Implications of Single Event Effect Characterization of Hybrid DC-DC Converters and a Solid State Power Controller

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Abstract

As part of National Aeronautics and Space Administration (NASA)/Goddard Space Flight Center's (GSFC) efforts in supporting spaceflight qualification for multiple programs, single event effect (SEE) characterization of various DC-DC power converters as well as a solid-state power controller (SSPC) was undertaken. The implications of these test results are further discussed.

I. INTRODUCTION

In the NASA world of shrinking spacecraft size and cost while increasing system performance, distributed power systems represent a potential savings to the spacecraft designer. Efforts to increase power efficiency and lower electromagnetic interference to sensitive loads have led designers to move away from a regulated power bus design to an unregulated bus with regulation and filtering performed at the loads. A spacecraft utilizing a distributed power system (non-Radioisotope Thermoelectric Generator or RTG) concept is shown in Figure 1.

Solar arrays, typically formed out of Si or GaAs cells, collect solar energy. This energy is converted to a single voltage that is regulated and used in conjunction with batteries to power the spacecraft. This voltage then can be either converted at the power subsystem level to user voltages (+/-5V, +/-15V, etc...) and bussed or it may be distributed on a unregulated spacecraft bus. The majority of these subsystems would either use this unregulated power directly (Payload 1) or they would require their own regulation in the form of local DC-DC converters to adjust the spacecraft bus voltage to their own user requirements (Payloads 2 and 3).

These local DC-DC converters are more commonly becoming hybrid devices containing power MOSFETs as well as assorted analog and digital electronics such as pulse width modulators (PWMs), diodes, and other support circuitry. It should be noted that the spacecraft power bus voltage is nominally 28V, but in unregulated battery bus systems may vary by +/-6 or 7V. Hence the local DC-DC converters must be able to handle this voltage range while providing their own regulated voltages to the subsystem electronics. These hybrids typically have reduced volume and weight versus older technology discrete circuitry DC-DC converters.

The SSPC is designed to replace traditional circuit breakers (electromagnetic) and solid state relays in spacecraft vehicle applications. These hybrid packages are usually much smaller and lighter than the systems they replace.

II. TEST METHOD AND DEVICES

A. Objectives

The objective of this study was to determine the threshold linear energy transfers (LETths) and saturation cross sections (when available) for single event upset (SEU) and for destructive single event conditions such as single event latchup (SEL) or single event gate rupture (SEGR) due to heavy ions. SEU LETth is defined as the minimum LET value to cause an effect at a fluence of 1E6 particles/cm2. SEL and SEGR LETth is defined as the maximum LET value at which no condition occurs at a fluence of 1E6 particles/cm2. The saturation cross section of the device is the point at which the cross section curve becomes asymptotic. An additional objective was to determine the spacecraft usability of these devices in a space radiation environment for SEEs.

B. Test Devices

Note that, the two AHE2815 devices contained two separate lots of the PWMs inside their respective hybrids. Test results are combined, however, since no statistical difference in the SEE response was observed. All test samples were delidded and denuded of conformal coatings in order to accommodate beam penetration limits of the test facility.

Table 1 provides a list of test devices while Table 2 summarizes the salient characteristics of those test devices. The general internal components of the DC-DC hybrids (PWM, MOSFETs, etc...) were known, but specifics (which MOSFET, etc...) were considered proprietary by the hybrid manufacturers. Items, normally of key interest such as internal biases or voltage and breakdown ratings on the power MOSFETs, were unknown. In some cases, as will be seen in section III, limited further analyses were performed if the device showed hazardous failure mechanisms.

Table 1. Test Devices

Device Type	Manufacturer	Date Code	Test Samples
AHE2815DF/ CH-SLV	Advanced Analog	9345	3
AHE2815D/HB	Advanced Analog	NA	2

MDI2690R-D15F	MDI	9324	2
MFL2815D	Interpoint	9443	2
MFL2815S	Interpoint	9442	2
MFL2812S	Interpoint	9442	2
MFL2805S	Interpoint	9442	2
SSP-21110-025	ILC Data Devices	NA	3

Table 2. Test Devices - Salient Characteristics

Device	Input Range	Outputs	Output Power (Max)	Effcy. (max)	Operating Temp. Range	Operating Frequency	Size
AHE2815D[1]	17 to 40V	+/-15V (dual)	15W	82%	-55 to +125C	250 kHz	2.12" x 1.12" x 0.495"
MDI2690R[2]	16 to 50V	+/-15V (dual)	6.5W	85%	-55 to +85C	200 kHz	2.12" x 1.12" x 0.495"
MFL2815D[3]	16 to 40V	+/-15V (dual)	65W	70%	-55 to +125C	600 kHz	3.0" x 1.5" x 0.39"
MFL2815S[3]	16 to 40V	+15V (sngl.)	65W	70%	-55 to +125C	600 kHz	3.0" x 1.5" x 0.39"
MFL2812S[3]	16 to 40V	+12V (sngl.)	65W	70%	-55 to +125C	600 kHz	3.0" x 1.5" x 0.39"
MFL2805S[3]	16 to 40V	+5V (sngl.)	65W	70%	-55 to +125C	600 kHz	3.0" x 1.5" x 0.39"
SSP-21110[4]	9 to 40V	9 to 40V	>700W	NA (max 7.7W pwr diss.	-55 to +125C	NA	2.74" x 1.34" x 0.33"

The SSPC (SSP21110) that was tested is rated up to 25A. Several lower current-rated models are available all using the same internals.

The SSP21110s are fairly novel. In the event of on overload, like a circuit breaker, they will trip and automatically remove device power. Control inputs must then be used to return device power. Trip time for an overcurrent condition is a function of the current level: the higher the overcurrent, the faster the SSPC will trip. Being built with power MOSFETs and custom monolithics as well as using thick-film hybrid technology, reliability of a solid state relay is achieved in a small package with a low power consumption.

The SSPC hybrid can be broken functionally into two portions: control and power sections. The control section consists of densely populated proprietary custom bipolar ICs and surface mount passive components. The power section utilizes mostly NMOS power MOSFETs.

C. Test Facility and Ion Beam Usage

These hybrids were evaluated using the Brookhaven National Laboratories (BNL) Single Event Upset Test Facility (SEUTF) on three separate test dates: February 24-25, July 29-August 1, and November 9-12, 1994. The setup at BNL utilizes a dual Tandem Van De Graaff accelerator suitable for providing ions and energies for SEU testing. The test devices are mounted on a device-under-test (DUT) board inside a vacuum chamber.

The SEUTF uses a computer-driven monitor and control program to provide a user-friendly interface for running the experiments. Hard copies of the test data and graphs are also made available.

Table 3 summarizes the ions used for testing. Additional effective LET values were attained by varying the angle of incidence of the ion beam to the device. All LETs discussed are in MeV*cm2/mg.

Table 3. Ion Utilization at BNL

Ion	Atomic No.	Energy in MeV	LET in MeV*cm2/mg
C	12	97	1.46
F	19	136	3.45
Cl	35	208	11.8
Ni	58	262	26.6
I	127	305	59.6
Au	197	329	81.2

D. Test Method

The test procedure was similar for all devices tested. All tests were dynamic in nature meaning that the devices were operating during the test as they would in a spacecraft application. First, power was supplied to the device (28V +/-6 or 7V). Outputs from the device were constantly monitored by either the Omnilab (PC-based tester) or a VXI-based test system and all errors logged until either fluence was reached or a destructive condition was seen. In the case of the latter, power and beam to the device were terminated and the test run ended prematurely. Unexpected observed conditions were typically handled by the addition of an event counter and, when possible, capture of the output and control signals. Two to three samples of each device type were used for testing as a compromise between test cost andstatistical validity. All DUTs were tested at a (nominal) 25 degrees Celsius due to a test setup limitation.

E. Device Test Conditions

Please note that due to the constrictions of the ion beam diameter at BNL and the size of the hybrids, the top (area of the device closest to pin 1) and bottom portions of each of these hybrid devices were irradiated separately. Since the hybrid devices' layouts were unknown, the SEE tests performed were analogous to a black box test method. Only when anomalous results (those that severely impact device functionality) had occurred was limited post-test analysis explored as to individual component usage inside the hybrids.

The individual hybrid device test loads were selected based on GSFC project requirements, existing test equipment, and thermal characteristics of the hybrids (constraints of using a vacuum chamber at BNL SEUTF).

Table 4 represents the test conditions for each DUT.

Table 4. Device Test Conditions

DUT	Input Conditions	Output Load
AHE2815	28V/350mA,	
34V/272mA	15V/375mA	
MDI2690R	28V/175mA	+/-15V, 150mA per channel
MFL2815D	28V/410mA	
34V/360mA	+-15V/500mA per channel	
MFL2815S	28V/340mA	
34V/315mA	15V/500mA	
MFL2812S	28V/280mA	12V/400mA
MFL2805S	28V/125mA	5V/300mA
SSP21110-025	35V/19A	NA

F. SEE Test Definitions

During irradiation, the DUT was operated in-step with a reference device while monitoring was performed for four possible "standard" types of errors . These error conditions were:
- steady state or level errors, which were discrepancies between reference and DUT outputs that lasted longer than one microsecond;
- glitch errors or transient errors, which were discrepancies between the reference and DUT outputs lasting less than 1 microsecond;
- destructive errors indicated by high current conditions (SEL and SEGR); and
- functional errors which will be described below as they pertain to each device.

Anomalous (non-standard) SEEs and observed conditions were explored on an individual device basis and are described in Section III.

III. TEST RESULTS

A. Test Summary

Table 5 summarizes the test results for each hybrid.

Table 5. Device Test Summary

DUT	Steady State or Glitch Errors	Destructive Conditions	Other Conditions
AHE2815	Both: LETth between 20-26	SEGR at 28V: test LET 59.6 SEGR at 34V: test LET 26.6	Device switchoff errors: LETth between 20-26
2690R-D15F	Not monitored	None to a max LET of 72 (34V input)	Spontaneous power reset: LETth between 4-8
MFL2815D	Special case steady state error occurred requiring power reset. LETth between 45-59.7	None to a max LET of 72 (34V input)	None observed
MFL2815S	None	None to a max LET of 72 (34V input)	None observed
MFL2812S	Glitch only. LETth ~50	None to a max LET of 72 (34V input)	None observed
MFL2805S	None	None to a max LET of 72 (34V input)	None observed
SSP21110 -015	None	None to a max LET of 80 (35V input)	None observed

B. AHE2815 Results

An error counter was added to the test setup in order to tabulate the number of times that the device went into a non-functional mode. Errors of this nature appeared to be a "Switchoff error" with the device being turned "off" (0V output) from an "on" (15V) position and requiring a strobing of device input power (power reset) to again resume normal operations. During this condition, DUT current consumption dropped from a nominal 350 mA to between 110-141 mA depending on the DUT sample tested. Additionally, the inhibit pin (a bidirectional control pin) of the device dropped to 0V from a nominal 10.5V.

The switchoff condition has been traced to a potential SEL occurring in a CMOS PWM IC inside the device [5]. This device is current limited by resistance, hence, the reason for not seeing a true high-current destructive condition to the hybrid. The manufacturer is currently considering several options including changing the epi-layer thickness of the PWM, as a solution. This will be tracked in the future.

This switchoff condition as well as SEGR were observed on the top half of the hybrid. As shown in Figure 2, the SEU threshold for switchoff errors was between the LET values of 20 and 26.6. A destructive condition (SEGR) was seen at an LET of 59.6 on a single DUT sample with a 28V input and at an LET of 26.6 on a single DUT sample utilizing the 34V input condition. Hybrid failure occurred in both SEGR cases. Symptoms of this failure observed during testing included increased hybrid current consumption and a 0V output. Visual analysis under a microscope confirmed our SEGR suspicions. Again, the manufacturer has considered replacing the MOSFET currently in the design with one of higher voltage ratings. We will track this in the future as it may help alleviate SEGR occurrence.

On the bottom half of the device, the types of errors that occurred were glitch and steady state. The SEU threshold for both types of errors is between LET values of 35 and 59.6. No high current destructive errors were detected on the bottom part of the device.

C. MDI2690R-D15F

An error counter was added to the test setup to count the number of events where the device performed what appeared to be a spontaneous power reset. During this condition, DUT output dropped from a nominal 15V down to 0V and then back to 15V. This event appeared similar to a typical device power reset hysteresis curve with a pulse width of approximately 10 msec. Because of the relative sensitivity of this device to the reset anomaly (which is in itself a transient event), this particular device SEE test did not look for standard transient output errors.

This reset error has been postulated to be a overcurrent error [6]. The symptoms observed mirrored what would occur if the overcurrent protection circuitry of the device tripped, thus halting device operation and performing an automatic power reset.

As demonstrated in Figure 3, the top half of this hybrid only exhibited reset errors while, no SEEs were observed for the bottom portion. The SEU threshold for reset errors was between the LET values of 4 and 8. No destructive conditions were detected on any sample at LETs up to a maximum tested LET of 72 even when utilizing a 34V input condition.

D. MFL2815D

A special condition of a steady state error was observed when the device output dropped from its nominal 15V to a steady state 14V. This condition required a power reset of the DUT to return to normal operations. The cause of this voltage drop has not been explored (project-specific requirements were met in terms of sufficiently high LET threshold of event occurrence).

The voltage drop condition, which occurred on the bottom half of the DUT, had an LETth between 45 and 59.7. With only sporadic occurrence during testing, no statistical cross section was measured. No other SEEs were observed during testing on any sample (top or bottom portions) at LETs up to a maximum tested LET of 72.

E. MFL2815S

No errors or destructive conditions were detected (top or bottom portions) on this device type at LETs up to a maximum tested LET of 72.

F. MFL2812S

A glitch error was observed on these devices. These spikes lasted < 20 nsec before output voltage returned to normal. (We were unable to determine the exact transient voltage amplitude, only that it was less than a 1V difference from the reference device output).

This voltage spike, which occurred on the bottom half of the DUT, had an LETth of ~50. Saturation cross section of this condition was 5E-6 cm2 per device. No destructive conditions were noted on any sample at LETs up to a maximum tested LET OF 72.

G. MFL2805S

No errors or destructive conditions were observed (top or bottom portions) on this device type at LETs up to a maximum tested LET of 72.

H. SSP21110-015

The SSPC's functional operation was monitored by the use of a strip chart recorder, high-speed oscilloscope, and device current consumption logger (for SEL or SEGR). Signals, such as control and SSPC output, were captured. Two test modes, as selected by a GSFC spacecraft power engineer, were used: output on and output off. No occurrence of any SEE was detected during testing up to a maximum LET of 80.

IV. IMPLICATIONS

Implications may be viewed from two perspectives: SEE testing concerns and spaceflight design usage.

A. Implications to SEE Testing

SEGR, being voltage or bias level sensitive, provides our first implication: be sure to test your power device using worst-case voltages/biases (and temperatures, if possible) as well as at nominal operating conditions. We originally tested the AHE2815 with a normal operating input voltage of 28V and did not observe SEGR until hybrid exposure to I-127. However, when we retested the devices with an input voltage of 34V, Ni-58 was able to cause SEGR.

As might seem obvious, transient errors will vary from device type-to-device type. I.e., the type of transient errors that will occur is not constant for all devices. We observed several type of steady state and glitch condition errors, though the test results were consistent from samples of each individual device type.

Using separate test runs to irradiate the top and bottom portions of the device provided extra care to be taken during testing. Items, such as making sure the entire hybrid device was irradiated or any potential overlap effects of irradiating the same area on a device during both top and bottom portion test runs, were taken into account. A major advantage of BNL's test setup is its laser pointing system for beam alignment to the test device. This ensured us of full hybrid coverage with a minimum of overlap.

In several particular instances, (AHE2815 and MDI2690) the knowledge of which half (top or bottom) of the device saw an anomaly aided the post-analysis as to which hybrid component may have been the cause.

It is surely true that a destructive event such as SEGR may overshadow other concurrent SEUs that occur. This, unfortunately, is true for most SEE testing and, as noted here, preempts complete SEU characterization (i.e., finding saturation cross section for SEU when SEGR occurs at Ni-58).

A last tester's implication concerns testing of device at beam incidence angles other than normal. For SEGR, of course, normal incidence testing is the worst case. However, for other devices, increasing the angle of incidence increases the effective LET. For hybrid power devices such as those tested, both normal incidence tests for SEGR and angular tests for other SEEs must be considered.

B. Implications to Spacecraft Designers

Spacecraft designers, we have found, prefer simple "go/no go" test results. Unfortunately, SEEs are never that simple.

We typically divide SEE test results into the following four categories.

Category 1 - Recommended for usage in all spaceflight applications.
Category 2 - Recommended for usage in spaceflight applications, but may require some SEE mitigation techniques.
Category 3 - Recommended for usage in some spaceflight applications, but requires extensive SEE mitigation techniques or SEL recovery mode.
Category 4 - Not recommended for usage in any spaceflight applications.

Category 1 devices are:
- SSP-21110, MFL2815S, MFL2805S
These devices experienced no SEEs during irradiation.

Category 2 devices are:
- MFL2815D, MFL2812S
The SEE LETths are high enough to possibly use these devices without any SEE mitigation.

However, spacecraft telemetry points to monitor the voltages and currents are recommended as a minimum requirement.

Category 4 devices are:
- AHE2815D
Both device versions exhibited four separate SEE effects, all of which must be of concern to the system designer. The LETths of all these conditions give a finite chance of anomaly occurrence in most orbits, albeit, at fairly low rates in low earth orbits (LEOs). Mitigation of SEGR is not feasible without a redesign of internal hybrid circuitry. It should be noted that the manufacturer is considering modifications to this hybrid that may improve its SEE characteristics.

- MDI2690R.
This device's self-reset syndrome occurred at low LETs and may even be susceptible to proton-

induced anomalies. This condition is difficult for spacecraft designers to mitigate. This condition could, at the very least, reinitialize a spaceflight instrument or subsystem.

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VI. REFERENCES

[1] Advanced Analog, "AHE2800D Series Hybrid - High Reliability DC/DC Converters", datasheet
[2] Modular Devices Inc, "4-6.5Watt Hybrid DC-DC Converters", datasheet
[3] Interpoint, "MFL Series 28-Volt DC-DC Converters", datasheet, 1994.
[4] ILC Data Device Corporation, "SSP-21110 28VDC Solid-State Power Controllers", datasheet, Dec 1991.
[5] R. Hansen, Advanced Analog, Private communication, 1994.
[6] G. Swift, Jet Propulsion Laboratory, Private communication, 1995.