}$

TD1 - PERMITS SWITCH TO OPEN BEFORE CHARGER ON

TD2 - DELAYS RESET TO PERMIT $I_c > I_1$, AFTER CHARGER TURN ON

Figure 10. Battery Controls Block Diagram Boost Charger and Discharge Switch



CHARGER TYPE: BOOST WHEN $V_{SA} < V_{BATT}$
BUCK WHEN $V_{SA} > V_{BATT}$
TD1 - PERMITS SWITCH TO OPEN BEFORE CHARGER ON
TD2 - DELAYS RESET TO PERMIT $I_C > I_1$ AFTER CHARGER TURN ON
TD3 - SETS "ON" TIME OF KICKER
I_1 - MINIMUM BATTERY CURRENT - INDICATES FULL CHARGE STATUS
V_R - BATTERY REVERSIBLE POTENTIAL - INDICATES NEED FOR LOAD SHARING

Figure 11. Battery Controls Block Diagram Boost Charger, Discharge Switch, and Line Booster

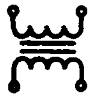
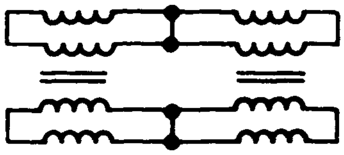
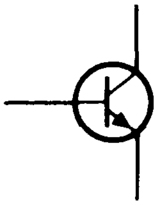
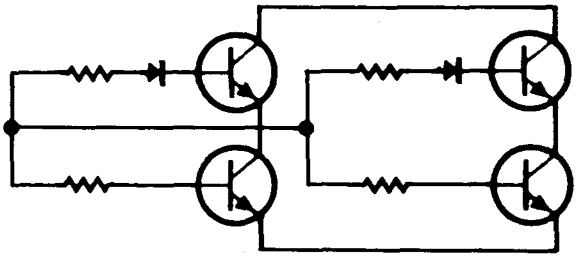
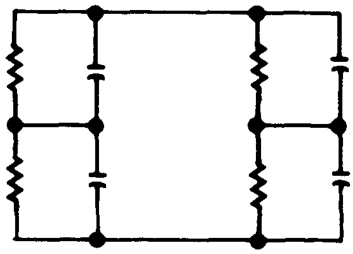
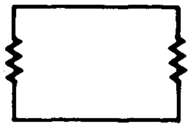
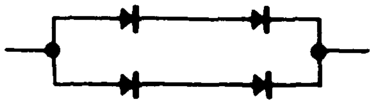
PART	REDUNDANT PART
a) MAGNETIC 	 INSULATE BETWEEN PRIMARY AND SECONDARY
b) TRANSISTOR 	
c) CAPACITOR 	
d) RESISTORS 	
e) DIODES 	

Figure 12. Methods of Implementing Part Redundancy

Figure 12b shows a transistor and its redundant equivalent which is composed of two parallel strings of two transistors in series. If one series transistor develops a short, the remaining good transistor maintains normal operations. The diode in the base circuit of the upper transistor protects against a collector to base short which could otherwise produce uncontrolled base current to the other transistors. The base resistors are needed to protect the current driving signal source if a transistor base to emitter short develops and to cause current sharing among the four transistors.

The disadvantages of this configuration are that the normal current gain is reduced to one-half, and all four transistors must have the same power rating as the single nonredundant transistor. The system must be designed to accommodate wide variations in gain both for normal and failure modes.

Figure 12c shows the nonredundant and the redundant capacitor configurations. The redundant capacitor has two parallel strings of two series capacitors. Resistors are placed in parallel with the capacitors to cause equal divisions of voltage. This is particularly important for tantalum capacitors where a normal unbalance in leakage current can cause unequal division of voltage. This unbalance in voltage may produce voltage reversal on the capacitors during discharge and a resultant failure.

The disadvantages of this configuration are its increased size and weight and the fact capacitance can vary from 0.5 C to 1.5 C. If not considered in the design this variation can produce excessive ripple or charge regulator instability.

The normal failure mode of the resistor is to drift, open or develop a partial short, and not a complete end-to-end short. The redundant resistor (Figure 12d) is two resistors in parallel. The problem of the redundant resistor is its resistance variation under failure mode conditions.

The redundant diode configuration (Figure 12c) contains two parallel strings of two diodes in series. The problem of the redundant diode is its increased power loss and change in output voltage when one diode shorts. The zener or reference diode cannot be implemented in this manner and still maintain the voltage accuracy required. Whenever a voltage must be sensed and compared to a reference in a redundant design, the majority voting circuit must be used to maintain a close regulation tolerance (± 1 percent). A precision voltage divider also cannot be obtained by the quad redundant approach.

The relays for discharge control are used in a circuit level majority voting redundant configuration.

In past equipment designs, current levels were normally detected by a magnetic current monitor and its associated ac inverter circuitry. This method does not lend itself to any redundant configuration without undue complexity. As a result the selected battery controls use a shunt to sense current and a dc amplifier circuit to amplify the low-level signal. This design is much easier to implement in a majority voting redundant configuration.

Tables VI and VII list the battery control parts counts for the non-redundant and redundant designs of each type of battery charger and its associated controls.

3.1.2.4 Battery

Silver-zinc batteries have been selected for the 0.3 and 5.2 AU probes. Silver-cadmium batteries have been chosen for the Mars, Venus and Jupiter orbiters. In each case the baseline configuration consists of a single battery containing 20 series connected cells. Two redundant configurations have been selected for analysis. The first of these consists of two parallel batteries; each containing 20 cells and capable of satisfying the total energy storage requirement. Each battery is used with its own control circuitry which may be either baseline or redundant. The second redundant battery configuration consists of three batteries in a majority voting configuration with each containing three series cells and each connected to the main power bus through a bucking charge regulator and a boosting discharge regulator.[1] This approach is only applied to those systems which are configured with a regulated main bus. Each of the three batteries has an installed capacity equal to one-half that of the baseline battery capacity. The principal advantage of the second redundant

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[1] This configuration represents one method of applying the TRW Modular Energy Storage and Control concept (MESAC). This concept has been developed and tested under a company sponsored research program.

Table VI. Battery Controls Baseline Parts Count Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Tran-sistor		Magnetics			Relays		Other/Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1 W	>1 W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	
Buck - Resis.		41	2	6	1	3			3	20						2	
Buck Resis & Kicker		69	2	8	4	4	2	1	6	31	2	3	2	1		2	
Buck Diss. Reg.		49	1	4	1	4		1	2	23	2					1	
Buck Diss. Reg. & Kicker		77	1	6	4	5	2	1	5	34	4	3	2	1		1	
PWM Buck		49	2	4	2	2	2	1	3	23	2		2			1	
PWM Buck & Kicker		77	2	6	5	3	4	2	6	34	4	3	4	1		1	
PWM Buck Boost		65	2	6	1	4	1	2	6	20	1	1	1	1		1	
PWM Buck Boost & Kicker		92	4	8	5	5	1	4	8	32	3	2	3	2			
Diss. Reg		13	5			1	1	2		4	3						
PWM Buck		21	4	13	1	2	2	2		6	2	2	2	1			

Table VII. Battery Controls Redundant Parts Count Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Transistor		Magnetics			Relays		Other/Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1 W	>1 W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	
Buck Resis.			2		1												Quad Comp.
		44		6		3			3	22						2	Majority Voting
Buck Resis. &		4	2		4		1	1			2	3	2	1			Quad Comp.
Kicker		65		8		4	1		6	33						2	Majority Voting
Buck Diss. Reg.		4	1		1			1			2						Quad Comp.
		45		4		4			2	25						1	Majority Voting
Buck Diss. Reg.		6	1		4		1	1			4	3	2	1			Quad Comp.
& Kicker		71		6		5	1		5	36						1	Majority Voting
PWM Buck		4	2	2	2			1			2		2				Quad Comp.
		45		2		2	2		3	25						1	Majority Voting
PWM Buck &		6	2		5		1	1			4	3	2	1			Quad Comp.
Kicker		71		6		3	3	1	6	36						1	Majority Voting
PWM Buck		2	2		1		1	2			1	1	1	1			Quad Comp.
Boost		65		6		4			6	22						1	Majority Voting
PWM Buck Boost		2	4		5		1	4			3	2	3	2			Quad Comp.
& Kicker		90		8		5			8	34							Majority Voting
Diss. Reg			5					2			3						Quad Comp.
		13				1	1			6							Majority Voting
PWM Buck		2	4	4	1		1	2			2	2	2	1			Quad Comp.
		19		9		2	1			8							Majority Voting

Note: Quantities listed are for each element of the applicable redundant configuration battery configuration is the reduction in number of series connected cells per battery and the attendant improvement in battery reliability. A second advantage is the reduced total battery weight (150 percent of baseline) in comparison to the first redundant approach (200 percent of baseline). The charge and discharge regulators may be either baseline or redundant.

3.1.2.5 Line Regulators

The following designs were selected for the line regulators:

- Pulse-width modulated series bucking regulator
- Series dissipative
- Pulse-width modulated boost regulator
- Pulse-width modulated buck-boost regulator.

Because of the requirement to minimize weight and losses, standby redundancy configurations are used for the line regulators. However, there will be momentary loss of power to the load equipment during the transfer to the redundant channel. Certain loads, for example a digital memory, must be protected during the power shutdown. This is normally done by having the failure sensing circuits give advance warning to these types of loads. Typically, this warning signal initiates required inhibit and sequencing functions within the load equipment before the output voltage of the power supply has deviated significantly from steady-state conditons.

Tables VIII and IX are the part counts for the baseline and redundant configurations of each line regulator.

3.1.2.6 Load Power Conditioner

The components used for load power conditioning have been analyzed with respect to the specific load requirements of each model spacecraft to define specific equipment groupings and performance requirements. The equipment for those systems using dc power distribution are as follows:

- 3 ϕ 400 Hz gyro inverter
- Central converter (dc to dc)
- Transmitter converter (high or low voltage)
- Computer — sequencer converter (low voltage)
- Television converter (high voltage)
- Experiment converter (low voltage)
- Experiment converter (high voltage)

Table VIII. Line Regulator Baseline Parts Count Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Tran-sistor		Magnetics			Relays		Other/Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1W	>1W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	
PWM Buck		21	4	13	1	2	2	2		6	2	2	2	1			
Diss. Series		13	5			1	1	2		4	3						
Boost		16	2	6	3	2	2	2		6	2	3	2	1			
Buck Boost		21	3	13	1	2	2	2		6	2	3	1	1			

Table IX. Line Regulator Redundant Parts Count Mission: Venus Orbiter No. 1

Item	Resistors			Diodes			Capacitors			Tran-sistor		Magnetics			Relays		Other/Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1W	>1W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	
PWM Buck		47	4	17	1	4	2	2	2	16	2	2	2	1		1	Standby
Diss. Reg.		39	5	4		3	1	2	2	14	3					1	Standby
Boost		42	2	10	3	4	2	2	2	16	2	3	2	1		1	Standby
Buck Boost		47	3	17	1	4	2	2	2	16	2	3	1	1		1	Standby

Note: Quantities listed must be doubled to determine total component parts count.

The equipment selected for systems using ac power distribution are as follows:

- $3\ \phi$ 400 Hz gyro inverter
- Main central inverter (dc to ac)
- Transmitter transformer-rectifier (TR) (high voltage or low voltage)
- Equipment TR
- Television TR — high voltage output
- Experiment TR — low voltage output
- Experiment TR — high voltage output

A distinction is being made between high voltage outputs and low voltage outputs. At high voltage, the transformer designs are heavier due to increased insulation requirements and the output filter capacitors are larger.

Each spacecraft will have its own set of equipment due to the variation in the equipment and the experiments to be performed. Standby redundancy has been selected for all the load power conditioning equipment.

Tables X through XIII list the parts counts for Venus Orbiter No. 1 Power Conditioning Equipment.

Table X. Load Power Conditioning Equipment Baseline Parts Count. Venus Orbiter No. 1 AC Distribution System

Item	Resistors			Diodes			Capacitors			Transistor		Magnetics			Relays			Other/Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1W	>1W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	Cap. Plastic	
Gyro Inv. (400~)		38	6	6	6		14	1	3	9	6	6	1					
Main Inv.		5		4			2	1		2	2	4	1					
Trans. Tr. (LV)					12				6			1						
Equip. Tr. (LV)					14				7			1						
T. V. TR (HV)	NOT REQUIRED																	
Exper. TR (LV)					6				3			1						
Exper. Tr. (HV)					12				3			1					3	

Table XI. Load Power Conditioning Equipment Redundant Parts Count Venus Orbiter No. 1 AC Distribution System

Item	Resistors			Diodes			Capacitors			Tran-sistor		Magnetics			Relays			Other/ Comment
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1W	>1W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	Cap. Plastic	
Gyro Inv (400~)		54	6	21	6	1	14	1	10	13	6	6	1			5		Standby
Main Inv		10		10		1	2	1	2	5	2	4	1			2		Standby
Trans. T.R. (LV)		15		6	12	1			8	3		1				1		Standby
Equipment T.R. (LV)		16		6	14	1			9	3		1				1		Standby
T.V. TR (HV)			NOT REQUIRED															
Exper. TR (LV)		12		6	6	1			5	3		1				1		Standby
Exper. TR (HV)		20		6	12	1			5	3		1				1	3	Standby

Note: Quantities listed are for each element of the applicable redundant configuration.

Table XII. Load Power Conditioning Equipment Baseline Parts Count Venus Orbiter No. 1 DC Distribution System

Item	Resistors			Diodes			Capacitors			Tran-sistor		Magnetics			Relays			Other/ Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	<1W	>1W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	Cap. Plastic	
Trans Converter (LV)		6		4	12		2	1	6	2	2	4	1					
Gyro Inv. (400~)		38	6	6	6		14	1	3	9	6	6	1					
Main Converter (LV)		6		4	12		2	1	6	2	2	4	1					
TV Converter (HV)		NOT REQUIRED																
Comm & Seq. Conv (LV)		6		4	8		2	1	4	2	2	4	1					
Exper. Conv. (HV)		6		4	12		2	1	3	2	2	4	1				3	
Exper. Conv. (LV)		6		4	6		2	1	3	2	2	4	1					

Table XIII. Load Power Conditioning Equipment Redundant Parts Count
Mission: Venus Orbiter No. 1
DC Distribution System

Item	Resistors			Diodes			Capacitors			Transistor		Magnetics			Relays			Other/ Comments
	Carbon Comp.	Metal Film	Wire Power	General Purpose	Rectifiers	Zener	Ceramic	Tantalum Foil	Tantalum Solid	< 1 W	> 1 W	Transformers	Chokes	Mag-Amps	General 4 Sets	Latching 2 Coil	Cap. Plastic	
Trans. Conv. (LV)		21		10	12	1	2	1	8	5	2	4	1			1		Standby
Gyro Inv. (400 ~)		54	6	21	6	1	14	1	10	13	6	6	1			5		Standby
Main Conv. (LV)		21		10	12	1	2	1	8	5	2	4	1			1		Standby
TV Conv. (HV)		NOT REQUIRED																
Comm. & Seq. Conv. (LV)		19		10	8	1	2	1	6	5	2	4	1			1		Standby
Exper. Conv. (HV)		24		10	12	1	2	1	5	5	2	4	1			1	3	Standby
Exper. Conv. (LV)		18		10	6	1	2	1	5	5	2	4	1			1		Standby

Note: Quantities shown must be doubled to determine total component parts count.

3.2 COMPONENT WEIGHT AND EFFICIENCY

Parametric curves have been prepared for each component design showing its weight and efficiency as functions of output power. Since the power system weight is largely determined by the weights of the battery and solar array, it is imperative that the efficiency of each series element in the system is taken into account in the system optimization calculations. The effects of implementing the preferred redundant configurations in each component on their weights and efficiencies have been calculated. The resultant data is shown in Figures 13 through 28.

Every attempt has been made to make the component weight and efficiency data representative of feasible designs. In calculating efficiency, the losses in all the following elements were accounted for:

- Input filter (capacitor and inductor)
- Transformers
- Rectifiers — both forward losses and recovery losses
- Output filter (capacitor and inductor)
- Transistor — both saturated and switching losses
- Error amplifier losses
- Logic losses
- Failure sensing losses.

The same items were accounted for in calculating the weight. An allowance was also made for the packaging of the components, the mechanical assembly, and the electrical connectors.

One of the most significant design parameters affecting component efficiency and weight is the switching frequency of the inverters and pulse-width modulated regulator circuits. Preliminary designs were made at switching frequencies ranging from 400 Hz to 20 kHz. A figure of merit relating both component efficiency and weight was selected as the product of the component losses in percent times the component weight. Comparisons of the figure of merit as a function of frequency for different types of switching components showed a minimum at 6 kHz. Figure 29 is a plot of the loss-weight product versus switching frequency for a 100-watt

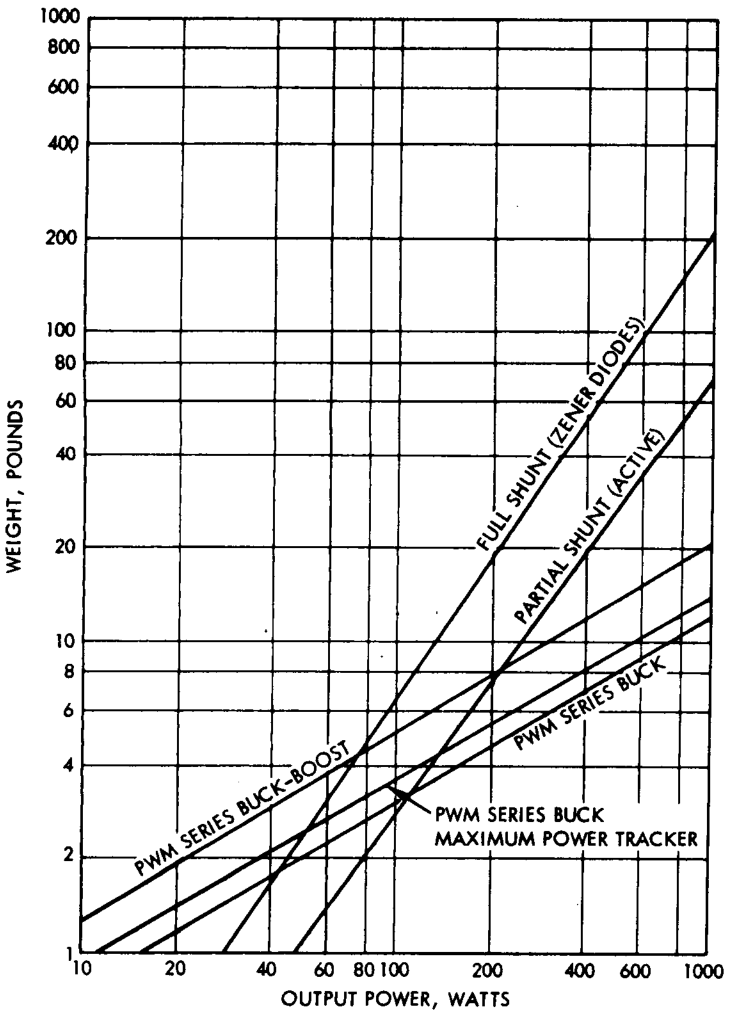

Figure 13. Array Controls Baseline Weight vs Power Output

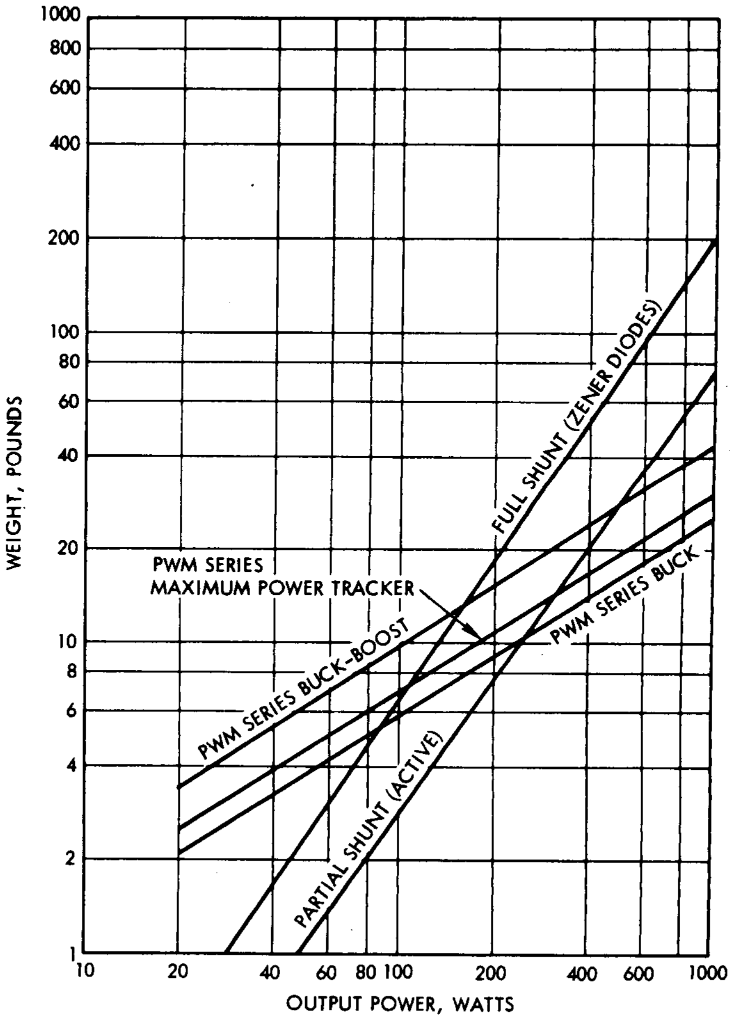

Figure 14. Array Controls Redundant Weight vs Power Output

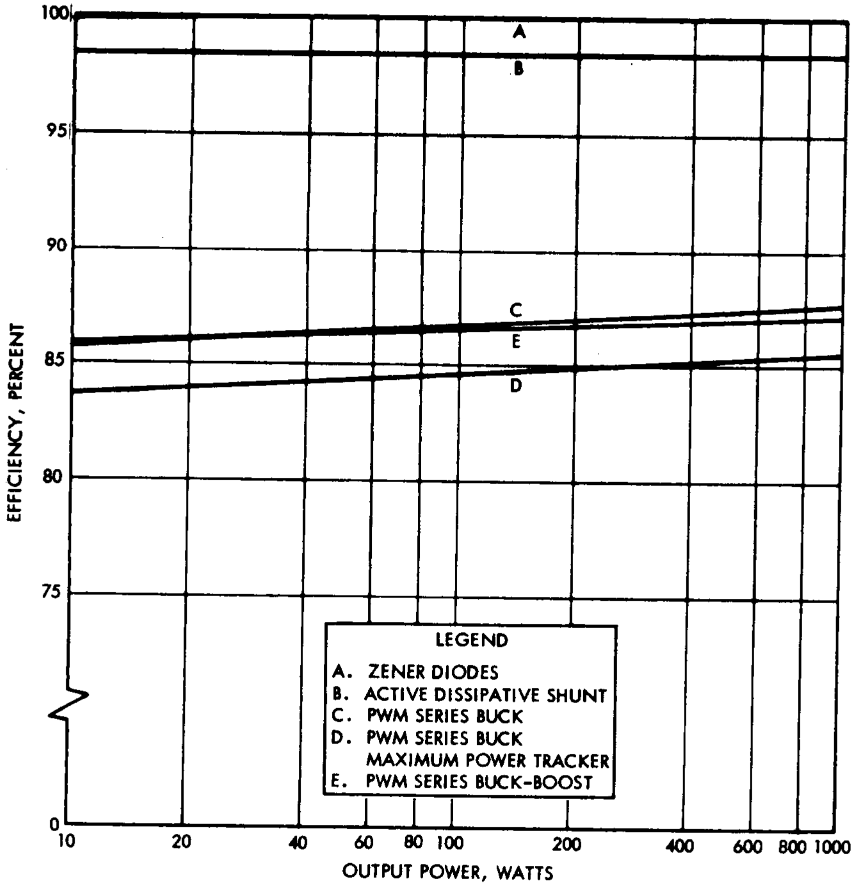

Figure 15. Array Controls Baseline Efficiency vs Power Output

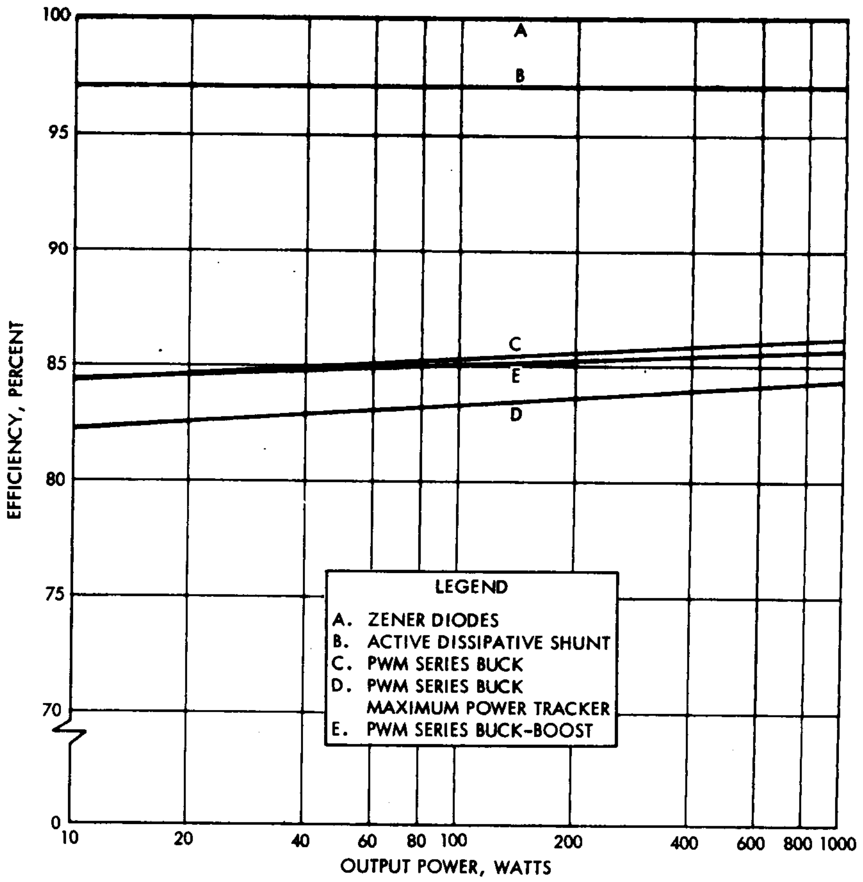

Figure 16. Array Controls Redundant Efficiency vs Power Output

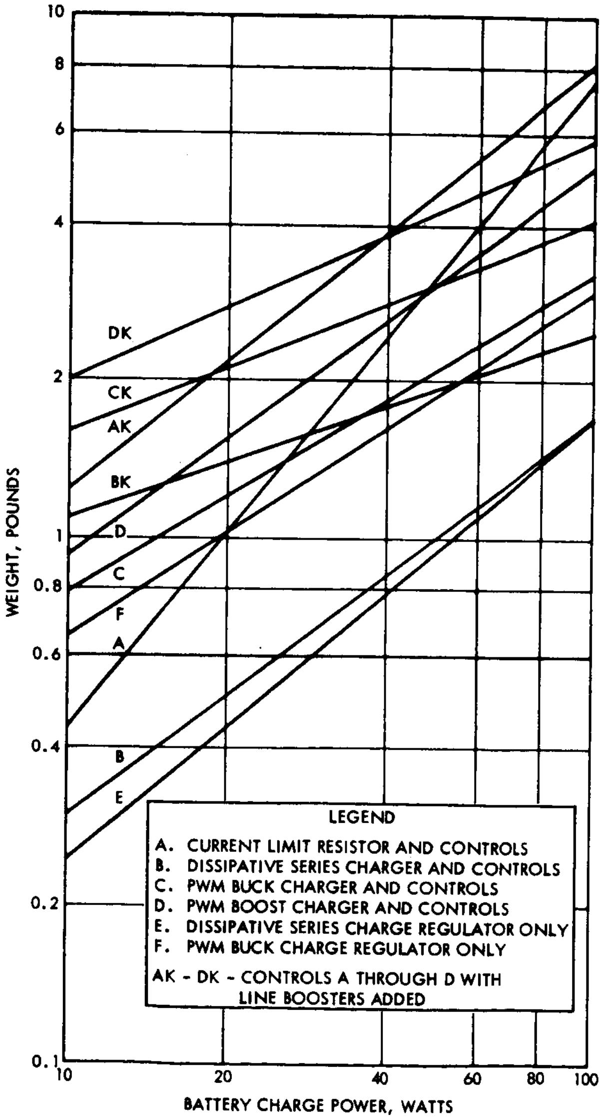

Figure 17. Battery Controls Baseline Weight vs Power Output

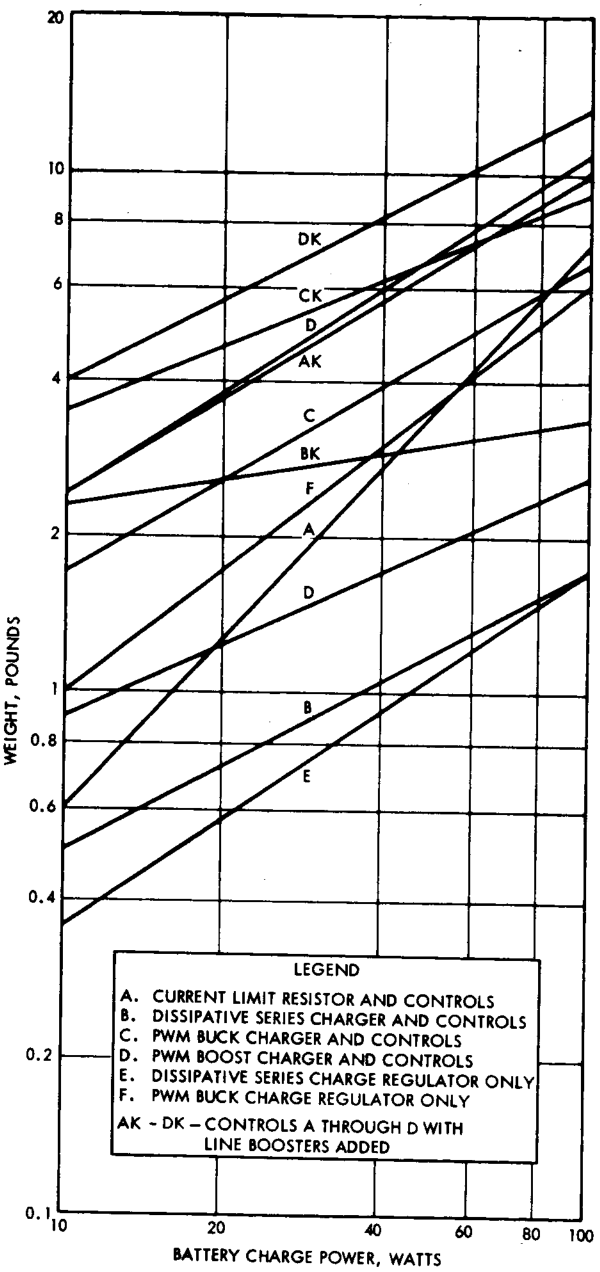

Figure 18. Battery Controls Redundant Weight vs Power Output

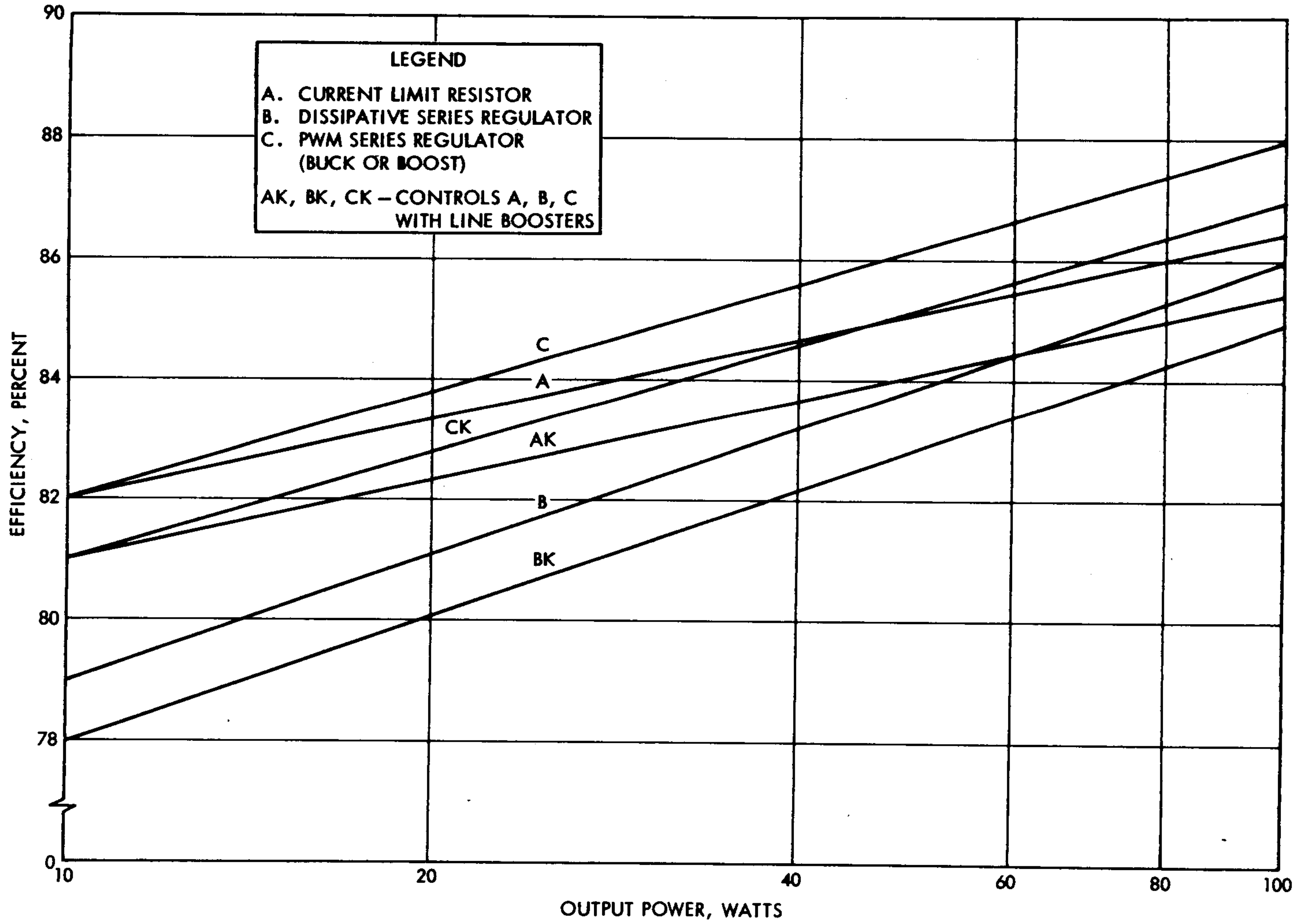

Figure 19. Battery Controls Baseline Efficiency vs Power Output

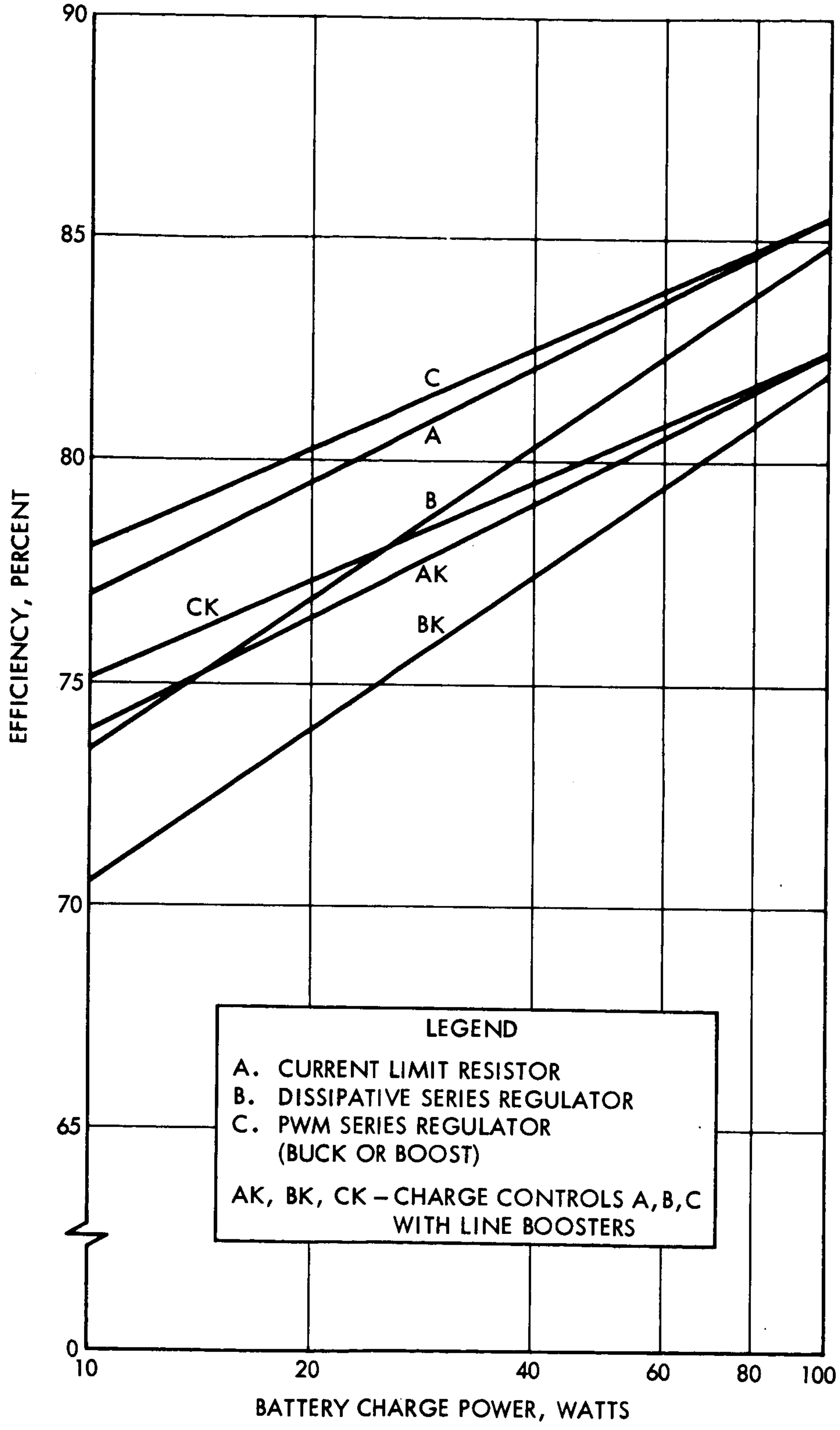

Figure 20. Battery Controls Redundant Efficiency vs Power Output

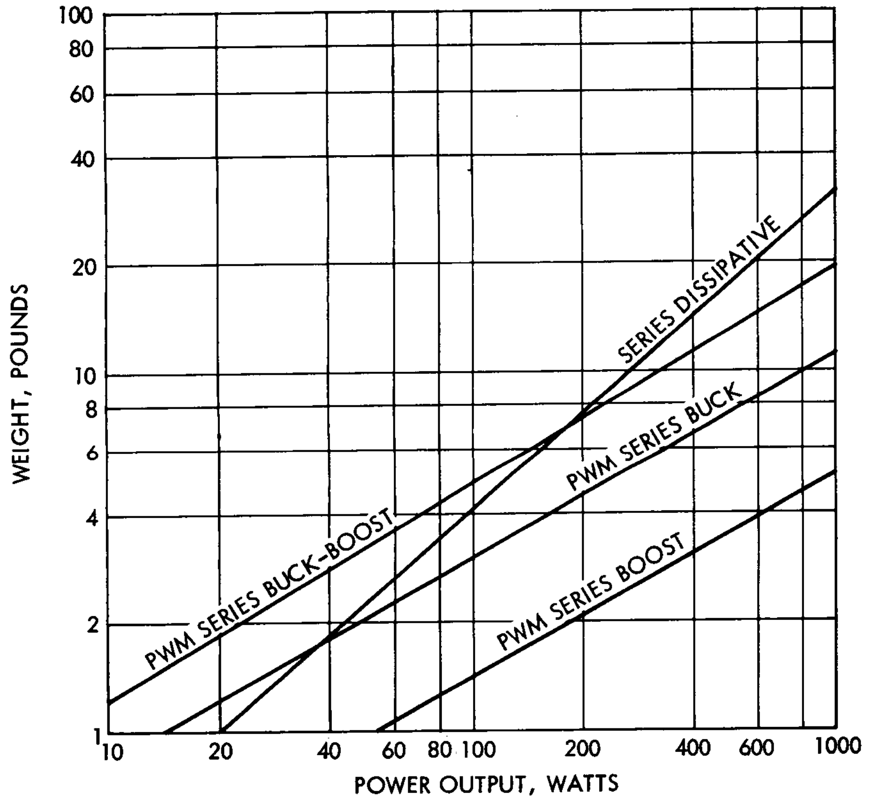

Figure 21. Line Regulator-Baseline Weight vs Power Output

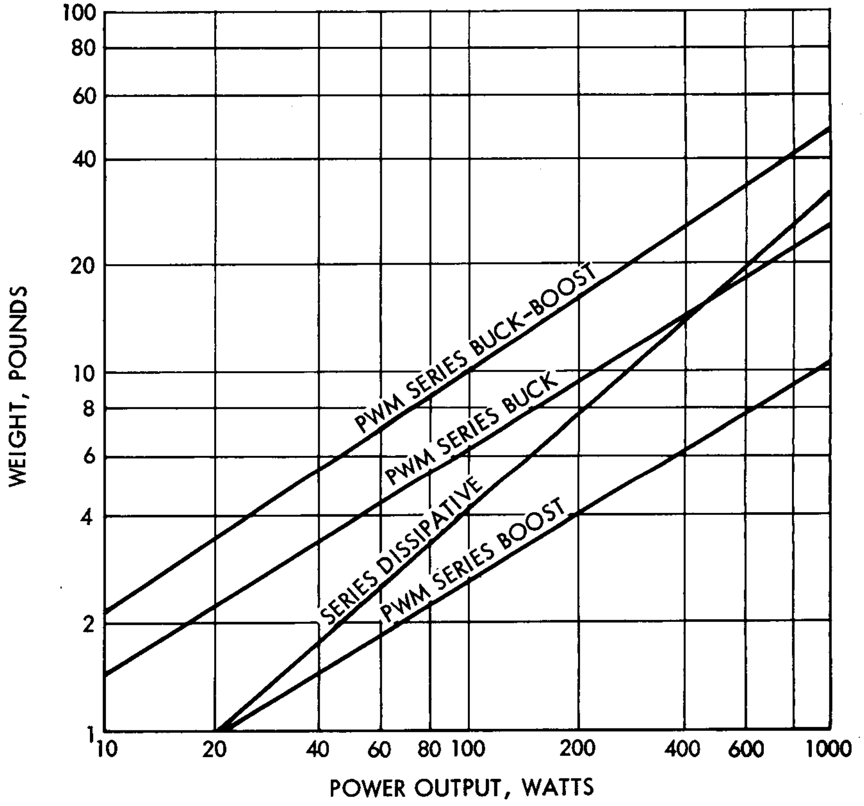

Figure 22. Line Regulator-Redundant Weight vs Power Output

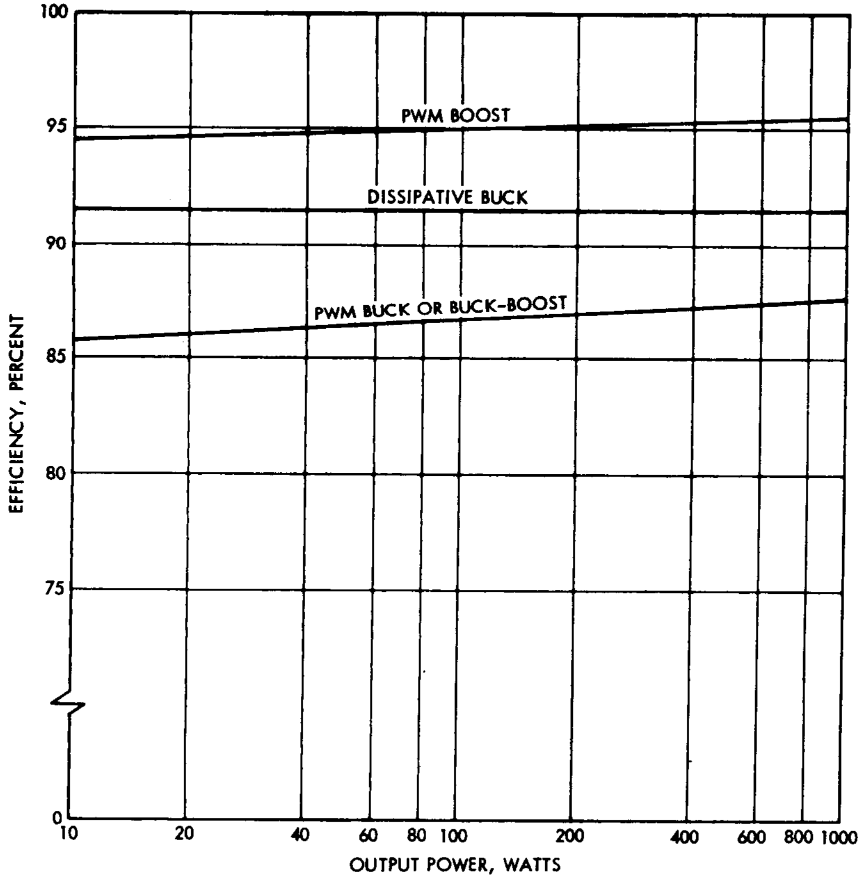

Figure 23. Line Regulator Baseline Efficiency vs Power Output

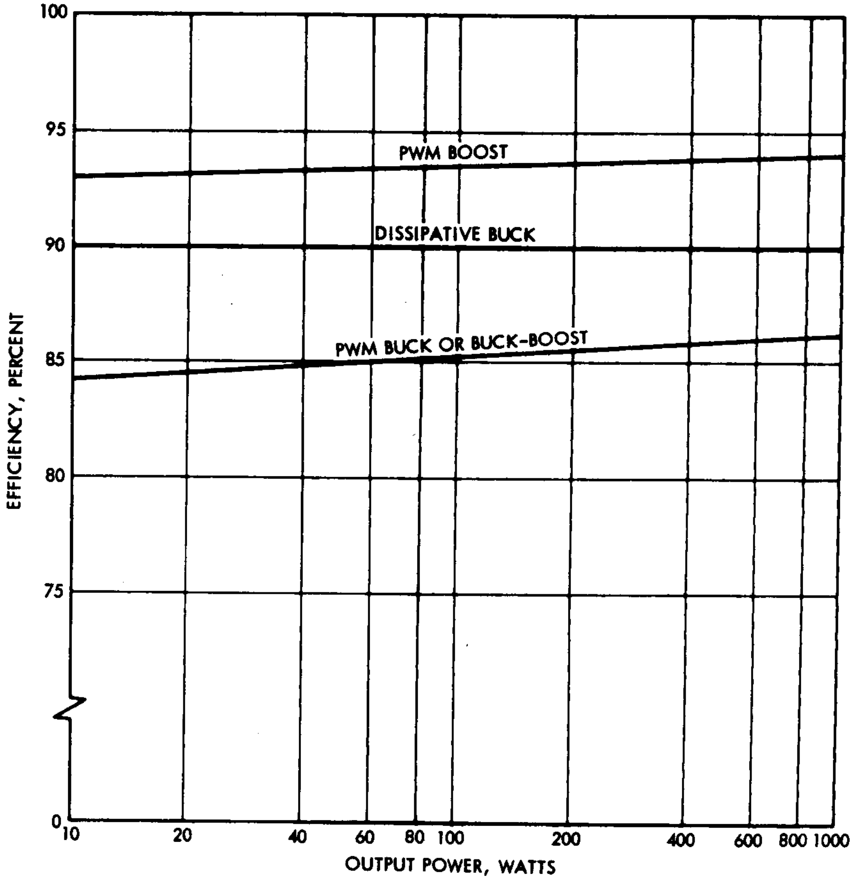

Figure 24. Line Regulators Redundant Efficiency vs Power Output

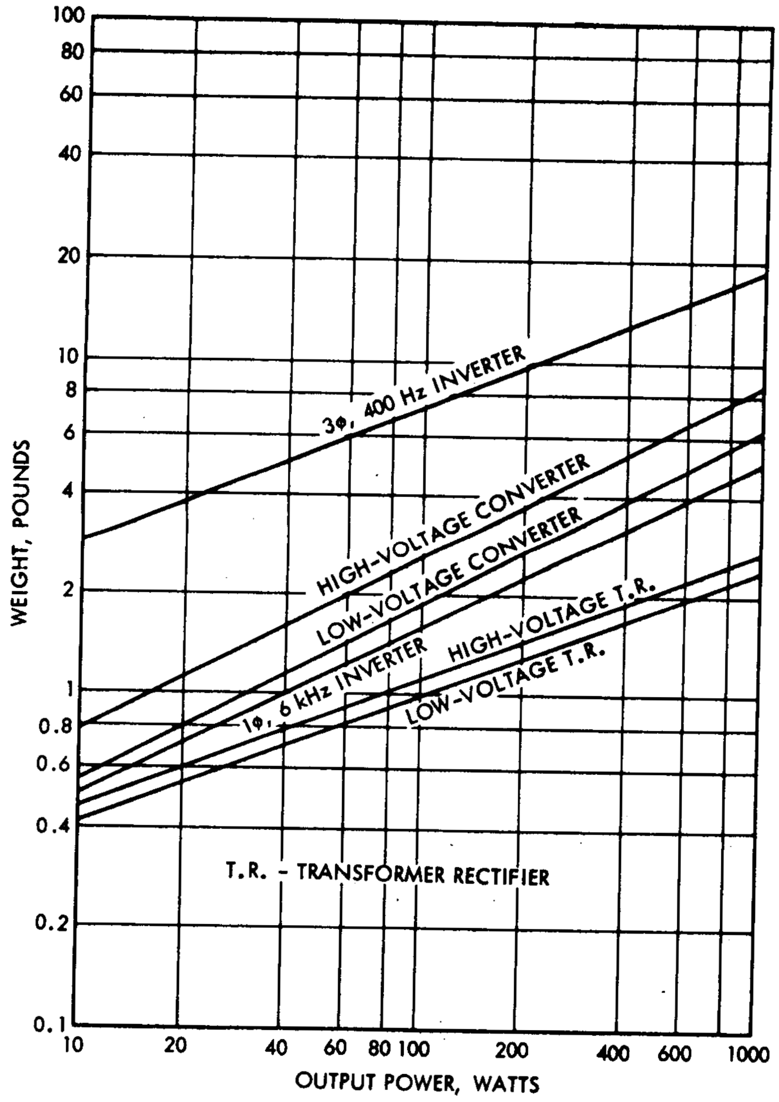

Figure 25. Load Power Conditioning Equipment Baseline Weight vs Power Output

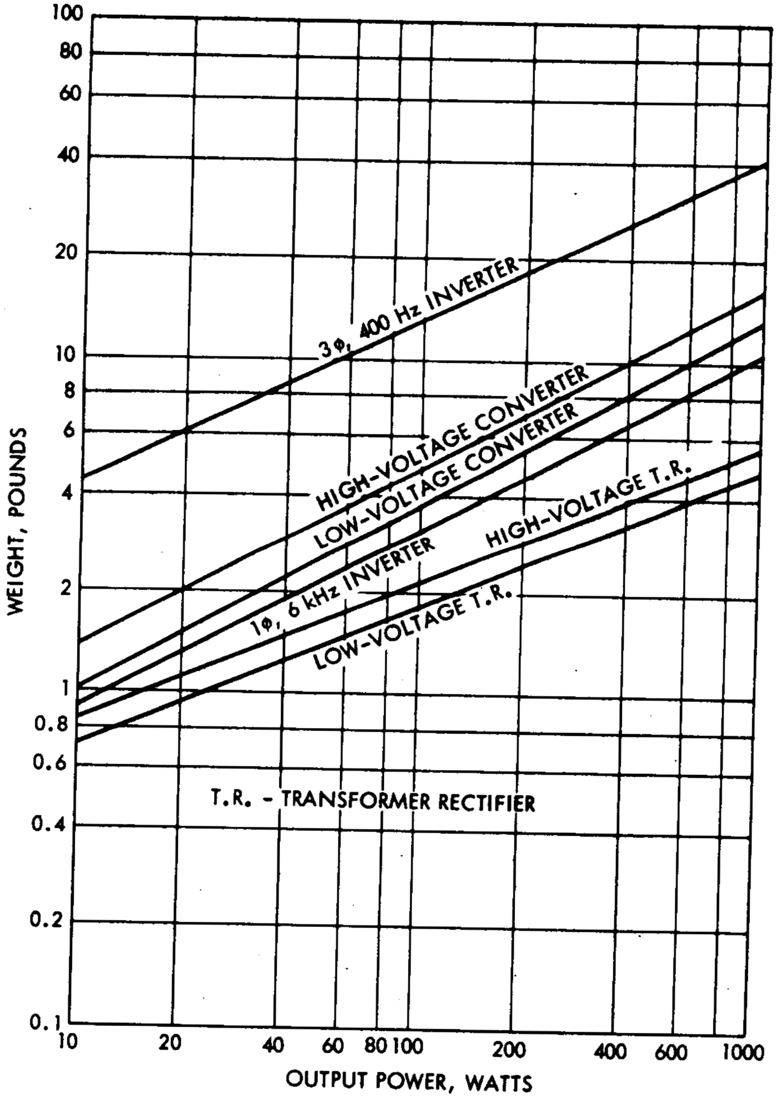

Figure 26. Load Power Conditioning Equipment Redundant Weight vs Power Output

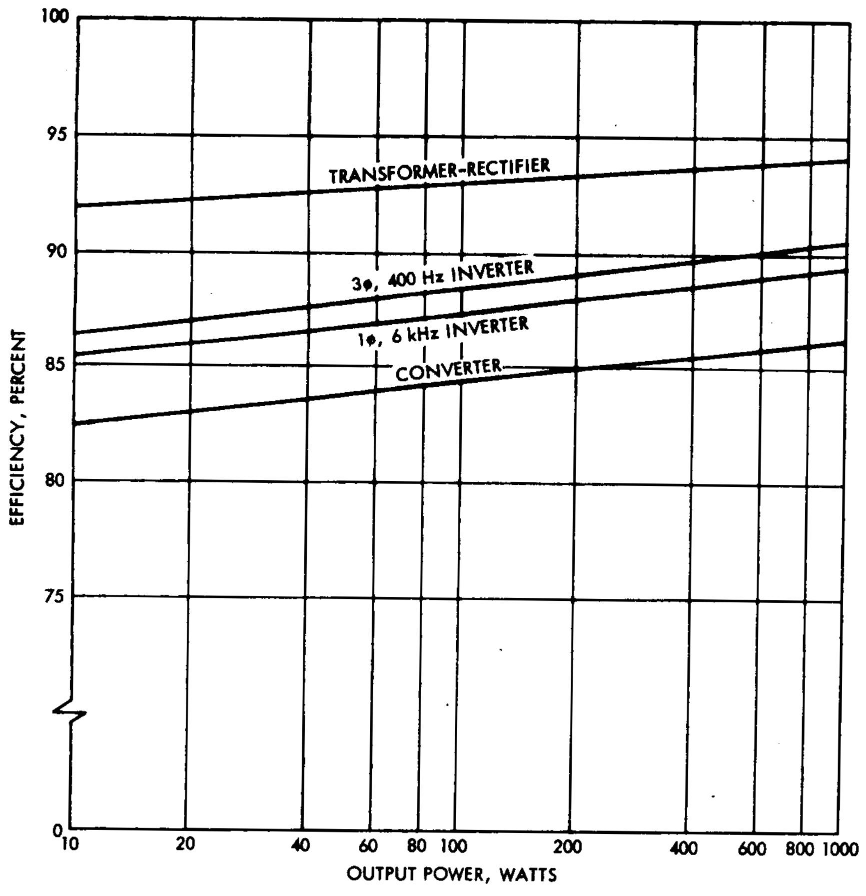

Figure 27. Load Power Conditioning Equipment Baseline Efficiency vs Power Output

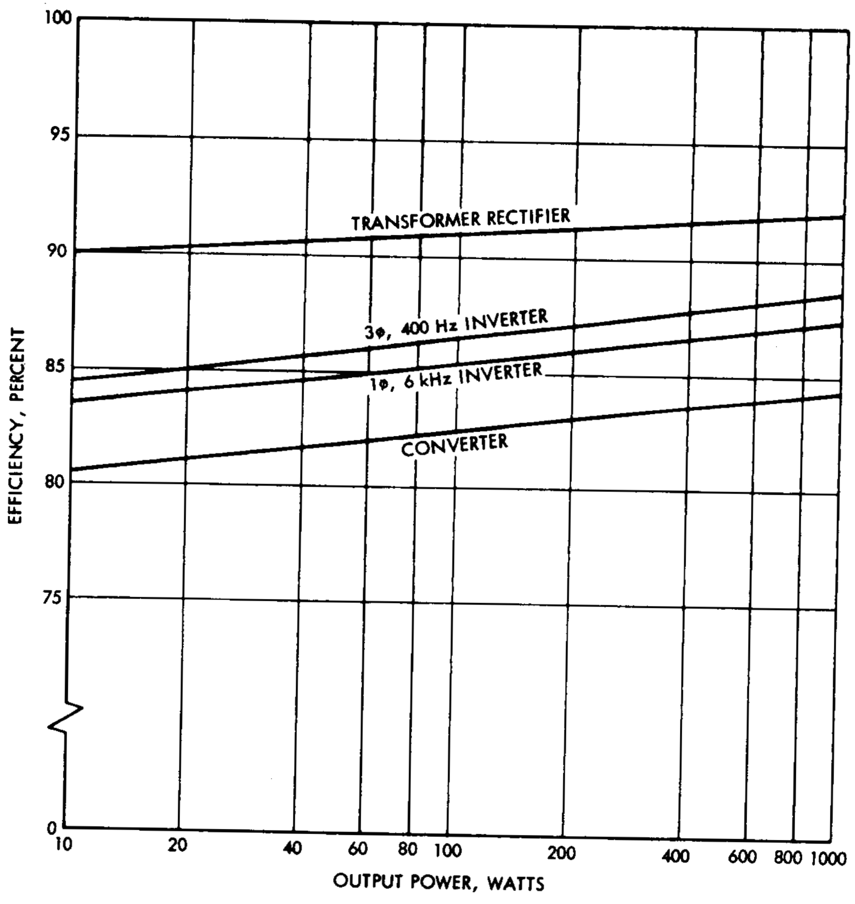

Figure 28. Load Power Conditioning Equipment Redundant Efficiency vs Power Output

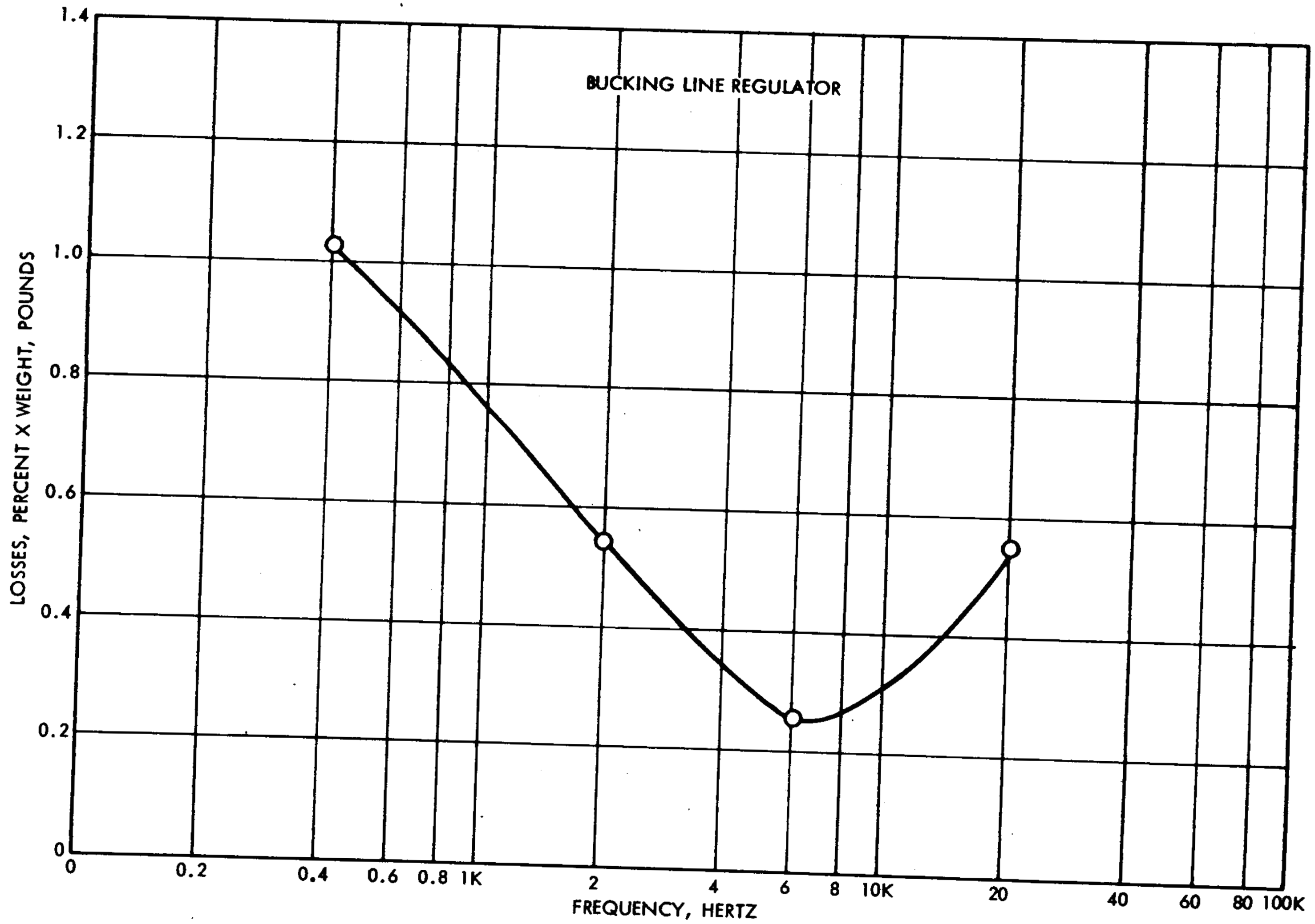

Figure 29. Bucking Line Regulator Power Loss Weight Product vs Switching Frequency

bucking series regulator. At frequencies lower than 6 kHz, the losses decrease but are more than offset by the increased weights of the magnetics and filters. At frequencies greater than 6 kHz, the weight decreases but the increased losses become the predominant characteristic. A 6-kHz switching frequency was selected, therefore, for all ac circuits with the exception of the gyro inverters, which require a 400-Hz output.

3.2.1 Solar Array Sizing

Solar array weight computations have been based on an assumed nominal 10-percent increase in the presently achievable maximum power output per unit array weight using conventional cells and panel construction techniques. With the exception of the Mars orbiter, all of the model spacecraft use deployed solar panels, which were assumed to yield a maximum of 10 watts per pound in space at 1.0 AU. The selected Mars orbiter model uses a fixed solar array with an insulated rear surface to minimize heat transfer from the array into the spacecraft equipment compartment. As a result of its higher operating temperature, this configuration was determined to produce a maximum power capability of 6 watts per pound at 1.0 AU.

For the majority of the power system configurations under consideration, the solar array must be capable of delivering required power over a range of operating voltages determined by the battery and its controls. As a result, operation at the maximum power point voltage of the array is not possible in many of the systems and the solar array must be oversized accordingly.

Analyses were performed, with the aid of a computer, to determine the required maximum power capability of the solar arrays at 1.0 AU for each of the seven missions and for each power system configuration, which satisfied the load requirements throughout the mission. These analyses also determined the critical design point in each mission at which the solar array capability was just adequate to support the load. At all other conditions of voltage, sun-spacecraft distance and load the existence of a positive power margin was verified. The operating voltage range was adjusted in these calculations to cause the array to operate as near as possible to its maximum power point voltage at the critical design point in the mission.

The results of these analyses were used to determine the installed solar array weight per unit power required at the critical design point. These values range from a worst case of 3.7 pounds per watt for certain of the systems in the Jupiter orbiter mission to 0.08 pounds per watt for several systems in the Venus orbiter mission. These factors are used in the reliability-weight optimization program to calculate array weight directly from the required power at the critical design point, taking into account the efficiencies of all the components in the various system configurations. A margin of 5 percent will be included in these calculations to correspond to the allowable array degradation due to cell and interconnection failures consistent with the solar array reliability value used.

3.3 RELIABILITY-WEIGHT OPTIMIZATION

The purpose of the reliability-weight optimization program is to determine the best combinations of redundant and nonredundant components within one system configuration as a function of either a reliability or weight allocation. The computer program enumerates all possible combinations of component redundancy, and selects those that provide minimum weight for system reliabilities ranging from a minimum of 0.90 to the maximum achievable. These selected combinations then represent the optimum reliability versus weight characteristic for a given system configuration. By comparing these characteristics for all candidate system configurations, the best designs for each mission will be determined.

The technique of enumerating all possibilities and then selecting the best combinations would appear to be a rather cumbersome approach in view of the classical mathematical approaches and dynamic programming techniques which have been used to solve many problems of this type in the past. The discontinuous nature of the component reliability-weight functions and the interdependence of component weights, efficiencies, and reliabilities, however, have prevented the adoption of a streamlined solution to the power system optimization problem.

The matrix shown in Figure 30 represents the basic arrangement of the computer program. Each column represents one essential component of the system, and each cell represents one of the alternative choices of redundancy in the component of the appropriate column. Several numbers may be associated with each cell in the matrix, plus additional numbers which are common to all the components of a column. For the cells, the numbers used are as follows:

R = component reliability for appropriate level of redundancy

M = intercept of log weight versus log power plot for particular component

N = intercept of efficiency versus log power plot for particular component

K = number of batteries

W = component weight (independent of other components)

η_E = component efficiency in eclipse (independent of other components)

η_D = component efficiency in daylight (independent of other components)

For the columns, the numbers used are as follows:

θ = slope of log weight versus log power plot for each component

π_E = load for particular component in eclipse*

π_D = load for particular component in daylight*

F = ratio of battery charge power to discharge power for particular mission and charge control.

The computer calculates efficiency and weight for the component configuration represented by each cell in the matrix according to the

---

* Represents only part of total load for array control, energy storage, and line regulator.

Solar Array	Array Control	Energy Storage	Line Regulator	PCE 1*
R_{SA} A_{SA} (Note 5)	θ_{AC} S_{AC} π_{UBD}	θ_{CR} θ_{B} θ_{DR} S_{CR} S_{DR} F π_{UBE} (Note 4)	θ_{LR} S_{LR} π_{RBD} π_{RBE}	π_{E1} π_{D1} ←
	R_{AC1} M_{AC1} N_{AC1}	R_{ES1} K_1 M_{CR1} M_{B1} M_{DR1} N_{CR1} N_{CR2}	R_{LR1} M_{LR1} N_{LR1}	R_{1P1} W_{1P1} η_{1P1E} η_{1P1D}
	R_{AC2} M_{AC2} N_{AC2}	R_{ES2} K_2 M_{CR2} M_{B2} M_{DR2} N_{CR2} N_{DR2}	R_{LR2} M_{LR2} N_{LR2}	R_{1P2} W_{1P2} η_{1P2E} η_{1P2D}
		R_{ES3} K_3 M_{CR3} M_{B3} M_{DR3} N_{CR3} N_{DR3}		
		R_{ES4} K_4 M_{CR4} M_{B4} M_{DR4} N_{CR4} N_{DR4}		
		R_{ES5} K_5 M_{CR5} M_{B5} M_{DR5} N_{CR5} N_{DR5}		
		R_{ES6} K_6 M_{CR6} M_{B6} M_{DR6} N_{CR6} N_{DR6}		
		R_{ES7} K_7 M_{CR7} M_{B7} M_{DR7} N_{CR7} N_{DR7}		
		R_{ES8} K_8 M_{CR8} M_{B8} M_{DR8} N_{CR8} N_{DR8}		
		R_{ES9} K_9 M_{CR9} M_{B9} M_{DR9} N_{CR9} N_{DR9}		

NOTES:

1. Each ve
2. Each ce
3. Parame
4. Energy
5. Solar a
6. For a-c

Gyro Inverter
π_{GD} π_{GE}
R_{G1} W_{G1} η_{G1E} η_{G1D}
R_{G2} W_{G2} η_{G2E} η_{G2D}

---

*Power Conditioning Equipment (Parallel Components)

PCE 2	PCE 3	PCE 4	PCE 5	PCE 6	PCE 7	PCE 8
π_{E2} π_{D2}	π_{E3} π_{D3}	π_{E4} π_{D4}	π_{E5} π_{D5}	π_{E6} π_{D6}	π_{E7} π_{D7}	π_{E8} π_{D8}
		(D-c Distribution System) →				
R_{2P1} W_{2P1} η_{2P1E} η_{2P1D}	R_{3P1} W_{3P1} η_{3P1E} η_{3P1D}	R_{4P1} W_{4P1} η_{4P1E} η_{4P1D}	R_{5P1} W_{5P1} η_{5P1E} η_{5P1D}	R_{6P1} W_{6P1} η_{6P1E} η_{6P1D}	R_{7P1} W_{7P1} η_{7P1E} η_{7P1D}	R_{8P1} W_{8P1} η_{8P1E} η_{8P1D}
R_{2P2} W_{2P2} η_{2P2E} η_{2P2D}	R_{3P2} W_{3P2} η_{3P2E} η_{3P2D}	R_{4P2} W_{4P2} η_{4P2E} η_{4P2D}	R_{5P2} W_{5P2} η_{5P2E} η_{5P2D}	R_{6P2} W_{6P2} η_{6P2E} η_{6P2D}	R_{7P2} W_{7P2} η_{7P2E} η_{7P2D}	R_{8P2} W_{8P2} η_{8P2E} η_{8P2D}

tical column represents single component design.

within column represents alternative redundant configuration of particular component.

rs in each column heading are common to all cells in that column.

orage includes battery, charge control and discharge control.

ay assumed to have single configuration.

istribution systems, replace PCE columns 1 - 8 with the following:

Main Inverter	TR 1	TR 2	TR 3	TR 4	TR 5	TR 6
θ_{MI} S_{MI}	π_{E1} π_{D1}	π_{E2} π_{D2}	π_{E3} π_{D3}	π_{E4} π_{D4}	π_{E5} π_{D5}	π_{E6} π_{D6}
R_{MI1} M_{MI1} N_{MI1}	R_{1T1} W_{1T1} η_{1T1E} η_{1T1D}	R_{2T1} W_{2T1} η_{2T1E} η_{2T1D}	R_{3T1} W_{3T1} η_{3T1E} η_{3T1D}	R_{4T1} W_{4T1} η_{4T1E} η_{4T1D}	R_{5T1} W_{5T1} η_{5T1E} η_{5T1D}	R_{6T1} W_{6T1} η_{6T1E} η_{6T1D}
R_{MI2} M_{MI2} N_{MI2}	R_{1T2} W_{1T2} η_{1T2E} η_{1T2D}	R_{2T2} W_{2T2} η_{2T2E} η_{2T2D}	R_{3T2} W_{3T2} η_{3T2E} η_{3T2D}	R_{4T2} W_{4T2} η_{4T2E} η_{4T2D}	R_{5T2} W_{5T2} η_{5T2E} η_{5T2D}	R_{6T2} W_{6T2} η_{6T2E} η_{6T2D}

Figure 30. Reliability - Weight Optimization Matrix

following general equations:

$$\text{Efficiency } (\eta) = S \log P + N$$

$$\text{Weight } (W) = MP^{\theta}$$

From the required output power, P, and the calculated efficiency, the computer determines the input power to each component. The program proceeds from specified output requirements back through the various series elements of the system to determine required component power levels and weights, taking into account the required operation of each in sunlight and eclipse.

The matrix is then scanned, and necessary calculations performed to determine total system weight and reliability for each possible combination of system components.

Specific calculation methods for the weight of the power system are shown in Tables XIV and XV. Terms for these calculations are listed in Table XVI.

Preliminary computer runs have been made for one system configuration for the Venus orbiter model No. 1. The results of these runs are listed in Table XVII. The system configuration was selected arbitrarily for these test cases from the total 148 baseline configurations developed during previous study phases. This configuration contains the following components:

Solar Array
Array Control - Active shunt voltage limiter
Battery Control - Series resistor and disconnect with momentary line booster
Battery - Silver-cadmium (20 cells)
Line Regulator - Series PWM buck-boost
DC Distribution - Gyro inverter (3ϕ, 400 Hz)
Transmitter converter
Main converter
Computer-Sequencer converter
High voltage experiment converter
Low voltage experiment converter

Referring to Table XVII, the optimized system represents the minimum weight combination for each given reliability constraint. This system is characterized by a gradually increasing weight as a function of reliability until the change to redundant batteries at a reliability value of approximately 0.97 is necessitated. This transition in the reliability-weight characteristic will be common to most systems because the battery weight is large in comparison to that of the other components. Similar reliability-weight characteristics will be generated for all of the candidate system configurations to permit their comparison for each model mission.

Table XIV. Weight Calculations for AC Distribution Systems

1. $P_{MIE} = \frac{\pi_{E1}}{\eta_{1TE}} + \frac{\pi_{E2}}{\eta_{2TE}} + \cdots + \frac{\pi_{EN}}{\eta_{NTE}}$

2. $P_{MID} = \frac{\pi_{D1}}{\eta_{1TD}} + \frac{\pi_{D2}}{\eta_{2TL}} + \cdots + \frac{\pi_{DN}}{\eta_{NTD}}$

3. P_{MIR} = greater of P_{MIE} or P_{MID}

4. $W_{MI} = M_{MI} P_{MIR}^{\theta_{MI}}$

5. $\eta_{MIE} = S_{MI} \log P_{MIE} + N_{MI}$

6. $\eta_{MID} = S_{MI} \log P_{MID} + N_{MI}$

7. $P_{LRE} = \frac{P_{MIE}}{\eta_{MIE}} + \frac{\pi_{GE}}{\eta_{GE}} + \pi_{RBE}$

8. $P_{LRD} = \frac{P_{MID}}{\eta_{MID}} + \frac{\pi_{GD}}{\eta_{GD}} + \pi_{RBD}$

9. P_{LRR} = greater of P_{LRE} or P_{LRD}

10. $W_{LR} = M_{LR} P_{LRR}^{\theta_{LR}}$

11. $\eta_{LRE} = S_{LR} \log P_{LRE} + N_{LR}$

12. $\eta_{LRD} = S_{LR} \log P_{LRD} + N_{LR}$

13. $P_{ES} = \frac{P_{LRE}}{\eta_{LRE}} + \pi_{UBE}$

14. $\eta_{DR} = S_{DR} \log \frac{P_{ES}}{K} + N_{DR}$

15. $P_{B} = \frac{P_{ES}}{\eta_{DR}}$

16. $P_{CR} = FP_{B}$

17. $W_{ES} = KM_{DR} P_{ES}^{\theta_{DR}} + KM_{B} P_{B}^{\theta_{B}} + KM_{CR} P_{CR}^{\theta_{CR}}$

18. $\eta_{CR} = S_{CR} \log \frac{P_{CR}}{K} + N_{CR}$

19. $P_{AC} = \frac{P_{LRD}}{\eta_{LRD}} + \frac{P_{CR}}{\eta_{CR}} + \pi_{UBD}$

20. $W_{AC} = M_{AC} P_{AC}^{\theta_{AC}}$

21. $\eta_{AC} = S_{AC} \log P_{AC} + N_{AC}$

22. $P_{SA} = \frac{P_{AC}}{\eta_{AC}}$

23. $W_{SA} = A P_{SA}$

24. $W_{SYS} = W_{SA} + W_{AC} + W_{ES} + W_{LR} + W_{1P} + W_{2P} + \cdots + W_{NP}$

Table XV. Weight Calculations for DC Distribution Systems

1. $P_{LRE} = \frac{\pi_{E1}}{\eta_{1PE}} + \frac{\pi_{E2}}{\eta_{2PE}} + \cdots + \frac{\pi_{EN}}{\eta_{NPE}} + \pi_{RBE}$

2. $P_{LRD} = \frac{\pi_{D1}}{\eta_{1PD}} + \frac{\pi_{D2}}{\eta_{2PD}} + \cdots + \frac{\pi_{DN}}{\eta_{NPD}} + \pi_{RBD}$

3. P_{LRR} = greater of P_{LRE} or P_{LRD}

4. $W_{LR} = M_{LR} \, P_{LRR}^{\theta_{LR}}$

5. $\eta_{LRE} = S_{LR} \log P_{LRE} + N_{LR}$

6. $\eta_{LRD} = S_{LR} \log P_{LRD} + N_{LR}$

7. $P_{ES} = \frac{P_{LRE}}{\eta_{LRE}} + \pi_{UBE}$

8. $\eta_{DR} = S_{DR} \log \frac{P_{ES}}{K} + N_{DR}$

9. $P_B = \frac{P_{ES}}{\eta_{DR}}$

10. $P_{CR} = FP_B$

11. $W_{ES} = KM_{DR} \, P_{ES}^{\theta_{DR}} + KM_B \, P_B^{\theta_B} + KM_{BR} \, P_{CR}^{\theta_{CR}}$

12. $\eta_{CR} = S_{CR} \log \frac{P_{CR}}{K} + N_{CR}$

13. $P_{AC} = \frac{P_{LRD}}{\eta_{LRD}} + \frac{P_{CR}}{\eta_{CR}} + \pi_{UBD}$

14. $W_{AC} = M_{AC} \, P_{AC}^{\theta_{AC}}$

15. $\eta_{AC} = S_{AC} \log P_{AC} + N_{AC}$

16. $P_{SA} = \frac{P_{AC}}{\eta_{AC}}$

17. $W_{SA} = A \, P_{SA}$

18. $W_{SYS} = W_{SA} + W_{AC} + W_{ES} + W_{LR} + W_{1P} + W_{2P} + \cdots + W_{NP}$

Table XVI. Glossary of Terms

Power Terms

$P_{MIE, MID}$ = Main inverter output power in eclipse, sunlight

P_{MIR} = Main inverter rated output power

$P_{LRE, LRD}$ = Line regulator output power in eclipse, sunlight

P_{LRR} = Line regulator rated output power

P_{ES} = Energy storage output power

P_{B} = Battery output power

P_{CR} = Battery charger output power

P_{AC} = Array control output power

P_{SA} = Solar array output power

$\pi_{E1, E2, EN}$ = Output power in eclipse for power conditioning equipments 1, 2, ---N

$\pi_{D1, D2, DN}$ = Output power in sunlight for power conditioning equipments 1, 2, ---N

$\pi_{GE, GD}$ = Output power for gyro inverter in eclipse, sunlight

$\pi_{RBE, RBD}$ = Direct connected regulated bus load in eclipse, sunlight

$\pi_{UBE, UBD}$ = Direct connected unregulated bus load in eclipse, sunlight

Efficiency Terms

$\eta_{ITE, 2TE, NTE}$ = Efficiency in eclipse of transformer rectifiers 1, 2, ---N

$\eta_{ITD, 2TD, NTD}$ = Efficiency in sunlight of transformer rectifiers 1, 2, ---N

$\eta_{MIE, MID}$ = Efficiency of main inverter in eclipse, sunlight

$\eta_{GE, GD}$ = Efficiency of gyro inverter in eclipse, sunlight

$\eta_{IPE, 2PE, NPE}$ = Efficiency in eclipse of power conditioning equipments 1, 2, ---N

Table XVI. Glossary of Terms (Continued)

Efficiency Terms (Continued)

$\pi_{IPD, 2PD, NPD}$ = Efficiency in sunlight of power conditioning equipments 1, 2, ---N

$\pi_{LRE, LRD}$ = Efficiency of line regulator in eclipse, sunlight

π_{DR} = Efficiency of discharge regulator

π_{CR} = Efficiency of charge regulator

π_{AC} = Efficiency of array control

K = Number of batteries

F = Ratio of battery charge power to battery discharge power

S_{MI}, N_{MI} = Slope and intercept of main inverter efficiency vs power curve

S_{LR}, N_{LR} = Slope and intercept of line regulator efficiency vs power curve

S_{DR}, N_{DR} = Slope and intercept of discharge regulator efficiency vs power curve

S_{CR}, N_{CR} = Slope and intercept of charge control efficiency vs power curve

S_{AC}, N_{AC} = Slope and intercept of array control efficiency vs power curve

Weight Terms

$W_{IP, 2P, NP}$ = Weight of power conditioning equipments 1, 2, ---N including main inverter when used

W_{MI} = Weight of main inverter

W_{LR} = Weight of line regulator

W_{ES} = Weight of energy storage

W_{AC} = Weight of array control

W_{SA} = Weight of solar array

A = Weight per unit power output of solar array at critical design point

Table XVI. Glossary of Terms (Continued)

Weight Terms (Continued)

K = Number of batteries

M_{MI}, θ_{MI} = Intercept and slope of main inverter weight vs power curve

M_{LR}, θ_{LR} = Intercept and slope of line regulator weight vs power curve

M_{DR}, θ_{DR} = Intercept and slope of discharge regulator weight vs power curve

M_B, θ_B = Intercept and slope of battery weight vs power curve

M_{CR}, θ_{CR} = Intercept and slope of charge control weight vs power curve

M_{AC}, θ_{AC} = Intercept and slope of array control weight vs power curve

Table XVII. Initial Optimization Program Computer Run Results

Constraints		No. of Possibilities	Optimized System		
No.	Reliability		Reliability	Weight	Configuration*
1	.900	964	.903773	74.02	1 2 1 1 1 1 1 2 2 2
2	.905	928	.906623	74.33	1 1 2 1 1 1 1 2 1 2
3	.910	876	.911319	74.69	1 2 2 1 1 1 1 2 1 2
4	.915	822	.915737	74.79	1 1 2 1 1 1 1 2 2 2
5	.920	755	.920480	75.15	1 2 2 1 1 1 1 2 2 2
6	.925	687	.926024	76.59	1 1 2 2 1 1 1 2 2 2
7	.930	607	.930821	76.96	1 2 2 2 1 1 1 2 2 2
8	.935	519	.939034	77.55	1 2 2 1 1 2 1 2 2 2
9	.940	433	.940132	78.94	1 2 2 2 1 2 1 2 1 2
10	.945	348	.948083	79.35	1 2 2 1 2 2 1 2 2 2
11	.950	266	.953792	80.81	1 1 2 2 2 2 1 2 2 2
12	.955	186	.958733	81.18	1 2 2 2 2 2 1 2 2 2
13	.960	128	.962983	83.75	1 1 2 2 2 2 2 2 2 2
14	.965	78	.967972	84.13	1 2 2 2 2 2 2 2 2 2
15	.970	45	.970248	112.21	1 2 3 2 2 2 1 1 2 2
16	.975	18	.978900	112.59	1 2 3 2 2 2 1 2 2 2
17	.980	6	.983240	115.68	1 1 3 2 2 2 2 2 2 2
18	.985	3	.988333	116.05	1 2 3 2 2 2 2 2 2 2
(Max. Achievable Rel.)		1	.98942387	116 +	1 2 4 2 2 2 2 2 2 2

*Configuration Key

1st Digit - Solar Array - Single Config.
2nd Digit - Array Control - 1 = Baseline 2 = Redundant
3rd Digit - Energy Storage - 1 = Single Battery + Baseline Control
2 = Single Battery + Redundant Control
3 = Two Batteries + Baseline Controls
4 = Two Batteries + Redundant Controls
4th Digit - Line Regulator - 1 = Baseline 2 = Redundant
5th-10th - Load Power Conditioning Equipment - 1 = Baseline 2 = Redundant

3.4 SYSTEM COMPARISONS

As discussed previously, systems selected on the basis of their optimized reliability and weight will be further evaluated qualitatively with respect to their interface characteristics, flexibility and growth potential. One of the most important interface considerations which influence the design of spacecraft power systems is that of electromagnetic compatibility (EMC). Since the power system has some type of conductive interface with each equipment on the spacecraft, interference generated by the power subsystem, will exist at these interfaces. In addition, interference generated by any of the equipments using this power can use the power subsystem as a coupling medium and couple interference to any other equipment.

As a result of this and the fact that ECM problems are often not fully appreciated by power system designers, emphasis has been placed on this aspect of the power system interface studies for this program. The following paragraphs summarize the investigations to date with respect to basic EMC considerations and specific control practices.

3.4.1 EMC Considerations

Typical problem areas of incompatibility occur in two somewhat distinctive areas:

a) Effects of electromagnetic interference on phenomena being measured by spacecraft experiements.

b) Effects of electromagnetic interference on spacecraft electronic systems by various coupling methods.

In the former case, the effect is generally due to the electric and magnetic fields created by the power system equipment and the distribution system. These fields may modulate or change the electromagnetic fields existing in and around the spacecraft or may dominate the space fields so as to make them unmeasurable.

In the latter case, interference may couple voltages and/or currents into sensitive electromic circuits and cause irregular behavior of the affected system.

Specifically, the primary compatibility problems relating to the spacecraft power system are due to:

1) Type of power distribution used (ac or dc)
2) Waveform of ac distribution
3) Frequency of ac distribution
4) Type of voltage regulator circuit used (dissipative or switching type)
5) Power circuit grounding
6) Power circuit wiring practices
7) Power converter " Bandpass Characteristic" to interference at its input.

These compatibility problems can be eliminated or minimized by the use of judicious circuit design and interference control measures, such as circuit grounding, bonding, shielding, circuit isolation, and filtering.

3.4.2 Specific Interference Control Practices

The conversion of dc power to ac for use by certain spacecraft equipment results in the generation of interference ranging from the converter switching frequency up to perhaps 10 to 100 MHz. This interference generation is due to the extremely fast switching of the inverter circuitry. The interference may be conducted out of the inverter via the dc input leads back onto the main dc bus and, in turn, into other interference-sensitive spacecraft equipment. In addition, this switching sets up electric and magnetic fields, which may induce interference voltages or currents into sensitive electrical-electronic equipment. Typical solutions for eliminating this interference or minimizing its effects are:

1) Choose an inverter switching frequency, which produces interference at frequencies which fall outside the spectrum used by on-board electronic equipment. (e. g., if there are on-board equipments whose bandwidths are zero to 2 kHz, choose an inverter switching frequency of 5 to 6 kHz.) The discrete line spectra produced by the inverter switching circuitry will range from the fundamental switching frequency of 5 to 6 kHz up to approximately 10 MHz, thus falling above the zero to 2 kHz frequency band. The inverter switching frequency chosen should not have discrete line spectra coinciding with the operating frequencies of other on-board electronic equipments.

2) Route power and control circuits, entering or leaving the inverter chassis, to minimize wire-to-wire coupling. Tightly twist each positive wire with its return and route the pair against the spacecraft's metal structure to minimize its electromagnetic field. Where practical, route the power wiring in such a way as to take advantage of the inherent shielding of the spacecraft's structure (e.g., route the power wiring along behind a structural bracket to achieve the "shading" effect of the well-grounded metal).

3) Shield all power cirucits entering and exiting the inverter to minimize coupling of radiated interference energy to sensitive spacecraft circuits. Terminate these shields to chassis at both the source and load ends and at any shield discontinuity in between. The shield terminations should be as short as practicable (preferably one in. or less).

4) Electrically bond all metal components of the power subsystem to the metal spacecraft structure to achieve a low impedance reference plane. The component-to-structure impedance should be 2.5 milliohms dc or less.

5) Incorporate LC-type interference filters on the power and control circuits entering or leaving the inverter chassis to prevent leakage of interference. This measure should be employed only when the techniques of Items 1 through 4 have failed to solve the interference problems since filters add weight to the spacecraft.

Both series and shunt-type voltage regulators used in spacecraft power systems may employ either switching (pulse-width-modulated) or dissipative techniques. From the interference generation standpoint, the dissipative type is preferable since it generates negligible interference. In contrast, the pulse-width-modulated type of regulator is a prolific generator of impulse-type interference. The interference control techniques employed for the dc/ac inverter discussed earlier are directly applicable to the control of regulator interference.

The dc/dc converter like the dc/ac inverter employs switching as a means of voltage conversion. This switching generates impulsive interference, generally in excess of 10 percent of the nominal line voltage, which appears at all multiples of the fundamental switching frequency up to approximately 10 MHz. The odd harmonics generally are predominate. The interference control measures normally employed to reduce converter interference are chassis and wire shielding, wire twisting and routing, circuit grounding, and judicious filtering.

Dc/dc converters characteristically exhibit a "bandpass filter" characteristic, which permits interference present at its power input to pass through to its output virtually unattenuated. The center frequency of this pass-band is centered at the clock frequency of the converter. The effects of the bandpass characteristic can be minimized by the judicious use of low-frequency interference filters at the converter's input and/or output.

The continuing analyses of the various model spacecraft and power system configurations with respect to EMC will include investigation of the selected load equipments, their sensitivity to interference, comparisons of power systems with respect to the generation of interference and control measures necessary to achieve electromagnetic compatibility.