TEST REPORT OF PROTON AND NEUTRON EXPOSURES OF DEVICES THAT UTILIZE OPTICAL COMPONENTS AND ARE CONTAINED IN THE CIRS INSTRUMENT

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I. INTRODUCTION

This study was undertaken to determine the radiation response of a set of devices utilized on the composite infrared spectrometer (CIRS), a Goddard Space Flight Center (GSFC) instrument on Cassini. Testing was performed to determine the degradation of several DC/DC converters (these contain an optocoupler), a laser diode, an LED, and several optocouplers, when exposed to protons and neutrons. Also, single event transient testing was performed to look for "dropouts" in output voltage for the DC/DC converter due to single proton interactions.

Protons, electrons, neutrons and elements of the periodic table that have sufficient kinetic energy to move through a medium are examples of particulate radiation. This type of radiation impacts the functionality of microelectronics by transferring its energy to the semiconductor material on atomic and nuclear scales. The energy is transferred in the following ways.

- **Elastic coulombic scattering between the incident radiation and the electrons surrounding the nucleus of the target semiconductor, freeing electrons (or charge) from their associated nucleus. This is known as ionization. Examples of induced effects in devices are total ionizing dose and single event effects.**

- **Elastic coulombic scattering, elastic nuclear scattering and inelastic spallation reactions occur between the incident radiation and the nucleus of the target semiconductor. The result of this interaction is to remove the atom from its crystal lattice site. In doing this electrons can be freed and secondary particles (i.e., neutrons, protons, etc…) are ejected. These secondary particles could in-turn transfer their energy to other atoms of the semiconductor. Examples of induced effects in devices are displacement damage and single event effects.**

All of these interactions can cause radiation-induced damage to the semiconductor, thereby altering the functionality of the devices fabricated on the semiconductor. Rate of energy transfer functions for a specific type of radiation and radiation damage defines the exact impact radiation has on device functionality.

A specific radiation damage known as displacement damage degrades signals in devices

that contain electo-optical components (the devices studied here are or contain electo-optical devices). Basically, the mechanism is to displace an atom from its crystal lattice site, as defined by the second method of transferring energy described above. After several atomic displacements have occurred, the optical properties of the device will be altered.

Displacement damage is a cumulative effect, much like total ionizing dose (TID). However, one cannot compute the expected displacement damage effects in a device from its known TID response. Total ionizing dose effects are produced by the liberation of electrons from their atoms. Whereas, displacement damage occurs when atoms are removed from their lattice sites.

Displacement damage can be induced by all types of radiation, each having different energy transfer rates. The energy transfer rate function for displacement damage is known as non-ionizing energy loss (NIEL). The response of a device to proton-induced displacement damage is typically thought to be the most important for space applications. This is because of the combination of the proton-induced NIEL in a semiconductor and the intensity of the proton environment in space.

The Cassini mission is utilizing radioisotope thermoelectric generators (RTGs) which bath the spacecraft with a high level of neutrons. The relative level of the NIEL for neutrons in semiconductors and the neutron exposure is also critical for this mission. Therefore, degradation due to proton and neutron displacement damage must be characterized for each device in this study.

II. DEVICES TESTED AND SUMMARY OF RESULTS

Previous tests by Ball Aerospace show that DC/DC converters manufactured by Interpoint degrade when exposed to radiation. We performed a series of radiation tests on several different Interpoint DC/DC converters. Table 1 describes each converter, the particle that was used during the irradiation, and the maximum measured particle fluence prior to any noticeable change in the measured parameters. The optocoupler manufacturer used in the DC/DC converters was provided by Interpoint. Fluences for neutron irradiations are given as 1 MeV neutron equivalent fluence. The optocoupler is believed to be the most radiation sensitive device in most of the converters tested. A detailed description of the test methods used, facilities used to carry out the irradiations, and the results will be presented later.

Table 1. Summary of Interpoint Devices

PART #	OPTOCOUPLER VENDOR	SERIAL #	LDC	PARTICLE	RADIATION FACILITY	FLUENCE (particles/cm^2)
MHF+2805S	Hamamatsu	3629	9603	Proton	LLUMC	4.4×10^{10}

MHF+2805S	**Hamamatsu**	**3834**	**9616**	**Proton**	**LLUMC**	**$5.2x10^{10}$**
MHF+2805S	**Hamamatsu**	**3837**	**9616**	**Proton**	**LLUMC**	**$4.3x10^{10}$**
MHF+2805S	**Hamamatsu**	**3838**	**9616**	**Proton**	**LLUMC**	**$4.6x10^{10}$**
MHF+2812D	**Hamamatsu**	**0650**	**9603**	**Proton**	**LLUMC**	**$4.4x10^{10}$**
MHF+2805S	**Hamamatsu**	**3840**	**9616**	**Neutron**	**SPR**	**$1.1x10^{11}$**
MHF+2805S	**Hamamatsu**	**3841**	**9616**	**Neutron**	**SPR**	**$2.2x10^{11}$**
MHF+2805S	**Hamamatsu**	**3842**	**9616**	**Neutron**	**SPR**	**$1.1x10^{11}$**
MHF+2805S	**Hamamatsu**	**3845**	**9616**	**Neutron**	**SPR**	**$2.2x10^{11}$**
MHF+2805S	**Hamamatsu**	**3848**	**9616**	**Neutron**	**SPR**	**$1.1x10^{11}$**
MHF+2805S	**?**	**2561**	**T9546**	**Proton**	**IUCF**	**$1.3x10^{11}$**
MHF+2815	**Isolink**	**1776**	**?**	**Proton**	**IUCF**	**$9.9x10^{11}$**
MHF+2815	**Isolink**	**2801**	**?**	**Proton**	**IUCF**	**$1.7x10^{11}$**
MHF+2815D	**Isolink**	**1784**	**T9711**	**Proton**	**IUCF**	**$1.4x10^{11}$**

Interpoint DC/DC converters from lot date code (LDC) 9603 are from the Cassini flight lot. Interpoint stated that devices from LDC 9616 are from the same design as flight lot. However, radiation data presented in section V indicate that there may be differences in the two designs. We plan to do physical analysis to investigate the differences in the converters. Interpoint has agreed to exchange the optocoupler in the irradiated devices with working ones. Subsequent functionality tests will define which converter failures were due to radiation damage in the optocouplers.

In addition to the DC/DC converters, irradiation with both protons and neutrons on several Hamamatsu P2824 optocouplers were performed; these optocouplers are contained in the Interpoint DC/DC converters. Radiation-induced degradation of the optocoupler is monitored as a change in the current transfer ratio (CTR). Displacement damage is thought to be the most significant mechanism for the degradation of optocouplers. Radiation failure levels measured during this study agree with the assertion that these optocouplers are the suspect device for most of the DC/DC converter failures. Detailed results will be presented in Section V.

Finally, Table 2 lists other devices that were exposed to neutrons. No degradation was observed for the Spectra Diode laser diode and the Hewlett Packard optocoupler after the

irradiations. The Micropak optocoupler and the Opto Diode LED noted operational degradation during the irradiations. A detail description of the test methods and results will be presented later.

Table 2. Neutron irradiations of these devices were carried out at SPR.

PART #	VENDOR	DESCRIPTION
4N48	Micropac	Optocoupler
6N134	Hewlett Packard	Optocoupler
OD880WJ	OPTO Diode	LED
SDL5601V1	Spectra Diode	Laser Diode

III. FACILITIES

The test facilities utilized were Indiana University Cyclotron Facility (IUCF), Loma Linda University Medical Center (LLUMC) and Sandia National Laboratory Pulse Reactor Facility (SPR). All energies are incident on the packages. Devices were not delidded.

A. Neutron Facility

Neutron step irradiations at SPR were carried out using a pulsed nuclear reactor applying radiation in a steady state mode. All irradiations were omnidirectional. All fluence data are given as 1 MeV neutron equivalent fluence. Maximum fluence was 2.1×10^{12} n/cm^2.

Figure 1 compares the neutron environment predicted for the Cassini mission to the environment of the reactor. The Cassini environment was normalized to the SPR environment for relative comparison. Agreement is good for energies greater than 0.04 MeV. A comparison of NIEL in GaAs for proton and neutron energies to the NIEL for 1 MeV neutrons is given in Figure 2. Neutrons below 0.01 MeV are significantly less damaging than those above 0.01 MeV. Therefore, neutrons with energies above 0.01 MeV will induce the majority of the damage in the electo-optical devices.

B. Proton Facilities

Proton irradiations at LLUMC synchrotron were performed with a tuned 100 MeV beam that was degraded to 51.8 MeV. The particle flux was approximately 8.6×10^7 p/cm^2/s. The maximum fluence ranged from 6.7×10^{10} p/cm^2 to 1.2×10^{11} p/cm^2. All irradiation were carried out at normal incidence.

Irradiations at IUCF were carried out with a tuned 195 MeV proton beam. The particle flux was between $1x10^8$ $p/cm^2/s$ and $1x10^9$ $p/cm^2/s$. Maximum fluences ranged from $1.5x10^{11}$ p/cm^2 and $1x10^{12}$ p/cm^2. Irradiations were carried out at normal and grazing angles of incidence.

During its mission, Cassini will be exposed to a complex proton environment that will cover a wide range of energies. A comparison of the device failure levels during testing to the space environment is achieved by weighting the space particle fluence spectrum as a function of energy, $F_s(E_i)$, with the ratio of the NIEL at E_i to the NIEL at the test energy, E_T. Or:

$$F_{eq}(E_T) = \sum F_s(E_i)\ NIEL(E_i)/NIEL(E_T)$$

Where $F_{eq}(E_T)$ is the equivalent fluence for a proton energy E_T: the test fluence required to induce an equivalent amount of damage produced by space environment. The validity of this technique relies on the accuracy of the NIEL curves. The typical electro-optical device has complex stoichiometry. This adds to the uncertainty when using standard NIEL curves for GaAs or Si to compute the equivalent fluence.

IV. TEST METHODS

A. DC/DC Converters

The DC/DC converter test setup for proton exposures is shown in Figure 3a. The loading is given in Table 3. Output voltage and supply current were monitored and recorded. All tests were done at room temperature. An oscilloscope was used to monitor the output of the device for transients during the IUCF tests.

It was not possible to actively monitor the devices during neutron irradiations. The irradiations were done in steps, i.e. irradiate – measure – irradiate – measure etc… until completion. The measurements were performed with the identical test setup described for proton irradiations.

Table 3: DC-DC converter loading for all irradiation.

VOLTAGE	+5 V	+12 V	-12 V
LOADING	500 mA	300 mA	100 mA

B. Optocouplers

The test setup required to measure the current transfer ratio (CTR) for the optocouplers is shown in Figure 3b. All tests were done at room temperature. Data were collected for

several drive currents. The supply current (I_f) and voltage drop (V_L) across the load resistor were monitored. The CTR was computed from:

$$CTR = (V_L/R_2) / I_f$$

C. Light Emitting Devices

Output power was measured. A detail description of the test setup will be given in the final report.

V. DETAILED RESULTS; DISCUSSION AND RECOMMENDATIONS

A. Interpoint MHF+ Series DC/DC Converter

In general, the failure mode observed for the DC/DC converters is a loss of regulation after exposure to a certain level of particle fluence. This fluence level depends on the species used to irradiate the devices and the energies of these species. We believe that displacement damage effects in the optocoupler internal to the converters is the failure mechanism for the converters (see the results of irradiations of the Hamamatsu P2824 for a detailed analysis). The supply currents and output voltages as a function of 51.8 MeV proton fluence for five devices irradiated at LLUMC synchrotron are shown in Figures 4a (supply current) and 4b (output voltage). Results from neutron exposures of five devices carried out at SPR are given in Figures 5a and 5b. IUCF 195 MeV proton results for four devices are plotted in Figures 6a and 6b.

A1. LLUMC Proton Exposures

The data in Figure 4 show that the flight lot devices (LDC 9603) began to stop regulating at $4.4x10^{10}$ p/cm^2. The LDC 9616 showed similar initial failure levels. The limitation of having only two flight lot devices forced us to use devices from LDC 9616 for other irradiations. Interpoint reported to us that the LDC 9616 design had the same sub-vendors of potentially sensitive components within the converter as LDC 9603.

There is a clear difference between the radiation response of the two LDCs. The flight lot (LDC 9603) shows one failure mode, i.e. an increasing output voltage and supply current with particle fluence until the power supply reaches its current limit of 800 mA. On the other hand, the devices from LDC 9616 show an increasing voltage and current initially, then they drop to zero. This indicates that the LDC 9616 devices have a low and a high fluence failure mechanism. Fluence failure levels of the flight lot and the low fluence failure level of LDC 9616 are similar. For this reason and because Interpoint claims consistency across the LDC 9603 and 9616, we assume that we can use LDC 9616 to represent the flight lot in other tests. We are speculating that the high fluence failure mode of the LDC 9616 devices is due to proton-induced TID effects in a MOSFET internal to the converter.

A2. SPR Neutron Exposures

Results of neutron step irradiations at SPR of the converters from LDC 9616 are given in Figure 5. This shows that three of the five converters have onset failure between 1.1×10^{11} and 2.2×10^{11} n/cm^2. The other two converters show onset failure between 2.2×10^{11} and 3.8×10^{11} n/cm^2.

A3. IUCF Proton Exposures

Figure 6 shows that the converters with LDCs other than 9616 and 9603 have onset failures at higher fluence. The characteristics of the failure resemble the high fluence failure mode of the LDC 9616 devices.

We believe that using the failure levels of the devices from LDCs other than 9603 or 9616 to predict the response of flight devices is not valid. It can be argued that the high fluence failure mechanism for LDC 9616 discussed in Section V.A1 is a TID effect. A comparison of the 195 MeV irradiations, shown in Figure 6, to the 51.8 MeV exposures in Figure 4 shows that the protons at 51.8 MeV will deliver a TID per particle fluence that is a factor of 2.7 higher than 195 MeV protons. Computation of the total ionizing dose at each energy shows that failures occurred around 8.5 kRad(Si) for both energies for all devices except one. The failures occur at the same dose level.

During the 195 MeV proton irradiations, we looked for "dropouts" in the output voltage. No dropouts were observed for the MHF+2805S or the MHF+2805D. No other device types were tested. It should be noted and taken as a potentially large source of error that the devices used for the dropout test were not of the same pedigree as the Cassini flight lot.

A4. Recommendation

We recommend performing a review of the parts list for radiation sensitive devices when using any Interpoint converter. If the converter in question contains an optocoupler or any other radiation sensitive device, one should determine the radiation response of this device via testing, and then compute the survivability of the device based on the predicted radiation environment for the mission.

For the MHF+ converters tested, we show that by combining the test results on the DC/DC converters from LDC 9616 with the Hamamatsu optocoupler data that follow, allows us to predict a lower limit on the failure levels for the LDC 9603 flight lot devices. This is addressed in the discussion on the Hamamatsu optocouplers.

B. P2824 - Hamamatsu optocoupler:

Interpoint reported to us that MHF+ series DC/DC converters with LCD 9603 and 9616 contain the Hamamatsu P2824 optocoupler. Other LDCs did not contain this optocoupler. We carried out proton and neutron step irradiations of the P2824 optocouplers at each facility listed above. Displacement damage in the light emitting or receiving portion of the

optocoupler is believed to be the mechanism for the degradation of the CTR. We will show the correlation or the lack of it between the DC/DC converter irradiations discussed above and the Hamamatsu optocoupler data given below.

The results from exposing six devices with a 51.8 MeV proton beam at LLUMC are shown in Figures 7a and 7b. Results from neutron exposures of six devices carried out at SPR are given in Figures 8a and 8b. IUCF 195 MeV proton results for two devices are plotted in Figures 9a and 9b. The pre-irradiation values are shown at zero fluence. The first plot, Figure a, in each set of figures shows the average CTR of the devices at each accumulated fluence for various drive currents. The legend shows the drive currents. Figures b in each set contains the same data in Figures a but plotted in a different format: the average CTR as a function on drive current for various fluence levels. The legend shows the fluence levels. The spread in the CTR for the devices tested is shown by the error bars.

B1. Average CTR Degradation

Interpoint stated that, for the DC/DC converter application, the optocoupler drive current is between 1.5mA and 3.0mA and that the CTR must remain above 17%. The solid horizontal line in Figures 7a, 8a and 9a is placed at 17%. Data collected at drive currents between 1.3mA and 3.5mA where the CTR falls below 17% represents situations where the converters could stop regulating.

The range of onset failure fluences for the DC/DC converters from Figure 4 is consistent with the failure being induced by degradation of the optocoupler. The vertical lines in Figure 7a show the onset failure levels of the converters when irradiated with 51.8 MeV protons. The lowest observed converter failure occurred at a fluence of 4.4×10^{10} p/cm^2, somewhat above the minimum value of 3.0 $\times 10^{10}$ p/cm^2 that would be predicted by the optocoupler 51.8 MeV proton irradiations. The conservative explanation is that the six converters tested happen to be devices that show less sensitivity to displacement damage. This explanation implies that it is possible to have DC/DC converters that contain optocouplers that fail near 3×10^{10} p/cm^2. Another, less conservative, explanation would be that a drive current less that 2.5 mA is never used in these devices, implying that the failure level never drops below 4.4×10^{10} p/cm^2. We believe the more conservative approach is the best.

Results from neutron exposures in Figure 8a show that at 1.1×10^{11} n/cm^2 none of the optocouplers drop below 17% CTR, implying that all DC/DC converters that use this optocoupler should remain functional at this fluence. The neutron data taken on the DC/DC converters shown in Figure 5 shows that the all converters did in fact survive to a fluence level of 1.1×10^{11} n/cm^2. The optocoupler data in Figure 8a show that the converters should have onset failure between 1.1×10^{11} n/cm^2 and 2.2×10^{11} n/cm^2, depending on the drive current. The data in Figure 5 show that three of the five converters stop regulating at 2.2×10^{11} n/cm^2. As with the 51.8 MeV proton data given in the pervious paragraph, the DC/DC converters survived to a slightly higher fluence level than would have been predicted by the optocoupler data and the range of drive currents that the Interpoint

converters use.

IUCF 195 MeV proton exposures of the Hamamatsu optocoupler are shown in Figure 9a. From this data one would predict that DC/DC converters containing the Hamamatsu optocoupler to fail between $5x10^{10}$ and $8x10^{10}$ p/cm^2, depending on the drive current used. The solid vertical line at $1.4x10^{11}$ p/cm^2 is placed at the minimum value that onset failure occurred for the Interpoint converters during exposures at this energy. In the Section V.A1 we showed that the failure mechanism for these devices is believed to be something other than the optocoupler and in this section we show that the fluence failure level is much higher than would be predicted. These facts lead to two possibilities: the DC/DC converters tested at IUCF do not contain Hamamatsu P2824 optocoupler or the drive current is greater than 6.2 mA. Interpoint reported to us the converters tested at IUCF did not contain the Hamamatsu optocoupler.

B2. Optimization of CTR to Mitigate Radiation-Induce Effects

Figures b in each set contains the same data as in Figures a but plotted in a different format: the average CTR as a function of drive current for various fluence levels. The legend shows the fluence levels. The peak in the pre-irradiation relationship of between CTR and drive current would lead one to believe that using drive currents of 4mA would be the best choice for design purposes. However, radiation degrades the CTR at a much higher rate when operating the device at this drive current. Therefore, it is best to use as high a drive current as possible in order to minimize the effects of radiation.

B3. Recommendation

We recommend that one use the Hamamatsu P2824 optocoupler in space applications only after careful evaluation of the application against the space radiation environment. The drive current needs to be sufficiently high so that degradation of the CTR during the mission does not affect performance of the circuitry utilizing the optocoupler. No attempt has been made to characterize this optocoupler for single event transient effects.

C. 4N48 – Micropak Optocoupler:

The Micropac 4N48 optocoupler was tested for displacement damage effects induced by neutrons by irradiating them at SPR. The average CTR after each step irradiation is shown in Figure 10. Degradations occurred only at the lowest drive currents. All devices had degraded to <1% CTR after an exposure of $6x10^{12}$. We recommend that one use the Micropac 4N48 optocoupler in space applications only after careful evaluation of the application against the space radiation environment. The drive current needs to be sufficiently high so that degradation of the CTR during the mission does not affect performance of the circuitry utilizing the optocoupler. No attempt has been made to characterize this optocoupler for single event transient effects.

D. OD880WJ - OPTO Diode Labs:

Figure 11 plots the output power as a function of the 1 MeV equivalent neutron fluence for step irradiation for the three LEDs at different drive currents. The error bars show the spread in the output power among the devices. We recommend that one use the OPTO Diode Labs OD880WJ LED in space applications only after careful evaluation of the application against the space radiation environment.

E. 6N134 – Hewlett Packard

Eight devices were tested. No degradation was observed for 1 MeV neutron equivalent fluence of 8.0×10^{11} n/cm^2. We recommend that one use the Hewlett Packard 6N134 optocoupler in space applications only after careful evaluation of the application against the space radiation environment. No attempt has been made to characterize this optocoupler for single event transient effects.

F. SDL5601V1 - Spectra Diode Labs

Six devices were tested. No degradation was observed for 1 MeV neutron equivalent fluence of 8.0×10^{11} n/cm^2. We recommend that one use the Spectra Diode Labs SDL5601V1 in space applications only after careful evaluation of the application against the space radiation environment.

VI. GENERAL RECOMMENDATIONS

Our recommendation is that all parts tested in this study are usable in space applications only after careful evaluation against the radiation environment expected for the mission.

VII. ACKNOWLEDGEMENTS

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VIII. REFERENCES

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