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FLASHING LIGHT SATELLITE SYSTEM
FOR
SNAP RADIATION ENVIRONMENTS

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IN NUCLEAR SCIENCE ABSTRACTS

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SANTA BARBARA LABORATORY
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FLASHING LIGHT SATELLITE SYSTEM
FOR SNAP RADIATION ENVIRONMENTS

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Extreme Environments Group

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I. INTRODUCTION

A study of design modifications (Phase I) has been performed on the EG&G Flashing Light Satellite System for reliable operation in a Space Nuclear Auxiliary Power (SNAP) nuclear radiation environment.

The purpose of Phase I was to:

1. Examine the components and materials of the present system and recommend radiation-tolerant replacement items where necessary;
2. Conduct a nuclear test program on present and replacement items which are sensitive to radiation effects, and determine their exact degradation in the SNAP radiation environment;
3. Recommend components, materials, construction techniques, and circuit modifications to be used in constructing the radiation-tolerant system for SNAP applications;
4. Determine Phase II.

II. RADIATION EFFECTS

A. General

The effect of nuclear radiation on a material is to produce changes in the physical and chemical properties of the material. These effects are either transient or permanent or both. Transient damage is dependent on radiation dose rate (primarily gamma), is reversible, and eventually

disappears when the radiation field is removed. In the SNAP applications, however, dose rate is not sufficient to produce significant transient effects.

Permanent damage to materials is irreversible, the amount of damage is dependent on the total radiation dose the material has received. Permanent effects are of concern due to large accumulated doses resulting from long operational time in SNAP applications.

The effects of radiation in materials alter component performance in a variety of ways. In some instances materials deteriorate as they would under normal conditions, the effect of radiation being simply to accelerate the deterioration, i.e., reduce the lifetime. On the other hand, there are specific effects of radiation that will lead to failures not encountered under normal conditions. For example, the evolution of gases from the irradiation of organic materials can result in rupture of the cases of hermetically sealed components. Some unusual types of failures which are not expected are possible, but in general, adequate useful lifetimes in a radiation environment can be predicted through careful selection of materials for a particular application.

The damages in materials by neutrons are due to energetic neutrons losing energy while colliding with atomic nuclei. The mechanisms by which neutrons lose energy through these collisions are elastic collisions, inelastic collisions, and nuclear absorption. Elastic scattering is the prime energy removal process for neutrons with energies below 1 Mev. Inelastic scattering becomes significant in most elements above 0.5 Mev. At higher neutron energies, inelastic scattering becomes more significant. The nuclear absorption reactions of interest at high energies are (n,p) and (n,α) . In thermal neutrons, radiative capture (n,γ) is the dominant mechanism.

An incident high-energy neutron undergoes many collisions in matter prior to thermalization (slowing down) and absorption. Almost every atom struck is knocked from its lattice position and in turn has further collisions producing displacements and ionizations until the displaced atom loses its kinetic energy.

As the knocked-on atom slows down, it travels shorter distances between collisions. As its final energy is dissipated, the knocked-on atom displaces almost all atoms in a small localized region. This gives rise to intense localized heating and disorders called displacement spikes. The processes which follow atomic displacements in materials are not well known. In general, the displaced atoms assume interstitial positions in the lattice and may diffuse through the solid. During this diffusion, they may become trapped at the surface of the material or may recombine with a vacancy in the lattice.

Thermal neutrons, for all practical purposes, undergo only absorptive interactions. The principal problem presented by thermal neutron absorption is that the material becomes radioactive. Large amounts of activation render the component or system nonserviceable from a health physics standpoint. A second effect of large amounts of activation is to increase the gamma dose rate seen by the component and, therefore, to increase the significance of the transient effect.

B Solid State Devices

The solid state devices are the most sensitive components in an electronic system to permanent damage effects. Their general behavior in a radiation environment can be predicted. The analysis of experimental data has indicated that permanent radiation damage induced in a transistor is

primarily due to a decrease of minority carrier lifetime. This decrease is expressed in analytical form by

$$\frac{1}{\tau} = \frac{1}{\tau_0} + \frac{\Phi}{K} \quad (1)$$

where

- τ_0 = Initial minority carrier lifetime (sec);
- τ = Minority carrier lifetime after irradiation (sec);
- Φ = Integrated fast neutron flux (neutrons/cm²);
- K = Neutron damage constant (neutrons-sec/cm²) for base material.

The reduction of minority carrier lifetime is evidenced by a decrease of the current gain and an increase of collector leakage current in the device. Taking the change in minority carrier lifetime as a description of the permanent damage sustained in a transistor, the common emitter current gain is given by

$$\frac{1}{h_{fe}(\Phi)} = \frac{1}{h_{fe}(0)} + \frac{W^2\Phi}{2DK} \quad (2)$$

where

- $h_{fe}(\Phi)$ = Common emitter current gain after irradiation;
- $h_{fe}(0)$ = Initial common emitter current gain;
- W = Width of base region (cm);
- D = Diffusion constant for minority carriers in base region.

The diffusion constant can be expressed in terms of diffusion length and minority carrier lifetime by

$$L = \sqrt{D\tau}$$

or

$$D = \frac{L^2}{\tau} \quad (3)$$

where L = diffusion length for minority carriers in base region

Combining Equations (1), (2), and (3),

$$\frac{1}{h_{fe}(\Phi)} = \frac{1}{h_{fe}(0)} + \frac{W^2 \Phi}{2L^2 \left(\frac{K}{\tau_0 \Phi} + 1 \right)} \quad (4)$$

Examination of the above expression shows that the transistors having narrow base regions and low initial minority carrier lifetimes should be more tolerant to radiation. This observation has been borne out in tests by the superiority of high-frequency devices over low-frequency types. The material from which a transistor is made also affects the radiation tolerance of the device, since the amount of energy required to produce a defect is a function of the material type.

These observations and the results of many radiation tests are summarized in the following general statements.

1. The current gain decreases with increasing neutron exposure.
2. Germanium transistors are generally more tolerant than silicon ones.
3. High-frequency devices (high gain-bandwidth product) are more resistant to radiation than low-frequency devices.
4. Diffused junction devices are more tolerant than either grown or alloy junction devices.
5. Field effect transistors indicate more tolerance than bipolar-type transistors.

This discussion of permanent radiation effects on transistors has been presented primarily with regard to degradation in current gain capabilities of the device. This approach has been used since this parameter is the principal design parameter for many circuit applications, and since significant variations in other parameters will, in most cases, be reflected in variation in the current gain

FIGURE I. FAST NEUTRON DAMAGE TO GERMANIUM AND SILICON TRANSISTORS

of the device. Circuit applications that depend primarily on frequency response or rise and recovery times with only minor dependence upon gain must be treated as special cases.

Figure 1 shows the amount of integrated fast neutron flux required to reduce the common emitter current gain (β) of several transistor types to 70% of its initial value plotted as a function of the device's gain-bandwidth product. The information in this figure is based on radiation studies of several transistor types performed by Dr. Lyndon Taylor of Texas Instruments, Inc. The specific application of these curves to transistor types used in the EG&G system must be made with caution; however, the general implications are valid. The use of this information in conjunction with actual reactor tests should allow a determination of the weak devices in the system and provide a basis for choosing replacements.

III. APPROACH

The performance and reliability of an electronic circuit in a radiation environment is primarily dependent upon the response of the individual components to the environment. The performance and reliability of the circuit is also affected by the cumulative effects of the various components in the combinations of circuit elements and basic circuits comprising a complete system.

Because of this, the approach used in this program must deal both with the individual component degradation and with effects of component degradations on a complex circuit.

The hardening design involves two steps. The first step in improving the radiation tolerance of a given system is to replace susceptible components with components known to be more radiation tolerant. The second step is to

evaluate how circuit performance is affected by the combination of various circuit component effects.

The components in the present EG&G system were first separated into three groups according to relative sensitivity to the proposed environment. These three groups are (a) sensitive, (b) moderately sensitive, and (c) non-sensitive. The division between each classification is somewhat arbitrary and is based more on experience than on any specific numerical values.

- Group 1. Sensitive transistors, silicon-controlled rectifiers.
- Group 2. Moderately sensitive diodes, electrolytic and film capacitors.
- Group 3. Non-sensitive resistors, ceramic capacitors, inductors.

The relative sensitivity of a device in any of the above groups is dependent upon its material type, construction, operating requirements, and other parameters. To determine the sensitivity of a particular component, information was obtained from previous work on comparable devices or from direct environmental test of the component.

Group 1. Sensitive Components

All the present components in this group (transistors and silicon-controlled rectifiers) are expected to suffer significant degradation in the SNAP environment. This will still be true where the present sensitive components are replaced by the most radiation-tolerant types. Therefore, all the present devices were tested to determine exactly their degradation in the SNAP environment. Also included in the test were potential replacement types, in case excessive degradation occurred in the types presently used.

A variety of silicon-controlled rectifiers were tested to determine if any were capable of acceptable operation in the SNAP environment.

Group 2. Moderatively Sensitive Components

Some of the components in this group (diodes, electrolytic and film capacitors) may suffer light damage. The electrolytic capacitors and diodes with large junction areas are the most likely to be significantly affected. However, no serious problems were expected.

The rest of the diodes, including zener, rectifiers, and computer types, should be satisfactory to 1 to 2 orders of magnitude above the SNAP environment.

To substantiate these predicted results, this group of components was exposed to the radiation environment (along with the sensitive group) and the degradation in their characteristics measured. No potential replacement items were included in the tests.

Group 3 Non-Sensitive Components

Based on information from previous radiation effects programs, it was possible to eliminate the components in the non-sensitive group, (resistors, ceramic capacitors, inductors, wire, plotting compound, standoffs) as probable sources of problems in this radiation environment.

IV. EXPERIMENTAL EVALUATION

Samples of all components in the EG&G system in the sensitive or moderately sensitive groups, along with a number of possible substitute devices, were obtained for test. The electrical characteristics of all these devices were measured. All the components were then irradiated in a nuclear reactor to a neutron exposure equivalent to the SNAP environment exposure. Next, they were irradiated in a Cobalt-60 gamma source to simulate the expected gamma radiation exposure of the SNAP radiation environment. After

TABLE 1. Present Transistors and
Possible Substitutes

<u>Present Device Number and Type</u>	<u>Substitute Number and Type</u>
2N404 (RCA) Germanium PNP	None required
2N635A (GE,Co.) Germanium NPN	None required
2N706 (Motorola) Silicon NPN	This is replacement for 2N772 and 2N775 already incorporated from considerations other than radiation.
2N859 (Philco) Silicon PNP	None Available
2N696 (Pacific) Silicon NPN	None required
2N1479 (RCA) Silicon NPN	2N635A (GE Co.) Germanium NPN
2N1653 (Bendix) Germanium PNP (power converter)	None available (Problem area)
	2N1304 (TI) Germanium NPN
	2N1406 (TI) Germanium PNP
	2N702 (TI) Silicon NPN
	2N726 (TI) Silicon NPN
	2N710 (TI) Germanium PNP
	2N797 (TI) Germanium NPN
	2N743 (TI) Silicon NPN

TABLE 2. Radiation Damage to Present Zener Diodes

<u>Manufacturer</u>	<u>Zener Voltage, volt</u>		<u>Zener Current, ma</u>
	<u>Before</u>	<u>After</u>	<u>Before and After</u>
<u>Motorola</u>			
1N992A-A	213.7	214.33	0.650
1N992A-B	213.4	215.00	0.650
1N992A-C	212.7	213.85	0.650
<u>Hoffman</u>			
1N1833A-A	68.35	69.15	50.0
1N1833A-B	69.86	69.15	50.0
1N1833A-C	67.48	67.08	50.0
1N1833A-D	69.65	69.25	50.0
<u>Motorola</u>			
1N749A-A	4.327	4.357	20.0
1N749A-B	4.427	4.279	20.0
1N753A-A	6.320	6.312	20.0
1N753A-B	6.392	6.408	20.0
1N754A-A	6.539	6.533	20.0
1N754A-B	6.983	6.998	20.0
<u>Transitron</u>			
SV1004-A	5.191	5.085	100.0
SV1004-B	5.277	5.173	100.0

TABLE 3. Radiation Damage to Present Capacitors
(Sprague)

	Rated Values		Zero Voltage				Rated Voltage					
			Capacitance, μf		Dissipation Factor		Capacitance, μf		Dissipation Factor		Leakage Current, μamp	
	μf	volts	Before	After	Before	After	Before	After	Before	After	Before	After
500	100	20	90.6	91.5	0.125	0.163	88.5	89.0	0.110	0.150	1.7×10^{-6}	1.33×10^{-5}
500	100	20	91.5	92.4	0.115	0.155	89.5	90.0	0.103	0.136	7.5×10^{-7}	1.15×10^{-6}
100	100	20	93.0	94.3	0.118	0.158	91.0	91.5	0.108	0.143	3.0×10^{-6}	1.70×10^{-6}
100	100	20	94.5	95.8	0.117	0.153	92.3	93.0	1.105	0.140	8.0×10^{-7}	1.30×10^{-6}
100	0.47	35	0.475	0.473	0.061	0.063	0.472	0.471	0.049	0.052	6.0×10^{-6}	1.25×10^{-7}
100	0.47	35	0.474	0.472	0.052	0.053	0.470	0.468	0.037	0.040	3.5×10^{-9}	1.05×10^{-7}
100	0.47	35	0.473	0.472	0.054	0.054	0.471	0.470	0.042	0.046	5.5×10^{-9}	1.20×10^{-7}
100	3.0	200	3.11	3.13	0.0057	0.008	3.14	3.13	0.0058	0.008	2×10^{-6}	1.0×10^{-7}
252	3.0	200	3.11	3.09	0.0056	0.008	3.10	3.09	0.0059	0.008	1.5×10^{-6}	1.0×10^{-7}
19592249	0.22	400	0.230	0.228	0.0035	0.004	0.230	0.228	0.0035	0.0040	2.8×10^{-5}	6.0×10^{-7}
452	0.22	400	0.231	0.229	0.0037	0.0042	0.231	0.229	0.0037	0.0042	2.3×10^{-8}	5.8×10^{-7}
	0.22	400	0.215	0.212	0.0030	0.0038	0.215	0.212	0.0030	0.0038	2.5×10^{-8}	5.8×10^{-7}
	0.22	400	0.218	0.215	0.0035	0.004	0.218	0.215	0.0035	0.0040	3.0×10^{-6}	5.0×10^{-7}
(0330d)	525	450	572	600	0.43	0.95	585	625	0.46	0.95	1.45×10^{-4}	3.4×10^{-4}
	525	450	581	625	0.42	0.93	596	650	0.44	0.98	1.95×10^{-4}	2.8×10^{-4}

allowing a period of time for radioactive decay of activated components, post-irradiation measurements of electrical characteristics were made. At this time, radioactivation in the devices was virtually unmeasurable.

A. Component Selection

Table 1 lists the transistor types used in the present system and possible direct replacements where little or no circuit modification is required. The list also includes some other types that may be used as substitutes where more extensive circuit modifications would be required. All of the types listed were tested in the reactor evaluation program.

The diodes used in the present system are expected to suffer little degradation in the SNAP environment; therefore, no replacements were tested in the radiation evaluation tests. These include the computer diodes, rectifier diodes and zener diodes that are all listed in Table 2.

No substitute capacitors were expected to be necessary, therefore, only the types used were tested. The capacitors are listed in Table 3.

One of the most critical and radiation sensitive components in the system was the silicon-controlled rectifier, (SCR). Information on the radiation tolerance of SCR's is limited. The only information¹ available at the time of this investigation was for the General Electric C35A which is not the particular device used in the EG&G system. The radiation effects data on the C35A are shown in Figures 2 and 3. These results show the SCR to be very sensitive to radiation, and indicate that serious degradation will probably occur in a

1. H. J. Lubatti, "GODIVA III Minuteman Radiation Effects Test," Boeing T2-2128, October, 1960.

FIGURE 2. FAST NEUTRON PRODUCED VARIATIONS IN THE GATE CURRENT OF SILICON-CONTROLLED RECTIFIERS

FIGURE 3. FAST NEUTRON PRODUCED VARIATIONS IN THE
BREAKOVER VOLTAGE CHARACTERISTICS
OF SILICON-CONTROLLED RECTIFIERS

TABLE 4. Radiation Damage to Some Silicon-Controlled Rectifiers
(Texas Instruments Company)

<u>Type</u>	<u>Gate Voltage, volts</u>		<u>Gate Current, ma</u>		<u>Breakover Voltage, volts</u>		<u>Comment</u>
	<u>Before</u>	<u>After</u>	<u>Before</u>	<u>After</u>	<u>Before</u>	<u>After</u>	
2N1604-A	1.37	> 25	5.97	> 20	635	-	Dead
2N1604-B	1.29	1.7	6.0	8	685	715	Normal
2N1602-A	2.45	> 25	9.25	> 20	545	-	Dead
2N1602-B	2.52	> 25	5.85	> 20	955	-	Dead
2N1602-C	1.74	> 25	5.50	> 20	590	-	Dead
2N1602-D	1.69	> 25	7.25	> 20	500	-	Dead
2N1597-A	2.16	6.2	4.77	33	650	-	Intermittent*
2N1597-B	1.89	5.6	4.33	31	770	-	Intermittent*
2N1597-C	2.60	4.0	5.23	12	500	515	Normal
2N1597-D	2.16	> 25	4.87	> 20	547	-	Dead
2N1597-E	1.33	> 25	4.87	> 20	730	-	Dead

*Intermittent means the device would turn on only during the duration of the gate pulse and remained on less than a full gate pulse cycle. Removal of gate signal resulted in zero collector current.

SNAP radiation environment. The large spread in the experimental data for different units of the same type indicates that prediction of the performance of an individual unit in a radiation environment would be difficult. Based on the available information, serious degradation of the SCR's parameters was expected in the environmental test. The types tested in this program are listed in Table 4.

B. Electrical Measurements

The measurement of collector characteristics of the transistors was achieved using a Tektronix Model 575 Transistor Curve Tracer. Photographs were taken of the family of curves for each device. The common emitter current gain was measured with the curve tracer set up for measurement of current gain. The measurement of I_{CBO} and BV_{CBO} were made using a Lambda Power Supply and Keithley Micro-Microammeter. The I_{CBO} was measured at V_{CBO} specified by the manufacturer in his spec sheets and BV_{CBO} was measured at specified I_{CBO} where available.

Zener diodes were measured for zener voltage at specified zener current using a John Fluke DC Differential Voltmeter and a Hewlett-Packard DC Vacuum-Tube-Volt-Ammeter. The accuracy of the measurements was 1/2% or better. Computer and rectifier diodes were measured by photographing the diode characteristics on the Tektronix Curve Tracer.

Capacitors were measured at zero voltage and at rated voltage using a General Radio 1650-A Impedance Bridge. Measurement of leakage current was made at rated voltage using a Keithley Micro-Microammeter.

Measurement of SCR characteristics was achieved using the circuits shown in Figure 4. The value of gate voltage and gate current was observed with a Tektronix 551A Dual Beam Oscilloscope.

A. CIRCUIT FOR MEASURING GATING CHARACTERISTICS

B. CIRCUIT FOR MEASURING BREAKOVER VOLTAGE

FIGURE 4. CIRCUITS FOR MEASURING SCR CHARACTERISTICS

The EG&G system also contains DIAN driver and shift register modules which were furnished by Boston to the Santa Barbara Laboratory for irradiation. Pre-irradiation and post-irradiation measurements were made by DIAN for Boston and are not reported here.

C. Radiation Environment and Irradiation

The simulation of the proposed environment required the following exposures:

neutron - 1×10^{12} neutrons/cm², E > 0.5 Mev

gamma - 2.3×10^8 ergs/gm(C), E_{average} ~1.0 Mev

The radiation fields of a pool-type reactor have a lower gamma-to-neutron ratio than required, therefore, the irradiation was carried out in two steps. The initial exposure was performed at the Battelle Memorial Institute (BMI) reactor at a low power level and at a distance from the core face. The purpose in achieving the initial exposure in this manner was to minimize radiation heating of the components.

The assembly of components, and the cadmium-lined chamber in which irradiation was performed, are shown in Figures 5 and 6.

Pre-irradiation dosimetry was performed by BMI in a chamber similar to that shown in Figure 6. The radiation dose received during the actual irradiation was determined by placing monitor foils in the chamber (Figure 6) along with the components. The results of these measurements indicate the dose received by the components was

neutron - 4.8×10^{12} n/cm², E > 0.5 Mev

gamma - 7.1×10^7 ergs/cm(C), E_{average} ~1.0 Mev

The reason for overexposure to neutrons by a factor of 4.8 is not known and is being investigated by BMI. The

FIGURE 5. CADMIUM-LINED CHAMBER AND COMPONENT SUBASSEMBLIES

FIGURE 6. CADMIUM-LINED CHAMBER AND COMPONENT ASSEMBLY

radioactive components were allowed to decay to a safe level and were shipped back to the Santa Barbara Laboratory. A few of the components were spot checked for change in electrical characteristics.

Since the components had received only one-third of the desired gamma dose, an additional exposure was next made in the Cobalt-60 facility at the Santa Barbara Laboratory.

Post-irradiation measurements of electrical characteristics were then made on all components.

D. Results and Analysis

1. Capacitors

Table 3 listed the complete set of measurements made on all the capacitors both before and after the irradiation. None of the parameters showed changes due to irradiation which would constitute a problem. The parameters measured were capacity, dissipation, and leakage current. Probably the most critical capacitor is the 525- μ f, 400-volt aluminum electrolytic unit. Although this unit received 4.8 times the expected neutron dose, the changes exhibited are tolerable.

2. Diodes (Computer and Rectifier)

None of the computer and rectifier diodes exhibited significant changes due to radiation. Curve tracer photographs of diode characteristics were similar for all units and an example of one is given in Figure 7. For the proposed radiation environment, the computer and rectifier diodes will not constitute a problem area.

3. Diodes (Zener)

The measurement of zener voltage at specified zener current both before and after irradiation is given in Table 2.

(a) PRE-IRRADIATION

(b) POST-IRRADIATION

FIGURE 7. IN547(A) DIODE CHARACTERISTICS
(TEXAS INSTRUMENTS, INC.)

The largest observed change was about -2.5% and was noted in one of the 1N479 units. There appeared to be no pattern to the change as one-half of all the units showed an increase in zener voltage and one-half of all the units showed a decrease in zener voltage. No decisions can be made at this time on the acceptability of the zener diodes since firm tolerance limits have not been specified.

4. Transistors

Tabulation of all transistor measurements is given in Tables 5 and 6. The transistors used in the system are listed in Table 5, and other transistor types that may be considered for substitutes are given in Table 6.

Transistor 2N1653 is a high power device used in the power convertor and as was expected, suffered considerable permanent damage. The efficiency of the power convertor will drop as a result of decreased beta and increased I_{CBO} . The continued use of this device will be determined by the operation of the system with the power convertor operating at reduced efficiency. Collector characteristics for the three units tested are shown in Figures 8, 9, and 10.

Transistor 2N1479, which exhibits extreme degradation, $\beta/\beta_0 \sim 0.03$, in the proposed radiation environment can be replaced readily with a 2N635A and is already being planned in view of other circuit requirements. The data on the 2N635A, Table 5, show considerably less degradation in comparison, however, the range of final β/β_0 is 0.56 to 1.08 for two samples. Figures 11 and 12 show the 2N635A collector characteristics for two units tested. Methods of dealing with this spread are considered later.

Transistor 2N859, Table 5, is also considered to exhibit excessive decrease in β . Figure 13 shows collector characteristics for one of the units tested. Suitable replacement for

TABLE 5. Radiation Damage to Present Transistors

Manufacturer	Common Emitter Current Gain (β) at Indicated Current, amp				Collector-to-Base Leakage Current (I_{CBO}), μa at Indicated Voltage				Collector-to-Base Breakdown Voltage (BV _{CBO}) at Indicated Current, ma				
	Before		After		β/β_0	Before		After		Before		After	
	β	amp	β	amp		μa	v	μa	v	v	ma	v	ma
<u>Bendix</u>													
2N1653-A	82.5	at 6.5				204	at 50			152	at 5		
2N1653-B	80.0	at 6.5	42.5	at 2.50	0.53	116	at 50	980	at 50	159	at 5	155	at 5
2N1653-C	61.5	at 2.2	23.0	at 0.78	0.37	195	at 50	1200	at 50	191	at 5	191	at 5
2N1653-D	85.0	at 8.0	45.0	at 3.75	0.53	118	at 50	940	at 50	170	at 5	176	at 5

Manufacturer	Common Emitter Current Gain (β) at Indicated Current, ma				Collector-to-Base Leakage Current (I_{CBO}), μa at Indicated Voltage				Collector-to-Base Breakdown Voltage (BV _{CBO}) at Indicated Current, μa				
	Before		After		β/β_0	Before		After		Before		After	
	β	ma	β	ma		μa	v	μa	v	v	μa	v	μa
<u>RCA</u>													
2N1479-A	9.6	at 0.24	0.3	at 0.006	0.015	0.92	at 30	4.7	at 30	194	at 100	192	at 100
2N1479-B	6.8	at 0.17	0.4	at 0.008	0.045	0.70	at 30	0.58	at 30	100	at 100	110	at 100
<u>Philco</u>													
2N859-A	34	at 0.72	13.5	at 0.235	0.397	0.021	at 40	0.13	at 40	52.1	at 20	52	at 20
2N859-B	44	at 0.90	26.0	at 0.440	0.590	0.018	at 40	0.10	at 40	74.7	at 20	73	at 20
<u>Pacific</u>													
2N696A-A	9.0	at 0.170	7	at 0.140	0.768	0.006	at 30	0.015	at 30	174	at 100	160	at 100
2N696A-B	7.6	at 0.132	6	at 0.115	0.780	0.110	at 30	0.018	at 30	168	at 100	186	at 100
<u>Motorola</u>													
2N706-A	42	at 1.06	42	at 1.06	1.00	0.0237	at 25	0.033	at 25	118	at 100	117	at 100
2N706-B	49	at 1.00	38	at 0.78	0.775	0.0270	at 25	0.021	at 25	160	at 100	160	at 100
<u>GE, Co</u>													
2N635A-A	88	at 1.70	95	at 2.0	1.08	2.40	at 25	4.6	at 25	51.5	at 100	52.2	at 100
2N635A-B	143	at 3.45	80	at 1.9	0.56	1.44	at 25	13.0	at 25*	58.2	at 100	48.5	at 100
<u>RCA</u>													
2N404-A	140	at 3.33	140	at 2.70	1.00	0.60	at 12	2.0	at 12	70.8	at 20	71.1	at 20
2N404-B	115	at 2.75	90	at 1.65	0.785	0.83	at 12	2.3	at 12	49.7	at 20	49.8	at 20

* These units were damaged during post-irradiation measurement
 * Drifted up from 3.8 μa

TABLE 6. Radiation Damage to Alternate Transistor Types
(Texas Instruments Company)

Transistor Type	Common-Emitter Current Gain (β) at Indicated Current, ma					S/ β_0	Collector-to-Base Leakage Current (I_{CBO}) at Indicated Voltage				Collector-to-Base Breakdown Voltage (BV_{CBO}) at Indicated Current, ma			
	Before		After				Before		After		Before		After	
	I, ma	β	I, ma	β	μ a		V	μ a	V	V	μ a	V	μ a	
2N700-A	115 at 2.60		90 at 2.15		0.78	1.20 at 5		2.0 at 5		75.7 at 100		76.1 at 100		
2N700-B	105 at 2.70		90 at 2.35		0.86	1.35 at 5		2.2 at 5		81.5 at 100		83.7 at 100		
2N700-C	115 at 2.30		120 at 3.20		0.96	1.50 at 5		1.9 at 5		92.7 at 100		93.8 at 100		
2N701-A	42 at 0.90		26 at 0.68		0.62	2.05 at 5		4.3 at 5		39.3 at 100		40.7 at 100		
2N701-B	100 at 2.15		54 at 1.26		0.54	2.55 at 5		3.1 at 5		36.1 at 100		36.7 at 100		
2N701-C	59 at 1.10		22 at 0.76		0.62	2.05 at 5		2.5 at 5		38.3 at 100		38.2 at 100		
2N702-A	15 at 0.28		9.5 at 0.17		0.63	0.27 at 12		0.47 at 12		43.6 at 100		43.8 at 100		
2N702-B	24 at 0.45		9.0 at 0.17		0.37	0.33 at 12		0.48 at 12		43.0 at 100		43.0 at 100		
2N702-C	23 at 0.42		19.5 at 0.36		0.85	0.31 at 12		0.36 at 12		46.0 at 100		45.9 at 100		
2N703-A	40 at 0.82		33 at 0.68		0.83	0.0037 at 10		0.0032 at 10		94.0 at 5		93.2 at 5		
2N703-B	50 at 1.14		44 at 1.11		0.78	0.0038 at 10		0.0034 at 10		91.2 at 5		89.1 at 5		
2N703-C	70 at 0.57		26 at 0.55		0.87	0.0041 at 10		0.0034 at 10		90.9 at 5		89.0 at 5		
2N705-A	9 at 0.13		8.0 at 0.132		0.89	0.57 at 5		0.32 at 5		25.8 at 100		25.7 at 100		
2N705-B	8 at 0.15		8.5 at 0.150		1.06	0.39 at 5		0.38 at 5		26.6 at 100		26.5 at 100		
2N705-C	21 at 0.37		23.0 at 0.400		1.09	0.28 at 5		0.36 at 5		26.1 at 100		26.1 at 100		
2N726-A	33 at 0.61		24 at 0.45		0.73	0.0045 at 10		0.0075 at 10		51.2 at 100		62.1 at 100		
2N726-B	20 at 0.38		18 at 0.39		0.90	0.0045 at 10		0.0082 at 10		59.9 at 100		59.8 at 100		
2N726-C	14 at 0.22		8 at 0.12		0.57	0.0720 at 10		0.11 at 10		60.2 at 100		61.6 at 100		
2N710-A	8.5 at 0.145		8.8 at 0.200		1.03	11.5 at 10		12.0 at 10		24.8 at 100		25.0 at 100		
2N710-B	17 at 0.275		14.0 at 0.225		0.82	0.26 at 10		0.4 at 10		26.2 at 100		26.1 at 100		
2N710-C	17 at 0.320		18.0 at 0.340		1.06	3.50 at 10		3.6 at 10		25.9 at 100		25.8 at 100		
2N797-A	105 at 2.25		80 at 1.60		0.76	0.130 at 5		0.12 at 5		24.9 at 100		24.9 at 100		
2N797-B	160 at 3.70		105 at 2.25		0.66	0.092 at 5		0.16 at 5		24.7 at 100		24.6 at 100		
2N797-C	190 at 4.20		145 at 3.20		0.76	0.135 at 5		0.15 at 5		23.1 at 100		23.1 at 100		
2N743-A	32 at 0.65		25 at 0.46		0.78									
2N743-B	44 at 0.91		Lost											
2N743-C	40 at 0.80		34 at 0.68		0.85

FIGURE 8. 2N1653(B) CHARACTERISTICS
 (BENDIX CORP.)

FIGURE 9. 2N1653(C) COLLECTOR CHARACTERISTICS
 (BENDIX CORP.)

EXPOSURE
 NEUTRON: $4.8 \times 10^{12} \text{ n/cm}^2$ ($E > 0.5 \text{ Mev}$)
 GAMMA: $2.3 \times 10^8 \text{ ergs/gm (C)}$ ($E_{av} = 1.0 \text{ Mev}$)

FIGURE 10. 2N1653(D) COLLECTOR CHARACTERISTICS
 (BENDIX CORP.)

(a) PRE-IRRADIATION

(b) POST-IRRADIATION

EXPOSURE

NEUTRON: $4.8 \times 10^{12} \text{ n/cm}^2$ ($E > 0.5 \text{ Mev}$)GAMMA: $2.3 \times 10^8 \text{ ergs/gm(c)}$ ($E_{\text{av}} = 1.0 \text{ Mev}$)

FIGURE II. 2N635A(A) COLLECTOR CHARACTERISTICS
(GENERAL ELECTRIC CO.)

(a) PRE-IRRADIATION

EXPOSURE
 NEUTRON: $4.8 \times 10^{12} \text{ n/cm}^2$ ($E > 0.5 \text{ Mev}$)
 GAMMA: $2.3 \times 10^8 \text{ ergs/gm (C)}$ ($E_{av} = 1.0 \text{ Mev}$)

(b) POST-IRRADIATION

FIGURE 12. 2N635A(B) COLLECTOR CHARACTERISTICS
 (GENERAL ELECTRIC CO.)

(a) PRE-IRRADIATION

(b) POST-IRRADIATION

FIGURE 13. 2N859(B) COLLECTOR CHARACTERISTICS
 (PHILCO CORP.)

FIGURE 14. 2N705(B) COLLECTOR CHARACTERISTICS
 (TEXAS INSTRUMENTS INC.)

FIGURE 15. 2N696A(B) COLLECTOR CHARACTERISTICS
 (PACIFIC SEMICONDUCTORS INC)

FIGURE 16. 2N706A(A) COLLECTOR CHARACTERISTICS
(MOTOROLA INC.)

FIGURE 17. 2N404(A) COLLECTOR CHARACTERISTICS
 (RADIO CORPORATION OF AMERICA)

this type is not available. Redesign of the basic circuit will be required using a transistor exhibiting acceptable radiation tolerance. The remaining types in Table 5, Figures 15, 16 and 17, 2N696A, 2N706, 2N404 show approximately equal degradations, $\beta/\beta_0 \sim 0.77$, and it is considered that little or no improvement can be expected by substituting other types.

Table 6 contains data on a number of transistor types which were chosen on the basis of the criteria listed for selecting transistors having relatively high tolerance to radiation environments.

It is of interest to plot the observed β/β_0 as a function of gain-bandwidth product of the device and material type for the neutron environment experienced by the transistors in this experiment. This information is shown in Figure 18. The general trend of higher frequency devices suffering less degradation than lower frequency devices is observed. The significant falloff in radiation tolerance for the germanium units at the high gain-bandwidth end is not presently understood. The generally smaller tolerance of the silicon devices compared to the germanium devices is also observed.

5. Silicon-Controlled Rectifier

It is evident (Table 4) that SCR 2N1604 presently used in the system has insufficient tolerance to survive the radiation environment. The two other types tested, 2N1602 and 2N1597, are also incapable of surviving the environment. On the basis of Figure 2 it is noted that this might be predicted by observing that at $4.8 \times 10^{12} \text{ n/cm}^2$, the failure rate is extremely high. Had the SCR devices received only $1 \times 10^{12} \text{ n/cm}^2$ as originally specified, it is possible that more of the units would have survived. However, the SNAP radiation environment is not accurately known under all conditions. Since it is mandatory that the device and the

FIGURE 18. FAST NEUTRON DAMAGE TO GERMANIUM AND SILICON TRANSISTORS

system be able to tolerate an environment somewhat in excess of the expected environment, the SCR devices are not suitable for this application.

V. CONCLUSIONS AND RECOMMENDATIONS

The following components in the EG&G Flashing Light Satellite System are considered to be sufficiently radiation tolerant to the proposed SNAP environment:

1. Resistors,
2. Capacitors, and
3. Computer and rectifier diodes.

The following components fall into an area of marginal radiation tolerance.

1. 2N404
2. 2N635A
3. 2N696
4. 2N706
5. All zener diodes.

The acceptance or rejection of these components for the radiation environment is dependent upon particular circuit applications. Tolerance limits must be specified and the irradiated components tried in a working circuit to determine acceptability.

The following components are considered to have excessive degradation in the proposed radiation environment. Listed with each component is a possible replacement component having much better tolerance to the radiation environment:

2N859	None available
2N1479	2N635A
2N1653 (power converter)	None available
2N1604 (SCR)	None available

Ultimately, the adequacy of the replacement will need to be established.

In the case of the last two items listed, 2N1653 and 2N1604, no direct replacements appear to be available. A separate effort is necessary to solve these two problem areas and are considered in the proposed Phase II section.

The number of samples of each component used in this Phase I effort are not considered sufficient to establish reliability numbers. The purpose of this Phase I effort was to identify probable problem areas and the problem areas thus determined are the guidelines upon which effort would be based during Phase II.

VI. PHASE II

From the results obtained in the Phase I study, the Phase II effort would be divided into two major investigations. One investigation would involve the resolution of the marginal areas of moderately radiation-sensitive components. These components would suffer some degradation in the proposed environment and the final acceptance of these components would have to be based on firmly established tolerance limits or on measured circuit performance. The second investigation would concern the components predicted to fail in the expected environment. The approach to be followed in this problem area would attempt to find radiation-tolerant devices or a combination of devices and circuit modifications which will reliably survive the expected radiation environment.

Few tolerance limits were specified for the components in the system for the Phase I study. Because of the high reliability that is required of the system, it will be necessary that tolerance limits for all components be determined. The number of samples used in the Phase I study was insufficient upon which to base reliability calculations.

Therefore, it is proposed that larger sample sizes be irradiated in order that meaningful reliability figures can be generated.

It also is planned that each radiation-sensitive component in the system be replaced by one which has been irradiated to the expected exposure level and the system performance evaluated. This procedure will establish with confidence those components which will need replacement and will further define the problem areas in the system. By this technique, the extent to which component selection can be used and the extent to which feedback and other circuit techniques must be used can be determined.

From the available data it appears that SCR's will require replacement with some other type of device, probably some type of gas tube device. Choice of the type of replacement will depend upon electrical requirements and tolerance to radiation, temperature, and mechanical environments.

The degradation of the power transistors in the power convertor is significant. One possible solution requiring study and evaluation is replacing each power transistor by two or more lower power units in parallel, having a total power rating equivalent to the unit replaced. Since lower power units normally have a narrower base region, the amount of neutron-induced damage will be less in each unit. Whether this procedure results in any over-all gain in tolerance to the radiation environment would need to be determined.