1J86-TOPS-479

15 OCTOBER 1969

SPACE
SYSTEMS

POWER CONDITIONING EQUIPMENT FOR A THERMOELECTRIC OUTER PLANET SPACECRAFT POWER SUBSYSTEM

QUARTERLY TECHNICAL REPORT

JPL CONTRACT NO. 952536

FACILITY FORM 602

N70-12070 (ACCESSION NUMBER)

(THRU) 1

64 (PAGES)

(CODE)

CR-107013 (NASA CR OR TMX OR AD NUMBER)

03 (CATEGORY)

GENERAL ELECTRIC

1J86-TOPS-479
15 October 1969

POWER CONDITIONING EQUIPMENT
FOR THE
THERMOELECTRIC OUTER PLANET SPACECRAFT

QUARTERLY TECHNICAL REPORT

JPL CONTRACT NO. 952536

GENERAL ELECTRIC COMPANY
VALLEY FORGE SPACE TECHNOLOGY CENTER
P. O. BOX 8555
PHILADELPHIA PENNSYLVANIA 19101

1J86-TOPS-479
15 October 1969

POWER CONDITIONING EQUIPMENT
FOR THE
THERMOELECTRIC OUTER PLANET SPACECRAFT

QUARTERLY TECHNICAL REPORT

JPL CONTRACT NO. 952536

"THIS WORK WAS PERFORMED FOR THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, AS SPONSORED BY THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION UNDER CONTRACT NAS 7-100."

Prepared by:

Roman W. Andryczyk
Frank R. Barry
Theodore J. Ebersole
Alexander Jeremenko
Russell R. Pellman
Paul R. Scherer

Approved by:

J H Hayden
J. H. Hayden, Program Manager
TOPS Power Conditioning Equipment

WR Becraft
W. R. Becraft, Manager
Electrical Subsystem Engineering

GENERAL ELECTRIC COMPANY
VALLEY FORGE SPACE TECHNOLOGY CENTER
P. O. BOX 8555
PHILADELPHIA, PENNSYLVANIA 19101

THIS REPORT CONTAINS INFORMATION PREPARED BY THE GENERAL ELECTRIC COMPANY UNDER JPL SUBCONTRACT. ITS CONTENT IS NOT NECESSARILY ENDORSED BY THE JET PROPULSION LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, OR THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION.

ABSTRACT

This report covers preliminary design and development activity of the power conditioning electronics for an unmanned outer planet scientific spacecraft with a twelve year life. Requirements of loads are defined; conceptual block diagrams of an inverter, a shunt regulator, a power controller, and a DC to DC converter are presented; and a minimum piece part circuit implementation is established to permit additional trade studies for optimum reliability, weight, efficiency, and cost.

The objective was a design to provide regulated power for engineering and science subsystems from a radioisotope thermoelectric generator, and to perform switching and control functions for the effective management and distribution of electrical power. The concept established provides an optimized design to match the power source with the electrical loads, and also provides Peltier cooling at all times to extend thermocouple life.

TABLE OF CONTENTS

Page

TECHNICAL DISCUSSION

LIST OF ILLUSTRATIONS

LIST OF TABLES

GLOSSARY

BEGINNING OF MISSION	BOM
BENCH TEST EQUIPMENT	BTE
END OF MISSION	EOM
NEAR ENCOUNTER	N.E.
POWER CONDITIONING EQUIPMENT	PCE
POWER SOURCE AND LOGIC	PS&L
RADIOISOTOPE THERMOELECTRIC GENERATOR	RTG
SILICON-GERMANIUM	SiGe
SPACECRAFT	S/C
TELEVISION	TV
THERMOELECTRIC OUTER PLANET SPACECRAFT	TOPS
TRAVELING WAVE TUBE	TWT

INTRODUCTION AND SUMMARY

This Quarterly Technical Report for the period 17 April 1969 through 30 June 1969 was prepared in accordance with Article 2.(c)(3) of Jet Propulsion Laboratory Contract 952536.

SUBJECT OF REPORT

The report covers activities of the first quarter, consisting primarily of defining the requirements of the Electrical Power Subsystem and its equipment, and the electrical and mechanical interface with the vehicle.

OBJECTIVES

The objective of this work is to develop, design and test new technology, circuits, processes and concepts to advance the state of the art in electronic power conditioning equipment. A parallel objective is to design and deliver hardware for integration and test.

WHY WORK IS BEING DONE

The work is being done to optimize power conditioning equipment and to develop confidence in meeting the twelve-year life requirement of interplanetary missions.

CONCLUSIONS

Interim conclusions are that the design must be versatile to meet the conflicting requirements of optimized design, vehicle constraints and continuing change.

RECOMMENDATIONS

The designs applicable to the twelve-year life requirement based on previous space power experience require significant sophistication and improvement to demonstrate confidence in successful mission completion.

SIGNIFICANCE

This effort is significant for long duration planetary missions since the equipment must be made free of failures or be capable of continuous satisfactory performance even after experiencing a failure. This is not presently within the state of the art of power conditioning design, and must be developed and demonstrated.

TECHNICAL DISCUSSION

SECTION 1. SYSTEM SUMMARY

The Thermoelectric Outer Planet Spacecraft (TOPS) mission is a minimum launch energy, gravity assisted tour of the outer planets; Jupiter, Saturn, Uranus, and Neptune, during the unique planetary alignment period that exists in the 1976-1980 time period.

The launch vehicle consists of a Titan III D/Centaur with a Burner II kick stage. With this propulsion energy, the first Jupiter opportunity occurs in 1972, but the earliest mission presently considered is a precursor Jupiter flyby in 1974 to check out operational subsystems, with several additional planetary options after 1975. The grand tour opportunity in 1978-1979 allows a single pass at four of the outer planets with a single mission, and is the baseline system considered for this study. The next such opportunity occurs in the year 2150. An alternative to the grand tour is a dual mission approach of one spacecraft to Jupiter, Saturn and Pluto; and a second to Jupiter, Uranus and Neptune. The dual approach allows two different visits to Jupiter, and permits avoiding the rings of Saturn.

The unmanned spacecraft will weigh approximately 1600 pounds, with an experimental payload of 50 to 150 pounds. The major challenge is the communications system, whose required power increases as the square of the distance from the earth. The one way propagation time at Jupiter encounter is four hours, and total distance to the outermost planet is thirty astronomical units. The total prelaunch checkout and travel time for the grand tour is in excess of one hundred thousand hours.

Figure 1-1 shows an artist's conception with relative equipment locations of the baseline system that was selected by the Jet Propulsion Laboratory for this study.

This mission requires highly reliable, sophisticated automatic spacecraft subsystems to perform the multi-planet tour with uninterrupted successful operation for ten to twelve years at great distances from the earth and sun and in the following unknown and hazardous environments:

1) Impact with a large number of small cometary fragments.

2) Traverse of the asteroid belt.

3) Intense radiation belts near Jupiter.

4) Possible penetration of the rings of Saturn.

THERMOELECTRIC OUTER PLANET SPACECRAFT

VERSION 12c

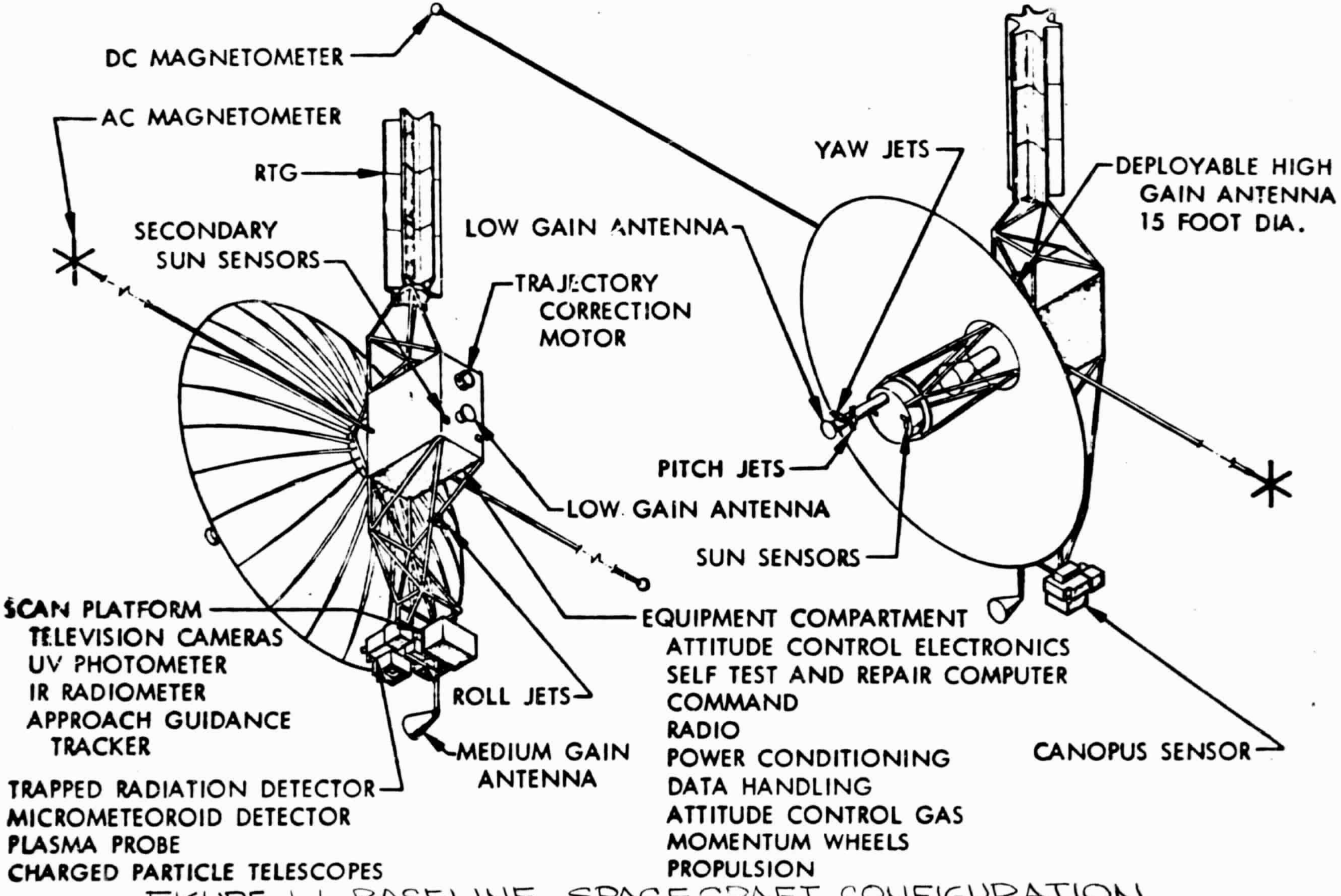

FIGURE 1-1. BASELINE SPACECRAFT CONFIGURATION

The mission has been described by the Jet Propulsion Laboratory in their TOPS Flight Sequence by eleven operational modes as listed in Table 1-1, with nine of the modes repeated at each planetary encounter. The representative arrival times for a grand tour trajectory are listed in Table 1-2, and these flight durations will be used for relative reliability studies to compute partial mission success. This information was obtained from Trajectory Analysis of a Grand Tour Mission to the Outer Planets by Louis Kingsland, Jr., AIAA Paper No. 68-1055, October 1968.

Physical data of the pertinent planets is tabulated for information only in Table 1-3, and this data was extracted from Space Facts, a handbook of basic and advanced space data for scientists and engineers, published by the General Electric Company in 1960.

Planet encounter spacecraft operations begin approximately thirty days before closest approach. The near encounter phase is defined as the twenty-four hour period of closest approach, with nominally one hour of occultation at each planet. Table 1-4 lists the duration of the planetary approach periods for a representative mission, and was extracted from To The Outer Planets by James E. Long, Astronautics and Aeronautics, June, 1969.

It should be noted that this information is presented for the sole purpose of serving as a baseline for analysis of the power subsystem performance. It provides a common source of data and timelines, and permits relative comparisons.

TABLE 1-1 OPERATIONAL MODES

	Launch Acquisition
Repeated for each Planet	Cruise Maneuver Burn Approach Guidance Far Encounter Encounter Enter Occultation Occultation Data Dump

TABLE 1-2 **BASELINE GRAND TOUR TRAJECTORY**

LEG PARAMETER	EARTH-JUPITER	JUPITER-SATURN	SATURN-URANUS	URANUS-NEPTUNE
Launch Date	1 Sept 1977	-	-	-
Departure Date	2 Dec 1977	28 Aug 1979	9 Sept 1981	6 Dec 1985
Departure Date Radius	920,000	44,800,000	42,800,000	51,700,000
Arrival Date	4 May 1979	16 June 1981	21 Sept 1985	20 Feb 1989
Arrival Radius	44,800,000	42,800,000	51,700,000	86,800,000
Periapsis Date	1 July 1979	29 July 1981	30 Oct 1985	-
Periapsis Distance (km)	635,000	144,000	98,600	-
Swingby Turn Angle (degs)	98.	84.	24.	-
Flight Time (days)	668.	759.	1554.	1210.
Total Flight Time (days)	668.	1427.	2981.	4191.

TABLE 1-3. PHYSICAL DATA OF THE OUTER PLANETS

	EARTH	JUPITER	SATURN	URANUS	NEPTUNE	PLUTO
Mean distance from Sun						
Millions of nautical miles	80.7	419.7	769.5	1548	2426	3183
Millions of km	149.5	777.8	1426.1	2869.1	4495.6	5898.9
Astronomical Unit (A.U.)	1.000	5.203	9.539	19.191	30.071	39.457
Diameter (Earth = 1)	1.000	10.97	9.03	3.72	3.38	0.45
Mean Diameter						
Nautical miles	6,875.74	75,427	62,088	25,578	23,240	3,094
km	12,742.46	139,785	115,064	43,070	43,070	5,734
Surface Gravity (Earth = 1)	1.00	2.65	1.17	1.05	1.23	.5?
Velocity of escape						
km/sec	11.2*	61.0	36.7	22.4	25.6	<5.3
ft/sec	36,700*	200,000	120,000	73,400	84,000	<17,300
Oblateness	1/(298.38)	1/15	1/(9.5)	1/14	1/40	?
Mass (Earth = 1)	1.0000	318.35	95.3	14.58	17.26	<0.1?
Mean Density (H_2O = 1)	5.52	1.33	0.71	1.56	2.47	<5.5?
Stellar Magnitude, Maximum	?	-2.5	-0.4	+5.7	+8.8	+15
Visual Albedo	0.39	0.51	0.50	0.66	0.62	0.16
Known Moons	1	12	9	5	2	0
Probable Surface Temperature °K	288	105	80	44	33	?
Measured Temperature °K	287 (Mean)	135	120	less than 90	?	?

* g_o taken as 32.2284 ft/sec.^{2}

TABLE 1-4 REPRESENTATIVE ENCOUNTER EVENTS

EVENT	Event Time (except occultation) days			
	Jupiter	Saturm	Uranus	Neptune
Initiate approach guidance measure	D-30	D-37	D-37	-
Perform trajectory-correction operation	D-24	-	D-30	D-100
Initiate far encounter TV operations (Record & playback daily to E-1)	D-21	D-36	-	D-30
Perform trajectory correction operations	-	D-12	D-12	-
Terminate approach-guidance measurements	D-5	D-5	D-5	D-5
Initiate near-encounter (N.E.) science	D-1	D-1	D-1	D-1
Terminate TV	D	D-1	D	D
Enter Earth-occultation (S/C on inertial control)	D+13.7	D+.2	D+2.4	D+2.6
Enter solar occultation	D+16.2	D+.3	D+2.7	D+2.7
Exit Earth occultation	D+16.6	D+1.5	D+3.4	D+4.0
Exit solar occultation	D+19.2	D+1.8	D+3.8	D+4.1
Terminate N.E. science	D+1	D+1	D+1	D+1
Playback N.E. stored data	D+1	D+1	D+1	D+1
Perform trajectory correction	D+20	D+20	D+20	-

TECHNICAL DISCUSSION

SECTION 2. DESIGN REQUIREMENTS AND CONSTRAINTS

The power conditioning equipment must be compatible with a radioisotope thermoelectric generator (RTG) power source. The design of the PCE shall emphasize long life, environmental immunity and emergency adaptability characteristics which would be required for use on a spacecraft capable of performing a multiple outer planet mission in the mid-seventies time period. The PCE design must include techniques for assuring compatibility with the RTG power source and the spacecraft subsystems. The design is to utilize the most advanced state-of-the-art technologies available today, which at the same time, provide a system design concept capable of accepting future technology improvements. The size of the technology jump demonstrated in the TOPS program must be large in order to contribute effectively to a Grand Tour type mission in the mid-seventies. The technology advancements must be such as to enhance performance, reliability, and cost effectiveness. To permit flight testing of the new technologies, a 1974 Grand Tour precursor mission is being considered. Hence, this technology proposed should be capable of accepting any state-of-the-art improvements available in 1971-1972.

The power source selected for spacecraft equipment is multiple Radioisotope Thermoelectric Generators (RTG) having a specific performance of 1.2 watts per pound at outer encounter--a conservative projection of present technology to new designs compatible with the long-life requirements.

The combined power capability of the generators at beginning of life will be in excess of 500 watts. Power output of the generators will be approximately 416 watts at the conclusion of twelve (12) years of operation. The power system design shall be such that no supplemental sources of power, such as batteries, shall be required. However, this restriction on the use of energy storage may be lifted if the need for energy storage and its effect on the PCE design can be significantly demonstrated during this study effort.

The TOPS Power Conditioning Equipment design shall have the following characteristics and requirements:

a) PCE design shall provide for operation with an input of 30 vdc nominal.

b) Shunt regulation shall be used to regulate the primary system voltage and maintain constant loading of the RTG(s).

c) Provisions shall be made in the PCE design to insure against open-circuiting of RTG(s).

d) Ripple current on the RTG(s) shall be minimized and under no circumstances shall it exceed 0.75 amperes peak to peak.

e) Switching transients on the RTG source shall be minimized.

f) The Power Source and Logic (PS&L) Assembly design shall provide for operation of the PCE from three (3) or more RTG power sources. PS&L assembly design shall provide for the connection of each RTG to the primary system bus.

g) A Power Distribution Assembly shall be provided for the switching of power to the various spacecraft subsystems by toggle command. Fail-safe circuitry shall be used to guarantee the switching functions.

h) Redundancy and fail-safe circuitry shall be employed in the PCE design to insure successful operation of the power subsystem for a mission life of twelve (12) years. No single piece-part failure shall be detrimental to the operation of the power subsystem.

i) Current limiting shall be included in the PCE design to eliminate fault propagation through the power subsystem.

j) Provisions shall be incorporated in the PCE for the telemetry of terminal voltage, current, pressure and temperatures of each RTG.

k) PCE design shall include sufficient telemetry monitoring points to determine the operational status of the power subsystem.

l) PCE shall be designed to provide a relatively transient-free system.

m) An inverter operating from the primary system bus shall be provided to support the AC power load requirements of the Attitude Control Subsystem.

n) PCE design shall provide regulated power to the radio frequency subsystem for operation of the RF power amplifier (TWT).

o) The specific weight goal for the PCE shall be 40 pounds/kilowatt.

p) The volume goal of the PCE shall be 1.0 cubic foot.

q) PCE shall contain components and circuitry which can perform in a radiation environment which produces the following total integrated doses:

1. Gamma dose 3.0×10^2 Rad
   or 3.0×10^4 erg/gm.

2. Neutron dose 3×10^{11} Nvt.

r) Power subsystem conversion efficiency goal shall be 92% for a nominal load of 400 watts.

s) PCE design shall provide for an operating life-time in excess of 12 years.

t) Reliability goal of the power subsystem shall be 0.95 for a confidence level of 95%.

u) PCE shall be designed to minimize electromagnetic interference.

v) TOPS power subsystem shall be capable of operating in the following environment:

1. Vibration: Random and sine wave vibration along three (3) orthogonal axes. The duration, levels and bandwidths are as follows:

   Random The random vibration shall be at 0.4 g^2/cps between 100 and 1100 Hz. The roll-off shall be at 6 db/octave. Time duration shall be one (1) minute per axis.

   Sine The sine wave vibration test shall be at 0.2" DA from 5 to 30 Hz, and 10g from 30 to 2000 Hz. The sweep rate shall be logarithmic at 1 octave/minute.

2. Shock: Equipment shall be subjected to shock along the same three (3) orthogonal axes as above. The spectrum of the applied shock shall envelope that of an 400g, 0.4 millisecond, ½ sine pulse. The shock shall be applied five (5) times along each axis.

TECHNICAL DISCUSSION

SECTION 3. BASELINE POWER SUBSYSTEM

Summary

The Electrical Power Subsystem presented in this section and the circuit configurations presented in Section 4 are the results of the principal effort during the period covered by this report. The objective was to identify the minimum circuitry required to accomplish the functional requirements and within the constraints of Section 2. This information was the subject of a Preliminary Design Review on 11 June 1969, with action items incorporated or noted for subsequent action.

The Electrical Power Subsystem may be summarized as a configuration of three radioisotope thermoelectric generators, and all the electronics located within the Power Conditioning Equipment. The Power Conditioning Equipment selects the RTG's to be on line; conditions the RTG power to constant voltage by means of active shunt regulation; inverts to ac to satisfy the single phase, two phase, and three phase power requirements of the attitude control subsystem; inverts to ac to satisfy an ac distribution system, if required; and provides switching to control the flow of power to user loads. The baseline power subsystem block diagram is shown in Figure 3-1, and a summary specification in Table 3-1.

Requirements and Constraints

The baseline subsystem meets the following limitations imposed in Section 2:

a) Nominal input of 30 vdc from three or more RTG's.

b) Shunt regulation to maintain essentially constant loading of the RTG's.

c) A Power Source and Logic Assembly to connect each RTG into the system.

d) A Power Distribution Assembly to switch power to users.

e) An inverter to support the ac load requirements of the Attitude Control Subsystem.

f) Provide regulated power to the radio frequency subsystem.

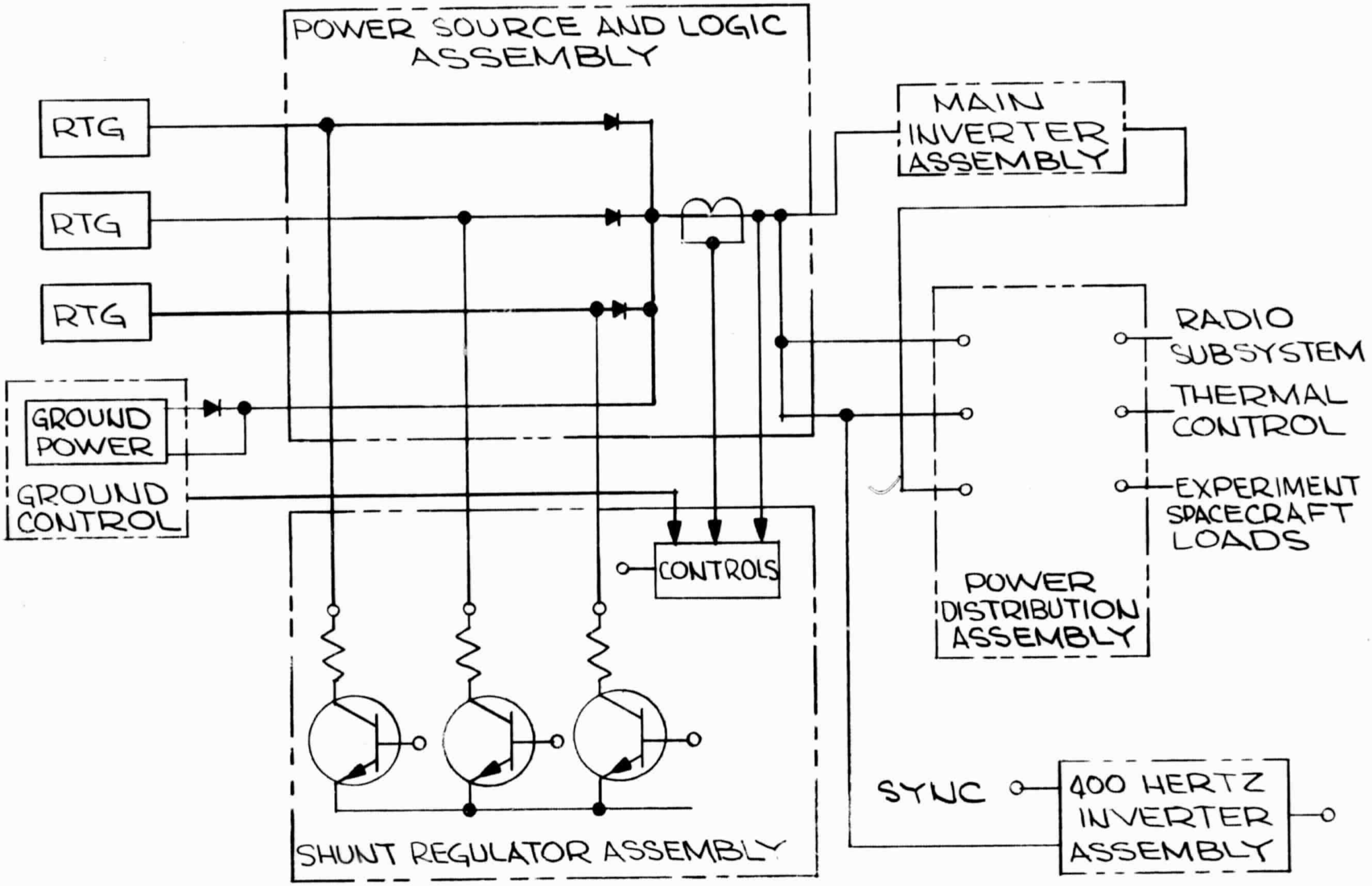

FIGURE 3-1. BASELINE POWER SUBSYSTEM

TABLE 3-1. ELECTRICAL POWER SUBSYSTEM PRELIMINARY SPECIFICATION

SUBSYSTEM FUNCTION

- Generate, control, condition and distribute electrical power for spacecraft loads.

PERFORMANCE CHARACTERISTICS

Beginning of Life Power	520 watts
End of Life Power	416 watts
Main bus voltage	30.0 VDC ± 1%
Main bus impedance	0 to 10 kHz 0.10 OHM
Power regulation	Active shunt regulator

RELIABILITY

Twelve year life	Greater than 0.95

PHYSICAL CHARACTERISTICS

Total subsystem weight	14.4 pounds
Total subsystem volume	1 cubic foot

LOAD CHARACTERISTICS

Turn-on transients	125% of nominal 200% during off-peak power

RTG Diode Isolation

A diode is provided between the RTG and the main bus to protect the bus from an internal RTG short circuit, or a fault in the cabling between the diode and vehicle ground. This diode allows each RTG to operate at constant voltage with its own shunt regulator, or to be short circuited if it proves desirable to increase RTG life probability by lowering the operating temperature through Peltier cooling. The discussion of the RTG in Section 5 indicates that electrical isolation is provided between the RTG cold frame and its vehicle mechanical mounting, and also between the cold frame and the thermocouples. Two failures in series would be required to provide a short circuit to ground with this configuration, and the assumption is that no single failure could cause a short circuit to ground at the RTG.

RTG Transient Behavior

Figure 3-2A shows a normal RTG volt-ampere characteristic with a steady-state short circuit capability of approximately eleven amperes. In Figure 3-2B, it can be seen that the Peltier cooling of the short circuit current lowers the hot junction temperature to approximately 920°C. If the RTG were open-circuited while at this temperature condition, the available voltage would be in the order of 45 volts, as shown on Figure 3-2C, and this new voltage would cause a volt-ampere characteristic that would intersect the constant voltage operating point at three amperes, and drift to the normal, steady-state operating current of six amperes as the hot junction temperature returned to steady-state conditions.

This indicates that if an RTG is operated at short circuit current, the transient available power at normal voltage is considerably less than steady-state power, and thermal equilibrium must be established at the normal operating point before full power is available. This characteristic makes it undesirable to operate the RTG's in the shorted mode, since available power is limited under sudden or emergency conditions.

RTG Peltier Cooling

The RTG imposes the requirement on the Power Conditioning Equipment that it not operate at open circuit for extended periods. The subsystem is configured to operate the RTG at constant voltage whenever it is electrically connected into the subsystem. This constant voltage operation essentially tracks the available peak power point, and optimizes Peltier cooling and available power. Provision should be made during transportation and handling of the fueled RTG to provide a shorting plug to protect the RTG. This shorting plug is removed after the RTG is mounted to the vehicle, and immediately prior to mating with the flight harness which connects the RTG into the power subsystem and the active shunt regulators. This arrangement will provide a comfortable environment for the RTG throughout its spacecraft life.

Subsystem Configuration

With these considerations, the isolation diodes may be removed, and the nominal 30 VDC can be delivered to users without additional in-line voltage drops. Additionally, the shunt regulator assembly becomes a single unit across the total bus as shown in Figure 3-3. This arrangement is the basis for the circuit discussions that follow in Section 4.

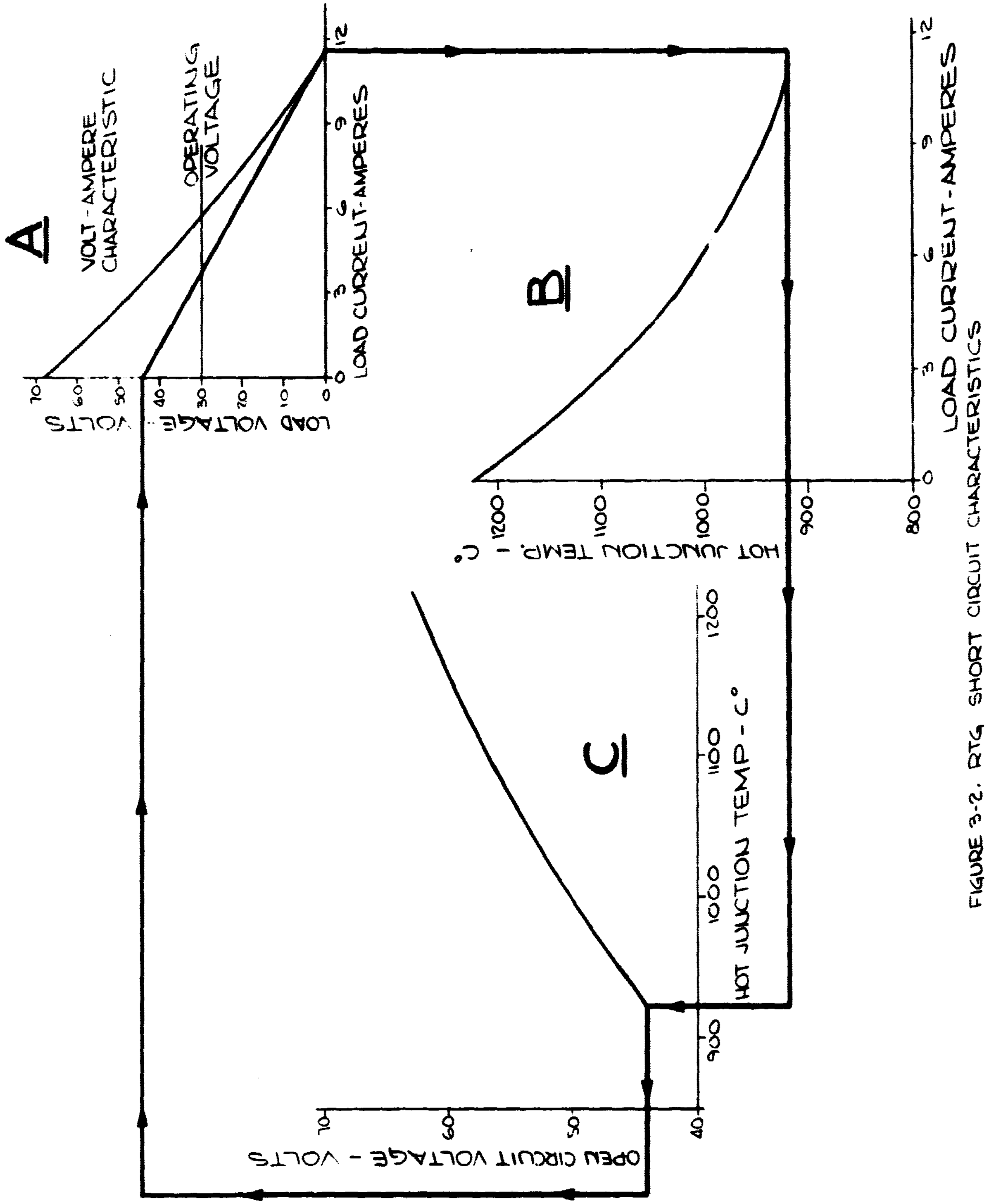

FIGURE 3-2. RTG SHORT CIRCUIT CHARACTERISTICS

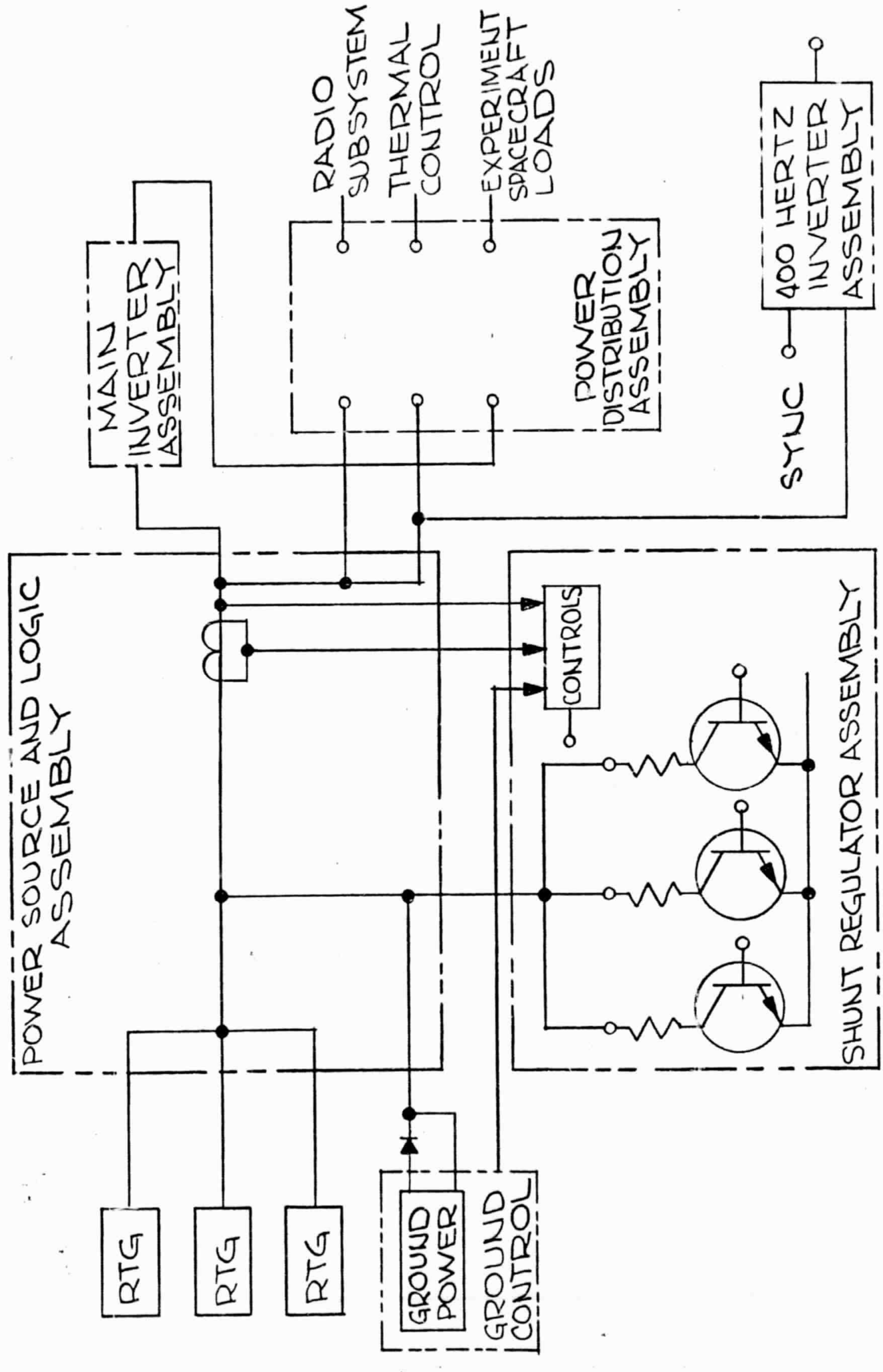

FIGURE 3-3. MODIFIED POWER SUBSYSTEM CONFIGURATION

TECHNICAL DISCUSSION

SECTION 4. COMPONENT DESCRIPTION

Main Inverter Assembly

With a primary energy source that is direct current, minimum complexity exists in the electric power subsystem when the loads can use the available energy without power conditioning. If the bulk of the energy can be used directly by most loads, power conditioning can be supplied at those discrete loads which require electrical source characteristics different from those available at the source. Where voltage levels do not correspond, some form of power processing must be utilized to achieve the desired new voltage level required by the load. All such processing is necessarily complex, and usually requires several orders of magnitude more electronic piece parts than voltage transformation from an ac source with a single transformer at the load.

The simplest voltage conversion is achieved with a square loop saturable transformer and a pair of switching transistors. The transformer furnishes base drive to the transistor that is ON, and reverse bias to the OFF transistor. The square wave of voltage from the transformer remains at constant amplitude during the conduction period. When the transformer starts to saturate, the base drive is inadequate to supply the increasing magnetizing current demand, and the transistor starts to pull out of saturation. This reduces the voltage that is available to the transformer, this in turn reduces the voltage available for base drive, and the transistor is pulled further out of saturation, cascading the process. In this fashion, the ON transistor goes from saturated to full OFF in a period of a few microseconds. The magnetizing current and the after saturation inductance of the winding reverses the voltages at the transformer windings, and effectively reverse biases the transistor that was just ON, and also supplies a transient base drive signal to the transistor that was OFF, driving it into saturation. This supplies voltage to the transformer of an opposite polarity, and the transistor is maintained in the ON condition by the base drive winding, and the process repeats until the transformer has been driven through its hysteresis loop.

Usual designs supply a forced base drive of about ten to insure that the transistor is fully saturated to minimize the conduction losses, and to guarantee conduction during the full half cycle for the nonlinear load. The transformer allows any level of voltage to be obtained on the secondary, based on a constant volts per turn for all windings. The secondary square wave of voltage is supplied to the load, but is electrically isolated from the source by the transformer.

The principal disadvantage of this circuit is that the high base drive and the rapid increase of magnetizing current causes the collector current to exceed the normal average current by an order of magnitude, imposing a pulse of high dissipation in the transistor as it goes from the ON condition to the OFF condition. The basic Royer circuit described above can be converted to a Jensen circuit by addition of a second, smaller saturable transformer with a volt-second capability less than the power transformer. This transformer supplies only the timing and the base drive, and greatly reduces the peak power dissipation in the switching transistors. In this arrangement, the magentizing current is limited by a resistor, and the collector current is based on the load demand. The power transformer does not saturate.

The preliminary specification in the original baseline subsystem is shown in Table 4-1, the block diagram on Figure 4-1, and the schematic on Figure 4-2.

The block diagram of Figure 4-1 shows the basic oscillator free running at 4.5 kilohertz, with provision for a 4.8 kilohertz driving signal from the central clock. Figure 4.2 shows the circuit implementation of the clocking signal, and indicates a unity voltage transfer of 30 volts DC input to 30 volts AC output to simplify design comparisons at this stage of the subsystem design.

TABLE 4-1. MAIN INVERTER ASSEMBLY PRELIMINARY SPECIFICATION

FUNCTIONS

- Converts the main bus voltage to 30.0 Vrms ac at 4.8 kHz.
- Provides reference frequency source.

PERFORMANCE CHARACTERISTICS

Input voltage	30.0 Vdc ± 1%
Output	
Voltage	30.0 Vrms
Regulation	+2, -3%
Load	90 watts minimum 200 watts maximum
Spikes	5 V max, 1 μ sec duration
Rise/Fall time	1 ± 0.5 μ sec
Power factor	0.95 lag min
Efficiency	90 percent at 200 watts output
Frequency	
Sync	4800 Hz ± .01%
Free run	4500 Hz ± 5%

REDUNDANCY

Frequency source and low level drive - Fail-safe

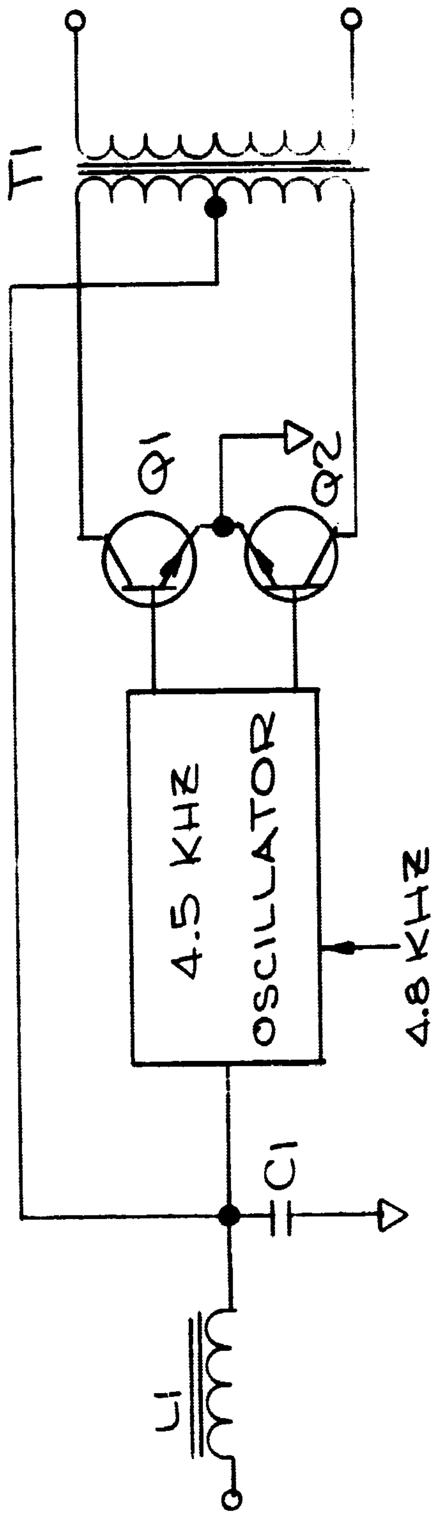

FIGURE 4-1. MAIN INVERTER BLOCK DIAGRAM

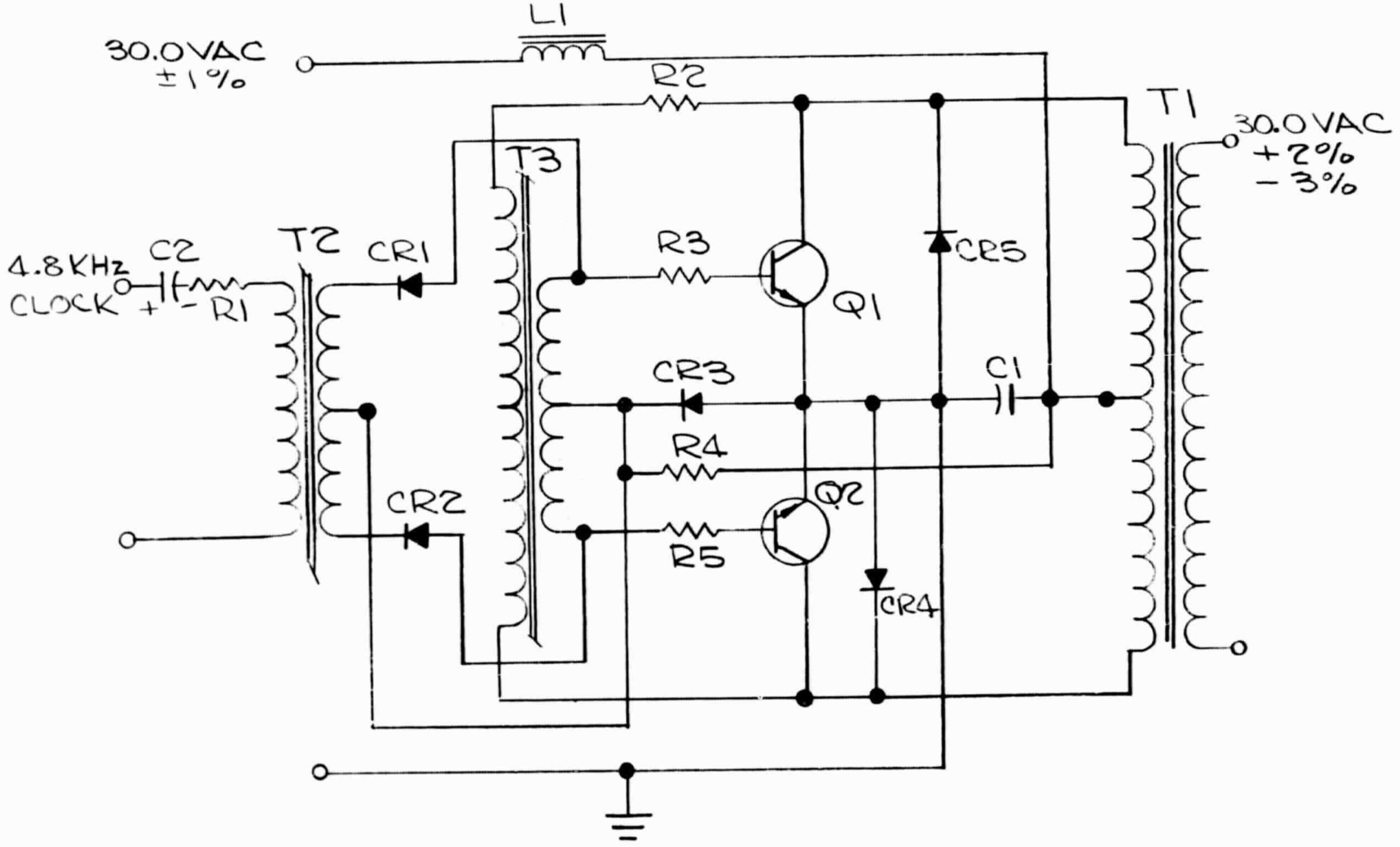

FIGURE 4-2 MAIN INVERTER SCHEMATIC

Shunt Regulator Assembly

A shunt regulator is the simplest method of maintaining an essentially constant voltage from a varying voltage source, since the regulating function can be accomplished with two piece parts as a minimum. In its rudimentary form, a shunt regulator is merely a constant voltage current sink placed in shunt with the load that is to be maintained at constant voltage. This shunt combination is put in series with a current limiting resistor. The shunt regulating element then draws that amount of extra current from the source to cause the excess voltage to be dropped across the current limiting resistor, and consequently, maintains the load at constant voltage.

For the device to be effective, a finite value of resistance must be provided to limit the current, or the bus must be powered by a high impedance source. The load does not enjoy the available voltage level, but must be satisfied with the minimum source voltage minus the voltage drop caused by the load current through the current limiting resistance.

Since the thermoelectric element depends on Peltier cooling for thermal balance, it is essential that the electrical power drawn from the thermoelectric converter be maximized, or at least maintained essentially constant. If the load requirement should decrease because of a change in real output power required, the shunt regulator will draw this difference of current from the thermoelectric converter, and its temperature will remain essentially constant.

A shunt regulator is most advantageous for this application, since the end of life losses of the regulator are essentially zero. The shunt regulator draws that amount of extra current from the source to cause the excess voltage to be dropped across the internal resistance of the source, consequently maintaining the output load at constant voltage. For a fixed characteristic source, the shunt regulator furnishes a constant current demand and satisfies the requirements of the thermoelectric junction and the variable load. A transistorized shunt regulator is the best choice of existing circuitry to optimize the environment of the radioisotope thermoelectric generator for reliable life.

For the actual conditions of decreased heat and increased internal resistance of the radioisotope thermoelectric generator, the shunt regulator will cause essentially a fixed ratio of actual power to available power to be drawn from the thermoelectric converter, maintaining an optimum thermal balance for minimum complexity when the load demand is constant. It will correct perfectly for increased source resistance, but will not correct for changes in voltage due to loss of series thermoelectric elements, or for lower temperature difference.

The shunt regulator does not draw excess power at beginning of life to provide maximum Peltier cooling. To accomplish this, it is necessary to operate beyond the maximum power point at a higher ampere demand than that required by the load, and would result also in the lower voltage on the bus.

The shunt regulator provides the necessary constant load, and redundancy prevents open-circuit operation. The requirement for the PCE to operate at minimum load (launch mode) at beginning of mission RTG power sizes the regulator for power dissipation. Figure 4-3 shows a minimum launch mode load of 273 watts. The maximum load at encounter of 416 watts sizes the RTG end of mission power. With a nominal twenty per cent degradation of power over mission life, the maximum RTG capability at launch must be 520 watts, and the shunt regulator must dissipate the 247 watt difference. These requirements are summarized in the preliminary specification of Table 4-2.

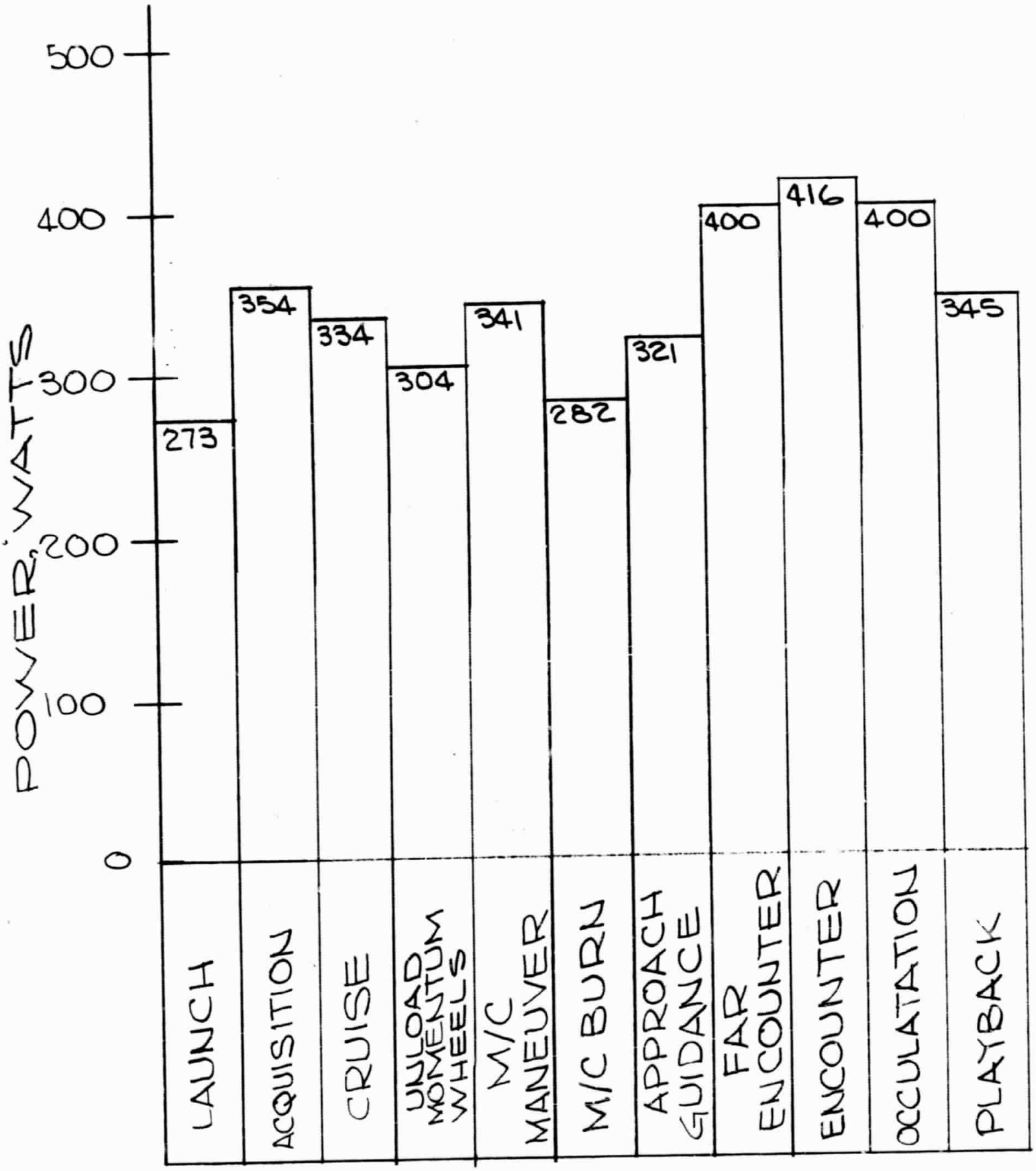

FIGURE 4-3: RTG POWER REQUIREMENTS

29-JUNE-1969

TABLE 4-2. SHUNT REGULATOR ASSEMBLY PRELIMINARY SPECIFICATION

FUNCTIONS

- Draws excess current from the RTG to maintain constant voltage.

PERFORMANCE

Open circuit voltage	67 VDC maximum
Total shunt current	8.3 ADC maximum
Output voltage	30.0 VDC
Regulation	± 1 percent against initial adjustment, input line variation, load range, temperature coefficient, and long term drift.
Efficiency	98% at end of life, 416 watts delivered.
Transient response	10 kilohertz
Dynamic impedance	0.10 ohms

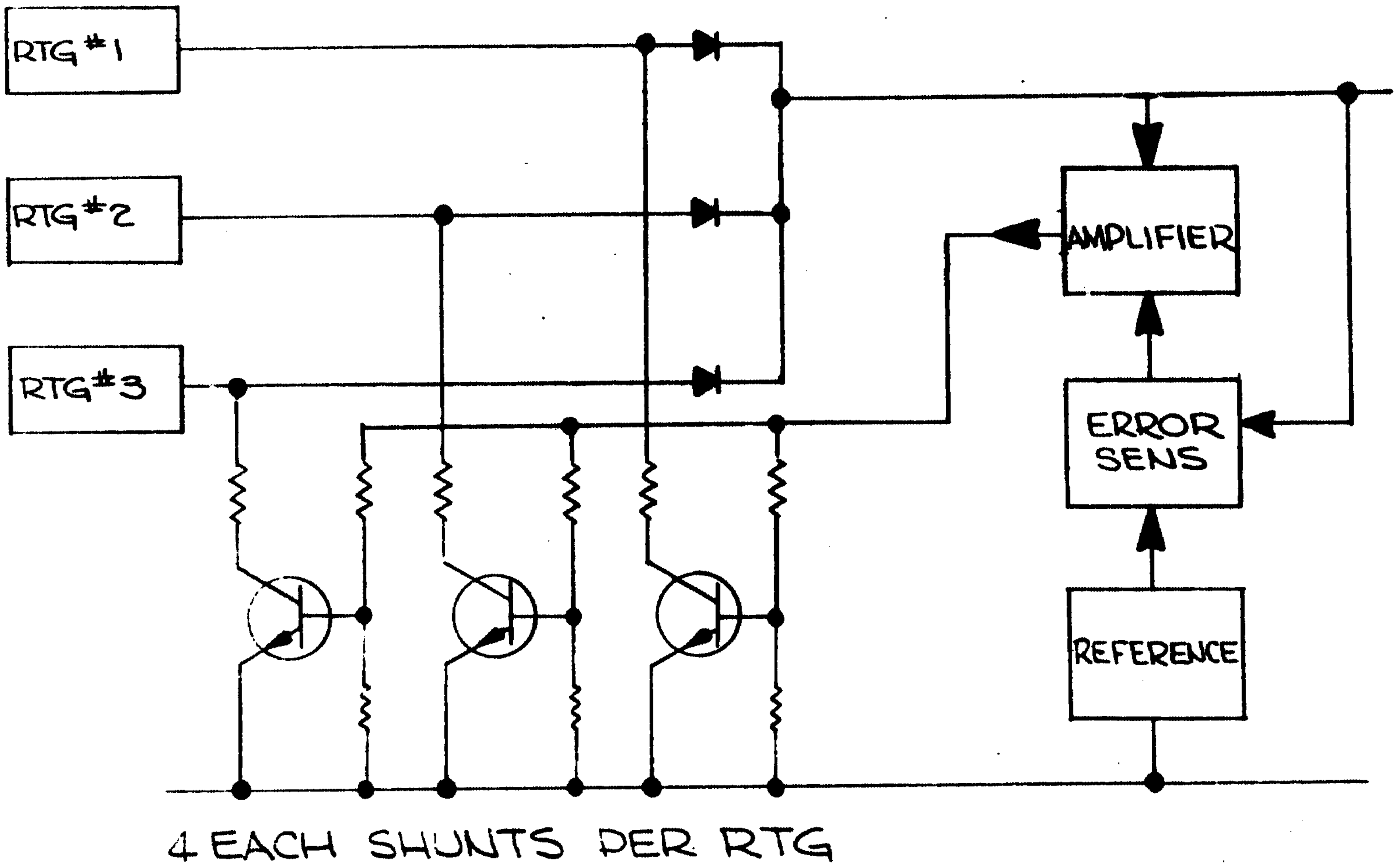

FIGURE 4-4. SHUNT REGULATOR BLOCK DIAGRAM

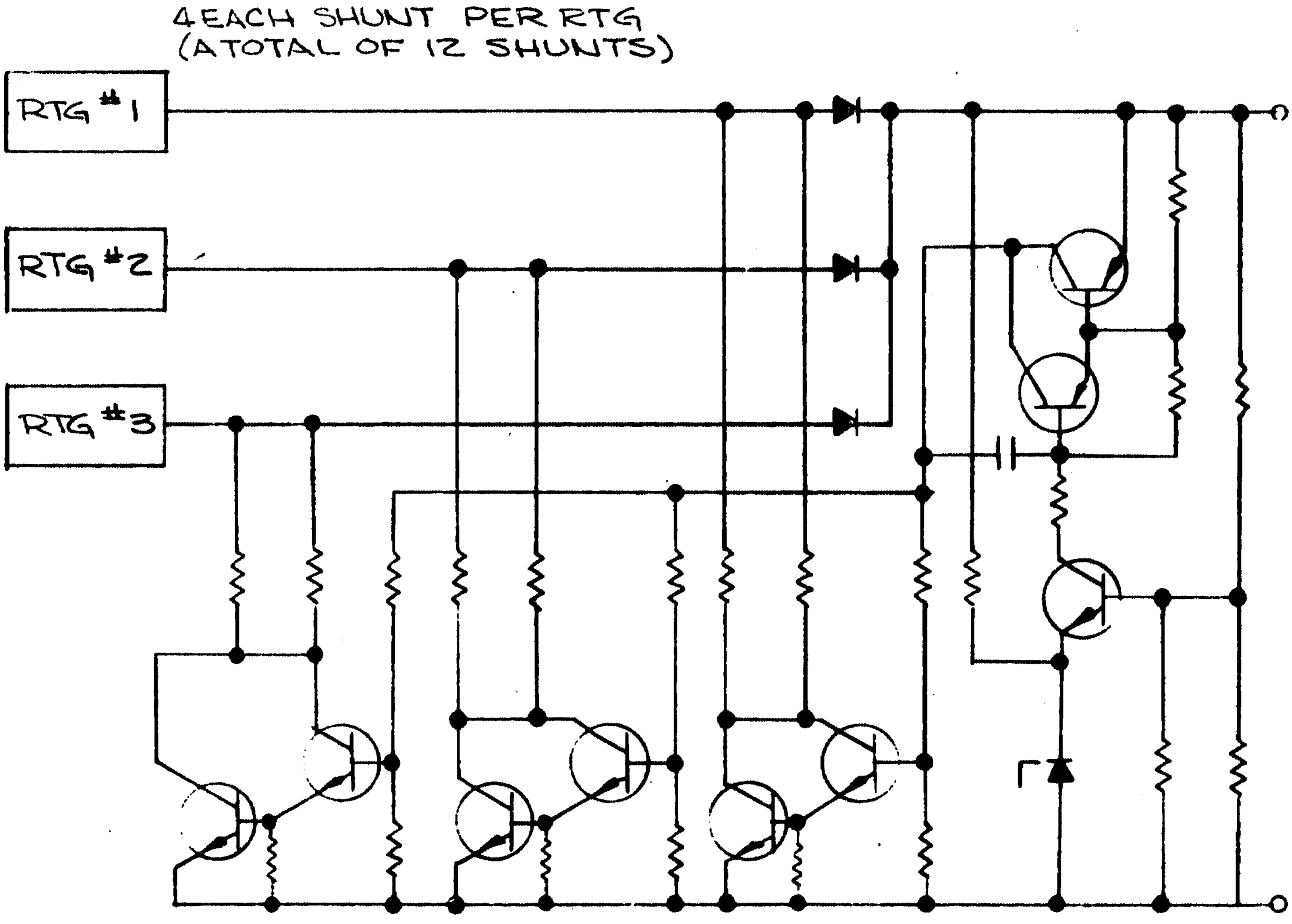

FIGURE 4-5. SIMPLIFIED SHUNT REGULATOR AND CONTROL SCHEMATIC

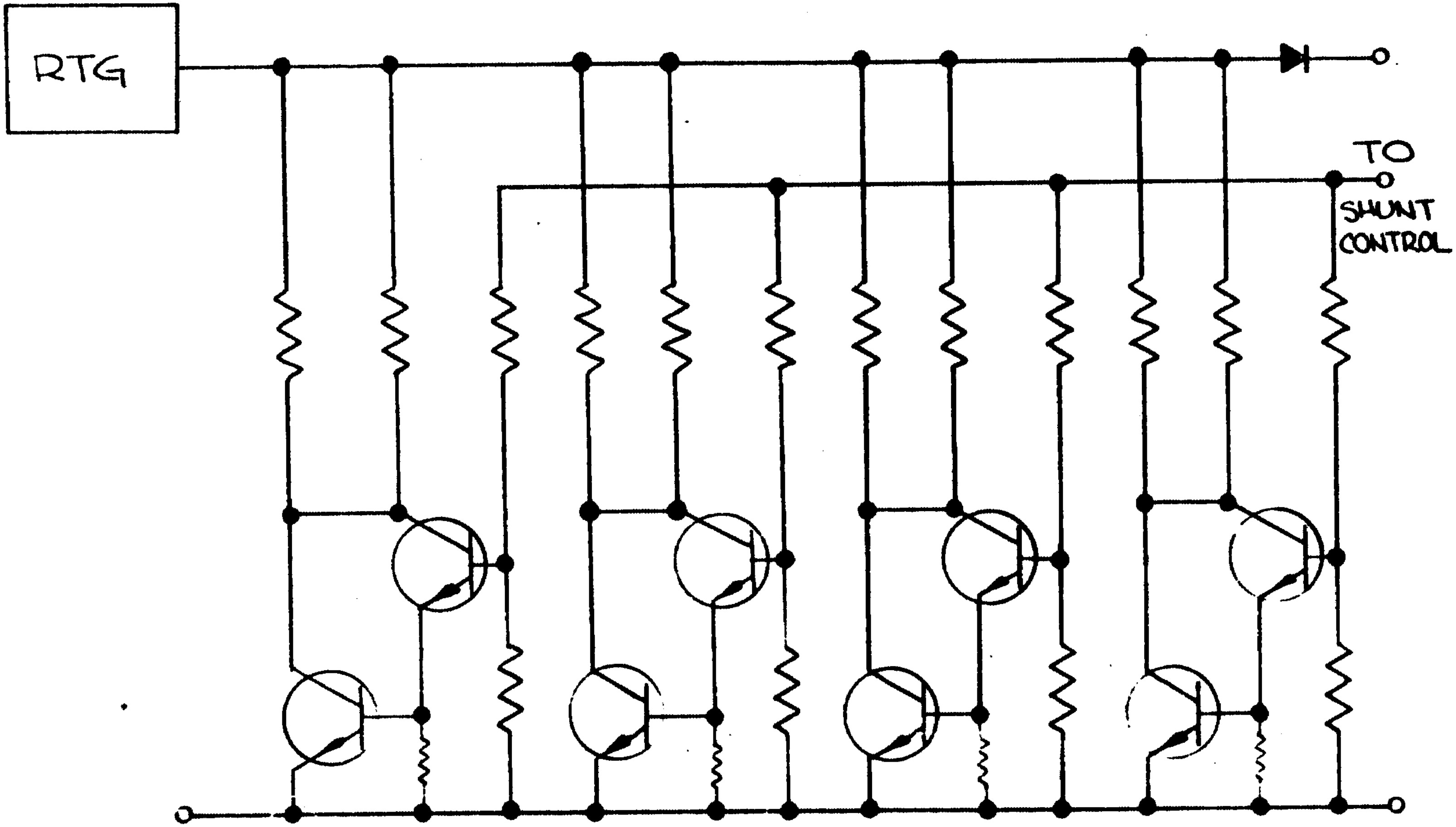

FIGURE 4-6. SHUNT REGULATOR SCHEMATIC FOR A SINGLE RTG

Power Source and Logic Assembly

This assembly selects the power source from the three RTG's or ground power, provides signal conditioning for telemetry of currents, voltages, and RTG temperature and pressure, and disconnects non-critical loads at system undervoltage.

No effort was expended to further define requirements or implement with circuit designs during the period covered by this report.

PRELIMINARY SPECIFICATION, POWER SOURCE AND LOGIC ASSEMBLY

FUNCTIONS

- Provides isolation for radioisotope thermoelectric generators
- Provides RTG shorting
- Provides control for external power source or internal RTG
- Provides current and voltage telemetry, and RTG pressure

PERFORMANCE CHARACTERISTICS

Maximum power dissipation planetary encounter	10.0 W in RTG isolation diodes

RELIABILITY

For 12 years

REDUNDANCY

PHYSICAL CHARACTERISTICS

Size

Weight

Power Distribution Assembly

Control of Electrical Power

Power control in spacecraft is accomplished most often by a command matrix which provides a positive voltage and a ground return simultaneously. The device that actually switches is an electromagnetic relay to provide complete electrical isolation between the command signal and the controlled power. Electromagnetic power switching is a life limited process, since the contact material is vaporized and eroded with each switching cycle, and the material loss is directly related to the amount of power switched. For this reason, simeconductors are sometimes used to provide static switching, and have a theoretically unlimited life.

Relays versus Static Switching

The static switch is considered as a system, and the composite reliability figures of the individual components are used when computing theoretical reliability, based on the actual stresses which the use will impose upon each device. Selection between a relay and a static switch may depend on the application. For example, consider a possible requirement to switch the single phase, two phase, and three phase AC power lines from one set of inverters to a redundant set. A six-pole relay has a reliability based on a single component, but a static switch circuit to perform this six-pole function would be extremely complex, and its total reliability considerably less than the single relay.

The relay is a general purpose device, and can handle low level to rated current, either ac or dc, without a component change. A relay can make and carry current two to four times rated with only a small increase in transfer time, but with accelerated aging. The power handling capacity is considerably more versatile than a static switch, which is generally custom designed for the expected loads.

Breaking inductive loads imposes significant stresses on both the relay and the solid state switch, and if not controlled will cause destruction of the static switch, but result in only a small increase in transfer time for the relay. There is no "bounce" characteristic associated with a solid state switch. The power is turned on or off cleanly. Relays exhibit bounce on the order of several milliseconds and of a duration dependent on the magnitude of current carried, the type of relay, its adjustment, and the application. Higher currents will sustain an arc across a pair of physically separated contacts much longer than a lower current and allow conduction to occur where bounce would normally appear at lower currents.

Contact resistance, or forward voltage drop, is important from the standpoint of loss in circuit voltage that can be tolerated, because current passing through a resistance causes damaging heat. The contact resistance characteristic of a relay is superior to a solid-state device for most uses, particularly when low-level currents are considered.

Inherently, the contact resistance of a relay can be made very low. Solid-state devices have a forward voltage loss of up to one volt, and this value may exceed the open circuit voltage available for most low-level applications. Relay applications are often practical in the microamp and microvolt region. Both relays and solid-state devices exhibit better resistance characteristics at higher temperature.

A solid-state switch retains its initial operational characteristics within relatively narrow limits as long as it is used within its ratings. The relay exhibits changes with life in its various parameters, including pull-in, drop-out, and contact resistance. This is due to the normal erosion and wear on other component parts of the relay. These characteristics must be compensated for in any design using a relay.

A comparison of the relative merits of the two switches is given in Table 4-3 and based on these parameters relay switching has been selected for the baseline design. Preliminary specification for the Power Distribution Assembly is given in Table 4-4. Since no command format has been defined, circuit designs are incomplete, but the loads to be switched are tabulated with the command source requirements and power type in Table 4-5.

TABLE 4-3. COMPARISON OF SWITCHING CHARACTERISTICS

	Electro-mechanical Relay	Solid State Switch
Reliability	Good	Good
Size	Small	Large
Versatility	Good	Poor
Circuit Capability		
Resistive load	Good	Good
Inductive load	Good	Poor
Overload	Good	Poor
Bounce	Poor	Good
Resistance	Low	High
Low Level Operation	Good	Poor
Life	Poor	Excellent
Signal Power Reqiured	Large	Small
Speed	Poor	Excellent
Susceptibility to Transients	Good	Poor
Electrical Isolation	Excellent	Poor
Temperature	Fair	Poor
Vibration and Shock	Fair	Excellent
Nuclear Radiation	Good	Poor
Life	Poor	Excellent

TABLE 4-4. POWER DISTRIBUTION ASSEMBLY PRELIMINARY SPECIFICATION

FUNCTIONS

- Accepts external commands and controls and distributes ac and dc power to experiments, heaters, and spacecraft power users.

PERFORMANCE CHARACTERISTICS

Input voltage	30.0 vdc 30.0 vac, 4800 Hertz 26.0 vac, single phase 26.0 vac, two phase 26.0 vac, three phase
Command signal	28 vdc pulse 30 millisecond duration
Redundancy	Quad redundancy

TABLE 4-5. POWER DISTRIBUTION ASSEMBLY REQUIREMENTS

LOAD	AC POWER	DC POWER	PRIMARY COMMAND	BACK-UP COMMAND	CONTINUOUS
DATA STORAGE	X				X
COMMAND	X				X
COMPUTER					X
TELEMETRY					X
APPROACH GUIDANCE			X	X	
RADIO RECEIVERS AND EXCITERS					X
RADIO TRACKING RECEIVERS			X	X	
RADIO S BAND TRANSMITTER 1		X	X		
RADIO S BAND TRANSMITTER 2		X		X	
RADIO X BAND TRANSMITTER 1		X	X		
RADIO X BAND TRANSMITTER 2		X		X	
PYRO CONTROL		X	X	X	
SINGLE PHASE, 400 HERTZ		X	X		
TWO PHASE, 400 HERTZ		X	X	X	
THREE PHASE, 400 HERTZ		X	X	X	
SUN SENSORS			X	X	
CANOPUS SENSOR	X		X	X	
ACCELEROMETER	X		X	X	
GYRO	X		X	X	
GAS VALVES		X	X	X	
GIMBAL ACTUATORS		X	X	X	
SCAN PLATFORM		X	X	X	
AUTO-PILOT			X	X	
ATTITUDE CONTROL ELECTRONICS			X	X	
THERMAL CONTROL		X	X	X	
PROPULSION		X			X
ATTITUDE CONTROL JETS		X	X	X	
SCIENCE BOOM		X	X	X	
CONTINGENCY		X	X	X	
DC MAGNETOMETER	X		X	X	
AC MAGNETOMETER			X	X	
TRAPPED RADIATION DETECTOR			X	X	
MICROMETER DETECTOR			X	X	
SOLAR PLASMA PROBE			X	X	
COSMIC RAY DETECTOR			X	X	
ULTRAVIOLET PHOTOMETER			X	X	
INFRARED RADIOMETER			X	X	
TELEVISION			X	X	
SCIENCE SCAN PLATFORM ACTUATOR		X	X	X	
SCIENCE SCAN PLATFORM ELECTRONICS			X	X	

SECTION 5. RADIOISOTOPE THERMOELECTRIC GENERATOR

Radioisotope Heat Sources

A by-product of nuclear fusion and fission is the waste material of active isotopes. In the decay of these isotopes to a stable form, energy is released as neutrons, alpha particles, and beta and gamma rays. As the energetic decay particles are slowed down, their energy is converted into heat which in turn can be converted into electrical power through the use of thermoelectric or thermionic direct energy conversion devices. Any artificially produced isotopic heat sources such as plutonium, curium and artificial or natural polonium can be used as energy sources.

Thermoelectric Converters

The energy conversion has been accomplished in flight systems to date by thermoelectric couples. The couples are mounted in series between the isotope heat source and a space radiator, forming the hot and cold junctions. Heat transferred through the thermoelectric junctions produces electrical power, and the waste heat is rejected to space. Electrical insulation isolates the thermocouples from the isotope container and the radiator.

Most thermoelectric materials are brittle, and encapsulation is usually necessary to enable the unit to withstand launch and powered flight vibrations, or to prevent sublimation at elevated temperatures.

Advantages and Disadvantages

Nuclear energy was selected over solar for the TOPS mission because of the wide variation in available solar power for outer planet encounter. The advantages of the radioisotope thermoelectric generator are that it is a completely static system, conducive to high reliability; it requires no special orientation of the vehicle or provisions for artificial gravity; it is of reasonable weight; and allows for high density packaging. It requires no pressure regulators but may use an active coolant loop with a permanent magnet electro-magnetic pump or a heat pipe to transfer heat from the cold junction to space.

Typical RTG Data

The performance characteristics shown in Figure 5-1 and Figure 5-3 were derived from Performance Characteristics of a Silicon-Germanium RTG in Long-Term Operation dated 29 April 1969, a Jet Propulsion Laboratory funded study. This information is useful and necessary to determine operating stress levels during the mission as the RTG degrades, and to show the effects of variations in power loading on the RTG performance. It should be noted that power levels and load currents are relative, and have been shown at the values required to meet the power demand of the spacecraft operational modes.

Performance Characteristics

a. Steady-state. Typically an RTG volt-ampere characteristic is represented as a straight line from some no-load value of voltage to a short-circuit value of current as shown in Figure 5-1. In fact, the steady-state characteristic usually has slight curvature; and, for a given RTG design and for long-term operation, ranges from some maximum characteristic at beginning of mission (BOM) to a minimum characteristic at end of mission (EOM). Among the factors which contribute to the spread are the following:

1. Manufacturing tolerances for the RTG, i.e., variations in the dimensions of the thermoelectric elements, variations in resistances of the thermoelectric bonds and interconnections, etc.
2. Variations in fuel loading.
3. Variations in ambient thermal conditions.
4. Aging - fuel decay, changes in element characteristics, etc.

The mission life spread in characteristics is typified by the curves, where the maximum curves represent an upper-limit RTG, BOM, max fuel loading, and the minimum curves represent a lower-limit RTG, EOM, minimum fuel loading, PCE design must take such a range of characteristics into account for proper integration, especially the effect of aging. Furthermore, PCE design, which governs the operating point of the RTG, should permit the RTG to operate at a voltage and current corresponding to peak RTG efficiency at EOM, and account for variations in the real load. Figure 5-1 also shows the intersection of a constant voltage operating mode with the volt-ampere characteristics, and the locus of constant voltage operation on the power characteristics.

b. Transient. If after achieving thermal equilibrium at a particular operating point, an RTG is suddenly open circuited or short circuited, the instantaneous values of open-circuit voltage or short-circuit current will differ from the steady-state values because, for the first instant, the junction temperatures of the thermocouples remain constant and do not reflect the change in cooling resulting from the change in current. Instantaneously on open circuit, the voltage is lower by about 20% than its final value and on short circuit, the current is higher by about 20% than final value. This effect is shown graphically on Figure 5-2. This factor is important in designing or selecting open-circuit and short-circuit protective devices.

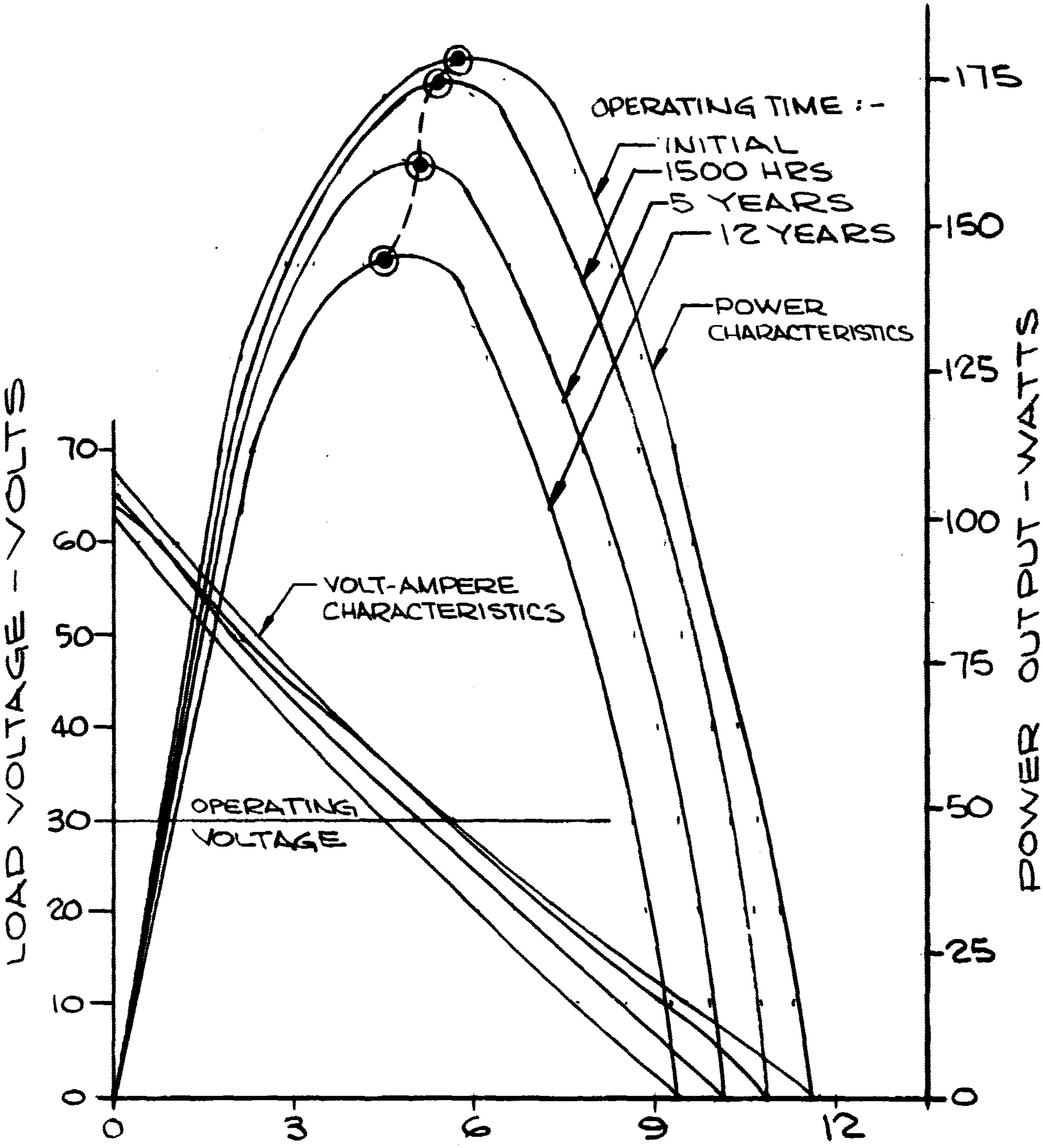

FIGURE 5-1. RTG OPERATING CHARACTERISTICS

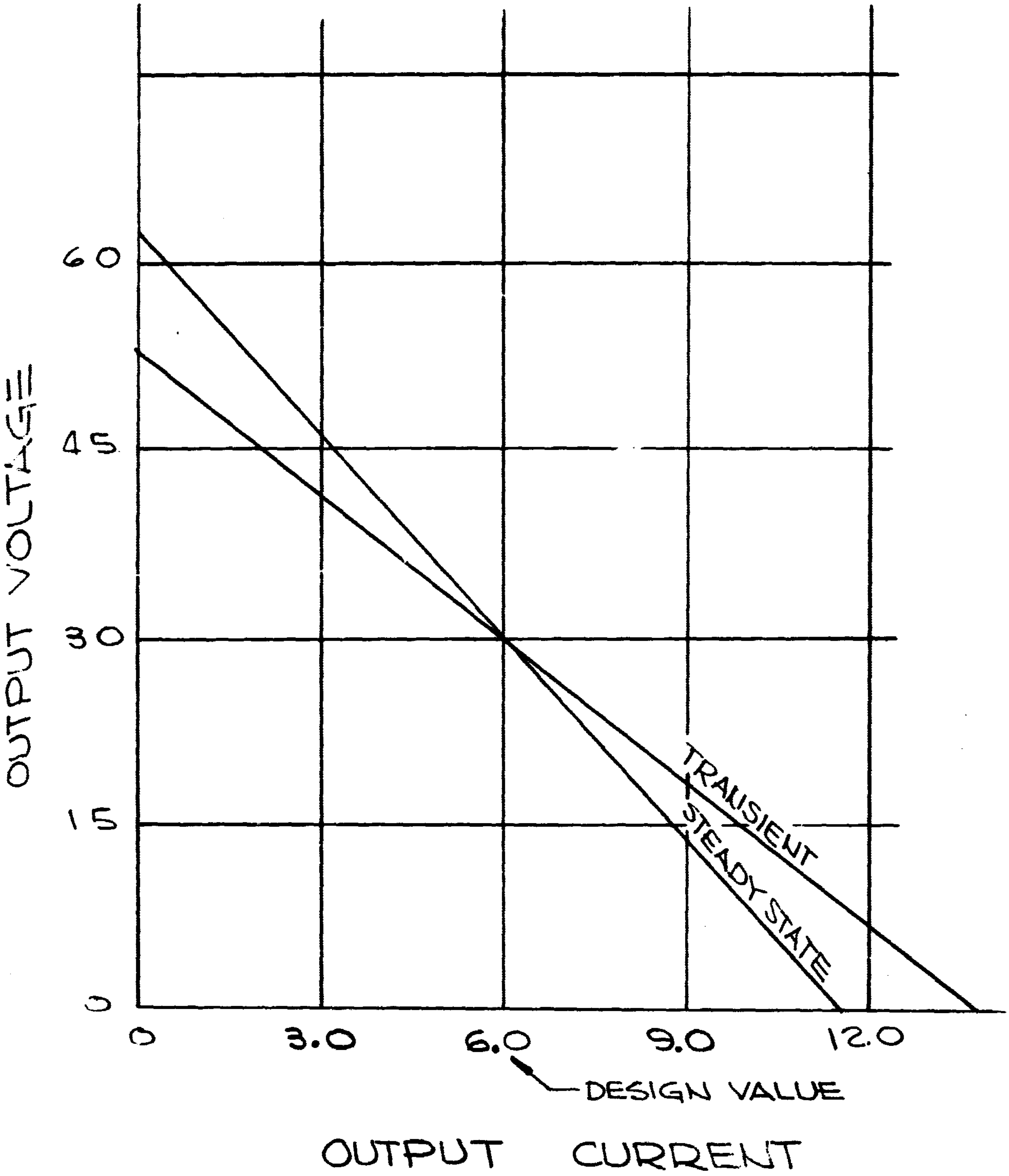

FIGURE 5-2. RTG TRANSIENT BEHAVIOR

Operating Characteristics

Two types of thermoelectric materials are commonly used in thermoelectric generators---lead telluride and silicon-germanium. The latter material is used in RTG's designed for hot-junction temperatures in the order of 1000°C, the former for temperatures of 1000°F. Both suffer severe degradation if operated at hot junction temperatures much above their design values. For RTG's using lead telluride, for example, it is estimated that a sustained 50°F increase in hot junction temperature above its design value at the levels of 1000-1100°F may increase the rate of degradation by a factor of four, and a decrease in temperature will correspondingly decrease the rate of degradation.

The interrelation between current and hot junction temperature represented by the Peltier effect places the PCE in a key role in the thermoelectric generator power system because generator current is under the control of the PCE. Figure 5-3 shows the variation in hot junction temperature for constant voltage operation over the proposed twelve year life.

The severe effect of excessive hot junction temperature on generator aging requires that the PCE prevent RTG operating current from dropping below the design value and especially that it not allow the generator to operate open-circuited for long periods of time. Thus, the PCE must provide stable voltage control over the duration of the mission and provide open-circuit protection. For this reason, tolerances, long-term drift, and radiation damage characteristics in reference voltage devices used in the voltage regulator require special attention.

Figure 5-3 also shows that drawing current in excess of peak power lowers the hot junction temperature, and results in less power being available at any operating point until the generator has been allowed to stabilize thermally at the new operating point, typically fifteen minutes.

Grounding

In thermoelectric generators, commonly the electrical thermocouple circuits are isolated from the RTG frame so that a single inadvertent internal short to ground does not make the entire system inoperative. As a result, if one side of the external electrical circuit is grounded solidly to vehicle structure, the RTG frame should be isolated electrically from the satellite structure and the frame should be grounded through a resistor. The resistor will bleed off any electrostatic charges that may accumulate on the frame, but will prevent loss of electrical output from the RTG in the event of an internal short-circuit between a thermoelectric element and frame. The design of fault detection circuits requires careful consideration of such grounding practices and resulting probable fault currents and voltages.

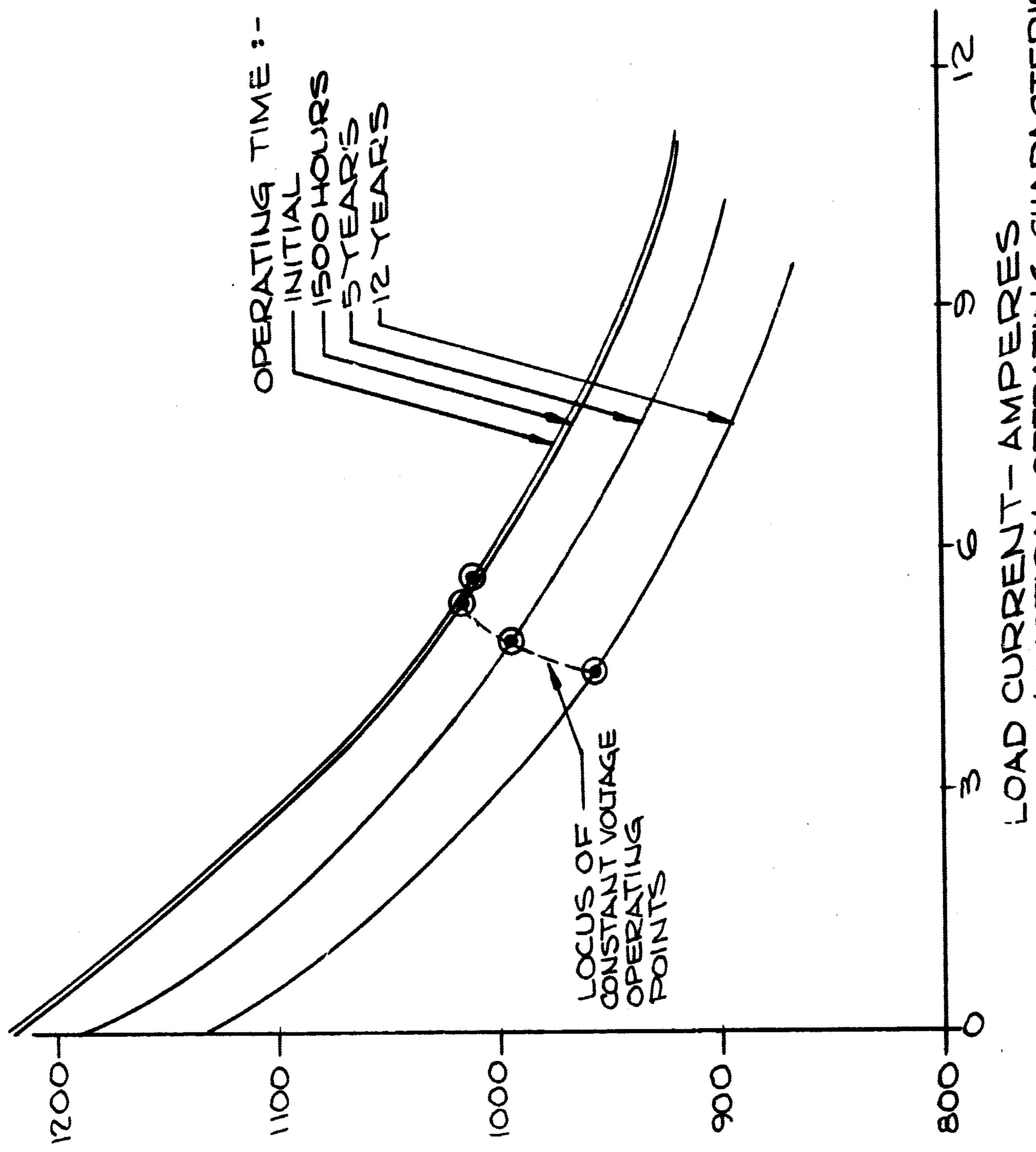

FIGURE 5-3. HOT JUNCTION OPERATING CHARACTERISTICS

Short Circuit Operation

As stated previously, the degradation rate can be reduced significantly by short circuit, since diffusion of the thermoelements will be slower under Peltier cooling. However, the available power from a previously short-circuited RTG would be limited to about 50% of normal power at constant voltage until the thermal time constant allows re-stabilization.

Reliability

This reliability analysis considers a SiGe type RTG, and concentrates on 150w and 200w power levels.

The RTG must be capable of delivering the required power for each RTG rating at the required voltage at end of 12 years (or at end of mission).

The system will be designed with sufficient beginning of mission (BOM) capacity to take care of expected normal degradation of fuel and normal changes in thermoelectric materials, and the structure will be designed to withstand the expected handling and launch environments without damage. The reliability problem, then, reduces to a consideration of random failures during the period of the mission.

A detailed reliability analysis must consider the probabilities of all types of failures, including:

- Unexpected degradation of thermal insulation within the RTG.
- Random failures of the RTG structure, including cold frame, fins, hardware, etc.
- Random failure of the fuel capsules, for example, by rupture of the sheath.
- Unexpected changes in the emissivity characteristics of the cooling fins by repeated meteoroid impingement or coating by cosmic dust.
- Random short circuits or open circuits in the power wiring between the RTG panels and the power terminals.

For the purposes of the present discussion, the probability of such failures will be considered extremely small and attention will be given to failures which may occur in the module itself. Although the probability of failure of individual thermoelements and thermocouples also is small, as will be shown, the fact that thermocouples are used in large numbers in the RTG warrants giving them special attention.

The purpose of this reliability analysis is to:

- Determine total reliability of the RTG.
- Assist in performing tradeoff studies involving different power system configurations.
- Assist in determining excess RTG capacity required for a given EOM power to compensate for internal short-circuits and multiple short-circuits to frame.
- If required, determine the total reliability of a given power system. including any conversion and regulating equipment.

Thermocouple Failure Modes and Effects

In general, there are three ways in which an individual thermocouple can fail:

- Open circuit
- Short circuit
- Short circuit to cold frame

A thermocouple open circuit can occur by fracture of the P or N thermocouple element, failure of the bond at the hot junction or the cold junction, or a break in the interconnecting straps between thermocouples.

If the thermopile consists of a single string of thermocouples all wired in series, any one of these failures will result in a complete open circuit of the generator and consequently, a complete RTG failure. If the thermopile consists of two parallel strings, cross-connected at every thermocouple or every several thermocouples, complete failure of the RTG requires a failure of two adjacent thermocouple branches or of their series interconnecting straps. Similarly, if a thermopile consists of three parallel strings cross-connected at every thermocouple or every several thermocouples, three adjacent branches or their series interconnecting straps must fail in order to constitute an RTG failure.

A thermocouple short circuit can occur if a piece of foreign conducting material wedges between the two thermocouple legs or between series connecting straps. In the case of such a failure, the RTG suffers a small reduction in output voltage and power corresponding to the voltage and power contributed by the individual thermocouple or by the thermocouple group in the case of cross-connected parallel strings. Failure then is not catastrophic. In general, several such failures must occur before a significant change in RTG capacity occurs.

Short circuits to the cold frame can occur if a piece of foreign conducting material becomes lodged between the interconnecting straps and the cold frame or if the insulation separating the thermocouples from the cold frame fractures or breaks down electrically. If the cold frame is electrically floating, then at least two such failures in non-adjacent thermocouples must occur in order for any effect to be felt. The effect is a reduction in the output voltage and the capacity of the RTG.

In view of the effects of these types of failures, a reliability analysis of the RTG is helpful in determining how the thermopile should be wired, whether in one or two or more parallel strings, and whether there is need for additional series thermocouple groups and additional fuel loading to compensate for loss of power due to possible short circuits. Previous analyses have shown that, in general, the optimum wiring arrangement from the reliability standpoint is two parallel strings cross-connected, or laddered at every thermocouple. For this reason, this wiring arrangement has been selected for configurations 1 and 2 detailed in Table 5-1. An estimate of their reliability is given in Section 7.

TABLE 5-1. RTG CONFIGURATIONS

	CONFIGURATION	
	1	2
Rated Power, watts	150	200
Number of Modules	10	14
Number of Couple-Pairs per module	15	15
Total number of thermocouples	300	210

SECTION 6. BREADBOARD ACTIVITIES

This effort will consist of fabrication and test of two identical tests of the breadboard, each consisting of the following assemblies:

1) a shunt regulator
2) a single phase, two phase, and three phase 400 Hz inverter
3) a main inverter
4) a power source and logic assembly
5) a power distribution assembly

No effort has been applied to this task during the period covered by this report.

TECHNICAL DISCUSSION

SECTION 7. ANALYSES

RTG Failure Rate

The key to a reliability analysis of the thermopile is an evaluation of the failure rate of the thermocouples. If test experience were not available on the types of thermocouples contemplated for use in the given RTG, estimates of probable failure rates would have to be made on the basis of experience with similar types of devices. For the type of silicon germanium thermocouple assemblies contemplated, test experience is available. For this type of thermocouple assemblies, RCA reports over 4,800,000 couple-hours of test without a single failure. If the chi-squared distribution analysis is applied, the reliability of one couple for a five-year mission (approximately 44,000 hours) is 0.9937 at a 50 percent confidence level. The corresponding total failure rate then is 1.43×10^{-7} failures per hour.

This figure represents the total failure rate for one thermocouple. If separate evaluations of the three types of failure modes (open, short and short-to-frame) are to be made, this figure must be divided into components representing failure rates for each type of failure. For lack of failure data, the apportionment must be made on the basis of judgment.

If it is assumed that the probability of an open circuit failure is 10 times that of both a short circuit and a short circuit to cold frame, the probable failure rates for each type of failure can now be computed. On the basis of this assumption, the three failure rates are:

$$\lambda_o = 1.3 \times 10^{-7}/\text{hr}$$

$$\lambda_s = 0.065 \times 10^{-7}/\text{hr}$$

$$\lambda_{sf} = 0.065 \times 10^{-7}/\text{hr}$$

The mathematical model which describes the reliability of a thermopile consisting of two parallel strings cross-connected at every thermocouple is represented by the following equation. This model applies equally well to a complete RTG or to a module.

$$R_T = \left[\sum_{X=N-MAXK}^{N} \binom{N}{X} P_1^{\,X} \cdot \sum_{y=y_1}^{N-X} \binom{N-X}{y} P_2^{\,y} \cdot P_3^{\,N-X-y} \right] \cdot \left[1-W \cdot Q^2_{SCP} \right]$$

$y_1 = 0$ if $2X \geq 2N-MAXK$

$y_2 = 2N-MAXK-2X$ if $2X < 2N-MAXK$

where:

$P_1 = R_o^{\,2} \cdot R_s^{\,2}$ = Probability of no opens or shorts

$P_2 = 2R_s^{\,2}\ (1-R_o)$ = Probability of one open and no shorts

$P_3 = 2R_o^{\,2}\ (1-R_s)$ = Probability of one short and no opens

MAXK = Maximum number of couple failures permitted via opens and shorts

N = Number of series - parallel groups

R_o = $\varepsilon^{-\lambda_o t}$ = Probability that a couple will not open circuit

R_s = $\varepsilon^{-\lambda_s t}$ = Probability that a couple will not short circuit

λ_o = Open circuit failure rate

λ_s = Short circuit failure rate

$Q_{SCP} = \lambda_{SCP}\, t$ = Probability that couple will short to cold frame

W = No. of ways 2 couples will short to cold frame resulting in loss of power equivalent to N - MAXK;

$$= 4 \sum_{x=1}^{N-n} x$$

The reliability of a complete RTG or of a single module can be predicted by applying this model to the example designs. Consider, for example, configuration 1 design, which produces 150 watts with 10 modules. We must, however, evaluate reliability in terms of the least reliable configuration which corresponds to the one utilizing the greatest nominal number of thermocouples, namely a 200-watt design which employs 14 modules. Since all of the modules are connected in series, and each is equally likely to fail, the total reliability of the RTG is the reliability of one module to the 14th power, neglecting the small contribution to unreliability of structure, fuel source, and items other than the thermopile. Thus, $R_T = R_M{}^{14}$.

To achieve a total reliability of 0.96 for the RTG, each module must have a reliability equal to the 14th root of 0.96, or 0.9971.

Evaluation of the reliability model for a module shows that the probability of realizing the required power at the end of mission despite possible failures (which is our definition of reliability) is 0.9975 if the module is constructed with 15 pairs of thermocouples instead of the nominally required 14. This allows two thermocouples to fail during the mission. These results are based on the failure rates given above. The impact of this conclusion on overall RTG reliability and power capacity is discussed in the following paragraphs.

A mathematical model for the reliability of a SiGe thermoelectric module has been developed and is applicable to the 150-watt SiGe RTG's described in this section to determine the probability of delivering 150-watts at the end of five years. The reliability is determined to be greater than 0.987 when the generator is designed with about 2½ percent EOM capacity to allow for power loss from possible thermocouple short circuits and open circuits. This extra capacity can be built in by providing three extra pairs of thermocouples slightly oversize. The probability of complete failure by the open-circuiting of two adjacent thermocouples is less than 0.005, for a reliability by this mode alone of over 0.995.

Previous analysis showed that the requisite reliability for individual modules for configuration 1 was attained with an extra pair of thermocouples, 15 instead of 14. For the 10-module 150-watt design, then, there are ten extra pairs of thermocouples instead of only the three extra pairs required from an RTG reliability standpoint. With 10 extra pairs, or a total of 300 thermocouples, the probability is about 0.975 that the RTG will survive a five year mission with no more than five thermocouple failures. For the 150-watt generator with 10 extra couple pairs, the reliability if only 5 failures are allowed is .58 for a 12-year mission. Hence, the generator will have about five percent excess power at end of mission.

For a 200-watt generator with 14 modules and 210 pairs of couples, the probability is greater than 0.963 that the RTG will survive for five years with no more than six couple failures and greater than 0.977 that it will survive with no more than seven couple failures. In each case, excess power at end of mission will be about 5 percent.

For both the 150-watt and the 200-watt RTG's constructed of the oversize modules, the allowable number of thermocouple failures for 100 percent EOM power is greater than the number allowable for a reliability of 0.96. Hence, RTG reliability based on the definition of probability of no less than 100 percent EOM power is substantially greater than 0.96 for 5 years, and likewise, will be substantially greater than .58 for 12 years.

This analysis indicates that the proposed multi-hundred watt RTG model meets the requirements imposed in the request for proposal, or a reliability of 0.96 for five years with a 0.50 confidence. It should be noted that the reliability model is based on insufficient data for a twelve year mission, and that the twelve year mission is not presently a requirement for the multi-hundred watt RTG design.

Electronic Piece Part Failure Rate

Information provided by the Jet Propulsion Laboratory and shown in Table 7-1 is the failure rate data for electronic piece parts that was used during this period for relative reliability.

Table 7-1

Recommended Part Failure Rate Data

Part Type	Failure Rate x 10^{-6} failures per hour
Capacitors	
Glass	.002
Ceramic	.005
Foil	.008
Tantalum	
Solid	.01
Wet	.1
Diodes	
Signal & Switching	.01
Zener	.02
Power	.05
Resistor	
Carbon Composition	.001
Film	.008
Wire Wound	.09
Transistors	
Small Signal bi-polar	.02
Power Bi-polar	.08
JFET	.02
Isolated Gate FET	.05
Silicon Controlled Rectifier/Switch	.07
I/C's (does not include MSI/LSI)	
Bi-polar Monolithic	.2
MOS Monolithic	.4
Relays (Mech)	2.0

SECTION 8. CONCLUSIONS

The stage of this effort does not permit any firm conclusions to be drawn at this time.

SECTION 9. RECOMMENDATIONS

The designs applicable to the twelve-year life requirement based on previous space power experience require significant sophistication and improvement to demonstrate confidence in successful mission completion.

The methods being explored to improve life confidence include the following:

1. Use of existing circuit designs that have demonstrated long and satisfactory performance.
2. Use of electronic piece parts that are in quantity production and use with a history of success.
3. Use of redundancy where appropriate to withstand individual failures without effecting performance.
4. Use of low stress levels to enhance the probability of successful operation.
5. Use of configurations to limit the effects of a failure to the minimum amount of equipment.

It is recommended that continued effort be expended to demonstrate present circuits and configurations, and to create more satisfactory arrangements to meet the life requirement.

SECTION 10. NEW TECHNOLOGY

No items of new technology have been identified during the period covered by this report.

SECTION 11. REFERENCES AND BIBLIOGRAPHY

1. Statement of Work, Contract No. 952536, Modification No. 1, dated 27 June 1969.

2. Design Requirements and Constraints for Thermoelectric Outer Planet Spacecraft (TOPS), Power Subsystem dated 24 April 1969.

3. TOPS Mission Objectives and Design Criteria No. TOPS-2-100 dated 17 February 1969.

4. TOPS-3-250 Functional Req., TOPS Power Profile and Allocation, June 16, 1969.

5. TOPS-4-2004 Functional Req., TOPS Power Subsystem, June 10, 1969.

6. TOPS Power Profile dated 21 March 1968.

7. TOPS Power Subsystem Requirements dated 10 April 1969.

8. Power Profile, 27 June 1969.

9. TOPS Flight Sequence, 20 March 1969.

10. TOPS Flight Sequence, 31 March 1969.

11. Performance Characteristics of a Silicon-Germanium RTG in Long-Term Operation, dated 29 April 1969.

12. Mariner Mars 1969 Electrical Interface and Electrical Grounding, dated 25 September 1968.

13. Preferred Parts List JPL Spec. ZPP-2061-PPL-K, dated 1 July 1969.

14. Candidates for the TOPS Recommended Parts List, dated 31 December 1968.

15. Screening Requirements for Electronic Parts, General Specification, dated 25 April 1966.

16. Failure rate for Mariner Mars Power System Study.

17. TOPS Recommended Parts Failure Rate Data, 10 April 1969.

18. Major System Design Problems for Deep Space Probes by William J. Dixon AIAA Paper No. 66-887, December 1967.

19. Design of an Unmanned, Automated Spacecraft for the Grand Tour by L. E. Hove, IAF Paper No. AS45, October 1968.

20. Earth-Based Navigational Capabilities for Planetary Missions by T. W. Hamilton, AIAA Paper No. 68-852 - August 1968.

21. Trajectory Analysis of a Grand Tour Mission to the Outer Planets by Louis Kingsland, Jr., AIAA Paper No. 68-1055, October 1968.

22. Bi-Weekly Progress Review Meeting Minutes, 8 May 1969.

23. Minutes of an Informal Meeting at ERC, 14 May 1969.

24. Bi-Weekly Progress Review Meeting Minutes, 26 May 1969.

27. Bi-Weekly Progress Review Meeting Minutes, 12 June 1969.

28. Specification for R&D Technical Reports Document 1000-8, dated 1 January 1967.

29. ERC/JPL Agreement for Power Processing Support of the TOPS Project dated 17 April 1969.

30. To the Outer Planets by James E. Long, Astronautics and Aeronautics, June 1969.

31. Space Facts Handbook of Basic and Advanced Space Flight and Environmental Data, General Electric Company, 1960.