Proton Damage in LED and phototransistor of Micropac 66179 Optocoupler

Farokh Irom, Gregory R. Allen, *Member IEEE*, Larry D. Edmonds and Bernard G. Rax

Abstract**-- This paper reports proton damage in LED and phototransistor of the Micropac 66179 optocoupler. Analysis of the test data reveals interesting information, such as the dependence of the transistor gain on irradiation and photocurrent.**

I. INTRODUCTION

Optocouplers are widely used in electronic systems to provide electrical isolation between different circuits. A diagram of a basic optocoupler is shown in Fig. 1. The normal parameter of interest is the current transfer ratio (CTR) defined as the ratio of the collector current of the transistor to the forward current through the light-emitting diode (LED).

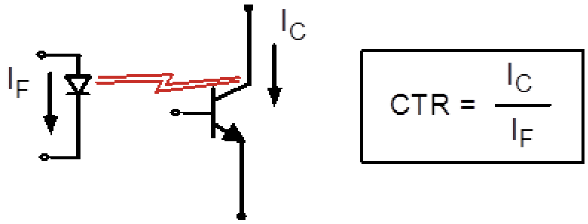

Fig. 1. Diagram of a basic optocoupler using a phototransistor [2].

Radiation degradation in optocouplers is an important issue for space applications [1]–[9]. There are three radiation issues affecting optocouplers for space flight applications: displacement damage (DD), total ionizing dose (TID) and single event transient (SET). TID and DD can both cause degradation in optocouplers and affect CTR. SETs can be induced by protons and heavy ions.

In general, LED of an optocoupler is effected by DD, coupling medium is degraded by TID and photodetector and amplification circuit is effected by TID and SET.

LED degradation has a super linear dependence on displacement damage. A linear relationship can be established using the following equation [1]:

$$\left[\left(\frac{L_o}{L}\right)^n - 1\right] = K\,\tau_o\,\Phi \tag{1}$$

where L_o is the pre-irradiation light intensity, L is the light intensity after irradiation, n is an exponent that is typically between 0.33 and 1, K is the damage factor, τo is the pre-irradiation minority carrier lifetime, and Φ is the particle fluence.

CTR Degradation of optocouplers with simple phototransistors due to radiation depends on several factors [2]:

1-Degradation of the internal LED.

2-Decrease in the effective gain of the phototransistor due to decreased light output (and consequently lower photocurrent) from the LED.

3-Degradation of gain and photoresponse of the phototransistor.

4-Degradation of the coupling medium between the LED and phototransistors.

In addition to these factors, temperature also plays a role in the degradation. Initially the CTR is higher for higher temperatures, but the positive temperature coefficient becomes negative after low levels of radiation exposure.

For optocouplers with amphoterically Si-doped Gallium Arsenide (GaAs) LEDs, the extreme sensitivity of the LED to radiation damage [1] causes the first mechanism to dominate the degradation, although there is some effect from the second mechanism as the LED light output decreases.

For optocouplers with other LED technologies, all four mechanisms can be important. This makes it far more difficult to evaluate radiation degradation for that type of

---

Manuscript received September 17, 2016. The research in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA). Copyright 2016 California Institute of Technology. Government sponsorship acknowledged.

Farokh Irom is with the Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109 (telephone: 818-354-7463, e-mail: Farokh.irom@jpl.nasa.gov

Gregory R. Allen is with the Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109 (telephone: 818-393-7558, e-mail: Gregory.r.allen@jpl.nasa.gov

Larry D. Edmonds is with the Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109 (telephone: 818-393-7558, e-mail: Larry.d.edmonds@jpl.nasa.gov

Bernard G. Rax is with the Jet Propulsion Laboratory, California Institute of Technology Pasadena, CA 91109 (telephone: 818-354-9799, e-mail: Bernard.g.rax@jpl.nasa.gov

optocoupler. Among the complications is far greater statistical variation in the radiation degradation of optocouplers, due to the dependence of optocoupler performance on several different factors [2].

Solar protons and trapped protons predominate the natural space environment and contribute to both TID and DD. Depending on an optocoupler primary degradation mode, proton irradiations can produce results that are either nearly identical to ^{60}Co TID tests or can show substantially more degradation than would be expected from TID alone [8]. Neutrons are important primarily for avionics and manmade nuclear environments and contribute almost exclusively to DD.

Ref [8] compares degradation ^{60}Co irradiation of a 4N49U type optocoupler to that for 195 MeV proton irradiation. Proton irradiations cause significantly larger degradation than gamma ray exposures at equivalent doses. This type of optocoupler radiation response is due to the greater amount of displacement damage for proton over gamma exposures [9].

For 4N49U type optocouplers the dominant mechanism for degradation is displacement damage from solar protons and protons trapped in a planet's radiation belts. Although there is a full spectrum of proton energies in the actual space environment, it is costly and impractical to test devices over the full spectrum of proton energies. The preferred approach is to do tests with protons at a single energy, relying on published studies of the energy dependence of proton damage to relate the measured results at a single energy to the effect of the broad spectrum of energies in the actual space environment [2].

II. DEVICE INFORMATION

This paper reports radiation test result for the following commercial optocoupler shown in Table I.

Table I.

MANUFACTURE	PART NUMBER	DATE CODE
MICROPAC	66179-003	1143

The Micropac 66179 is a single channel optocoupler, consisting of a single 660 nm GaAlAs LED and a single silicon phototransistor mounted and coupled in a miniature surface mount hermetic leadless chip carrier. Electrical parameters are similar to the JEDEC registered 4N49U optocoupler, but with better CTR radiation degradation characteristics.

III. EXPERIMENTAL PROCEDURE

We use the concept of non-ionizing energy loss (NIEL) to define an equivalent 1-MeV neutron fluence to interpret displacement damage. In other words, radiation environments of protons, neutrons and electrons are regarded as equivalent if they produce the same nonionizing dose when proper NIEL factors for protons, neutrons and electrons are used to calculate the dose. Although, the devices being studied in this report are not silicon based, we nonetheless choose to report fluences in 1 MeV neutron equivalent in silicon as this is a standard way that many missions report their environment. DD measurements were performed with proton beams at the 1×10^{11}, 5×10^{11}, 1×10^{12} and 2×10^{12} equivalent 1-MeV neutron fluences in silicon. These fluences were converted to proper proton fluences using the NIEL factor for beam energy used for irradiation in different facilities and proper based material used in the devices being irradiated.

Four samples of the optocoupler were provided for radiation testing. The devices were tested at the University of California at Davis (UCD) using 67-MeV protons. The devices were exposed at room temperature to a series of radiation steps with electrical and optical measurements made before irradiation and between each step. All parts were in an unbiased condition during irradiation (all pins grounded) to make the test conditions unambiguous. DD effects are, to first order, insensitive to bias conditions during irradiation. The circuit shown in Fig. 2 was used to measure radiation degradation of the Micropac 66179.

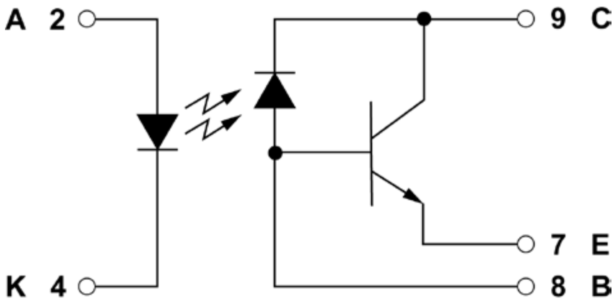

Fig. 2. 66179 test circuit.

After each irradiation level, the electrical parameters were measured for a set of values of the forward current (I_F) through the LED using the HP 4156 Semiconductor Parameter Analyzer. The current was varied from 1 to 10 mA as shown in Table II. Electrical measurements included the following:

1. Diode-based measurements (emitter of the phototransistor open, with the base connected to ground), using a collector voltage of 5 V and a series of forward currents shown in Table II (1 to 10 mA). This allows the LED output to be evaluated separately, without the added effects of phototransistor gain.
2. Optocoupler CTR with a collector voltage of 5 V, using a series of forward currents shown in Table II (1 to 10 mA). The phototransistor base terminal was left unconnected with the emitter terminal grounded (the transistor gain is turned on). The forward voltage of the LED was also measured.

Table II. Measurement Parameters for the Optocouplers

MEASUREMENT	CONDITIONS
CURRENT TRANSFER RATIO	I_F = 1, 2, 4, 6, 8 AND 10 mA

When the transistor gain is turned off (diode-based measurements) the collector current is the rate that charge carriers are generated in the transistor base region by light emitted by the LED (this generation rate is multiplied by the elementary charge to produce the units of electric current). This photo-generation rate of charge carriers (multiplied by the elementary charge) is called the photocurrent and denoted I_{ph}. While the physical interpretation is a photo-generation rate, the experimental definition of I_{ph} is the collector current when the transistor gain is turned off. The notation I_C will be used for the collector current when measured with the transistor gain turned on (normal operation). Some of the figures and tables will refer to ratios (e.g., a post-irradiated value divided by a pre-irradiated value) of intensities of the light emitted by the LED. The physical interpretation of the photocurrent implies that it is proportional to the light intensity, denoted L, so ratios of L values given in figures and tables are calculated as ratios of photocurrents.

IV. TEST RESULTS AND DISCUSSION

A. Pre-Irradiation Measurements

Electrical parameters prior to proton irradiation establish the baseline that post-irradiated parameters will be compared to in the next sections. The pre-irradiated values of I_{ph}, I_C, and CTR are denoted $I_{ph,0}$, $I_{C,0}$, and CTR$_0$. Average (over device samples) measured values corresponding to selected values of I_F are shown in Table III.

Table III. : Pre-irradiated values of I_{ph}, I_C, and CTR corresponding to selected values of I_F.

I_F (mA)	1	2	4	6	8	10
$I_{ph,0}$ (mA)	0.0094	0.0224	0.0509	0.0813	0.1126	0.1445
$I_{C,0}$ (mA)	1.16	2.99	7.32	12.07	17.03	22.03
CTR$_0$	1.16	1.5	1.83	2.01	2.13	2.20

B. Radiation Degradation of the Micropac 66179 LED (660 nm)

Fig. 3 displays the normalized LED optical power (the post-irradiated value divided by the pre-irradiated value), averaged over four device samples, versus the 1 MeV neutron equivalence fluences for each tested value of I_F (1, 2, 4, 6, 8 and 10 mA).

The averaged optical power after an equivalent 1 MeV neutron fluence of 1× 0^{12} is very small and it was decided to skip the last step of irradiation at 2×10^{12}.

C. Radiation Degradation of the Micropac 66179 CTR

Fig. 4 displays the normalized CTR (the post-irradiated value divided by the pre-irradiated value), averaged over four device samples, and versus the 1 MeV neutron equivalence fluences for each tested value of I_F (1, 2, 4, 6, 8 and 10 mA).

The CTR after accumulation of 1×10^{12} is very small and it was decided to skip the last step of irradiation at 2×10^{12}.

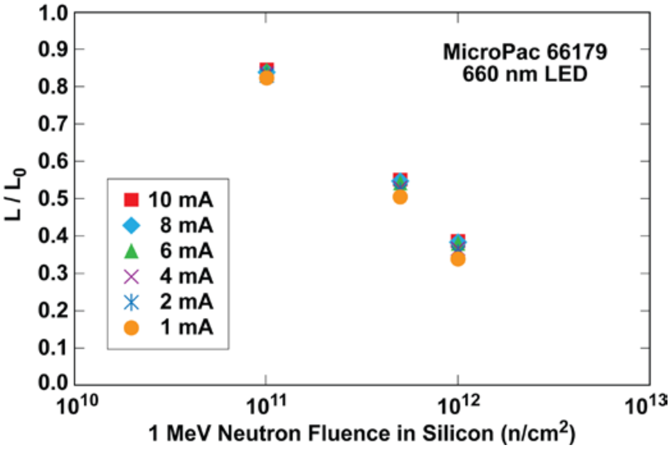

Fig. 3. Normalized light intensity versus the radiation level for the Micropac 66179.

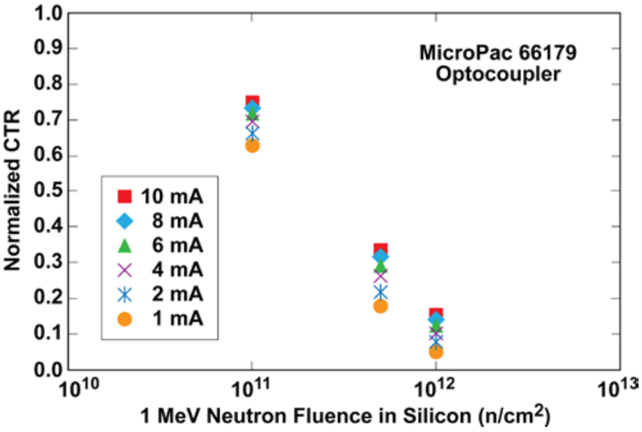

Fig. 4. Normalized CTR versus the radiation level for the Micropac 66179.

D. Analysis of the Data

Analysis of the test data reveals interesting information, such as the dependence of the transistor gain on irradiation and photocurrent. Also, analytical fits to the data provide a means to interpolate between data points. The data are summarized in Table IV.

We begin with an analysis of the I_{ph} data by noting that the carrier generation rate is proportional to the LED intensity so (1) can be written as

$$\left[\left(\frac{I_{ph,0}}{I_{ph}}\right)^{n} - 1\right] = K\,\tau_o\,\Phi \qquad (2)$$

where $I_{ph,0}$ is the pre-irradiation generation rate and I_{ph} is the post-irradiation generation rate produced by the same I_F, and the other symbols have already been explained. This equation suggests a different plotting format for the same data shown in Fig. 3. The alternate plotting format suggested by [2] plots the left side as a function of fluence. To the extent that (2) is valid, a suitably selected n will make the left side proportional to fluence (a straight line with unit slope in a log-log plot). A subset of the data in Fig. 3 (2 and 10 mA) are plotted in this format in Fig. 5 (note that $I_{ph,0}/I_{ph} = L_0/L$) using a value of n that produces a good fit to a straight line with unit slope in a log-log plot. This choice for n is 2/3.

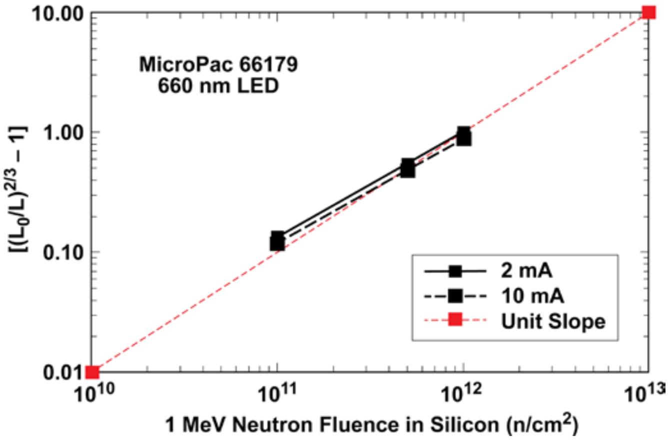

Fig. 5. Values of $[(L_0/L)^{2/3} – 1]$ for $I_F = 2$ and 10 mA for the 66179 LED. Note the linear behavior of that quantity with fluence.

The value of K is determined from Fig. 5. Note that K does not depend on Φ but does have a slight dependence on I_F. With n set equal to 2/3 and K determined from Fig. 5 for each I_F, the above equation gives an approximation for I_{ph} in terms of both Φ and I_F via

$$I_{ph} \approx I_{ph,0} \left(K\tau_o \Phi + 1\right)^{-3/2} \qquad \text{(3a)}$$

The fitting parameters, for two example values of I_F, are $I_{ph,0}$ (taken from Table III) and $K\tau_0$ (determined by the fits in Fig. 5) given by

$$I_{ph,0} = \begin{cases} 0.0224\ \text{mA} \ @\ I_F = 2\ \text{mA}, \\ 0.1445\ \text{mA} \ @\ I_F = 10\ \text{mA} \end{cases} \qquad \text{(3b)}$$

$$K\tau_o = \begin{cases} \left[1.02\times 10^{12}/\text{cm}^2\right]^{-1} \ @\ I_F = 2\ \text{mA} \\ \left[1.18\times 10^{12}/\text{cm}^2\right]^{-1} \ @\ I_F = 10\ \text{mA} \end{cases}$$

The plotting format used for Fig. 5 can be applied to the CTR data, as seen in Fig. 6. The data points for CTR/CTR$_0$ with this plotting format do not produce a straight line with unit slope with as much accuracy as was seen for the $I_{ph}/I_{ph,0}$ data in Fig. 5 because the CTR data are influenced by the gain of the phototransistor. Because of this influence, there is no physical basis for a straight line in Fig. 6 (in contrast, there is a physical basis for a straight line with unit slope in Fig. 5) which makes Fig. 6 an unreliable way to extrapolate data. A more reliable extrapolation, and a more accurate fit to the data, is obtained by investigating the transistor gain and then combining this information with the LED data in Fig. 5.

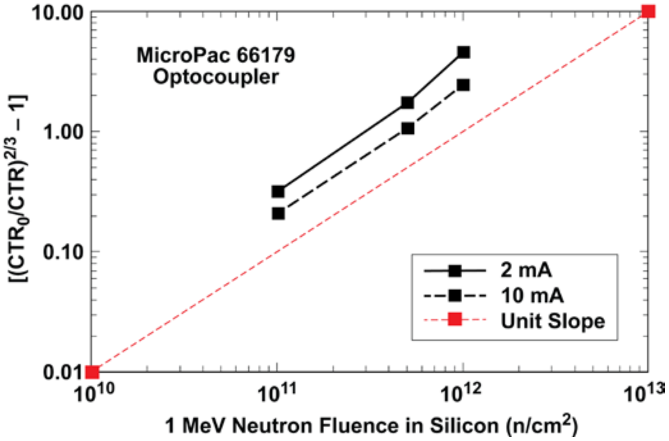

Fig. 6. Values of $[(CTR_o/CTR)^{2/3} – 1]$ for $I_F = 2$ and 10 mA for the 66179. These points do not conform to a straight line with as much accuracy as was seen in Fig. 5 because the CTR data are influenced by the gain of the phototransistor.

The transistor gain, denoted h, is defined by

$$h \equiv \frac{I_C}{I_{ph}} \qquad \text{(4)}$$

where I_C and I_{ph} have already been explained. Depending on the optocoupler, the gain may or may not be sensitive to the irradiation level when the gain is expressed as a function of I_{ph}. However, even if the gain does not depend on the irradiation level when expressed as a function of I_{ph}, it still has an implicit dependence on the irradiation level because the gain depends on I_{ph} and I_{ph} depends on the irradiation level. For some optocouplers, the gain also has an explicit dependence on the irradiation level in addition to this implicit dependence. The explicit dependence is most clearly seen by comparing different h versus I_{ph} curves when each curve varies I_{ph} by varying I_F at a constant irradiation level. This produces Fig. 7 for the Micropac 66179. It is clear from the figure that the transistor gain has a strong explicit dependence on the irradiation level because the curves for different irradiation levels are significantly different. Note, however, that each curve follows a power law (a straight line in a log-log plot). Fig. 7 is useful for separating the LED degradation from the transistor gain degradation.

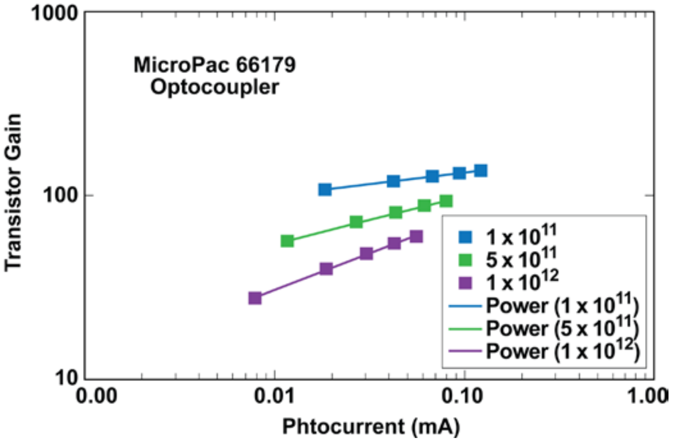

Fig. 7: Transistor gain versus photocurrent for each of several irradiation levels.

Table IV: Summary of test data for the Micropac 66179. Data apply at room temperature. Other test conditions are in the columns under I_F and Φ. Data in the columns under I_C and I_{ph} are averaged over four sample devices. Data under CTR were calculated by dividing I_C by I_F. Data in the columns under $I_{ph}/I_{ph,0}$ and CTR/CTR$_0$ are averages (over four devices) of ratios, which are nearly (not exactly) the same as ratios of averages, and used to construct some of the plots. Data under *h* were calculated by dividing the I_C table entries by the I_{ph} entries.

I_F (mA)	Φ (cm^2)	I_C (mA)	I_{ph} (mA)	*CTR*	*Iph/Iph,0*	*CTR/CTR$_0$*	*h*
2	0	2.99	0.0224	1.50	1	1	133
4	0	7.32	0.0509	1.83	1	1	144
6	0	12.07	0.0813	2.01	1	1	148
8	0	17.03	0.1126	2.13	1	1	151
10	0	22.03	0.1445	2.20	1	1	152
2	9.92×10^{10}	1.980	0.0185	0.99	0.828	0.661	107
4	9.92×10^{10}	5.090	0.0424	1.27	0.833	0.696	120
6	9.92×10^{10}	8.659	0.0680	1.44	0.836	0.718	127
8	9.92×10^{10}	12.511	0.0947	1.56	0.841	0.734	132
10	9.92×10^{10}	16.544	0.1220	1.65	0.845	0.751	136
2	4.96×10^{11}	0.656	0.0116	0.33	0.519	0.219	56
4	4.96×10^{11}	1.928	0.0270	0.48	0.531	0.263	71
6	4.96×10^{11}	3.531	0.0438	0.59	0.539	0.293	81
8	4.96×10^{11}	5.373	0.0614	0.67	0.546	0.315	87
10	4.96×10^{11}	7.397	0.0798	0.74	0.552	0.336	93
2	9.92×10^{11}	0.219	0.0079	0.11	0.352	0.073	28
4	9.92×10^{11}	0.745	0.0186	0.19	0.366	0.102	40
6	9.92×10^{11}	1.473	0.0304	0.25	0.374	0.122	48
8	9.92×10^{11}	2.358	0.0429	0.29	0.381	0.138	55
10	9.92×10^{11}	3.371	0.0560	0.34	0.388	0.153	60

E. De-Ratings

Because of part-to-part variations, some statistical data reflecting these variations are needed for mission risk assessments. Data presented here are based on the one-sided tolerance method of analysis. This method is based on results for a small test sample, taken at random from a parent population of devices. An upper tolerance will be given so the statistic of interest is the reciprocal of the normalized CTR, i.e., CTR$_0$/CTR because this quantity increases with increasing radiation damage. We assume that the mean and standard deviation, σ, of CTR$_0$/CTR are known for the test sample, in this case from the radiation test results. The design limit for the parent population is then calculated from the mean and the σ of the test sample for a specified probability and confidence limit. The usual practice is to use 99% probability at 90% confidence. A value denoted T is called an upper bound for CTR$_0$/CTR with 90% confidence for 99% of the parent population, denoted a (0.99, 0.90) value, if we are 90% confident that 99% of the parent population is less than T. The 99 represents the proportion of the population bounded and 90 represent the confidence level.

The statistical limit provided by this analysis is

Design limit value = mean + k * σ

where k, not to be confused with the upper case K in (1) through (3), is a factor that depends on the test sample size, as well as the probability and confidence. For the 99% 90% case with a sample size of four devices, k = 5.44.

Mean and statistically de-rated values of CTR$_0$/CTR at room temperature are shown in Table V. To illustrate the use of Table V for de-rated values, note that the table refers to the reciprocal of the normalized CTR (the reciprocal of the averages in the table are close to but not exactly the same as the averages of the normalized CTR) because this is the parameter that increases with degradation. Suppose, for example, that the device will operate at 10 mA in an equivalent 1 MeV neutron fluence of 1×10^{12} n/cm^2. The de-rated value in Table V for this condition is 10.171. This means that the project should be prepared for a CTR$_0$/CTR value that can be as large as 10.171, i.e., the project should be prepared for a normalized CTR as small as 1/10.171 or about 10%. The table also shows that more degradation (either mean or de-rated) occurs when the optocoupler is used at lower forward currents. For example, referring to the mean values at a fluence of 5×10^{11} n/cm^2, 21.7% of the initial CTR remains for I_F = 2 mA, whereas 33.5% of the initial CTR remains for devices used with I_F = 10 mA.

The same statistical interpretation discussed above for the CTR data is also used for the LED light intensity data and the results are shown in Table VI. At an equivalent 1 MeV neutron fluence of 1×10^{12} n/cm^2 and operating at a forward current of 10 mA, the optical power of the LED will be reduced to 39% of the initial value without de-rating, or 29% with de-rating. As shown in the table, slightly more severe degradation occurs for lower values of forward current.

Table V. Post radiation values of the CTR_0/CTR for Micropac 66179 at room temperature

Forward Current (mA)	*Statistical Condition of 4 Samples*	*1 x 10^{11} n/cm^2*	*5 x 10^{11} n/cm^2*	*1 x 10^{12} n/cm^2*
2	Mean CTR_0/CTR	1.513	4.615	13.689
2	Mean + 5.44 * σ	1.607	6.773	28.506
4	Mean CTR_0/CTR	1.438	3.816	9.769
4	Mean + 5.44 * σ	1.518	5.137	18.052
6	Mean CTR_0/CTR	1.394	3.430	8.133
6	Mean + 5.44 * σ	1.467	4.413	13.963
8	Mean CTR_0/CTR	1.362	3.178	7.174
8	Mean + 5.44 * σ	1.431	3.973	3.651
10	Mean CTR_0/CTR	1.332	2.984	6.498
10	Mean + 5.44 * σ	1.395	3.651	10.171

Table VI. Post radiation values of the L_0/L for Micropac 66179 LED (660 nm) at room temperature

Forward Current (mA)	*Statistical Condition of 4 Samples*	*1 x 10^{11} n/cm^2*	*5 x 10^{11} n/cm^2*	*1 x 10^{12} n/cm^2*
2	Mean L_0/L	1.208	1.931	2.858
2	Mean + 5.44 * σ	1.254	2.355	3.934
4	Mean L_0/L	1.201	1.888	2.750
4	Mean + 5.44 * σ	1.248	2.271	3.712
6	Mean L_0/L	1.195	1.859	2.683
6	Mean + 5.44 * σ	1.243	2.221	3.581
8	Mean L_0/L	1.189	1.835	2.632
8	Mean + 5.44 * σ	1.238	2.178	3.486
10	Mean L_0/L	1.184	1.814	2.590
10	Mean + 5.44 * σ	1.233	2.144	3.407

V. CONCLUSIONS

This paper summarizes the results of radiation tests of Micropac 66179 optocoupler.

Analysis of the test data reveals interesting information, such as the dependence of the transistor gain on irradiation and photocurrent. It shows that the micropac 66179 phototransistor gain has a strong explicit dependence on the irradiation level.

The degraded CTR from a fluence of 5×10^{11} 1-MeV n/cm^2, when used with a forward current of 10 mA, is 34% (without de-rating) of the initial CTR. This is reduced to 27% when including de-rating to account for part-to-part variations. The degradation (with or without de-rating) becomes more severe at smaller values of the forward current.

The degraded LED optical power from an equivalent 1 MeV neutron fluence of 5×10^{11} n/cm^2, when used with $I_F = 10$ mA, is 55% (without de-rating) of the initial value. This is reduced to 47% when including de-rating to account for part-to-part variations. The degradation (with or without de-rating) becomes more severe at smaller values of the forward current.

Although a low forward current helps LED reliability, using an optocoupler with a low forward current makes the photocurrent closer to the phototransistor noise level so overall performance becomes more sensitive to small changes in phototransistor properties, such as leakage current, or gain reduction due to impurities or water vapor. A combination of data and analysis indicated that a forward current of 2 mA in the 5×10^{11} 1-MeV n/cm^2 DD level produces a photocurrent that is close to this noise level. Furthermore, degradation from displacement damage has a greater impact when the forward current is small. It is recommended that the forward current used in applications be greater than 2mA. Degradations stated above assumed 10mA.

Additional de-rating is required for reliability associated with aging, which has not already been accounted for in this study. Reliability models are reasonably well established for LEDs, with dependences on operating temperature and operating current. Optocoupler reliability is less straightforward because other factors –such as the coupling compound used between the LED and phototransistor – also affect long-term performance. A minimum adjustment factor of 10% is recommended to account for aging.

VI. REFERENCES

[1] C. E. Barnes, "A comparison of gamma-irradiated-induced degradation in amphoterically Si-doped GaAs LED's and Zn- diffused GaAs LED's," IEEE Trans. Elec. Dev., vol. 26, no. 5, pp. 739-745, May 1979.

[2] A. H. Johnston and T. F. Miyahira "Hardness Assurance Methods for Radiation Degradation of Optocouplers," IEEE Trans. Nucl. Sci., 50(6), pp. 2649-2656, Dec. 2005.

[3] L. Edmonds, "Predicting Micropac 4N49 Optocoupler Degradation in a Radiation Environment," unpublished JPL report, Aug. 8, 2006.

[4] C. E. Barnes, "Radiation effects in electroluminescent diodes," IEEE Trans. Nucl. Sci., vol. 18, pp. 322–331, Dec. 1971.

[5] A. H. Johnston and T. F. Miyahira, "Characterization of proton damage in light emitting diodes," IEEE Trans. Nucl. Sci., vol. 47, no. 6, pp. 2500–2507, Dec. 2000.

[6] T. F. Miyahira, F. Irom and A. H. Johnston, "Measurements of Radiation Effects on Optoelectronics Conducted by the Jet Propulsion Laboratory," NSREC Data Workshop Record, 2006.

[7] F. Irom, G. R. Allen and B. G. Rax, "Proton Displacement Damage Measurements in Commercial Optocouplers," NSREC Data Workshop Record, 2015.

[8] R. A. Reed, P.W. Marshall, A.H. Johnston, J.L. Barth, C.J. Marshall, K.A. LaBel, M. D'Ordine, H.S. Kim and M.A. Carts, "Emerging Optocoupler Issues with Energetic Particle-Induced Transients and Permanent Radiation Degradation," IEEE Trans. Nucl. Sci., 45(6), pp. 2833-2841, Dec. 1998.

[9] B.G. Rax, C.I. Lee, A.H. Johnston, C.E. Barnes, "Total Dose and Displacement Damage in Optocouplers", IEEE Trans. on Nuclear Science, Vol. 43, no. 6, pp. 3167-3173, Dec. 1996.