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SNAP 19 PROGRAM
ELECTRICAL INTEGRATION CONCEPTUAL STUDY

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SNAP 19 PROGRAM
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Summary

The data contained in this report was reviewed by the AEC, NASA-Goddard and Martin at the Nimbus electrical interface meeting of 22 May '64. Several combinations of 30 and/or 60 watt converters and the 30 generators, with auxiliary switching and sensing units as required, were analyzed for potential efficiency, reliability and weight characteristics.

At this meeting a configuration was selected which involved the use of two 30 watt generators in combination with two converters with a 60 watt capacity. Two generator-converter systems are paralleled to provide a 60 watt package. Appropriate switching and sensing elements provide the capability for an external A/D converter system to signal removal of a failed converter unit from the system.

In the course of preparing this report, and subsequent to the above referenced meeting, it became apparent that any consideration of the relative merits of any redundant configurations, must include the effect of the reliability of the external A/D Converter System. From Figure #15 of Appendix C of the report, below a reliability of 0.97 for the A/D converter, for a 1 year mission time, there is no overall advantage in providing redundant characteristics in the power system configurations.

1.0 Introduction

This report covers the Electrical Integration Conceptual Study for selected converter-generator configurations. This study was accomplished to provide a basis for selection of a combination of converters, generators and auxiliary components which would optimize efficiency, reliability and weight for a thermoelectric power system producing a 60 watt output. Both redundant and non-redundant configurations are compared.

2.0 Specification

Following are the electrical requirements which are pertinent to the study:

Input Voltage:	2.4 or 4.8 volts d.c. nominal
Output Voltage:	$-24.5^{+0.5}_{-0.0}$ volts d.c.
Power In:	30 or 60 watts (End of Life)
Power Out:	50 watts minimum
Failure Signal:	0 to -6 volts d.c.
Ripple:	Less than 100 millivolts
Temperature Ambient:	-5° to +55°C
Package:	Module as per drawing number NIM-81-D (3-3-64)
Constraints:	Component part derating factors (Goddard Document - No Number)

2.1 Requirements

A power system configuration meeting was held on April 22, with NASA, AEC, and Martin. As a result, the using agency required the establishment of a standard 30 watt generator-converter package which could be paralleled to multiples of 30 watt systems.

It was decided to perform an initial study of four cases with respect to size, weight, efficiency, reliability and circuit complexity. In block diagram the four cases are shown in Figure 1.

Case 1 - consists of two - 30 watt generators each of which independently supplies power to a 30 watt converter, and the outputs of two converters are paralleled to give a 60 watt system. The terminal or loaded output voltage of each generator is 2.4 volts d.c.

Case 2 - consists of two - 30 watt generators, each supplying power to a 60 watt converter, and the outputs of two converters are parallel to give a 60 watt system. The converters normally handle 30 watts of power but are designed to efficiently and safely handle 60 watts. Relay circuitry as indicated in the diagrams shows the normal condition and in the event of a converter failure, contact K3 closes and either K1 or K2 contacts open depending on converter C1 or C2 failure. The terminal or loaded output voltage of each generator is 2.4 volts d.c.

CASE 1

CASE 2

CASE 3

CASE 4

Figure 1

Case 3 - consists of two-30 watt generators in series so that the terminal or loaded output voltage of the combined generators is 4.8 volts d.c. with a power capability of 60 watts. The generators supply power to a single 60 watt converter.

Case 4 - is similar to case 3 except that the two parallel 60 watt converters are connected to the series set of generators through relay circuitry. The converters normally handle 30 watts of power but are designed to efficiently and safely handle 60 watts. All relay contacts are closed during normal operation and in the event of a converter failure K1 or K2 contacts will open depending on converter C1 or C2 failure.

Consideration was given to potential use of either of two of the latest power switching transistors available and other part substitutions in the analysis of each case.

3.0

Converter Analysis

There are various methods of converting electrical energy from one voltage level to another, which are distinctive with respect to efficiency, size, complexity and performance in various environments. Converter systems using tunnel diodes as switching elements are not considered suitable at present for this application since the highest efficiencies possible are 65% for germanium and 45% for silicon. The power loss for germanium devices is much smaller than silicon devices when operated as closed switches therefore, silicon transistors and silicon controlled rectifiers were not considered as acceptable. Single ended and flyback type circuits are limited to approximately 70% efficiency, therefore, these types of circuits were not considered. An example is shown in Figure 2. The best circuit approach for high efficiency is a push-pull type using germanium power transistors.

Experience and analysis on past and existing SNAP programs has shown that the optimum circuit for low voltage power conversion is the oscillator-driven, power stage type. A schematic of this type of circuit is shown in Figure 3.

The oscillator is of the overdriven, push-pull, transformer coupled type which supplies base drive switching current to the power stage. The oscillator includes parts Q_1 , R_1 , R_2 , C_4 , and T_1 . Q_1 consists of two transistors which alternately switch the input D.C. voltage across the primary windings

Tunnel Diode Static Converter

Transistor Converter

Transistor Push Pull Static Converter

Figure 2

Tunnel Diode Static Converter

Transistor Converter

Transistor Push Pull Static Converter

SNAP 19

Tentative Schematic

E_0 = 25 volts and established by regulated buss

-E_f = 0 to -6 volts signal for 3K Ω A-D converter load

Figure 3

of T_1 . This voltage is changed by transformer action to a secondary voltage which is used to supply base drive power for Q_2 , and Q_3 . R_1 and R_2 effectively forward bias Q_1 into conduction, and as much assure self-starting of the oscillator. C_4 is used for de-spiking purposes.

Q_2 and Q_3 are power transistors which are alternately driven into conduction to supply square-wave power to T_2 . This voltage is stepped up by transformer action, and after rectification and filtering applied to the load terminals. An additional winding on T_2 will provide a failure sense voltage for an A-D converter. The sense voltage will range from 0 to -6 with -4 volts established as referring to a full load condition.

T_1 is a saturating transformer using a square-loop hysteresis type of magnetic material. The parameters of T_1 establish the frequency of oscillation. It can be shown from Faraday's Law that $f = \frac{E_1}{4 N \Phi_S}$ where E_1 (input voltage) is constant and f (frequency) is inversely proportional to the number of turns on T_1 and the saturation flux level of the magnetic material used. T_1 is operated at a low power level.

T_2 is a power transformer and is operated out of saturation to minimize losses.

A review of characteristics of magnetic material resulted in a selection of square Permalloy 80 for T_1 since it has low loss plus high squareness ratio. Supermalloy

was selected for T_2 since it exhibits the lowest loss in watts per pound. The material for both T_1 and T_2 will be one-mil tape wound toroidal cores. The cores are packaged in aluminum boxes and have an external epoxy mold to prevent stresses on the magnetic material and are available as standard stock items.

3.1 Design Consideration

In order to achieve a minimum power loss in the converter, consideration was given to the relationships depicted in Figure 4.

Figure 4

- A = Total Loss
- B = Transistor Loss
- C = Transformer Loss
- f_0 = Optimum Frequency

Optimum frequency of oscillation occurs when power transistor losses equal power transformer losses

A graph of P_c (total conduction power loss) versus I_B (Base drive current) with I_c (collector current) as a parameter for a transistor as a closed switch is shown in Figure 5.

Figure 5

In Figure 5 $P_c = I_B V_{BE} + I_C V_{CE}$ where V_{BE} is the base-emitter voltage and V_{CE} is the collector-emitter voltage. OA is the locus of minimum losses for various values of I_C . Test data of P_c vs I_B exists in Martin Company files for various transistors and collector currents. This data was used to determine losses.

3.2 Design Formulas

The mathematical expression used to design DC-DC converters using two power transistors are as follows:

Total Transistor Losses - P_t (watts)

$$P_t = P_D + P_S + P_C$$

$$P_D = \text{Base Drive Losses} = \frac{E_B I_C}{B}$$

$$P_S = \text{Switching Losses} = \frac{2}{3} (V_S \times I_C \times f \times t_S)$$

$$P_C = \text{Conduction Losses} = V_{CESat} I_C (1 - 2 \times f \times t_S)$$

where:

$$E_B = \text{Base-Emitter Voltage}$$

$$I_C = \text{Collector Current}$$

$$B = \text{DC Current Gain}$$

$$V_S = \text{Source Voltage}$$

$$f = \text{Frequency in cycles per second}$$

$$t_S = t_f + t_R = \text{Switching time in seconds}$$

$$t_R = \text{Rise time of square wave}$$

$$t_f = \text{Fall time of square wave}$$

$$V_{CESat} = \text{Collector - Emitter Saturation Voltage}$$

Rectifier Losses - P_R (watts)

$$P_R = E_R I_L$$

where:

$$E_R = \text{Voltage across rectifier diode}$$

$$I_L = \text{Load Current}$$

Power Transformer Losses - P_T

$$P_T = P_i + P_{cu}$$

$$P_i = \text{Magnetic Iron Losses} = \frac{B_2}{B_1} H dB$$

(taken from manufacturers data sheets)

$$P_{cu} = \text{Magnet wire losses} = I_L^2 R$$

where: H = Magnetomotive force

B = Flux Density

R = Resistance of magnetic wire

Optimum Frequency

Optimum frequency occurs when

$$P_T = P_t = P_D + \frac{2 V_S I_c f t_S}{3} + V_{CES} I_c (1 - 2 f t_S)$$

$$f = \frac{P_T - P_D - V_{CES} I_c}{2 I_c t_S \left(\frac{V_S}{3} - V_{CES} \right)}$$

where: V_{CES} is the collector-emitter saturation voltage.

Transformers

Transformers are designed for square-wave operation using the following relationship:

$$E_1 = 4N AfB 10^{-8}$$

where: N = number of primary turns
 A = area in square centimeters
 B = flux density in Gauss
 f = frequency in cycles/sec

3.3 Converter Design

In order to satisfy the requirements of 2.1 it was necessary to perform trial designs for converters in each of the cases.

The design approach consisted of calculating transistor losses, optimum frequency and transformer design. Component parts weight and volume were tabulated to give total converter weight and volume for each case.

The results are summarized in Table 1.

Table 1

<u>Case #</u>	<u>Converter Input Voltage E₁</u>	<u>Power Capability P₁</u>	<u>Wt(lbs)</u>	<u>Vol(in³)</u>	<u>f(KC)</u>	<u>% Eff. N 30W</u>	<u>% Eff. N 60W</u>	<u>Power Transisto: Part Number</u>
1A	2.4	30	4.3	72	0.3	92.5	--	2N2305
1B	2.4	30	5.25	108	1.3	93.7	--	2N2101
2A	2.4	30/60	2.84	50	1.0	90.7	90.7	2N2305
2B	2.4	30/60	5.93	122	1.0	93.7	93.4	2N2101
3A	4.8	60	9.37	110	0.082	91.2	89.4	2N2732
3B	4.8	60	2.79	47	1.3	88.3	91.3	2N2732
3C	4.8	60	3.0	54	1.0	92.3	94.0	2N2305
4A	4.8	120	18.74	220	0.164	91.2	89.4	2N2732
4B	4.8	120	5.58	94	2.6	88.3	91.3	2N2732
4C	4.8	120	6.00	108	2.0	92.3	94.1	2N2305

Q Power relates to Minneapolis Honeywell power transistors.

Since the above information is based on one converter unit, and cases 1, 2 and 4 require two converters per power supply system, the weights and volumes must be doubled. Converter efficiency, size and weight information for case 4 is similar to case 3.

Results on a watts per pound basis, using only the highest efficiency in each case, are tabulated in Table 2.

Table 2

<u>Case #</u>	<u>Watts lb.</u>		<u>Converters System</u>	<u>Redundancy</u>	<u>min. p.s. Modules</u>
3C	20	0.94	1	No	60W
4C	10	0.94	2	Yes	60W
1B	5.7	0.937	2	No	30W
2B	55.05	0.934	2	Yes	30W

Case 2B converters were designed with a capability of 60 watts continuous operation but would operate efficiently at 30 watts also. The results indicate the increase in weight required to achieve redundancy.

4.0 Generator-Converter System Reliability Estimate

4.1 Analysis (Unit Reliabilities)

The Sub-system is comprised of the generator, converter, trouble sensor and relay switching circuit units. Various arrangements of these basic units, or building blocks, comprise the 4 different configurations of Figure 1. The analysis of each unit follows.

4.1.1 DC to DC Converter

A converter, in a given configuration, may be comprised of more than one possible arrangement of parts (See Appendix C). The various arrangements are depicted by

Figure 7(a), and the reliability of each combination is unique. To best describe the use of the chart of Figure 7(b) a few examples are given:

- (1) 1-A-30 and 2-A-30 have parts list A, a 30 watt power level, and an input voltage of 2.4 volts in common, therefore; they are grouped together in column I.
- (2) Although 4-A-30 has the same parts list and power level as those in col. I, the input voltage differs (4.8V). Since no other combination has all these in common with 4-A-30, it alone comprises column II.

The 9 columns above represent the sets of circuits at identical stress levels. Since the electrical stresses on parts lists A, B, and C are so similar when the input voltage is alike for each, they are considered the same. This reduces the 9 previous combinations (Figure 7(b)) to 4 (Figure 7(c)). The 4 stress and failure rate charts of Figures 8-11 are compiled on the basis of the above reasoning. Since the reliabilities of all of these cases are so nearly alike, the same figure of merit has been chosen to represent each.

A circuit diagram of the converter is shown in Figure 3. Peak voltages and currents were estimated at all nodes

for use in the determination of part stress. This procedure was repeated for each of the converter combinations.

A failure mode may be categorized as drift or catastrophic. Drift failures are inherently no problem in a well-designed switching circuit such as this. The cause of circuit failures may, therefore, be attributed to the catastrophic mode which includes opens and shorts.

Environmental conditions, reliability math models, failure-rate data and stress analysis, have been utilized in the determination of all reliability figures herein, with the references 1 through 4 used as guides.

Radiation effects shall be considered insignificant due to the mechanical and shielding protection given to similar "SNAP" system converters.

The converter reliability model is a simple series type, where the total failure-rate (λ_c) is the sum of the (i) parts failure rates (λ_{ci}):

$$\lambda_c = \sum_{i=1} \lambda_{ci} \quad \begin{array}{l} \text{Converter Failure Rate - } (\lambda_c) \\ \text{(\% failures/1000 hrs)} \end{array}$$

$$MTBF_c = \frac{1}{\lambda_c} \quad \begin{array}{l} \text{Converter mean-time between failures} \\ \text{= (MTBF}_c\text{)} \\ \text{(hrs)} \end{array}$$

Converter Reliability Figure of
Merit - $R_c(t)$

$$R_c(t) = e^{-\lambda_c t} \quad \text{where } 0 \leq R_c(t) \leq 1$$

Mission Time(s) - (t)

$$t = 1, 3, 5 \text{ (years)}$$

4.2.2 Trouble sensing circuit shown in Figure 3 is present only on configurations 2 and 4. Failure rates may be determined from the stress charts (Figures 8-11) independently of the converter. A reliability estimate has been made based on the model:

Trouble Sensor Failure-Rate - (λ_s)

$$\lambda_s = \sum_{i=1}^n \lambda_{si} \quad (\% \text{ failures/1000 hrs})$$

Trouble Sensor Mean-time Between
Failure - ($MTBF_s$)

$$MTBF_s = \frac{1}{\lambda_s} \quad (\text{hrs.})$$

Trouble Sensor Reliability Figure
of Merit - $R_s(t)$

$$R_s(t) = e^{-\lambda_s t} \quad \text{where } 0 \leq R_s(t) \leq 1$$

Mission Time(s) - (t)

$$t = 1, 3, 5 \text{ years}$$

4.2.3 Switching Circuits

Relay switches implement the redundant configurations 2 and 4 by providing an alternate operating system under certain conditions of system failure. Latching type relays are desired to provide the switching with maximum power conservation and minimum number of required parts, together with maximum reliability. The chart of Figure 12(a) depicts the number of relays and contacts required for each system configuration. A relay type has not been definitely specified yet, but a rough idea of its characteristics and quantities are known. A reliability estimate, based on MIL-HDBK-217 (Ref #2). Criteria for relays, was made (See Figure 12(b)).

Relay Failure-Rate - (λ_s)

$$\lambda_{K_j} = \sum_{i=1}^n \lambda_{K_i} \quad (\% \text{ failures/1000 hrs})$$

where K_i = ith contribution to failure (as defined by MIL-HDBK-217)

Relay mean-time between failure -

($MTBF_{K_j}$)

$$MTBF_{K_j} = \frac{1}{\lambda_{K_j}} \quad (\text{hrs.})$$

Relay Reliability Figure of Merit -

$R_{K_j}(t)$

$$R_{K_j}(t) = e^{-\lambda_{K_j}t} \quad \text{where } 0 \leq R_{K_j}(t) \leq 1$$

Mission Time(s) - (t)

t = 1, 3, 5 years

Any non-Martin Company equipment, such as the A/D converter, which is placed in series (reliability sense) with the trouble sensor and between the input and output of the relay switches, must be assumed to detract from the reliability of the power sub-system.

A parametric study of system reliability as a function of A/D converter reliability allows insight into the equipment interdependence, and the true worth of a redundant system. Appendix C presents the computer program and results of this study.

Switching Circuit Reliability Figure of Merit

A model for the switching circuits includes one or more relays, therefore; the joint probability of success of n relays represents the sub-system reliability.

$$R_K(t) = R_{K_j}(t) \cdot R_{K_K}(t) \cdot R_{K_1}(t) \dots R_{K_n}(t),$$

and if all relays have the same failure rate,

$$R_K(t) = [R_{K_j}(t)]^n \text{ where } n = \text{no. of relays}$$

4.2.4 Generator

System analysis shows the interrelationship of converter efficiency and number of generator cell failures in a given failure mode. Cell failures correspond to the lost power operation capability.

Generator reliability is based on the number of cell failures and the way in which they fail. Cell reliability is based on a 90% confidence level of cell test data SNAP 17 discussed in reference 4. From the reliability model below, a reliability figure of merit has been estimated.

$$R_S \approx \sum_{i=0}^j \left[3^i \binom{n}{i} (R_c)^{3n-i} (1-R_c)^i \right]$$

where: R_S = Reliability of series-parallel thermoelectric system

n = No. of 3 cell groups

j = Maximum allowable failures of groups

4.3.0 System Reliability

System configurations 1 through 4 of Figure 1 each have their unique sets of reliability models. Very basically, all models utilize the following general properties of probability:

For 1 unit there are 2 combinations

$$(A_1 + \bar{A}_1) = 1 \quad \text{where } 0 \leq 1$$

For 2 units there are 4 combinations

$$\bar{A}_1 \bar{A}_2 + \bar{A}_1 A_2 + A_1 \bar{A}_2 + A_1 A_2 = 1$$

For n units there are 2^n combinations

$$\bar{A}_1 \bar{A}_2 \dots \bar{A}_n + \bar{A}_1 \bar{A}_2 \dots A_n + \dots + A_1 A_2 \dots A_n - 1$$

$$\text{let } \bar{A}_i = (1-A_i)$$

Now, let A_1 denote the probability of a successful generator (reliability) and $\bar{A}_1$ that of a failed one. Let A_2 denote the probability of a successful converter and $\bar{A}_2$ that of a failed one ... etc. All possible combinations will be accounted for since the probabilistic sum of all possible combinations must be unity. Actually, in each of the models, only a small portion of these possibilities exist. Models for the various systems are charted in the digital form of truth tables ("1" = A_i , "0" = $\bar{A}_i$) depicting the successful modes of operation (rows), the sum of which is the system reliability. (See Figure 7).

5.0 Review with Procuring and Using Agencies

The electrical integration study results were reviewed during a meeting with AEC and NASA at Goddard on May 22, 1964. Operation of the circuit as illustrated by the schematic in Figure 3, was explained. The design considerations and the selection of power transistors and transformer materials was discussed.

A general discussion of the summary resulted in a decision to use Case 2B for the Nimbus Program. It was also decided to protect the converters in the event of an open circuit. Justification for the selection of 2B was that a standard 30 watt power system which could be used in parallel multiples of 60 watt systems would be in general demand on NASA programs, as well as the Nimbus Program. Further justification was the redundant feature of two converters. The user agency was agreeable to the increased weight of 2B versus 3C or 4C.

6.0 Selected System Concept

In block diagram the system which was selected for the Nimbus Program is shown in Figure 6.

Figure 6

Each converter will normally operate at 30 watts with K1 and K2 normally closed and K3 normally open. In the event of a converter failure K1 or K2 would open and K3 close depending on C1 or C2 failure.

The area within the dotted lines or both converters plus the relays will be in a single enclosure as per NIM-81-D.

The converter outputs will be connected to fuses by the user. The user is to supply fuses. The power system will be paralleled after the fuses and connected to load terminals which are regulated bus voltage lines.

The circuit for each converter will be essentially as shown in Figure 3. Components will be added during final design to minimize radio frequency interference. It is intended to design the package so that each converter is a sub-assembly of the power system and also to maintain physical isolation between input and output for minimum interference.

CONVERTER ANALYSIS COMBINATIONS FIG. # 7

THERE ARE 3 POSSIBLE PARTS ARRANGEMENTS: A, B, C, EACH CAPABLE OF PERFORMING AT EITHER OF 2 POWER LEVELS: 30 or 60 WATTS.

FIG. 7(a)

STRESS ANAL. #	I	II	III	IV	V	VI	VII	VIII	IX
COMB	1-A-30	1-B-30	4-A-30	4-B-30	4-C-30	2-A-60	4-A-60	4-B-60	4-C-60
SET	2-A-30					2-B-60	3-A-60	2-B-60	3-C-60
INPUT VOLTAGE	2.4V	2.4V	4.8V	4.8V	4.8V	2.4V	4.8V	4.8V	4.8V

FIG. 7(b)

STRESS ANAL. #	I	II	III	IV
COMB.	1-A-30	4-A-30	2-A-60	4-A-60
SET	2-A-30	4-B-30	2-B-60	3-A-60
	1-B-30	4-C-30		4-B-60
				3-B-60
				4-C-60
				3-C-60
INPUT VOLTAGE	2.4V	4.8V	2.4V	4.8V

FIG. 7(c)

STRESS AND FAILURE-RATE CHART

NO. W. FACTS	ITEM NO.	PART SYMBOL	COMMERCIAL OR MIL DESIGNATION	PART TYPE	VALUE	UNITS	RATED STRESS	OPER. STRESS	STRESS UNITS	% OFF. 10 YEARS	λ_i
1	1	C ₁	SPRAGUE MM 350D226X9050S2	SOLID TANT.	22	μf	50	25	volts	.5	.003
	2	C ₂	"	"	"	"	50	25	volts	.5	.003
	3	C ₃	"	"	"	"	50	25	volts	.5	.003
	4	C ₄	AEROVOX 90A2-6	CERAMIC	.1	μf	100	4.8	volts	.1	.001
	5	C ₅	SPRAGUE MM 350D157X9015S2	SOLID TANT.	150	μf	15	2.4	volts	.2	.0003
	6	CR ₁	TEXAS INSTR. IN645	DIODE (Si)	—	—	.6	.5mW	watts	.1	*.010
	7	CR ₂	"	"	—	—	.6	.5mW	watts	.1	*.010
	8	CR ₃	"	"	—	—	.6	.5mW	watts	.1	*.010
	9	CR ₄	"	"	—	—	.6	.5mW	watts	.1	*.010
	10	CR ₅	MOTOROLA IN752A (5%)	DIODE, ZENER	5.6	V	.4	0	watts	.1	*.010
	11	* L ₁		INDUCTOR, CHOKER	1.0	mH	3	1.2	amps	.4	.050
	12	Q ₁	FAIRCHILD 2N2060 (1/2)	NPN Si DUAL TRANSISTOR	—	—	.3	12.5mW	watts	.1	.020
	13	Q ₂	FAIRCHILD 2N2060 (1/2)	NPN Si DUAL TRANSISTOR	—	—	.3	12.5mW	watts	.1	.020
	14	Q ₃	MHT 2305 MHT 2101	PNP GE TRANSISTOR	—	—	85	.6	watts	.1	.020
	15	Q ₄	MHT 2305 MHT 2101	PNP GE TRANSISTOR	—	—	85	.6	watts	.1	.020
	16	Q ₅	MOTOROLA 2N1365	PNP GE TRANSISTOR	—	—	90	.24	watts	.1	.020
	17	Q ₆	MOTOROLA 2N1365	PNP GE TRANSISTOR	—	—	90	.24	watts	.1	.020
	18	R ₁	RNGOC 2741 F	RESISTOR, FILM	—	KΩ	.125	.004	watts	.1	.0315
	19	R ₂	RNGOC 2211 F	RESISTOR, FILM	—	KΩ	.125	.003	watts	.1	.0315
	20	* T ₁	MAGNETICS INC.	SAT. COIL PULSE XFORMER	—	—	—	—	—	—	.030
	21	* T ₂	MAGNETICS INC.	POWER TRANSFORMER	—	—	—	—	—	—	.050
Y	22	—	—	35 SOLDER JOINTS	—	—	—	—	—	—	.025

CONFIG. SET	$\sum \lambda_i$	$\sum \lambda_s$	R(5)	R(3)	R(1)
1-A-30	.3483	.050	.856	.911	.369
2-A-30	h	h	h	h	h
1-B-30	h	h	h	h	h

FIG. #8

* IN-HOUSE CONSTRUCTION AND DESIGN

* ALTHOUGH THESE DIODES ARE PART OF THE PHYSICAL CONVERTER, IN A RELIABILITY SENSE THEY COMPRISE THE SEPARATE TROUBLE SENSOR AND ARE NOT INCLUDED IN THE CONVERTER λ_i TALLY.

D.C. to A.C. CONVERTER

P-11

STRESS AND FAILURE RATE CHART

NO. V-FACTS	ITEM NO.	PART SYMBOL	COMMERCIAL OR MIL DESIGNATION SPRAGUE MM	PAK TYPE	VALUE	UNIT	TA ₅₀ °C	DETA ₅₀ °C	STRESS VOLT	W ₅₀ W	W ₅₀ W	λ_i
1	1	C ₁	350D226X9050S2	SOLID TANT.	22	μF	50	25	VOLTS	.5	.003	
	2	C ₂	"	"	"	"	50	25	VOLTS	.5	.003	
	3	C ₃	"	"	"	"	50	25	VOLTS	.5	.003	
	4	C ₄	AEROVON 92A2-6	CERAMIC	.1	μF	100	9.6	VOLTS	.1	.001	
	5	C ₅	SPRAGUE MM 350D157X92V5S2	SOLID TANT.	150	μF	15	4.8	VOLTS	.3	.0004	
	6	CR ₁	TEXAS INSTR. 1N645	DIODE (50)	—	—	.5	.5mW	VOLTS	.1	*.010	
	7	CR ₂	"	"	—	—	.5	.5mW	VOLTS	.1	*.010	
	8	CR ₃	"	"	—	—	.5	.5mW	VOLTS	.1	*.010	
	9	CR ₄	"	"	—	—	.5	.5mW	VOLTS	.1	*.010	
	10	CR ₅	MOTOROLA 1N752A (5%)	DIODE, ZENER	5.6	V	.4	0	VOLTS	.1	*.010	
	11	* LI		INDICATOR, CIRCLE	1.0	mA	3	1.2	VOLTS	.4	.050	
	12	Q _{1A}	FAIRCHILD 2N2060 (1/2)	NPN SI, DUAL TRANSISTOR	—	—	.3	12.5mW	VOLTS	.1	.020	
	13	Q _{1B}	FAIRCHILD 2N2060 (1/2)	NPN SI, DUAL TRANSISTOR	—	—	.3	12.5mW	VOLTS	.1	.020	
	14	Q ₂	2N2732 MHT 2305	PNP GER TRANSISTOR	—	—	85	.3	VOLTS	.1	.020	
	15	Q ₃	2N2732 MHT 2305	PNP GER TRANSISTOR	—	—	85	.3	VOLTS	.1	.020	
	16	Q ₄	MOTOROLA 2N1365	PNP GER TRANSISTOR	—	—	90	.24	VOLTS	.1	.020	
	17	Q ₅	MOTOROLA 2N1365	PNP GER TRANSISTOR	—	—	90	.24	VOLTS	.1	.020	
	18	R ₁	RYGOC2741 F	RESISTOR, FILM	—	KΩ	.125	.002	VOLTS	.1	.0315	
	19	R ₂	RYGOC2211 F	RESISTOR, FILM	—	KΩ	.125	.003	VOLTS	.1	.0315	
	20	* T ₁	MAGNETICS INC.	SAT. COIL PULSE XFORMER	—	—	—	—	—	—	.030	
	21	* T ₂	MAGNETICS INC.	POWER TRANSFORMER	—	—	—	—	—	—	.050	
✓	22	—	—	SOLDER JOINTS	—	—	—	—	—	—	.025	

CONFIG. SET	$\sum \lambda_i$	$\sum \lambda_s$	R _c (5)	R _c (3)	R _c (1)
4-A-30	.3484	.050	.856	.911	.969
4-B-30	↓	↓	↓	↓	↓
4-C-30	↓	↓	↓	↓	↓

FIG. #9

* IN-HOUSE CONSTRUCTION AND DESIGN

* ALTHOUGH THESE DIODES ARE PART OF THE PHYSICAL CONVERTER, IN A RELIABILITY SENSE THEY COMPRISE THE SEPARATE TRC FILE SENSOR AND ARE NOT INCLUDED IN THE CONVERTER λ_i TALLY.

R.C. & P.C. CONVERTER

STRESS AND FAILURE RATE CHART

NO. V-MES	ITEM NO.	PART SYMBOL	COMMERCIAL OR MIL DESIGNATION 3226C.18" MM	PART TYPE	VALUE	UNIT	TEST LEVEL	DIFF. COEFF.	STRESS IN %	% OFF TO 100%	λ_i
1	1	C ₁	350D226X9050S2	SOLID TANT	22	μf	50	25	volts	.5	.003
	2	C ₂	"	"	"	"	50	25	volts	.5	.003
	3	C ₃	"	"	"	"	50	25	volts	.5	.003
	4	C ₄	AEROVON 92A2-6	CELESTIC	.1	μf	100	4.8	volts	.1	.001
	5	C ₅	SPRAGUE MM 350D157X925S2	SOLID TANT.	150	μf	15	2.4	volts	.2	.0003
	6	CR ₁	TEXAS INSTR. 1N645	DIODE (Si)	—	—	.6	.5mW	volts	.1	*.010
	7	CR ₂	"	"	—	—	.6	.5mW	volts	.1	*.010
	8	CR ₃	"	"	—	—	.6	.5mW	volts	.1	*.010
	9	CR ₄	"	"	—	—	.6	.5mW	volts	.1	*.010
	10	CC ₅	MOTOROLA 1N752A (5%)	DIODE, ZENER	5.6	V	.4	0	volts	.1	*.010
	11	* L ₁		INDUCTOR, COIL	1.0	mh	3	2.4	volts	.8	.050
	12	Q _{1A}	FAIRCHILD 2N2060 (1/2)	NPN 100 mA TRANSISTOR	—	—	.3	12.5mW	volts	.1	.020
	13	Q _{1B}	FAIRCHILD 2N2060 (1/2)	NPN 100 mA TRANSISTOR	—	—	.3	12.5mW	volts	.1	.020
	14	Q ₂	MHT 2305 MHT 2101	PNP 100 TRANSISTOR	—	—	85	1.2	volts	.1	.020
	15	Q ₃	MHT 2305 MHT 2101	PNP 100 TRANSISTOR	—	—	85	1.2	volts	.1	.020
	16	Q ₄	MOTOROLA 2N1365	PNP 60 TRANSISTOR	—	—	90	.48	volts	.1	.020
	17	Q ₅	MOTOROLA 2N1365	PNP 60 TRANSISTOR	—	—	90	.48	volts	.1	.020
	18	R ₁	ANGOC 2741 F	RESISTOR, FILM	—	kΩ	.125	.004	volts	.1	.0315
	19	R ₂	ANGOC 2211 F	RESISTOR, FILM	—	kΩ	.125	.003	volts	.1	.0315
	20	* T ₁	MAGNETICS INC.	SAT. COIL PULSE XFORMER	—	—	—	—	—	—	.030
	21	* T ₂	MAGNETICS INC.	POWER TRANSFORMER	—	—	—	—	—	—	.050
Y	22	—	—	SOLDER JOINTS	—	—	—	—	—	—	.025

CONFIG. SET	$\sum \lambda_i$	$\sum \lambda_s$	$R_i(5)$	$R_i(3)$	$R_i(1)$
2-A-60	.3483	.050	.856	.911	.969
2-B-60	↓	↓	↓	↓	↓

FIG. #10

* IN-HOUSE CONSTRUCTION AND DESIGN

* ALTHOUGH THESE DIODES ARE PART OF THE PHYSICAL CONVERTER, IN A RELIABILITY SENSE THEY COMPRISE THE SEPARATE TROUBLE SENSOR AND ARE NOT INCLUDED IN THE CONVERTER λ_i TALLY.

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P.C. & P.C. CONVERTER
STRESS AND FAILURE-RATE CHART

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NO. V-FACTS	ITEM NO.	PART SYMBOL	COMMERCIAL OR MIL DESIGNATION SPRAGUE MM	PART TYPE	VALUE	UNITS	RATE SECS	OPER. STRESS	STRESS UNITS	% OFF. RATE	λ_i
1	1	C ₁	350D226X9050S2	SOLID TANT.	22	uf	50	25	volts	.5	.003
	2	C ₂	"	"	"	"	50	25	volts	.5	.003
	3	C ₃	"	"	"	"	50	25	volts	.5	.003
	4	C ₄	AEROVOX 90A2-6	CERAMIC	.1	uf	100	9.6	volts	.1	.001
	5	C ₅	SPRAGUE MM 350D157X925S2	SOLID TANT.	150	uf	15	4.8	volts	.3	.0004
	6	CR ₁	TEXAS INSTR. 1N645	DIODE (Si)	—	—	.6	.5mw	watts	.1	*.010
	7	CR ₂	"	"	—	—	.6	.5mw	watts	.1	*.010
	8	CR ₃	"	"	—	—	.6	.5mw	watts	.1	*.010
	9	CR ₄	"	"	—	—	.6	.5mw	watts	.1	*.010
	10	CR ₅	MOTOROLA 1N752A (5%)	DIODE, ZENER	5.6	v	.4	0	volts	.1	*.010
	11	* L ₁		INDUCTOR, CHOLE	1.0	mh	3	2.4	amps	.8	.050
	12	Q _{1A}	FAIRCHILD 2N2060 (1/2)	NPN SI DUAL TRANSISTOR	—	—	.3	12.5mw	watts	.1	.020
	13	Q _{1B}	FAIRCHILD 2N2060 (1/2)	NPN SI DUAL TRANSISTOR	—	—	.3	12.5mw	watts	.1	.020
	14	Q ₂	MHT 2305	PNP GC TRANSISTOR	—	—	85	.6	watts	.1	.020
	15	Q ₃	MHT 2305	PNP GC TRANSISTOR	—	—	85	.6	watts	.1	.020
	16	Q ₄	MOTOROLA 2N1365	PNP GC TRANSISTOR	—	—	90	.48	watts	.1	.020
	17	Q ₅	MOTOROLA 2N1365	PNP GC TRANSISTOR	—	—	90	.48	watts	.1	.020
	18	R ₁	RN60C2741F	RESISTOR, FILM	—	k Ω	.125	.002	watts	.1	.0315
	19	R ₂	RN60C1821F	RESISTOR, FILM	—	k Ω	.125	.003	watts	.1	.0315
	20	* T ₁	MAGNETICS INC.	SAT. COEFF. PULSE FORMER	—	—	—	—	—	—	.030
	21	* T ₂	MAGNETICS INC.	POWER TRANSFORMER	—	—	—	—	—	—	.050
	22	—	—	SOLDER JOINTS	—	—	—	—	—	—	.025

750

CONF. SET	$\Sigma \lambda_i$	$\Sigma \lambda_s$	R _e (5)	R _e (3)	R _e (1)
4-A-60	.3484	.050	.856	.911	.969
3-A-60	↓	↓	↓	↓	↓
4-B-60	↓	↓	↓	↓	↓
3-B-60	↓	↓	↓	↓	↓
4-C-60	↓	↓	↓	↓	↓
3-C-60	↓	↓	↓	↓	↓

FIG. # 11

* IN-HOUSE CONSTRUCTION AND DESIGN

* ALTHOUGH THESE DIODES ARE PART OF THE PHYSICAL CONVERTER, IN A RELIABILITY SENSE THEY COMPRISE THE SEPARATE TRIANGLE SENSOR AND ARE NOT INCLUDED IN THE CONVERTER λ_i TALLY.

RELAY APPORTIONMENT

FIG. #12

CONFIGURATION	2	4
NO. OF RELAYS	3	2
CONTACTS/RELAY	2	2
TOTAL USED CONTACTS	5	4

FIG. 12(a)

RELAY FAILURE RATE (SEE MIL-HDBK-217, P. 163, FIG. 46)

OPERATION (STRESS LEVEL)	TYPE	FAILURE RATE	
		% PER 1000 OPERATIONS	% PER 1000 HOURS
NORMAL	F	.010	.020
EXTENDED:	↓		
(a) COIL POWER		.100	
(b) SHOCK			.020
(c) VIBRATION			.020
(d) TEMP.		.010	.050
	↓		
SUB-TOTALS		* .120	.110
			negl.
		TOTAL	.110

$$\left(\frac{\%}{1000 \text{ HRS.}} \right) = \lambda_{kf}$$

* $\frac{\%}{1000 \text{ OPS.}} \times \frac{\text{OPS.}}{\text{HR}} = \frac{\%}{1000 \text{ HRS.}}$, WHICH IN THIS CASE IS NEGLIGIBLE DUE TO THE EXTREMELY SMALL NO. OF OPERATIONS.

FIG. 12(b)

APPENDIX A

Sample Calculations - Converter Design

Case 2B

E_1 - 2.4 volts I_1 - 25 amps P_1 - 60 watts E_o - -24 volts DC

Power Transistor MHT 2101

Tentative Transistor Specifications

$V_{CE(SAT)}$ - 0.030 I_C - 25 amps
 V_{BE} - 0.3 I_B - 1.0
 t_{sw} - 25×10^{-6}

Optimum Frequency Determination

Assume a power transformer efficiency of 97%

$$P_T = 0.03 \times 60 = 1.8 \text{ watts}$$

Minimum converter losses occur at a frequency where transistor losses equal transformer losses.

Then $P_T = P_t = 1.8$ watts

P_t = Total transistor losses

$$P_t = P_D + P_S + P_C$$

$$P_D = \text{Base Drive Losses} = V_{CE} I_B$$

P_C = Conduction losses (closed switch portion of switching cycle)

$$P_C = V_{CE(SAT)} I_C - 2 f t_s V_{CE(SAT)} I_C$$

$$P_S = \text{Switching Losses} = \frac{2 E_1 I_C f t_s}{3}$$

Where E_1 = Input Voltage = 2.4

I_C = Peak Collector Current = 25

f = Frequency in cycles per second

t_s = Switching time in seconds = 25×10^{-6}

$V_{CE(SAT)}$ = Collector - Emitter saturation voltage = 0.030

V_{BE} = Base - Emitter voltage = 0.3

I_B = Base drive Current = 1.0

APPENDIX A

$$P_t = V_{BE} I_B + V_{CE(SAT)} I_C (1 - 2 f t_s) + \frac{2 E_1 I_C f t_s}{3}$$

$$f = \frac{P_t - V_{BE} I_B - V_{CE(SAT)} I_C}{2 I_C t_s \left[\frac{E_1}{3} - V_{CE(SAT)} \right]} = 780 \text{ cps}$$

Transistor Losses

Base Drive Losses for Q₂ and Q₃

$$P_D = V_{BE} I_B = 0.3 \times 1.0 = 0.3 \text{ watts}$$

Conduction Losses for Q₂ and Q₃

$$P_C = V_{CE(SAT)} I_C (1 - 2 f t_s) = 0.03 \times 25 (1 - 2 \times 780 \times 25 \times 10^{-6})$$

$$P_C = 0.72$$

Switching Losses for Q₂ and Q₃

$$P_S = \frac{2 E_1 I_C f t_s}{3} = \frac{2 \times 2.4 \times 25 \times 780 \times 25 \times 10^{-6}}{3}$$

$$P_S = 0.78$$

Total Transistor Losses

$$P_t = 0.78 + 0.72 + 0.3 = 1.8 \text{ watts}$$

Rectifier Losses

$$P_R = E_R I_L = 0.3 \times 2.25 = 0.675 \text{ watts}$$

Total estimated losses for converter operating at 60 watts

$$P_{TOT} = P_t + P_R + P_O, \text{ where } P_O = \text{Oscillator Losses}$$

$$P_O = P_D = 0.3 \text{ watts} \quad P_{TOT} = 1.8 + 1.8 + 0.675 + 0.3 = 4.6 \text{ watts}$$

Estimated Efficiency at 60 watts

$$= \frac{P_1 - P_{TOT}}{P_1} = \frac{60 - 4.6}{60} = 92.3\%$$

APPENDIX B
SNAP 19 DC to DC Converter
Tentative Parts List

	<u>Description</u>	<u>Part No.</u>	<u>Case No.</u>	<u>Mfg</u>	<u>Quantity</u>
Q ₁	Diff Amp	2N2060	All	Fairchild	1
Q ₂ , Q ₃	Ge Tran. PNP	MHT 2305	1A, 2A, 3C	Minn. Honeywell	2
Q ₂ , Q	Ge Tran. PNP	MHT 2101	1B, 2B	"	2
Q ₂ , Q ₃	Ge Tran. PNP	2N2732	3A, 3B	"	2
Q ₄ , Q ₅	Ge Tran. PNP	2N1365	All	Motorola	2
C ₁ , C ₃	Capacitor, Electrolytic	3500226 X905052	All	Sprague	3
C ₄	Capacitor, Ceramic	90A2-6	All	Aerovox	1
C ₅	Capacitor, Electrolytic	3500157 X901552	All	Sprague	1
R ₁	Resistor, Film	RN60C272F	1A, 1B, 2A, 2B 3A, 3B, 3C		1
R ₂	Resistor, Film	RN60C222F	1A, 1B, 2A, 2B		1
R ₁	Resistor, Film	RN60C182F	3A, 3B, 3C		1
T ₁	Transformer, Saturating			Martin Co.	1
T ₂	Transformer, Power			Martin Co.	1
CR ₁ , CR ₄	Si, Diode	1N645	All	Texas Inst.	4
CR ₅	Si, Diode, Ref	1N752A	All	Motorola	1
L ₁	Inductor, D.C.	1MH, 3ADC	All	Martin Co.	1

APPENDIX C

A gross failure mode analysis was conducted to obtain a more objective reliability estimate of each of the four configurations for periods of 1, 3 and 5 years. The results are tabulated in Figure 13. These estimates were compared with A/D reliabilities ranging from 0.6 to 1.0 since A/D reliability is unknown. Thus, A/D reliability is bracketed and its effect on system reliability can be observed in Figure 14.

Using the data from Figure 14, the reliabilities of the best series configuration, Case 3, can be compared with the best redundant configuration, Case 4, in such a way that the effect of A/D reliability is easily discernible, reference Figure 15. In Figure 15, the ordinate represents system reliability and the abscissa, a range of A/D reliability. The plot shows that for a mission time of one year, generator system redundancy does not improve system reliability unless A/D reliability is 0.97 or better. Corresponding A/D reliability values for 3 and 5 year mission times are easily read from the plot.

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B/K

SNAP 19

GENERATOR-CONVERTER SYSTEM RELIABILITY ESTIMATE (RELIABIL. OF A/D=1)

CONFIG.	UNITS										5 YR.	3 YR.	1 YR.	5 YR.	3 YR.	1 YR.
	* Π (UNITS)															
1	G ₁	G ₂	C ₁	C ₂												
	1	1	1	1							.6148	.8101	.9370	$\Sigma \Pi =$.6148 .8101 .9370		
2	G ₁	G ₂	C ₁	C ₂	S ₁	S ₂	K ₁	K ₂	K ₃	A/D						
	1	1	1	1	1	1	1	1	1	1	.5154	.7292	.9047			
	1	1	0	1	1	1	1	1	1	1	.0867	.0712	.0281			
	1	1	1	0	1	1	1	1	1	1	.0867	.0712	.0281			
	1	1	1	1	0	1	1	1	1	1	.0116	.0096	.0036			
	1	1	1	1	1	0	1	1	1	1	.0116	.0096	.0036			
	1	1	1	1	1	1	0	1	1	1	.0231	.0195	.0082			
	1	1	1	1	1	1	1	0	1	1	.0231	.0195	.0082			
	1	1	1	1	1	1	1	1	0	1	.0231	.0195	.0082			
	1	1	0	1	1	1	1	0	1	1	.0039	.0020	.0002			
	1	1	1	0	1	1	0	1	1	1	.0039	.0020	.0002			
	1	1	1	1	1	0	0	1	1	1	.0005	.0003	.0000			
	1	1	1	1	0	1	1	0	1	1	.0005	.0003	.0000			
	1	1	1	1	1	1	0	0	0	1	.0001	.0000	.0000			
	1	1	1	1	1	1	0	0	1	1	.0010	.0005	.0001			
	1	1	1	1	1	1	0	1	0	1	.0010	.0005	.0001			
	1	1	1	1	1	1	1	0	0	1	.0010	.0005	.0001	$\Sigma \Pi =$.7932 .9554 .9934		
4	G ₁	G ₂	C ₁	C ₂	S ₁	S ₂	K ₁	K ₂	A/D							
	1	1	1	1	1	1	1	1	1		.5385	.7487	.9129			
	1	1	0	1	1	1	1	1	1		.0906	.0731	.0284			
	1	1	1	0	1	1	1	1	1		.0906	.0731	.0284			
	1	1	1	1	0	1	1	1	1		.0122	.0099	.0036			
	1	1	1	1	1	0	1	1	1		.0122	.0099	.0036			
	1	1	1	1	1	1	0	1	1		.0242	.0203	.0083			
	1	1	1	1	1	1	1	0	1		.0242	.0203	.0083			
	1	1	0	1	1	1	1	0	1		.0041	.0020	.0002			
	1	1	1	0	1	1	0	1	1		.0041	.0020	.0002			
	1	1	1	1	0	1	1	0	1		.0005	.0003	.0000			
	1	1	1	1	1	0	0	1	1		.0005	.0003	.0000			
	1	1	1	1	1	1	0	0	1		.0011	.0005	.0001	$\Sigma \Pi =$.3029 .9604 .9940		
3	G ₁	G ₂	C ₁													
	1	1	1								.7182	.8893	.9671	$\Sigma \Pi =$.7182 .8893 .9671		

* PRODUCT OF G₁ X G₂ X C₁ ... ETC. USING VALUES FROM FIG. 10(a).

FIG. 13

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SUB-SYSTEM RELIABILITY ESTIMATE

UNIT RELIABILITIES - ALL CONFIGURATIONS

G	$\bar{G}$	C	$\bar{C}$	S	$\bar{S}$	K	$\bar{K}$	A/D	$\bar{A/D}$	YES
.999	.001	.969	.031	.996	.004	.991	.009	*	*	1
.988	.012	.911	.089	.987	.013	.974	.026			3
.916	.084	.856	.144	.978	.022	.957	.043			5

* Parameter to be varied.

CONFIG	A/D	5yr	3yr	1yr
1		.615	.810	.937
2	.6	.476	.573	.596
	.7	.555	.668	.695
	.8	.634	.764	.795
	.9	.714	.859	.894
	1.0	.793	.955	.993
3		.718	.889	.967
4	.6	.482	.576	.596
	.7	.562	.672	.696
	.8	.642	.768	.795
	.9	.723	.864	.894
	1.0	.803	.960	.994

SUB-SYSTEM RELIABILITY
WITH VARIATION OF A/D
CONVERTER PARTIAL
RELIABILITY.

FIGURE 14

APPENDIX C

FIGURE 15

APPENDIX D

REFERENCES

1. Reliability Estimation -
Martin Company Handbook MR-19123A 6/62
2. Reliability Stress and Failure Rate
Data for Electronic Equipment -
Military Standardization Handbook MIL-HDBK-217 8/62
3. Failure Rate Determination for Type
350 D HYBRID SE - (Minuteman) Solid
Tantalum Capacitors, Sprague Technical
Paper. No. 62-15
4. SNAP 17-A Final Report -
Generator Reliability MND-3307-33