A Compendium of Recent Optocoupler Radiation Test Data

K.A. LaBel[1], S.D. Kniffin[2], R.A. Reed[1], H.S. Kim[3], J.L. Wert[4], D.L. Oberg[4], E. Normand[4],
A.H. Johnston[5], G.K. Lum[6], R. Koga[7], S. Crain[7], J.R. Schwank[8], G.L. Hash[8],
S. Buchner[9], J. Mann[9], L. Simpkins[9], M. D'Ordine[10], C.A. Marshall[1],
M.V. O'Bryan[11], C.M. Seidleck[11], L.X. Nguyen[11], M.A. Carts[11],
R.L. Ladbury[2], J.W. Howard[3],

NASA/Goddard Space Flight Center[1]; Orbital Sciences Corporation[2];
Jackson and Tull Chartered Engineers[3]; Boeing Corporation[4]; NASA/Jet Propulsion Laboratory[5];
Lockheed Martin Space Systems Company, Missiles and Space Operation [6];
The Aerospace Corporation[7]; Sandia National Laboratories[8]; Naval Research Laboratories[9];
Ball Aerospace and Technologies Corporation[10]; Raytheon Systems Corporation[11]

Abstract**–**We present a compendium of optocoupler radiation test data including neutron, proton and heavy ion Displacement Damage (DD), Single Event Transients (SET) and Total Ionizing Dose (TID). Proton data includes ionizing and non-ionizing damage mechanisms.

I. INTRODUCTION

Optocouplers, also known as optoisolators, are hybrid devices that are typically used by spaceflight designers to provide electrical isolation between circuits such as subsystem-to-subsystem interfaces. These devices usually consist of a light emitting diode (LED) transmitter coupled with a p-intrinsic-n (PIN) photodiode or phototransistor receiver and, for certain devices, additional circuitry. Figure 1 illustrates a typical optocoupler [1]. It should also be noted that optocouplers are not just standalone devices, they are often components in other devices such as DC/DC converters.

This compendium compiles optocoupler radiation data that has been gathered by a wide range of test organizations. This includes both government and industry data obtained from a number of test facilities utilizing various test methods.

Figure 1: Typical Optocoupler Block Diagram

II. RADIATION ISSUES

There are three major radiation issues affecting optocouplers for space flight utilization.

A. Displacement Damage

Primarily, neutrons and protons cause displacement damage. It is important to remember that while the protons are causing DD, they are also contributing to TID, thus depending on the prime degradation mode, some results appear identical to TID. The time that it takes for DD to affect a device a certain amount is generally much shorter than the expected time that it would take for TID to cause equivalent damage. Though many optical components degrade from DD, the optocoupler devices that seem to be the most sensitive are those that use amphoterically doped or single heterojunction [2,3,4] light emitting diodes (LEDs); double heterojunction LEDs appear to be less sensitive to DD. Issues involving DD were first noted by in-flight degradation on the TOPEX/Poseidon satellite. Several non-critical status signals that utilized optocouplers failed during the mission. This radiation issue was first described by Johnston, et al. [2]. Further work in this area has been done to characterize DD effects in optocouplers [3,4,5,6,7]. DD is known to affect the current transfer ratio (CTR) of these devices and may affect other performance parameters such as timing. CTR is defined as Phototransistor collector current (I_C) divided by the LED forward current (I_F). $CTR = \frac{I_C}{I_F}$

Issues such as particle energy, mapping of test energies to in-flight predictions, application-specific interpretation of test data, initial device CTRs, sample-to-sample variance, temperature and aging effects all must be considered for device selection and use.

B. Single Event Transients

SETs are induced by protons and heavy ions in higher speed devices (>1 Mbps) and induced by heavy ions in slower devices. The first incident that brought the SET issue to the forefront were anomalies observed by NASA's Hubble Space Telescope (HST) following the installation of two instruments that contained high-speed optocouplers during Servicing Mission 2. These anomalies prompted an investigation that found SET sensitivity in these optocouplers [1]. Further work has since explored the mechanisms of these transients, the size of the transients which vary by device performance and energetic particle characteristics, circuit-specific effects, types of particles that induce SETs, and angular dependence [5,8,9].

C. Total Ionizing Dose

Historically, TID was the prime radiation concern for optocouplers. TID issues for optocouplers are well known and usually serve as the basis for parts procurement decisions. Optocoupler TID test data typically utilizes Co-60 sources (ionizing radiation). However, in some cases proton damage testing, which acts as a combination of TID and DD, has been used in place of Co-60. The parameter most sensitive to TID is usually the CTR. When significant degradation in CTR occurs, mitigation measures can be added to some applications by derating the part sufficiently to cover the expected loss during mission lifetime [2].

III. TEST FACILITIES

Table 1 shows the test facilities utilized in testing parts by the organizations contributing to this compendium. Proton testing was conducted at the Harvard Cyclotron Facility (HCL), the Indiana University Cyclotron Facility (IUCF), the Loma Linda University Medical Center (LLUMC), the TRI-University Meson Facility (TRIUMF), University of California at Davis, Crocker Nuclear Laboratories (UCD/CNL), and Lawrence Berkley Laboratories (LBL). Heavy ion testing was conducted at LBL, Brookhaven National Laboratories (BNL) and Michigan State University National Superconducting Cyclotron Laboratory (MSU/NSCL). Neutron testing was performed at the Sandia National Laboratory Pulse Reactor Facility (SPR). TID testing was performed at Sandia National Laboratory Radiation Hardness Assurance Department (SNL/RHA).

TABLE 1: TEST FACILITIES AND PARTICLES

Facility	Particle	Particle Energies Used
HCL	Proton	73 – 149MeV
IUCF	Proton	54 – 197MeV
LLUMC	Proton	51MeV
TRIUMF	Proton	50 – 500MeV
UCD/CNL	Proton	26.6 – 63MeV
LBL	Proton/He	35 – 55MeV p+, 48MeV He
BNL	Heavy Ion	57MeV Li-7, 110MeV C-12, 150MeV F-19, 210MeV Cl-35, 227MeV Ti-48, 278MeV Ni-58
MSU/NSCL	Heavy Ion	240MeV He-4, 720MeV C-12, 1200MeV Ne-20, 2160MeV Ar-36, 5040MeV Kr-84, 7740MeV Xe-129
SPR	Neutron	TRIGA* Reactor, pulse spectrum
SNL/RHA	Co-60 γ	1.17, 1.33MeV

*TRIGA = Training, Research, Isotopes, General Atomics nuclear reactor.

IV. TEST METHODS

A number of organizations have tested optocouplers for various effects at several different test facilities. The parameter of interest determines how the device is set up for testing. All devices presented were tested at nominal room temperature. Table 2 presents an overview of the test methods used by each organization. All methods, results and data use the following abbreviation conventions:

I_F = Forward current of LED
I_C = Output current of the photodiode
V_{CE} = Voltage drop across the collector/emitter of the photodiode
V_{CC} = Voltage drop across the load and LED
R_C = Capacitive load applied as input feedback
R_F, C_F = Passive filter (resistor/capacitor combination) for SET testing
Load = The resistive load applied to the photodiode
Forward Load = The resistive load applied to the input to vary I_F for a constant V_{CC}
CTR = I_C/I_F
CTR_O = Initial CTR
Degradation of CTR = CTR/CTR_O (Normalized)
GSFC = NASA Goddard Space Flight Center
JPL = Jet Propulsion Laboratories
LMSSC MSO = Lockheed Martin Space Systems Company, Missiles and Space Operation
NRL = Naval Research Laboratories
SNL = Sandia National Laboratories
Mfg = Manufacturer
HP = Hewlett Packard (now Agilent)
Mii = Micropac
TI = Texas Instruments
LDC = Lot Date Code

A. Displacement Damage Testing

In displacement testing, CTR, is typically the parameter of interest. The device is generally set up as in Figure 2 below. Testing is usually done in step irradiations either biased or unbiased. Measurements are generally done after each step centering on certain parameters (I_F, V_{CE}, V_{CC}, and Load), with variations of holding a parameter constant while sweeping another. Some measurements have been made in-situ assuming that there is one bias condition during the testing (no sweep). See Table 2 for test conditions arranged by test organization.

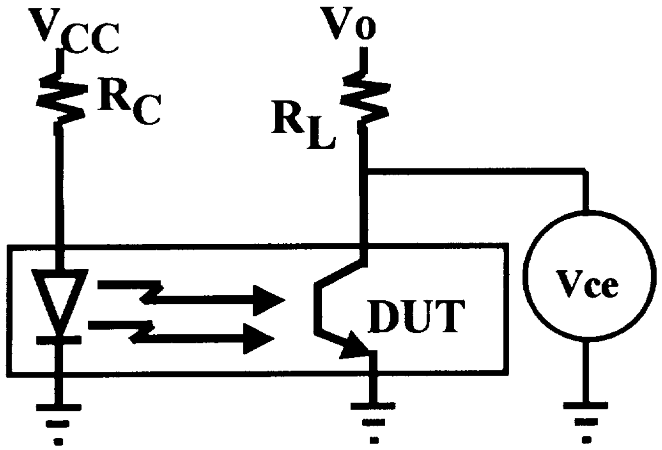

Figure 2: Schematic of experimental setup to measure CTR degradation [5].

B. SET Testing

SET testing is generally performed in a set up similar to that in Figure 3. The bias condition should be such that the LED is off. When the LED is biased on, SET sensitivity is negligible [1]. Transients can be measured directly at the output of the optocoupler, the output of a TTL device, or some other filtering device.

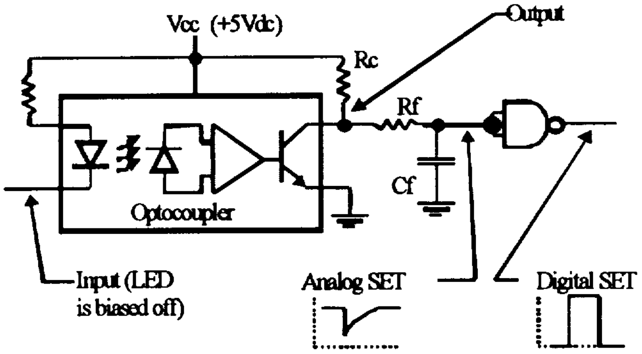

Figure 3: Schematic representation of a SET test circuit showing the filter network and the two probe locations for analog and digital transient capture [5].

C. Total Ionizing Dose Testing

The devices tested for TID by SNL presented here were unbiased and irradiated with Co-60 gamma rays stepwise to 1Mrad(Si). The parts were electrically tested between steps.

Table 2. Test Methods

Displacement Damage						
Organization	**Input**	**Vce**	**Rc (Load)**	**Note**	**Parameters Measured**	**Particles**
Aerospace	Sweep If	Constant	Variable	step irradiation	CTR	Protons, Helium
Ball Aero	Sweep If	Constant	Variable	step irradiation	CTR	Protons
Boeing	Sweep If	Constant	Constant	step irradiation	CTR	Protons
	Off	Sweep	Constant	step irradiation	Leakage	
GSFC	Sweep If, Fixed Vcc	Constant	Constant	in situ	CTR, Switching, Leakage	Protons, Neutrons, Heavy Ions
	Sweep If, Sweep Vcc	Sweep	Variable	step irradiation		
JPL	Sweep If	Constant	Constant	step irradiation	CTR	Protons
LMSSC MSO	Constant	Constant	Constant	step irradiation	CTR	Protons
NRL	Sweep If	Constant	Constant	step irradiation	CTR	Protons
SRL	Sweep If	Sweep	Constant	step irradiation	CTR	Neutrons
SET						
Organization	**Note:**				**Parameters Measured**	**Particles**
GSFC	The part should be biased in such a way that the diode is off. If the diode is on, SET sensitivity is negligible.				SET	Protons, Heavy Ions
JPL					SET	Protons, Heavy Ions
LMSSC MSO					SET	Protons
NRL					SET	Protons
Total Ionizing Dose						
Organization	**Input**	**Vce**	**Rc (Load)**	**Note**	**Parameters Measured**	**Particles**
SNL	Constant	Sweep	Constant	step irradiation	CTR	Co-60 Gamma Rays

V. SUMMARY OF TEST RESULTS

All tests were performed at nominal room temperature unless otherwise noted. Table 3 summarizes the proton, neutron and heavy ion DD results. For the Results/Notes column, the number given is fluence (particles/cm^2) of the particle indicated. If the part degraded, the fluence given represents the level where degradation started. If there was no degradation, then the number given represents the end of test fluence. Table 4 summarizes the proton and heavy ion SET results. If the part had no SET, the number is the total fluence given to the device. Table 5 summarizes the TID results. The Note gives the onset of degradation; these parts were tested to 1Mrad(Si).

Table 3: Proton, Neutron and Heavy Ion Displacement Damage Summary

Device	Mfg	LDC	Device Speed	Test Organization	Test Facility	Energy/Particles Used	Results/Notes
4N24	TI	8850	400kbps	Aerospace	LBL	45MeV Protons, 48MeV He	CTR Degradation at 5.8E10 p+, 5.2E8 He
4N49	TI	9408	400kbps	Aerospace	LBL	35, 55MeV Protons	CTR Degradation at 4.8E9 35MeV, 6.8E10 55MeV
4N49	TI	9408	400kbps	Aerospace	LBL	55MeV Protons, 48MeV He	CTR Degradation at 6.8E10 p+, 5.2E8 He
OLF400	Isolink	9713	400kbps	Aerospace	LBL	55MeV Protons	No CTR degradation at 8.1E11
4N49	Mii	9518	400kbps	Ball	UCD/CNL	63MeV Protons	CTR Degradation at 4.5E10
OMT1062	Optek	9628	50kbps	Ball	UCD/CNL	63MeV Protons	CTR Degradation at 4.5E10
66092	Mii	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
66099	Mii	9650	50kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at 3E10
4N48	Mii	9550	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N48	Mii	9618	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	TI	8646	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9327	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9329	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	TRW	9439	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 3E10
4N49	Mii	9504	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9511	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 3E10
4N49	Mii	9529	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9550	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N49	Mii	9648	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 1E10
4N55	HP	9337	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to 3E10
4N55	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at 3E10
6N134	Mii	9645	10Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at 3E10
6N140	HP	9711, 15, 16	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
6N140 (66058)	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at 3E10
DIH126	Dionics	9521	N/A	Boeing	UCD/CNL	63MeV Protons	Degradation of Relay (Part is a Power MOSFET PV Relay) at 9E9
FB00KBY	Teledyne	9531	N/A	Boeing	UCD/CNL	63MeV Protons	Degradation of Relay (Part is a Power MOSFET PV Relay) at 9E9
HCPL-5231	HP	9632, 9633	2Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at 3E10
HCPL-5430	HP	9644	40Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at 3E10
HCPL-5431	HP	9618	40Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at 3E10
HCPL-5530	HP	9642	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
HCPL-5531	HP	9632, 9633	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
HCPL-5630	HP	9716	10Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at 3E10
HCPL-5701	HP	9315	400kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at 3E10
HCPL-5730	HP	9701	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
OLH149	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
OLH249	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
OLH304	Isolink	Unknown	1Mbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
OLH349	Isolink	Unknown	1Mbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
OLH400	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at 3E10
66088	Mii	Unknown	625kbps	GSFC	UCD/CNL	63MeV Protons	No CTR degradation to 1E9
66088	Mii	Unknown	625kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at 2E10
66099	Mii	Unknown	50kbps	GSFC	TRIUMF	58MeV Protons	No CTR degradation to 2E10
66123	Mii	Unknown	10Mbps	GSFC	TRIUMF	58MeV Protons	No Parametric degradation to 2E10
3C91C	Mitel	Unknown	200kbps	GSFC	UCD/CNL	63, 31, 21, 14MeV Protons	Degradation of CTR at <1E10 for all energies
4N48	Mii	Unknown	400kbps	GSFC	SPR	Neutrons	Degradation of CTR at 2E11
4N48	Optek	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at 2E10
4N49	Mii	Unknown	400kbps	GSFC	TRIUMF	58MeV Protons	No CTR degradation to 2E10
4N49	TI	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at 2E10
6N134	HP	Unknown	10Mbps	GSFC	SPR	Neutrons	No Parametric degradation to 8E11 1MeV equiv.
6N140	Mii	Unknown	400kbps	GSFC	TRIUMF	63, 58MeV Protons	No CTR degradation to 2E10
HCPL-6651	HP	Unknown	10Mbps	GSFC	TRIUMF	Various Protons	No Parametric degradation at 2E10 58MeV
HSSR-7110	HP	9637	N/A	GSFC	UCD/CNL	63MeV Protons	Leakage and On/Off Time degradation at 2.3E11 (Part is a Power MOSFET)
OLH400	Isolink	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at 4E11
OLS700	Isolink	Unknown	1Mbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at 3.8E11
P2824	Hamamatsu	Unknown	333kbps	GSFC	TRIUMF, LLUMC, IUCF, SPR	Various Protons, Neutrons	Degradation of CTR at 2E10 (TRIUMF 58MeV p+), 1.7E10 (LLUMC 52MeV p+), 2.5E10 (IUCF 195MeV p+), 5.4E10 (SPR 1MeV equiv. Neutrons)
4N49	Mii	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR
4N49	Optek	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR at 5E10
4N49	TI	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR
6N134	HP	Unknown	10Mbps	JPL	IUCF, UCD/CNL	192, 50MeV Protons	Degradation of CTR
6N140	HP	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR
HCPL-5230	HP	Unknown	2Mbps	JPL	UCD/CNL	50MeV Protons	Degradation of CTR
OLH1049	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at 1E10
OLH1049.0002	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at 1E10
OLH1049.0003	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at 1E10
4N35	Mii	Unknown	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at 5E11
4N49	Mii	CEJG M9628	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at 1E11
4N49	Mii	66092-101S special process	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at 4E11
6N140	Mii	8836 8302401EC 31757	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at 1E11
HCPL-2201	HP	9538	20Mbps	LMSSC MSO	IUCF	192MeV Protons	No CTR degradation at 6E11
HCPL-2430	HP	9630	5Mbps	LMSSC MSO	IUCF	192MeV Protons	No CTR degradation at 6E11
61082-300 photodiode	Mii	9827	500Hz Operation	LMSSC MSO	HCL	73MeV Protons	Iout degradation at 2E10
62017 GS3040-3 LED	Mii	Unknown	500Hz Operation	LMSSC MSO	HCL	73MeV Protons	If degradation at 2E10
OP224 LED	Optek	GeAlAs IR, 890nm	3Hz Operation	LMSSC MSO	HCL	73MeV Protons	If degradation at 2E10
OP604 phototransistor	Optek	npn silicon	3Hz Operation	LMSSC MSO	HCL	73MeV Protons	Iout degradation at 2E10
MC099	Mii	Unknown	50kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at 3.8E10
OLI400	Isolink	9841	400kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at 1.5E11
QCPL-5729	HP	Unknown	400kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at 3.8E10
OLH249	Isolink	400kbps	400kbps	SNL	SPR	Neutrons	Degradation of CTR at 1E12
S4N49	Mii	400kbps	400kbps	SNL	SPR	Neutrons	Degradation of CTR at 1E12

Table 4: Proton and Heavy Ion SET Summary

Device	Mfg	LDC	Device Speed	Test Org.	Test Facility	Energy/Particles Used	Results/Notes
66099	Mii	Unknown	50kbps	GSFC	TRIUMF	58MeV Protons	No SET to 2E10
66123	Mii	Unknown	10Mbps	GSFC	TRIUMF	58MeV Protons	SETs observed
66123	Mii	Unknown	10Mbps	GSFC	TRIUMF	68-225MeV Protons	SETs observed
4N48	Optek	9644	400kbps	GSFC	UCD/CNL	38.2MeV Protons	No SET to 1E9
4N49	Mii	9628 + Special Process	400kbps	GSFC	TRIUMF	63, 58MeV Protons	No SET to 2E10
4N55	HP	9702	400kbps	GSFC	UCD/CNL	38.2MeV Protons	No SET to 1E9
6N136	Mii	9624	400kbps	GSFC	UCD/CNL	38.2MeV Protons	No SET to 1E9
6N140A	HP	9707	400kbps	GSFC	UCD/CNL	38.2MeV Protons	No SET to 1E9
6N140	Mii	Unknown	400kbps	GSFC	TRIUMF	63, 58MeV Protons	SETs observed
HCPL-5401	HP	9642	40Mbps	GSFC/Ball	UCD/CNL	38.2MeV Protons	SETs observed
HCPL-5631	HP	9427, 9707	10Mbps	GSFC/Ball	UCD/CNL	38.2MeV Protons	SETs observed
HCPL-6651	HP	Unknown	10Mbps	GSFC	UCD/CNL, TRIUMF	Various Protons	SETs observed
OLH249	Isolink	Unknown	400kbps	GSFC	MSU/NSCL	Various Heavy Ions	SETs observed
OLH5601	Isolink	Unknown	10Mbps	GSFC	MSU/NSCL	Various Heavy Ions	SETs observed
P2824	Hamamatsu	Unknown	333kbps	GSFC	TRIUMF	58MeV Protons	No SET to 2E10
6N134	HP	Unknown	400kbps	JPL	BNL, IUCF, UCD/CNL	Various Heavy Ions, 192, 50MeV Protons	SETs observed
6N134	Mii	Unknown	400kbps	JPL	BNL, IUCF, UCD/CNL	Various Heavy Ions, 192, 50MeV Protons	SETs observed
6N140	HP	Unknown	400kbps	JPL	BNL, UCD/CNL	Various Heavy Ions, 50MeV Protons	No SETs with protons, SETs observed with heavy ions
4N35	Mii	Unknown	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to 5E11
4N49	Mii	CEJG M9628	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to 4E11
4N49	Mii	66092-101S special process	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to 4E11
6N140	Mii	8836 8302401EC 31757	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to 8E11
HCPL-2201	HP	9538	20 Mbps	LMSSC MSO	IUCF	44 to 192MeV Protons	SETs observed
HCPL-2430	HP	9630	5 Mbps	LMSSC MSO	IUCF	44 to 192MeV Protons	SETs observed
61082-300 photodiode	Mii	9827	500Hz Operation	LMSSC MSO	HCL	73, 145MeV Protons	SETs observed
OP604 phototransistor	Optek	Unknown	3Hz Operation	LMSSC MSO	HCL	75, 145MeV Protons	SETs observed
QCPL-6637	HP	9611	10Mbps	NRL	UCD/CNL	63MeV Protons	SETs observed

Table 5: Total Ionizing Dose Summary

Device	Mfg	LDC	Device Speed	Test Org.	Test Facility	Particles Used	Results/Notes
OLH249	Isolink	Unknown	400kbps	SNL	Sandia RHA	Co-60 gammas	Degradation of CTR at 100krads
4N49	Mii	Unknown	400kbps	SNL	Sandia RHA	Co-60 gammas	Degradation of CTR at 100krads

VI. TEST DATA

A. Proton, Neutron and Heavy Ion Displacement Damage Effects

1) The Aerospace Corporation

a. 4N24 (TI)

The 4N24 was tested biased with 45MeV protons and 48MeV Helium ions at LBL. Test parameters were set at $I_F = 5mA$, $V_{CC} = 1.5V$, $V_{CE} = 8V$. I_F was swept for CTR measurements. CTR degradation was noted in both cases. See Figures 4 and 5.

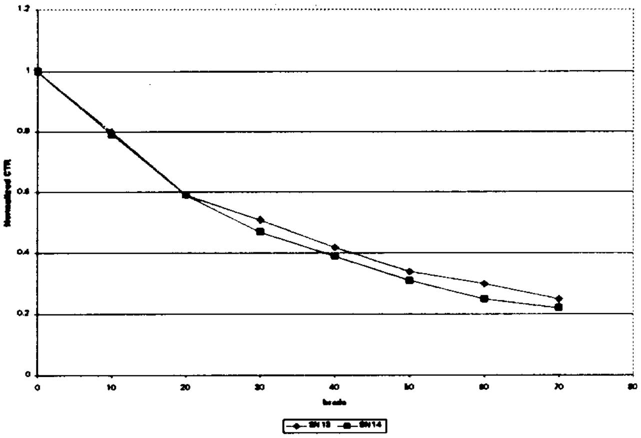

Figure 4: 45MeVProton Induced CTR Degradation Measurements for TI 4N24.

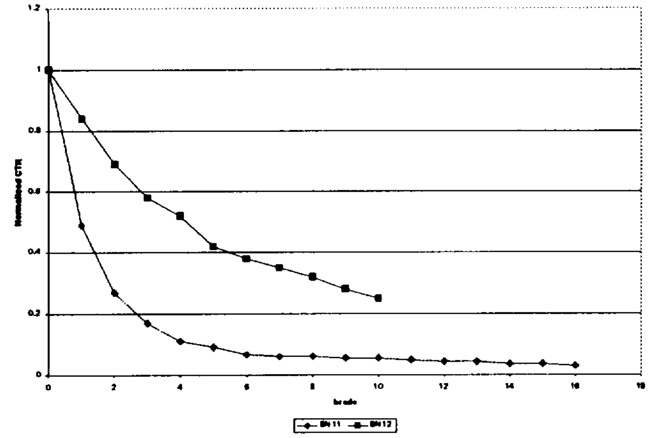

Figure 5: 48MeV He Induced CTR Degradation Measurements for TI 4N24.

b. 4N49 (TI) Multiple Tests

Four 4N49s were tested biased, two each with 35 and 55MeV protons at LBL. Test parameters were set at V_{CC} = 5V, V_{CE} = 5V, series resistors were chosen to set I_F to 1, 2, 5, and 10mA. I_F was swept for CTR measurements. CTR degradation was noted in all cases, see Figures 6-9.

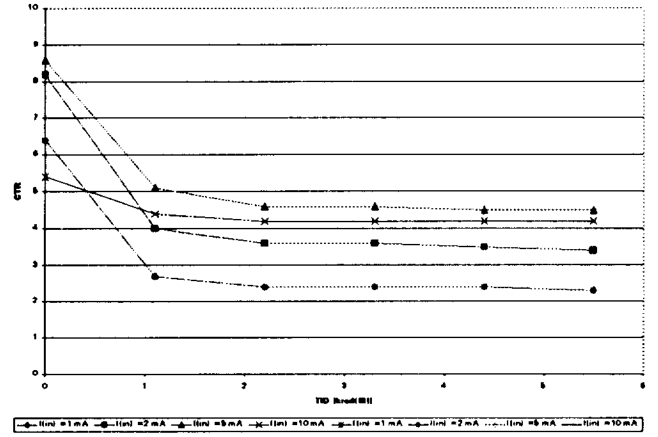

Figure 6: 35MeV Proton Induced CTR Degradation Measurements for TI 4N49 (SN2).

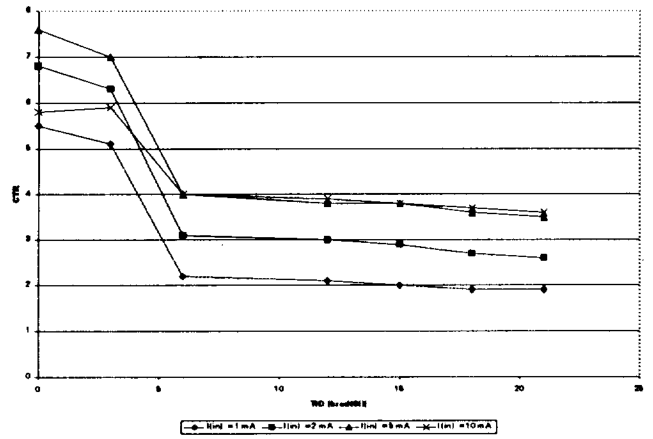

Figure 7: 35MeV Proton Induced CTR Degradation Measurements for TI 4N49 (SN3).

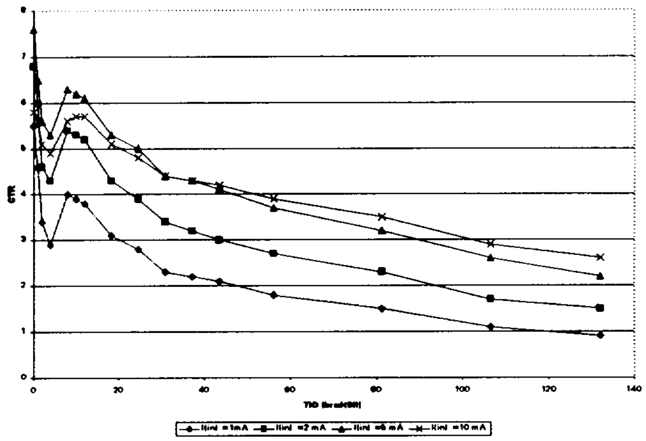

Figure 8: 55MeV Proton Induced CTR Degradation Measurements for TI 4N49 (SN1).

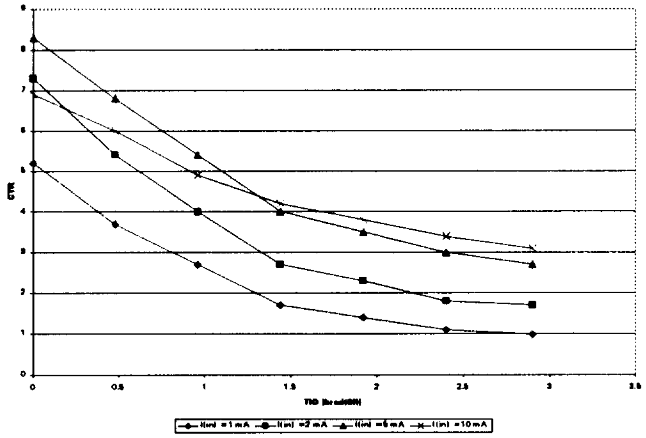

Figure 9: 55MeV Proton Induced CTR Degradation Measurements for TI 4N49 (SN4).

The 4N49 was tested biased with 55MeV protons and 48MeV Helium ions at LBL. Test parameters were set at I_F = 2mA, V_{CC} = 5V, V_{CE} = 5V. I_F was swept for CTR measurements. CTR degradation was noted in both cases. See Figures 10 and 11.

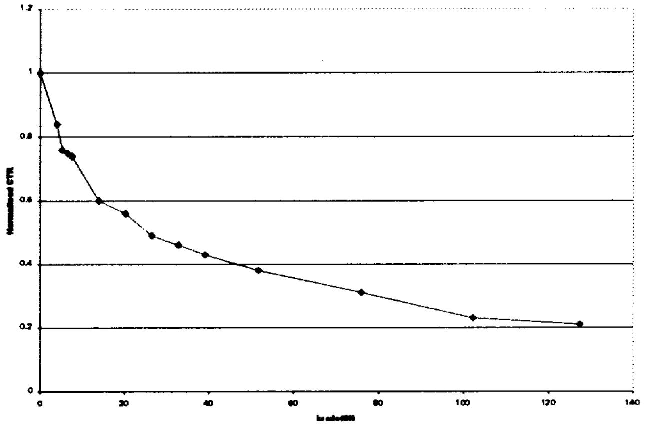

Figure 10: 55MeV Proton Induced CTR Degradation Measurements for TI 4N49.

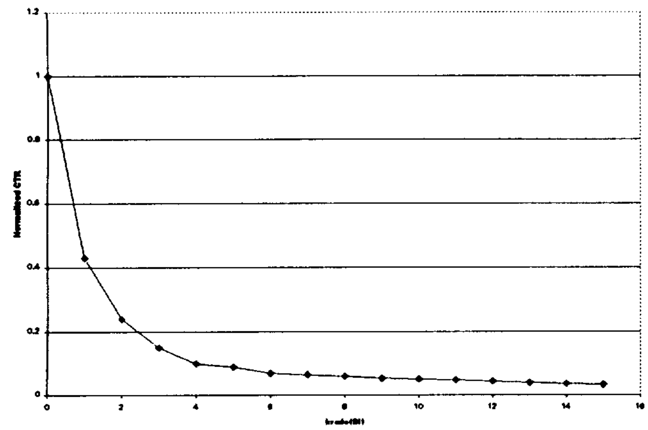

Figure 11: 48MeV Helium Induced CTR Degradation Measurements for TI 4N49.

c. OLF400 (Isolink)

The OLF400 was tested with 55MeV protons at LBL. Test parameters were set at V_{CC} = 5V, V_{CE} = 5V, the output resistance was 300Ω. The input resistance was varied (R_F = 8kΩ, 10kΩ, 16kΩ, 20kΩ, 30kΩ, and 40kΩ) to give I_F = 0.429mA, 0.344mA, 0.216mA, 0.173mA, 0.166mA, and 0.087mA respectively. Output current was measured at each step with each of the resistors. The results show a decrease in output current with increasing proton dose, hence CTR degradation. Results are presented in Figure 12.

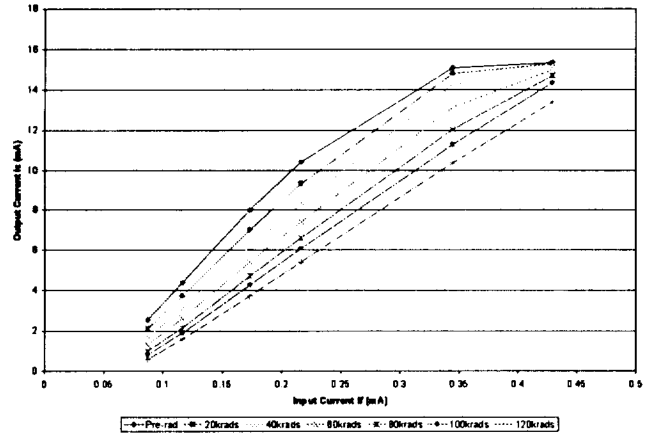

Figure 12: 55MeV Proton Induced CTR Degradation in Isolink OLF400.

2) Ball Aerospace NASA/JPL

a. 4N49 (Mii)

The 4N49 was tested with 63MeV protons at UCD/CNL. The ten samples were divided into two groups. Five were irradiated with the LED off (I_F = 0mA, V_{CE} = 5V) and the other group was irradiated with the LED on (I_F = 5mA, V_{CE} = 28V). The parts were tested after each step irradiation. In both groups, the input resistance was varied to produce I_F = 1, 3, 5, and 8mA. These bias conditions are representative of the proposed space application. For proton fluences less than 1E11 p/cm^2, there is only a slight difference in the radiation response between the two 4N49 groups. However, at the highest proton fluence tested (4.2E11 p/cm^2), the normalized CTR for the group irradiated with the LED off is roughly half of the normalized CTR for the group irradiated with the LED on. Figures 13 and 14 present the mean normalized CTR versus proton fluence for the two groups tested [6].

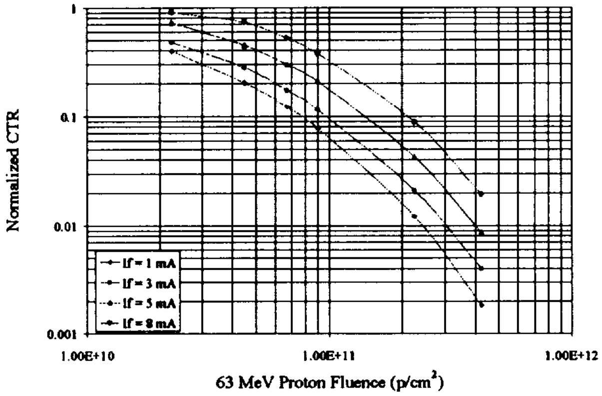

Figure 13: Micropac 4N49 Mean Normalized CTR vs. Proton Fluence (Bias Conditions during Irradiation: If = 0 mA, Vce = 5V.)

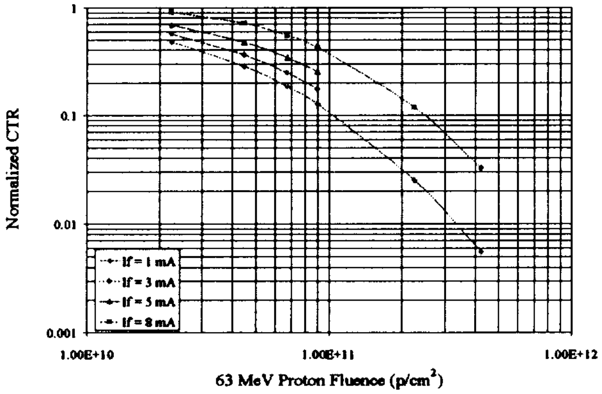

Figure 14: Micropac 4N49 Mean Normalized CTR vs. Proton Fluence (Bias Conditions during Irradiation: If = 5 mA, Vce = 28V.)

b. OMT1062 (Optek)

The OMT1062 slotted optical switch was tested with 63MeV protons at UCD/CNL. Six samples were irradiated with the LED biased on (I_F = 15mA, V_{CE} = 5V) which reflects its application. The parts were tested after each step irradiation. In both groups, the input resistance was varied to produce I_F = 5, 10, 15, and 20mA. The mean, normalized CTR is plotted versus proton fluence in Figure 15. Other test samples from this date code were previously evaluated for TID from gamma rays and those test results for I_F = 10mA have been included. Note that 7.4E9 p/cm^2 (63MeV protons) imparts a total ionizing dose of ~1.0krad(Si). This data suggests that ionizing dose damage contributes about 2% of the combined ionizing dose and displacement damage (at 2.2E11p/cm2) [6].

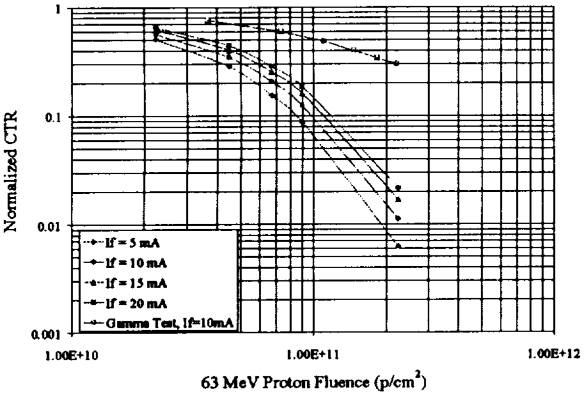

Figure 15: Optek OMT1062 Mean Normalized CTR vs. Proton Fluence (Bias Conditions during Irradiation: If = 15 mA, Vce = 10V.)

3) Boeing

a. 66092 (Mii)

The 66092 was tested with 63MeV protons at UCD/CNL. V_{CC} and V_{CE} were held constant while I_C was measured for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was no significant change in CTR to a fluence of 3E10 p/cm².

b. 66099 (Mii)

The 66099 was tested with 63MeV protons at UCD/CNL. V_{CC} and V_{CE} were held constant while I_C was measured for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was no significant change in CTR to a fluence of 3E10 p/cm².

c. 4N48 (Mii) Multiple Tests

The 4N48 was tested with 63MeV protons at UCD/CNL. V_{CC} and V_{CE} were held constant while I_C was measured for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was some degradation in CTR, see Figure 16.

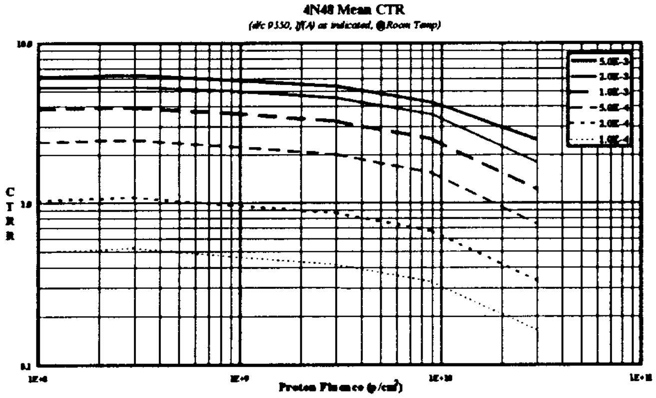

Figure 16: 4N48 Proton Induced CTR Degradation.

The 4N48 was tested with 63MeV protons at UCD/CNL. V_{CC} and V_{CE} were held constant at 5V while I_C was measured for I_F = 0.5, 1.0, 2.0, 5.0 and 10mA. There was some degradation in CTR, see Figure 17.

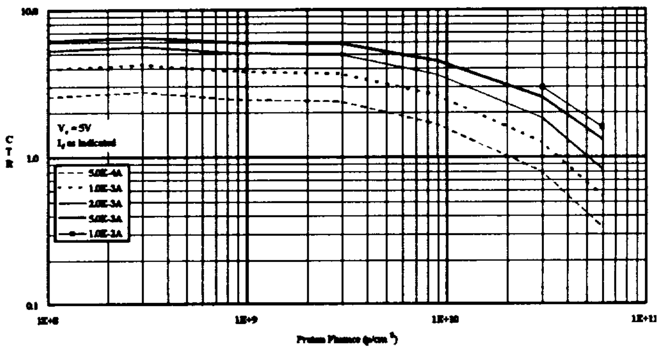

Figure 17: 4N48 Proton Induced CTR Degradation.

d. 4N49 Multiple Tests, Multiple Vendors

The TI 4N49 (LDC8646) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.5V, 5.0V and 9.5V for I_F = 0.2, 0.5, 1.0, 2.0, 5.0, 10, and 20mA at each V_{CE}. There was a similar amount of degradation in CTR for all three cases, see Figure 18 (V_{CE} = 5V).

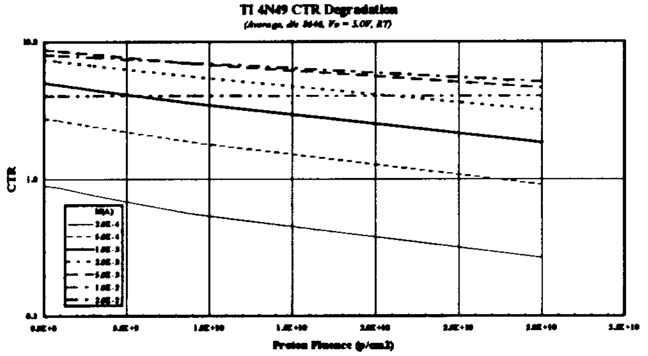

Figure 18: 4N49 (Mii LDC8646) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9327) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.5, 1.0, 2.0, 5.0 and 10mA. There was some degradation in CTR, see Figure 19.

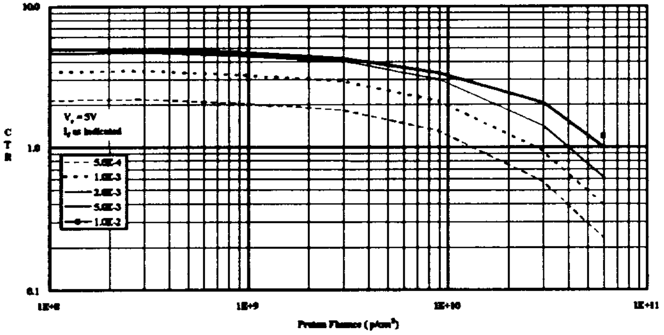

Figure 19: 4N49 (Mii LDC9327) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9329) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was some degradation in CTR, see Figure 20.

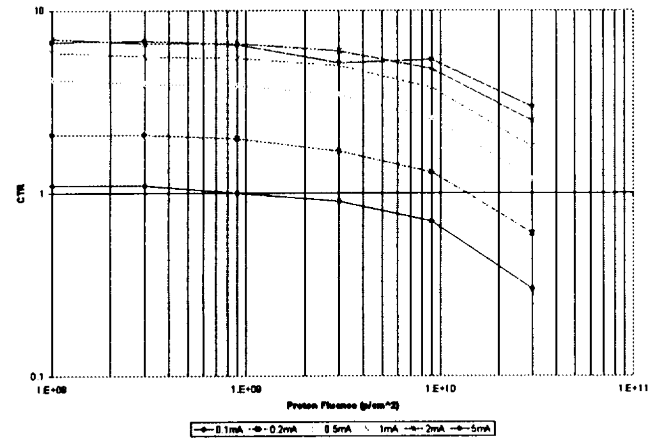

Figure 20: 4N49 (Mii LDC9329) Proton Induced CTR Degradation.

The TRW 4N49 (LDC9439) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.5, 1.0, 2.0, 5.0 and 10mA. There was some degradation in CTR, see Figure 21.

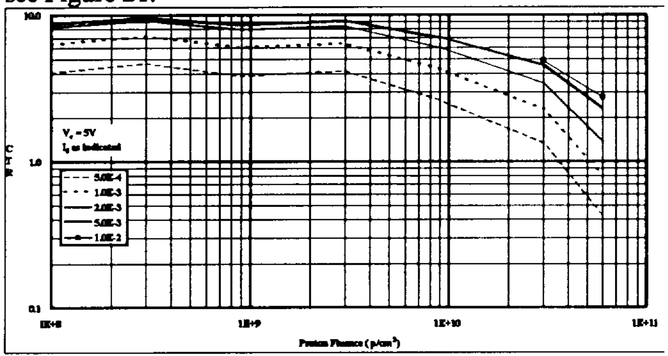

Figure 21: 4N49 (TRW LDC9439) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9504) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.5, 1.0, 2.0, 5.0 and 10mA. There was some degradation in CTR, see Figure 22.

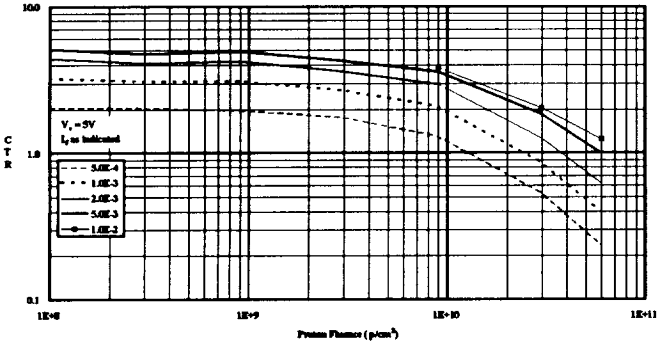

Figure 22: 4N49 (Mii LDC9504) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9511) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.5, 1.0, 2.0, 5.0 and 10mA. There was some degradation in CTR, see Figure 23.

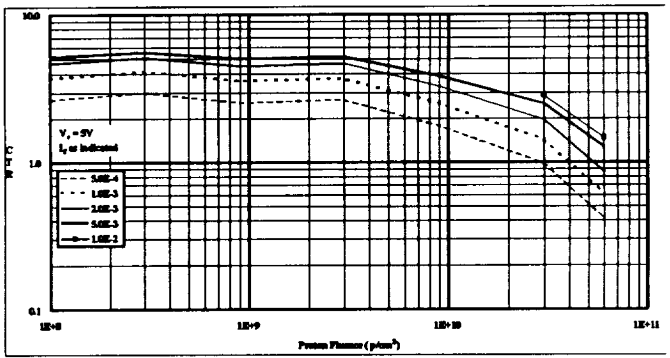

Figure 23: 4N49 (Mii LDC9511) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9529) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.5V, 5.0V and 9.5V for I_F = 0.2, 0.5, 1.0, 2.0, 5.0, 10, and 20mA at each V_{CE}. There was a similar amount of degradation in CTR for all three cases, see Figure 24 (V_{CE} = 5V).

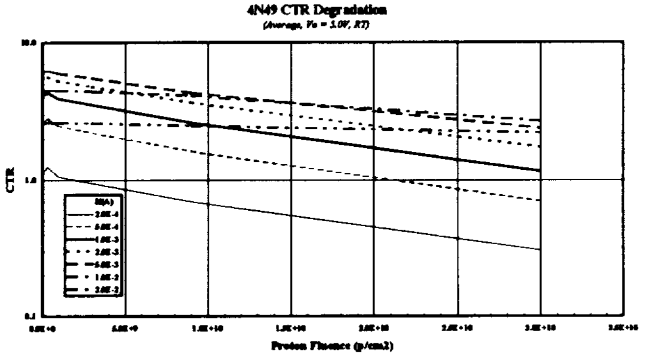

Figure 24: 4N49 (Mii LDC9529) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9550) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was some degradation in CTR, see Figure 25.

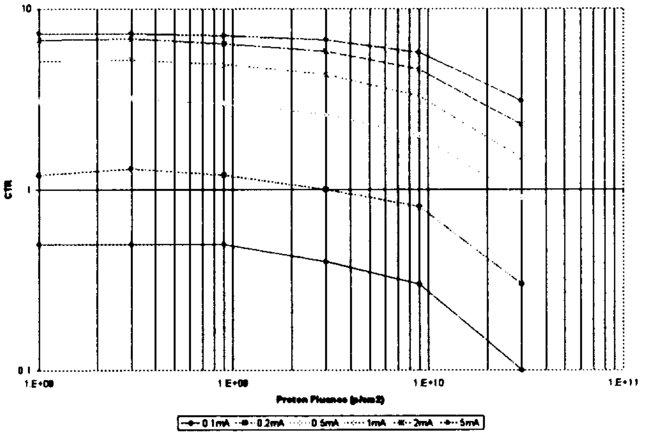

Figure 25: 4N49 (Mii LDC9550) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9623) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, 5.0, 10 and 20mA. There was some degradation in CTR, see Figure 26.

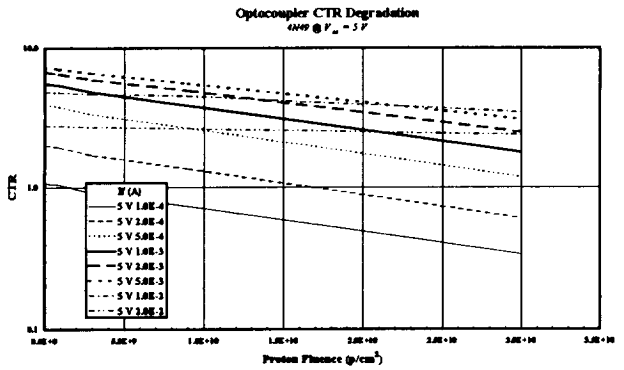

Figure 26: 4N49 (Mii LDC9623) Proton Induced CTR Degradation.

The Mii 4N49 (LDC9648) was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V for I_F = 0.1, 0.2, 0.5, 1.0, 2.0, and 5.0mA. There was some degradation in CTR, see Figure 27.

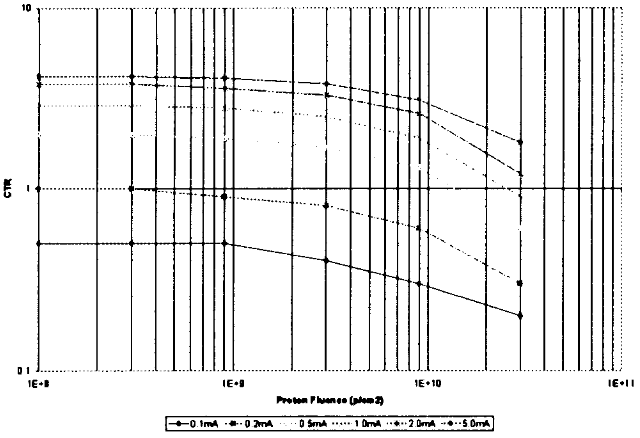

Figure 27: 4N49 (Mii LDC9648) Proton Induced CTR Degradation.

e. 4N55 Multiple Tests Multiple Vendors

The HP 4N55 was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.4V at V_{CC} = 5V and 10V for I_F = 0.2, 0.5, 1.0, 2.0, 5.0, 10, and 20mA. There was no CTR degradation in either V_{CC} condition to 3E10p/cm^2.

The Mii 4N55 was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.4V at V_{CC} = 5V for I_F = 5.0, 10, and 20mA. There was no CTR degradation to 3E10p/cm^2.

f. 6N134 (Mii)

The 6N134 was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.6V at V_{CC} = 5.5V for a continuous I_F sweep from 0 to 10mA. There was no parametric degradation to 3E10p/cm^2.

g. 6N140 (HP) LDCs 9711, 9715, 9716

The 6N140 was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V at V_{CC} = 5V for a continuous I_F sweep from 0 to 1mA. There was no CTR degradation to 3E10p/cm^2.

h. 6N140 (Mii) (66058 type)

The 6N140 was tested with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 0.4V at V_{CC} = 4.5V for a continuous I_F sweep from 0.1 to 10mA. There was some CTR degradation, see Figure 28.

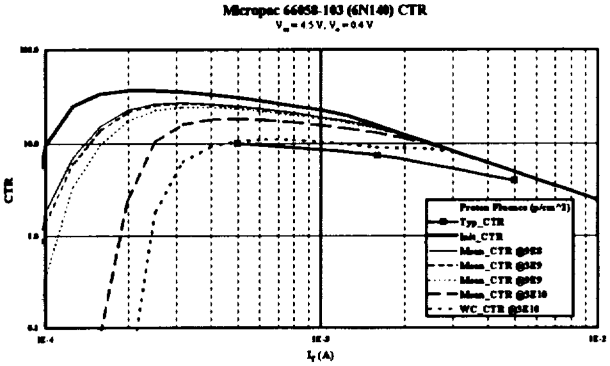

Figure 28: 6N140 (Mii LDC9623) Proton Induced CTR Degradation.

i. DIH126 (Dionics)

The DIH126 PV Relay was tested with 63MeV protons at UCD/CNL. There was relay degradation in both the forward and reverse directions and for V_D = 5V and 100V. The results for V_D are very similar to those seen for direction in Figure 29.

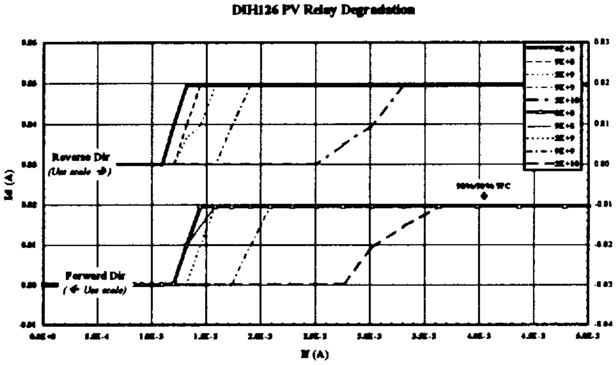

Figure 29: DIH126 Proton Induced Forward/Reverse Relay Degradation.

j. FB00KBY (Teledyne)

The FB00KBY PV Relay was tested with 63MeV protons at UCD/CNL. There was relay degradation in both the forward and reverse directions and for V_D = 5V and 100V. The results for V_D are very similar to those seen for direction in Figure 30.

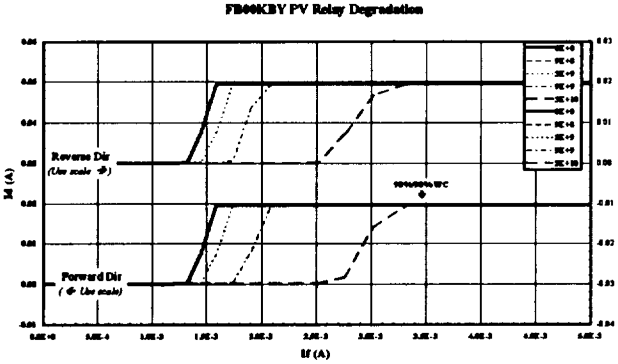

Figure 30: FB00KBY Proton Induced Forward/Reverse Relay Degradation.

k. HCPL-5231 (HP)

The HCPL-5231 was tested with 63MeV protons at UCD/CNL. There was leakage degradation at room temperature and at 125°C. The bias conditions were I_F = 8mA and V_{CC} = 4.5V. See Figure 31. There was no significant change in output voltage for V_{CC} = 5V or 15V and I_F = 7 to 8mA to a fluence of 3E10p/cm^2.

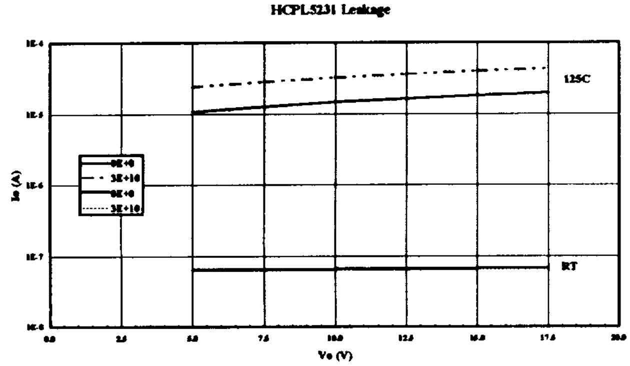

Figure 31: HCPL-5231 Proton Induced Leakage Degradation.

l. HCPL-5430 and HCPL-5431 (HP)

The HCPL-5430 and HCPL-5431 were tested with 63MeV protons at UCD/CNL. There was no parametric degradation for a bias condition of V_{CC} = 5V and I_F = 0 to 7mA for both parts to a fluence of 3E10p/cm^2.

m. HCPL-5530 and HCPL-5531 (HP)

The HCPL-5530 and HCPL-5531 were tested with 63MeV protons at UCD/CNL. There was no degradation of CTR for these parts with V_{CE} = 0.4V, I_F = 0.1 to 10mA to a fluence of 3E10p/cm^2.

n. HCPL-5630 (HP)

The HCPL-5630 was tested with 63MeV protons at UCD/CNL. There was no parametric degradation for this part with V_{CE} = 0.6V, V_{CC} = 5.5V and I_F = 0 to 10mA to a fluence of 3E10p/cm^2.

o. HCPL-5701 (HP)

The HCPL-5701 was tested with 63MeV protons at UCD/CNL. There was very little CTR degradation for this part with V_{CE} = 0.4V, V_{CC} = 5V or 10V, I_F = 0.5, 1, 2, 5, and 10mA to a fluence of 3E10p/cm^2. Data was obtained at both room temperature and 125°C. See Figures 32 and 33.

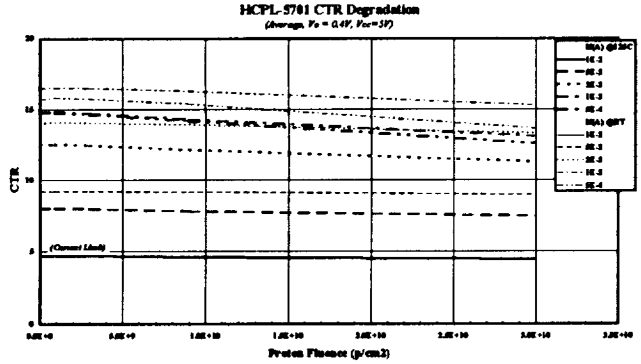

Figure 32: HCPL-5701 Proton Induced CTR Degradation at Room Temperature and 125°C for V_{CC} = 5V.

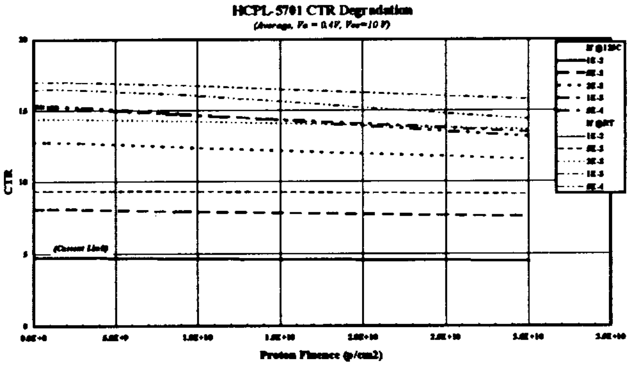

Figure 33: HCPL-5701 Proton Induced CTR Degradation at Room Temperature and 125°C for V_{CC} = 10V.

p. HCPL-5730 (HP)

The HCPL-5730 was tested with 63MeV protons at UCD/CNL. There was no CTR degradation for this part with V_{CE} = 0.4V, V_{CC} = 5V, I_F = 0.5, 1, 2, 5, and 10mA to a fluence of 3E10p/cm^2. Data was obtained at both room temperature and 125°C. See Figure 34.

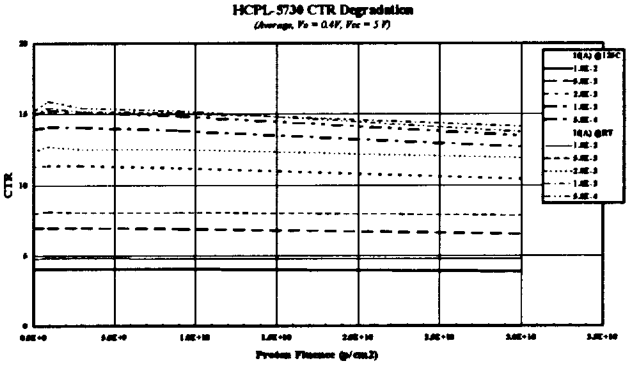

Figure 34: HCPL-5730 Proton Induced CTR Degradation.

q. OLH149, OLH249, OLH304, and OLH349 (Isolink)

These Isolink parts were tested with 63MeV protons at UCD/CNL. There was no significant degradation in CTR for any of the parts tested. The bias conditions were V_{CC} = 5V and I_F = 0.5, 1, 2, and 5mA. The parts were tested to a fluence of 3E10p/cm^2.

r. OLH400 (Isolink)

The OLH400 was tested with 63MeV protons at UCD/CNL. There was no CTR degradation for this part with I_F = 1, 2, 5, 10, and 20mA to a fluence of 3E10p/cm^2. Data was obtained at both room temperature and 125°C.

4) Goddard Space Flight Center, NASA

a. 66088 (Mii) Multiple Tests

The 66088 was tested at UCD/CNL with 63MeV protons. CTR degradation measurements were taken for I_F = 10, 15 and 20mA, V_{CC} = 5V. No degradation of CTR was observed for the application tested [3].

The 66088 was tested at UCD/CNL with 63MeV protons. I_F = 4.1, 10, 15.4, and 19.7mA with constant V_{CC} = 5V [7]. See Figure 35.

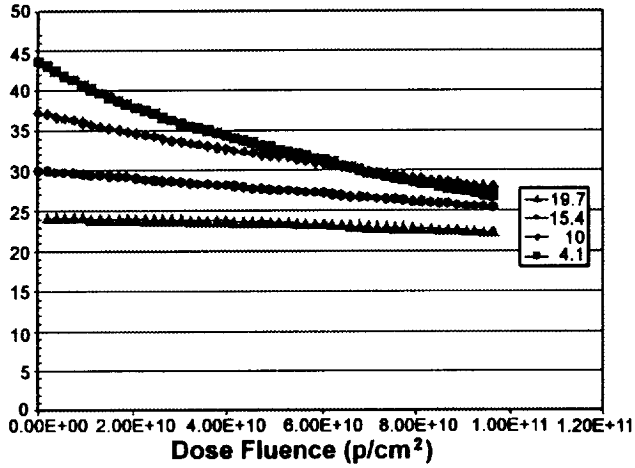

Figure 35: 66088 Application Specific Proton Induced CTR Degradation.

b. 66099 (Mii) Multiple Tests

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}$p/cm^2. Micropac's 66099 was tested and showed no CTR degradation [3].

The 66099 was tested with 63MeV protons at UCD/CNL. There was significant CTR degradation with I_F = 1mA and 5mA with a load of 0 or 1kΩ, and V_{CE} = 5V. See Figure 36.

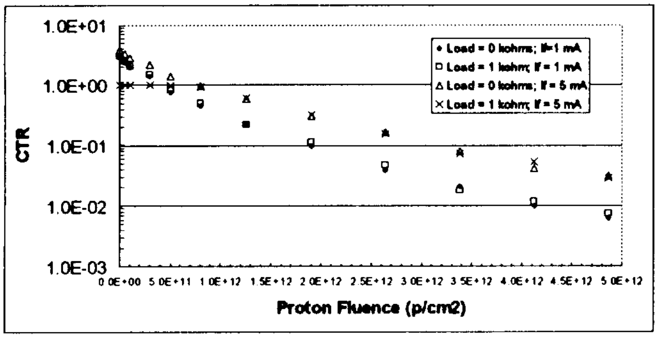

Figure 36: 66099 Proton Induced CTR Degradation.

c. 66123 (Mii)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}$p/cm^2. Micropac's 66123 was tested and showed no parametric degradation [3].

d. 3C91C (Mitel)

Several 3C91C devices were tested at UCD/CNL with 63, 31, 21, and 14MeV protons. The Mitel 3C91C contains an amphoterically doped LED. Figure 37 shows in situ measurements made when irradiated with 63 and 31MeV protons. The test parameters were IF = 5mA and Vce = 5V. Notice that 31MeV protons induce more degradation than 63MeV protons at an equivalent fluence. Results from the 21 and 14MeV protons are similar to that of the 31MeV data. Significant part to part variability was also observed (See Figure 38). Annealing measurements were not made [7].

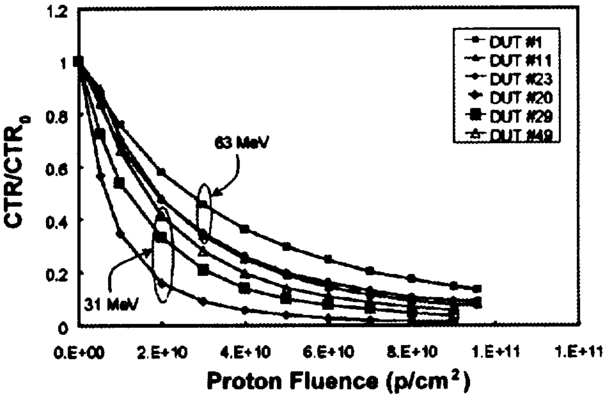

Figure 37: 63 and 31MeV Proton Induced CTR Degradation in 3C91C.

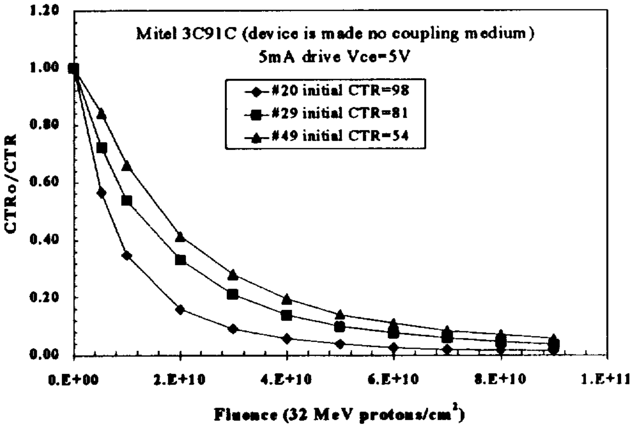

Figure 38: Part to Part Variability in CTR Degradation in 3C91C.

e. 4N48 Multiple Tests, Multiple Vendors

The Mii 4N48 was tested with neutrons at SPR. The average CTR after each step irradiation is shown in Figure 5 for I_F varying from 1.65 to 6.2mA. Degradation occurred only at the lowest drive currents for this application. All devices had degraded to <1% CTR after an exposure with 1MeV equivalent neutrons of $6x10^{12}$n/cm^2 [3,10].

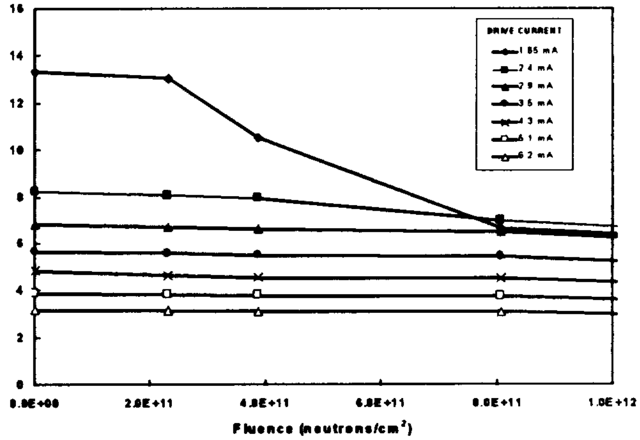

Figure 39: 1 MeV Equivalent Neutron Irradiations of Mii 4N48 at SPR.

The Optek 4N48 was tested at UCD/CNL with 63MeV protons. The Optek 4N48 contains an amphoterically doped

LED. Figure 6 gives in situ measurements of CTR. I_F varied between 1.4 and 20.8mA with initial CTR peaking between 1.4 and 3mA. For this application, the collector current is saturated for drive currents greater than 2.5mA. Operating a device in this mode leads to a more radiation tolerant application [7]. See Figure 40.

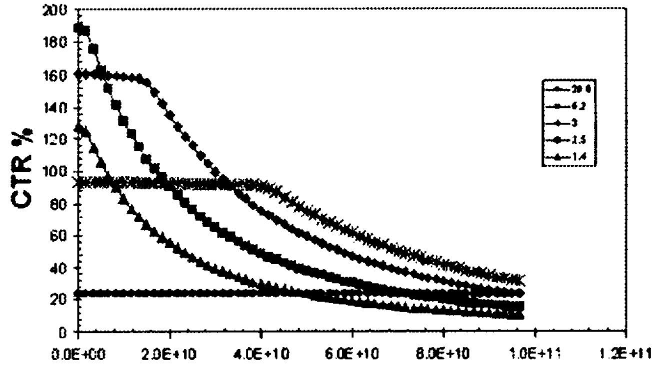

Figure 40: Optec 4N48 Application Specific Proton Induced CTR Degradation.

f. 4N49 Multiple Tests, Multiple Vendors

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^2 p/cm^2$. Micropac's 4N49 was tested and there was no CTR degradation [3].

The TI 4N49 was tested at UCD/CNL with 63MeV protons. Figure 7 gives in situ measurements of CTR. I_F was varied between 1.2 and 11mA and V_{CE} = 6V [3].

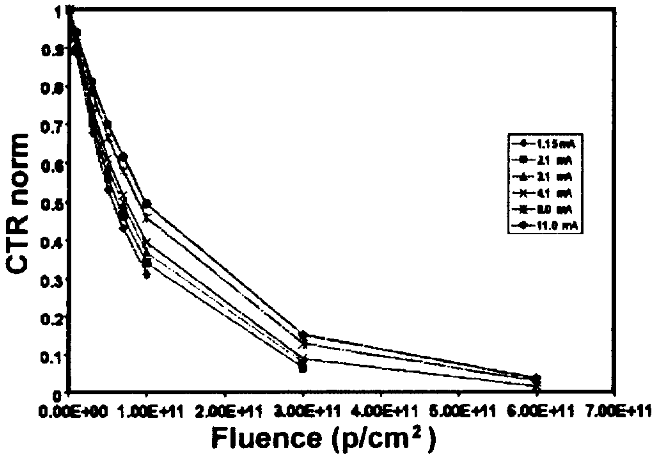

Figure 41: TI 4N49 Proton Induced CTR Degradation.

g. 6N134 (HP)

The 6N134 was tested with neutrons at SPR. Eight devices were tested to a 1MeV equivalent fluence of $8x10^{11} n/cm^2$. I_F was varied from 4 to 26mA with V_{CC} = 5V. No parametric degradation was observed [10].

h. 6N140 (Mii)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10} p/cm^2$. Micropac's 6N140 was tested and there was no CTR degradation [3].

i. HCPL-6651 (HP)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10} p/cm^2$. HP's HCPL-6651 was tested and there was no parametric degradation [3].

j. HSSR-7110 (HP)

The HP HSSR-7110 Power MOSFET that contains an optocoupler, was tested with 63MeV protons at UCD/CNL. The test conditions were I_F = 10mA, V_{OUT} = 28V, input square wave of 1Hz to 1kHz was applied. The parts were irradiated to a total dose of 50krads and annealed for two weeks. After 30krads, the part was well above the specification of 250μA for output leakage and by 50krads, the part became unusable due to leakage of 150 to 300mA. In spite of significant recovery after annealing, the parts continued to exceed the leakage specification by a factor of 10. Additionally, the turn on/turn off times were above the specification limit by a factor of 4 to 5 after annealing [11]. See Figures 42-44 for further details.

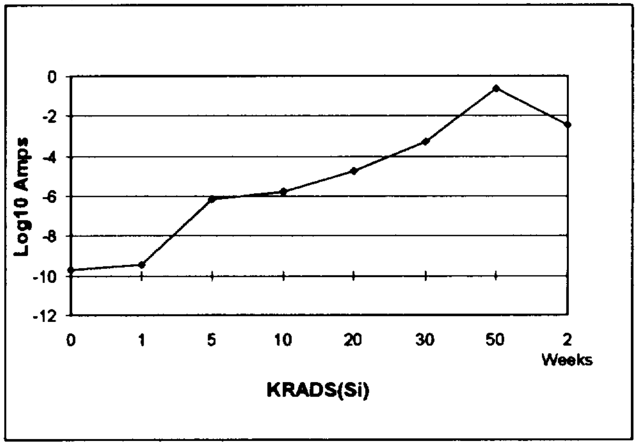

Figure 42: HSSR-7110 Proton Induced Output Leakage Current Degradation.

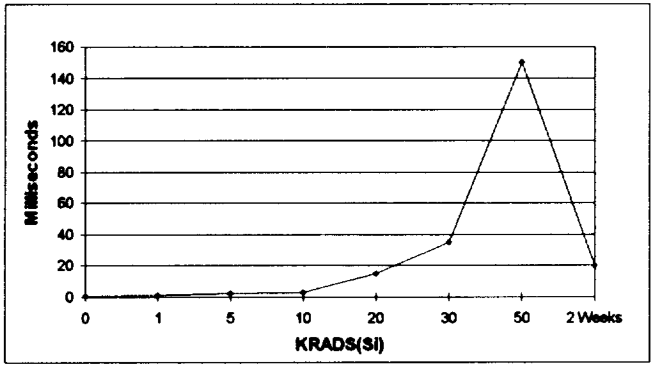

Figure 43: HSSR-7110 Proton Induced Turn-On Time Degradation.

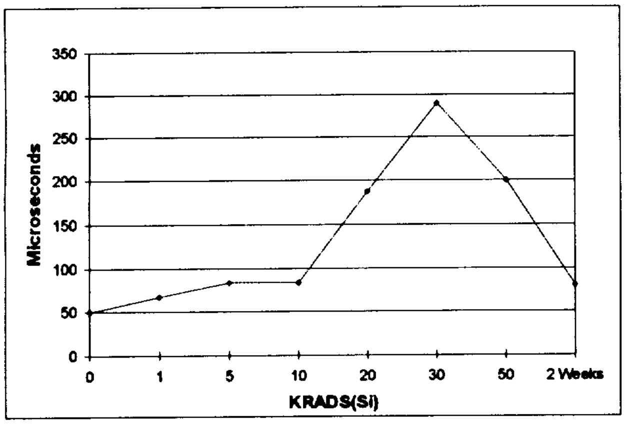

Figure 44: HSSR-7110 Proton Induced Turn-Off Time Degradation.

k. OLH249 (Isolink)

The OLH249 was irradiated with 195MeV protons at IUCF. I_F was swept from 4 to 26mA with V_{CE} = 5V. CTR degradation was observed at 6E11p/cm^2.

l. OLF400 (Isolink)

The OLF400 was irradiated with 63MeV protons at UCD/CNL. Some degradation of CTR was noted at 1.3E12 p/cm^2 at low I_F [12]. See Figure 45.

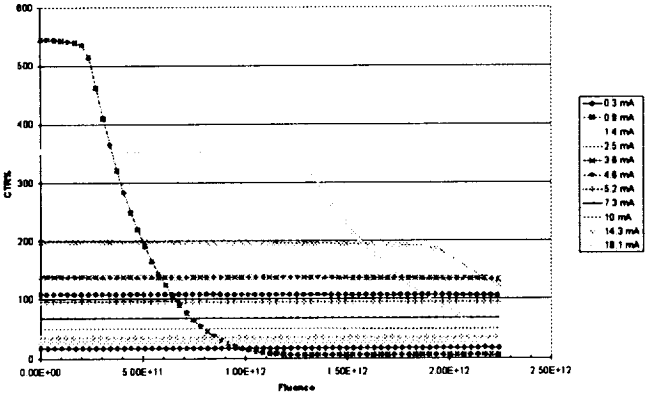

Figure 45: OLF400 Proton Induced CTR Degradation.

m. OLS700 (Isolink)

The OLS 700 was tested with 63MeV protons at UCD/CNL. Significant degradation of the detector was observed at 2E11p/cm^2 [12].

n. P2824 (Hamamatsu) Multiple Tests

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of 2x10^{10}p/cm^2. The Hamamatsu P2824 was tested and CTR degradation was observed [3].

Interpoint reported to us that the MHF+ series DC/DC converters with LDC 9603 and 9616 contain the Hamamatsu P2824 optocoupler. Other LDCs did not necessarily contain this optocoupler. We carried out proton and neutron step irradiations of the P2824 optocouplers at LLUMC, SPR, and IUCF.

The results from exposing six optocouplers with a 51.8 MeV proton beam at LLUMC are shown in Figure 46. Results from neutron exposures of six devices carried out at SPR are given in Figure 47. IUCF 195 MeV proton results for two devices are plotted in Figure 48. The pre-irradiation values are shown at zero fluence. Each plot shows the average CTR of the devices for various I_F shown [3,10].

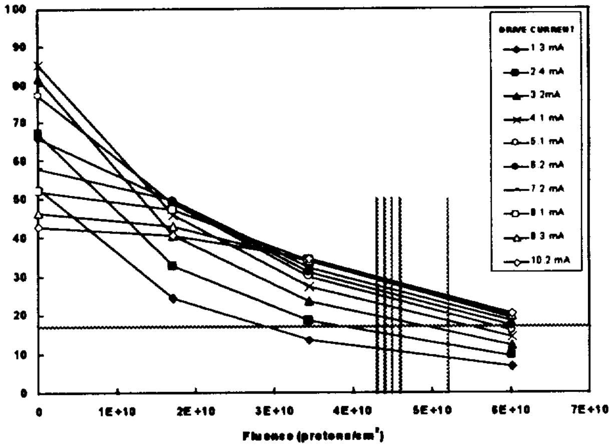

Figure 46: P2824 Proton Induced CTR Degradation (Testing at LLUMC).

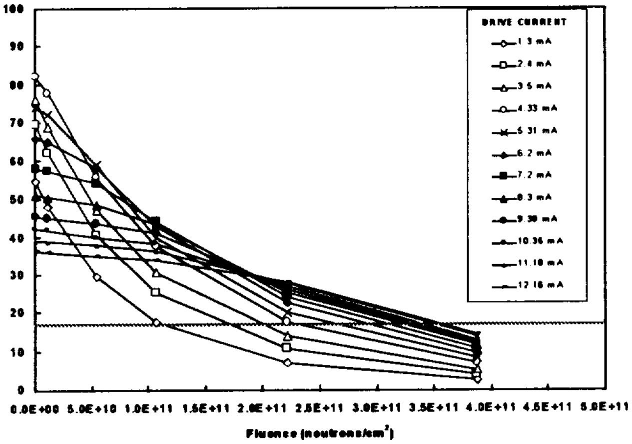

Figure 47: P2824 Neutron Induced CTR Degradation (Testing at SPR).

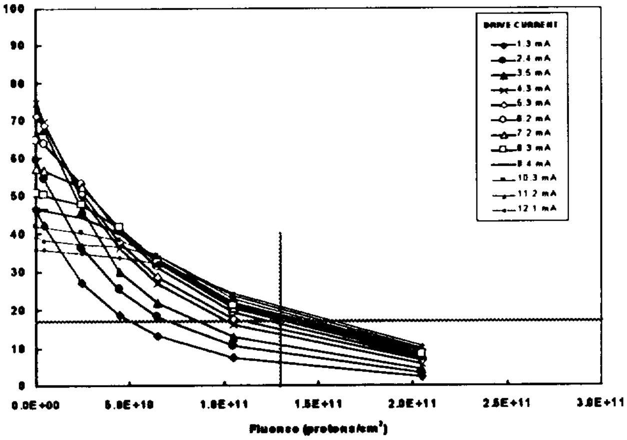

Figure 48: P2824 Proton Induced CTR Degradation (Testing at IUCF).

5) Jet Propulsion Laboratories, NASA

a. 4N49 Multiple Tests, Multiple Vendors

The Mii 4N49 was irradiated with 192MeV protons at IUCF.

The Optek 4N49 was irradiated with 192MeV protons at IUCF.

The TI 4N49 was irradiated with 192MeV protons at IUCF.

b. 6N134 (HP)

The 6N134 was irradiated with 192MeV protons at IUCF and 50MeV protons at UCD/CNL.

c. 6N140 (HP)

The 6N140 was irradiated with 192MeV protons at IUCF.

d. HCPL-5230 (HP)

The HCPL-5230 was irradiated with 50MeV protons at UCD/CNL.

e. OLH1049 (Optek) Multiple Tests

The OLH1049 was irradiated with 50MeV protons at UCD/CNL.

6) Lockheed Martin Space System Company, Missiles & Space Operations

a. 4N35, 4N49, 6N140 (Mii)

The Mii 4N35, 4N49 and 6N140 optocouplers were tested with 192MeV protons at IUCF. CTR degradation was noticeable in the Mii devices with I_F = 1mA and V_{CC} = 5V at 1E11 protons/cm^2 as shown in Figure 49. A special process Mii 4N35 was tested that showed improvement in the hardness against CTR degradation.

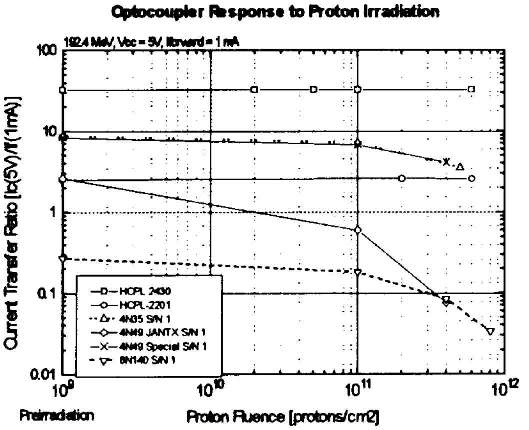

Figure 49: CTR measurements on the Mii 4N35, 4N49, 6N140 and HP HCPL 2430, HCPL 2201 optocouplers.

b. HCPL-2201, HCPL-2430 (HP)

HP HCPL-2201 and HCPL-2430 optocouplers were tested with 192MeV protons at IUCF. Test conditions were I_F = 1mA and V_{CC} = 5V. These devices did not show any noticeable CTR degradation up to 6E11 protons/cm^2. Also see Figure 49.

c. 81082-300 photodiode (Mii)

The Mii 81082 photodiode was tested with 73MeV protons at HCL. The photodiode showed degradation with increasing fluence. (Pre irradiation I_C = 3.0μA, 2E10p+/cm2 = 2.1μA, 1.2E11p+/cm2 = 0.6μA, 4.2E11p+/cm2 = 0.2μA.)

d. 62017 (GS3040-3 LED) (Mii)

The Mii 62017 (GS3040-3 LED) was tested with 73MeV protons at HCL. The LED showed little change with increasing fluence. (Pre irradiation I_F = 15 mA, 2E10 p+/cm2 = 15.4 mA, 1.2E11 p+/cm2 = 15.3 mA, 4.2E11 p+/cm2 = 15.07 mA, (0.90 mW output at If = 50 mA))

e. OP224 LED/OP604 phototransistor (Optek)

The Optek OP224 GaAlAs LED and OP604 phototransistor were tested with 73MeV protons at HCL. Displacement damage was observed in the OP604 with V_{CE} = 15V at a fluence of 2E10p/cm^2. See Figures 50 and 51.

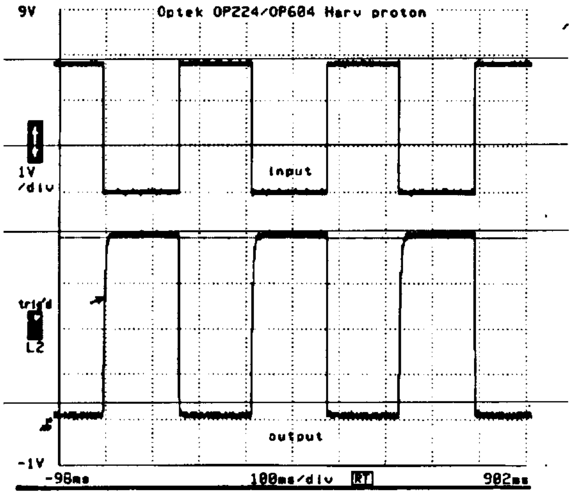

Figure 50: Bottom trace is the output from the OP604 after 2E10 protons/cm^2 at 73.3MeV. Note that the output has risen by at least 1.7V.

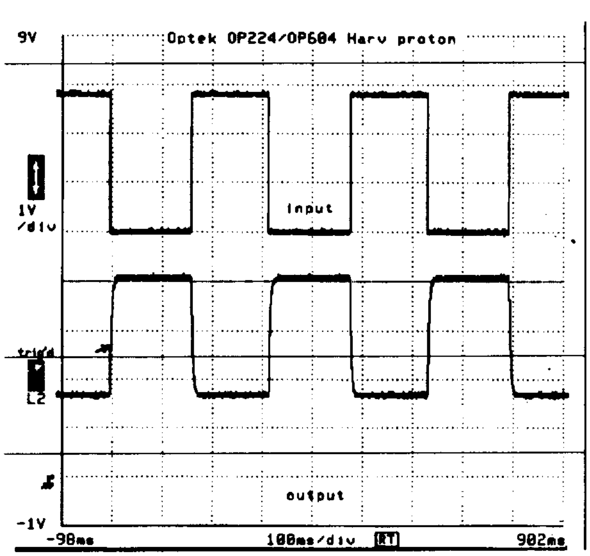

Figure 51: Bottom trace is the output from the OP604 after 1.2E11 protons/cm^2 at 73.3MeV. Similar results were observed at 148MeV.

7) Naval Research Laboratory

a. MC099 (Mii)

The MC099 was tested with 63MeV protons at UCD/CNL. The test conditions were I_F = 1, 3, 5, 7.5, 10, and 20mA and V_{CE} = 5V. Figure 52 shows Gain degradation.

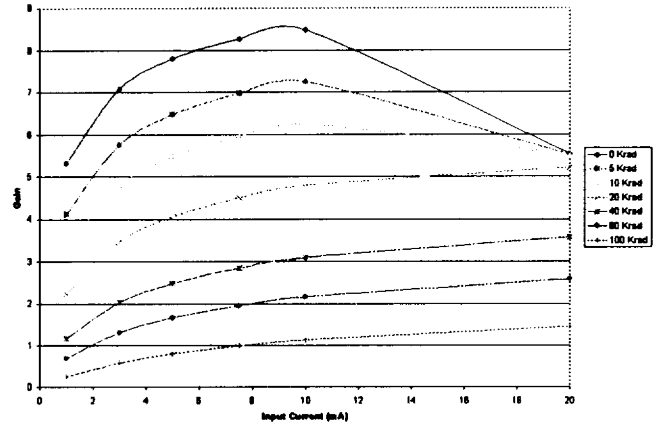

Figure 52: MC0099 Proton Induced Gain Degradation.

b. OLI400 (Isolink)

The OLI 400 was tested with 63MeV protons at UCD/CNL. The test conditions were I_F = 0.3, 0.5, 1.0, 1.6, 3.0, 5.0, and 10mA, V_{CC} = 4.5V and V_{CE} = 0.4V. Figure 53 shows Gain degradation.

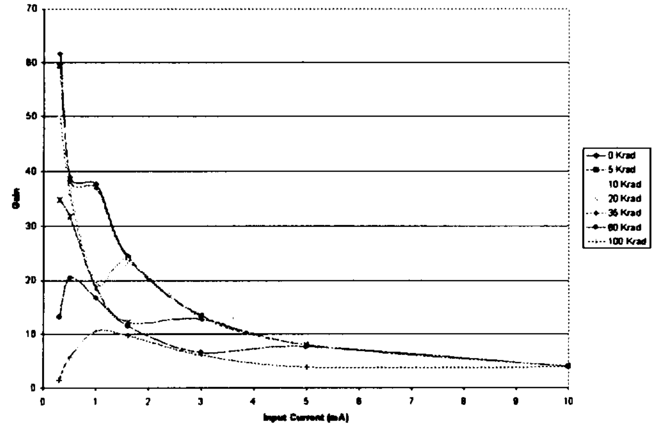

Figure 53: OLI400 Proton Induced Gain Degradation.

c. QCPL-5729 (HP)

The QCPL-5729 was tested with 63MeV protons at UCD/CNL. The test conditions were I_F = 0.5, 1.0, 1.6, 3.0, and 5.0mA, V_{CC} = 4.5V and V_{CE} = 0.4V. Figure 54 shows Gain degradation.

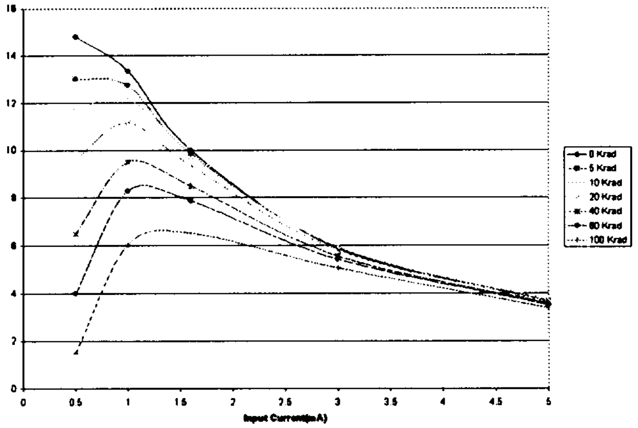

Figure 54: QCPL-5729 Proton Induced Gain Degradation.

8) Sandia National Laboratories

Five Mii 4N49 and five Isolink OLH249 optocouplers were irradiated with neutrons at SPR. Immediately after irradiation, the output current (I_C) was measured for V_{CE} ranging from 0 to 10V and for I_F ranging from 0.5 to 20mA. Figures 55 and 56 show CTR with irradiation conditions of I_F = 1 mA and V_{CE} = 2, 5, and 8V.

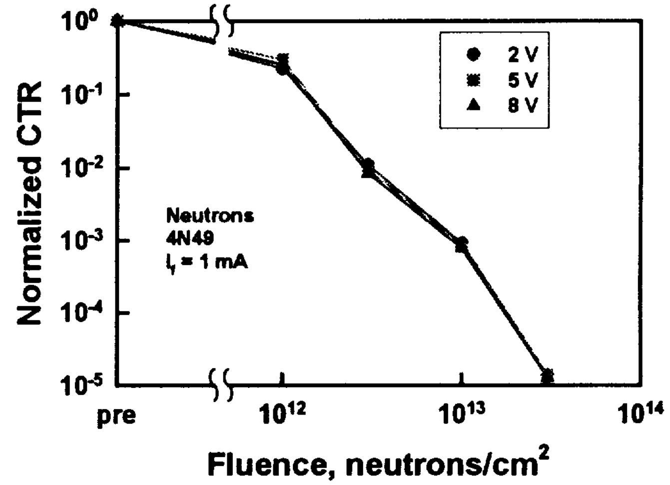

Figure 55: 4N49 1MeV Equivalent Neutron Induced CTR Degradation.

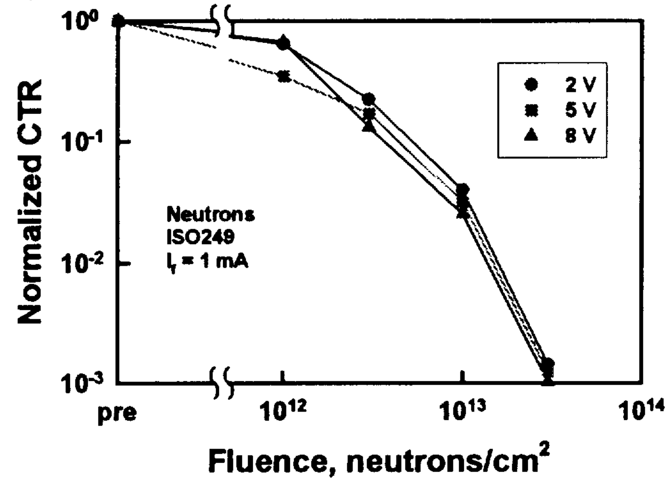

Figure 56: OLH249 1MeV Equivalent Neutron Induced CTR Degradation.

B. Proton and Heavy Ion Single Event Transients

1) Goddard Space Flight Center, NASA

a. 66099 (Mii)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}p/cm^2$. Micropac's 66099 was tested and no SETs were observed [3].

b. 66123 Multiple Tests

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}p/cm^2$. Micropac's 66123 was tested and SETs were observed [3].

The Mii 66123 was tested with 68 to 225MeV protons at TRIUMF [7]. SETs were observed at various angles and energies [5]. Figure 2 gives the results.

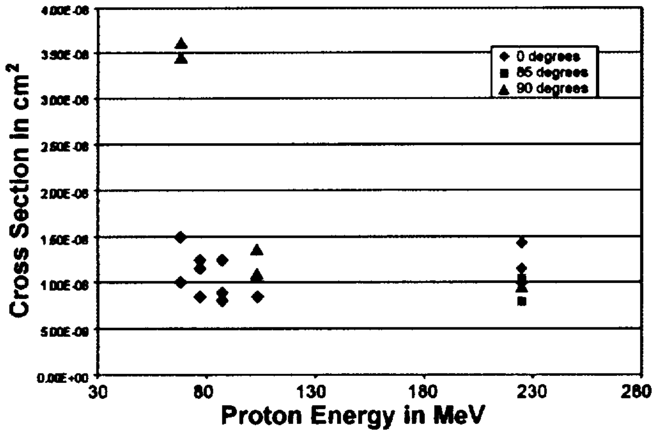

Figure 57: SET Measurements vs. Proton Energy and Angle of Incidence on the Output of the Micropac 66123.

c. 4N48 (Optek)

The Optek 4N48 was tested with 38.2MeV protons at UCD/CNL. No SETs were observed with the bias off. Complete technical data, along with test procedures and results are available [3,13].

d. 4N49 (Mii)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}p/cm^2$. Micropac's 4N49 was tested and no SETs were observed [3].

e. 4N55 (HP)

The HP 4N55 was tested with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off. Complete technical data, along with test procedures and results are available [1,3,13].

f. 6N134 (Mii)

The 6N134 was tested with 58MeV protons at TRIUMF. Transients were observed with the bias off. See Figure 58.

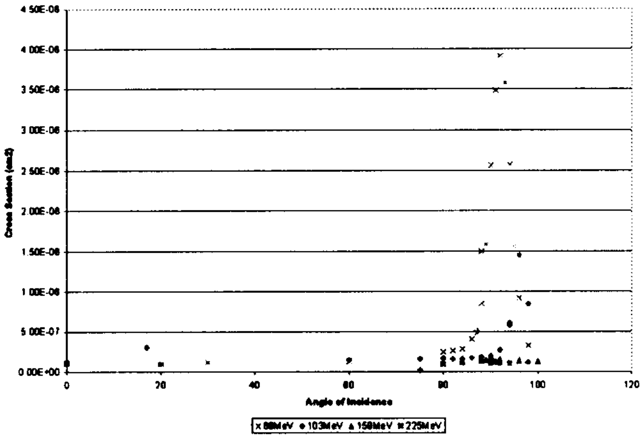

Figure 58: SET Cross Section vs. Angle of Incidence for Various Proton Energies.

g. 6N136 (Mii)

The Micropac 6N136 was tested with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off. Complete technical data, along with test procedures and results are available [1,3,13].

h. 6N140A (HP)

The HP 6N140A was tested with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off. Complete technical data, along with test procedures and results are available [1,3,13].

i. 6N140 (Mii)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of $2x10^{10}p/cm^2$. Micropac's 6N140 was tested and no SETs were observed [3].

j. HCPL-5401 (HP)

The HP HCPL-5401 was tested with 38.2MeV protons at UCD/CNL. Transients (20-25ns) were observed with the bias off. The cross section was $8.5x10^{-8}$ cm^2/channel. Complete technical data, along with test procedures and results are available [1,3,13].

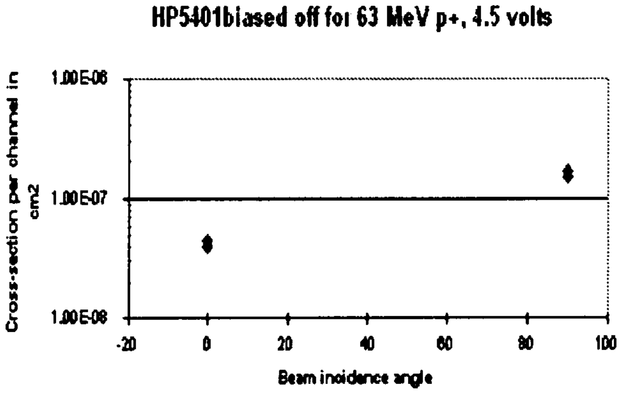

Figure 59: HP5401SET Cross Section vs. Angle of Incidence.

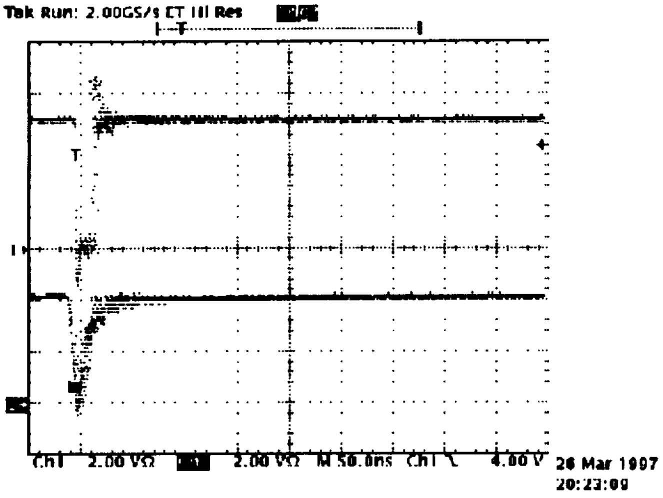

Figure 60: Capture of Transient for HP5401.

k. HCPL-5631 (HP)

The HP HCPL-5631 was tested with 38.2MeV protons at UCD/CNL. Transients were observed with the bias off and on. With the bias off, the transients were 20-60ns with a channel error cross section of 8.5x10^{-8}cm^2. With the bias on, no transients were detected at V_{CE} = 5.0V; however, there were transients of ~50ns with a channel error cross section of ~5x10^{-8}cm^2 at V_{CE} = 4.5V. There was an angle of incidence effect for both bias conditions. Complete technical data, along with test procedures and results are available [3,13].

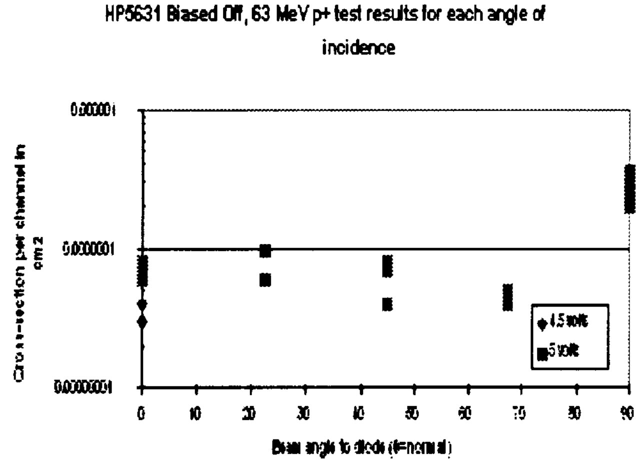

Figure 61: HCPL5631 Cross Section Data for Different V_{CE}.

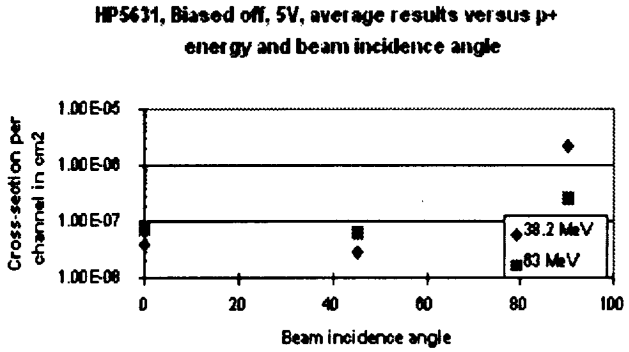

Figure 62: HCPL5631 Cross Section Data for Various Angles of Incidence at 38 and 63MeV.

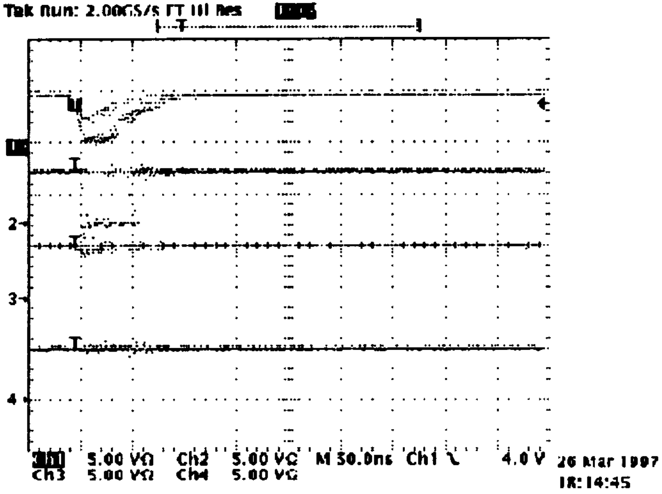

Figure 63: Capture of a Transient in the HP5631.

l. HCPL-6651 (HP)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of 2x10^{10}p/cm^2. Three series of tests were run on the HP HCPL-6651. With no filter, SETs were observed. With the passive and active filter tests, no SETs were observed [3]. Some angle of incidence data was taken as well. See Figure 64.

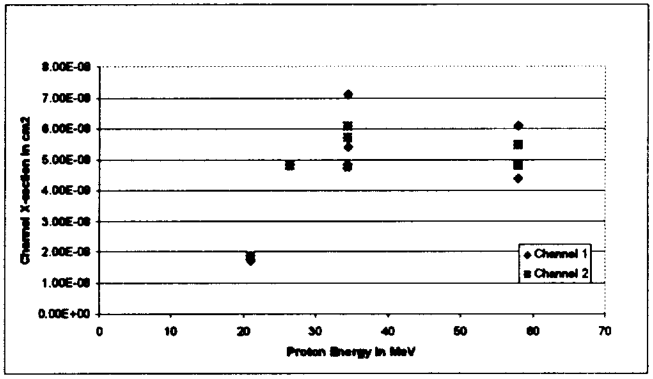

Figure 64: SET Cross Section vs. Proton Energy for HCPL6651.

Proton and heavy ion induced SETs were observed for various angles and proton energies at TRIUMF and 240MeV He ions at MSU/NSCL. A complete description is given in [1,5]. For this application, the proton cross section at 220MeV was 1x10^{-8}cm^2 per optocoupler channel and did not vary with angle. However, there was angular dependence with 70MeV protons. The proton cross-section at 0 degrees was 1x10^{-8}cm^2 and at 90 degrees it was 1x10^{-7}cm^2. Limited heavy ion data are available in [5][3].

m. OLH249 & OLH5601(Isolink)

Heavy ion SET testing was performed at MSU/NSCL. SETs were observed on these two devices at a LET of 37 MeV•cm^2/mg for both devices. Cross sections were not computed [5,7].

n. OLH5601(Isolink)

Heavy ion SET testing was performed at TRIUMF. SETs were observed in this device at a LET of 37 MeV•cm^2/mg for both devices. See Figure 65.

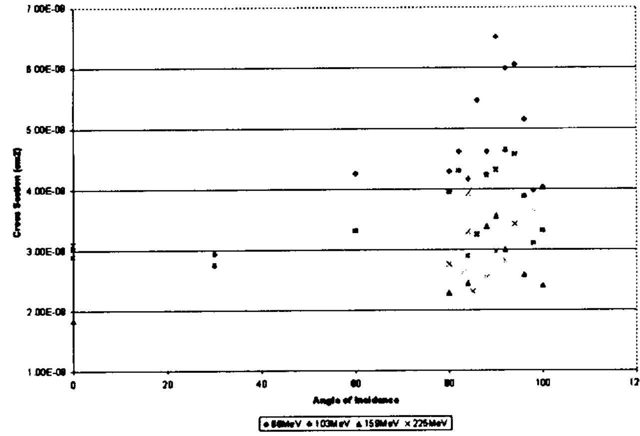

Figure 65: OLH5601 Cross Section vs. Angle of Incidence for Various Proton Energies.

o. P2824 (Hamamatsu)

Validation of an optocoupler spaceflight experiment that is to be flown on STRV-1d was done at TRIUMF using 58MeV protons with a minimum fluence of 2x10^{10}p/cm^2. The Hamamatsu P2824 was tested and no SETs were observed [3].

2) Jet Propulsion Lab, NASA

a. 6N134 (HP)

The HP 6N134 was tested with various heavy ions at BNL, 192MeV protons at IUCF and 50MeV protons at UCD/CNL.

b. 6N134 (Mii)

The Mii 6N134 was tested with various heavy ions at BNL, 192MeV protons at IUCF and 50MeV protons at UCD/CNL.

c. 6N140 (HP)

The HP 6N140 was tested with various heavy ions at BNL and 50MeV protons at UCD/CNL.

3) Lockheed Martin Space System Company, Missiles & Space Operations

a. 4N35, 4N49, 4N49 special process, 6N140 (Mii),

The Mii 4N35, 4N49, 6N140 optocouplers were tested with 44 to 192MeV protons at IUCF. The protons were at normal incidence to the devices under test with V_{CE} = 5V. The trigger level was set to capture 0.5V or greater transients. The 4N35 showed no SETs to 5E11p/cm^2, both 4N49s showed no SETs to 4E11p/cm^2 and the 6N140 showed no SETs to 8E11 p/cm^2.

b. HCPL-2201, HCPL-2430 (HP)

The HCPL-2201 and HCPL-2430 were tested with 44 to 192MeV protons at IUCF. The protons were at normal incidence to the devices under test with V_{CE} = 5V. The trigger level was set to capture 0.5V or greater transients. The transient upset cross sections measured for these devices are shown in Figure 66.

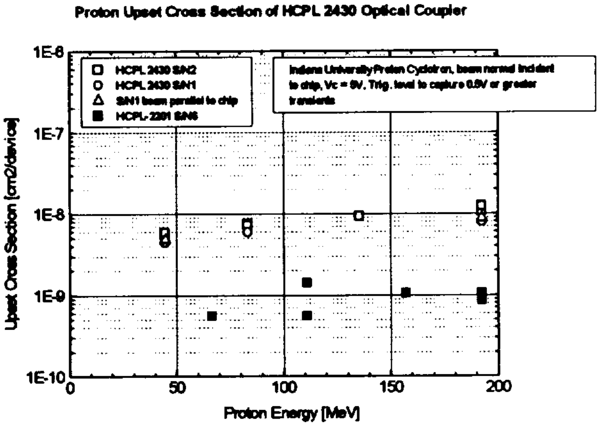

Figure 66: HCPL2201 and HCPL2430 Cross Sections for Various Proton Energies.

c. 61082-300 photodiode (Mii)

The 61082-300 photodiode was tested with 73 and 145MeV protons at HCL. Figures 3a and 3b are traces of the transients captured. With 10mV logic signals, transient glitches as large as 4mV were detected superimposed on the LO and HI digital signals. The top trace is the input signal, while the lower trace, magnified also, is the output signal from the photodiode. The latter trace's horizontal scale is magnified 5X to resolve the glitches further. Due to time, quantitative measurements of the frequency of these glitches as a function of incident angle and proton energy were not performed.

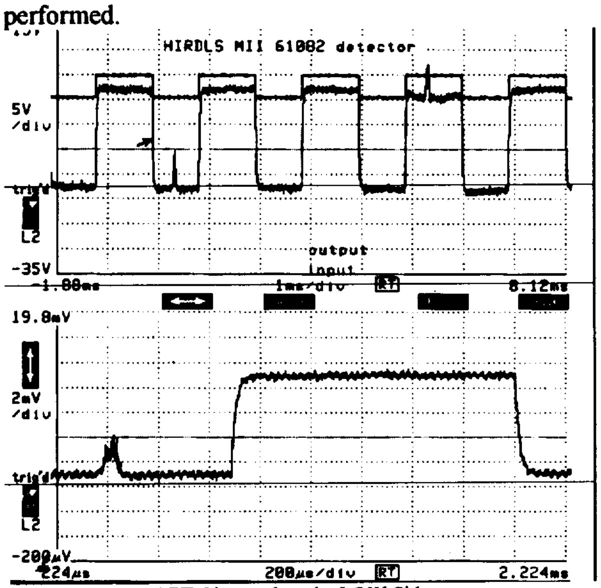

Figure 67: 61082 SET Observed on the LOW Side.

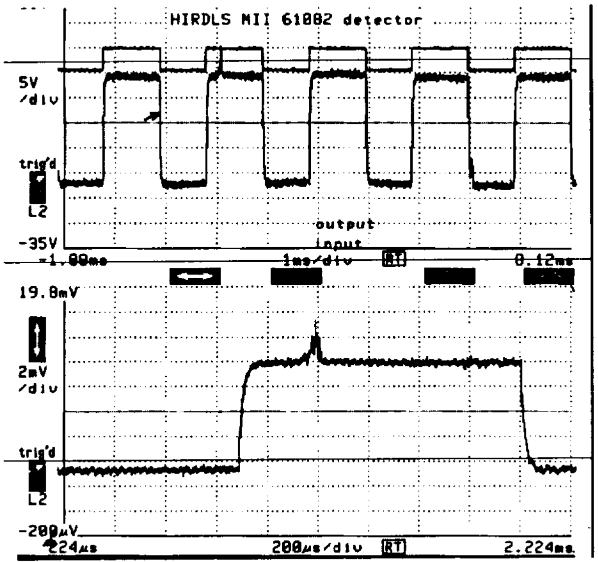

Figure 68: 81082 SET Observed on the HIGH Side.

d. OP604 phototransistor (Optek)

The OP604 phototransistor was tested with 75 and 145MeV protons at HCL with V_{CE} = 5V. No transients were observed in the phototransistor.

4) Naval Research Labs

QCPL-6637 (HP)

The QCPL-6637 was tested with 63MeV protons at UCD/CNL. The protons were normal incidence with V_{CE} = 5V. There were output conditions. With a 20pf capacitor, σ = 3.7E-8cm^2/channel and with a 100pf capacitor, σ = 2.8E-8 cm^2/channel. The latter condition was measured with a 1GHz oscilloscope and the output transients were 55ns ±10%.

C. Total Ionizing Dose

Sandia National Labs

Five 4N49 and five OLH249 optocouplers were irradiated at Sandia National Laboratories Radiation Hardness Assurance Department Co-60 irradiator and characterized for their response to total-dose irradiation. Optocouplers were irradiated to total doses of 1 Mrad(Si) in logarithmic steps with Co-60 gamma rays with zero input and output bias (all pins shorted together) at a dose rate of 50rad(Si)/s. Immediately after irradiation, the output current (I_C) was measured for output voltages (V_{CE}) ranging from 0 to 10V and for input currents (I_F) ranging from 0.5 to 20mA. Figures 3 and 4 show degradation of CTR with I_F = 1mA and with V_{CE} = 2, 5, and 8V for 4N49 and OLH249 optocouplers, respectively. As noted in the figures, the 4N49 optocouplers show considerably more degradation in CTR with total dose than the OLH249 optocouplers.

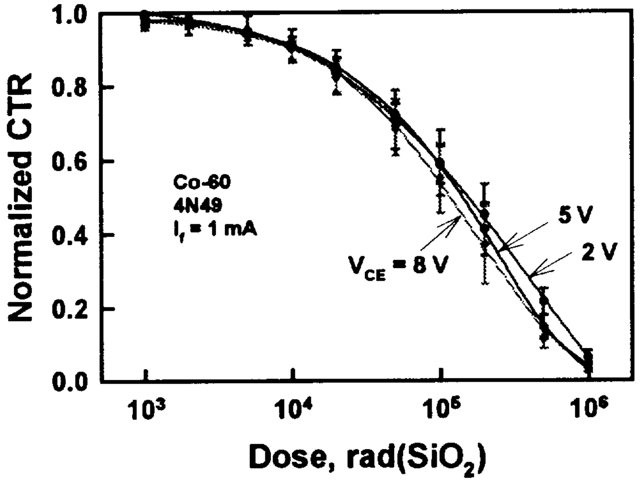

Figure 69: 4N49 Co-60 TID Induced CTR Degradation.

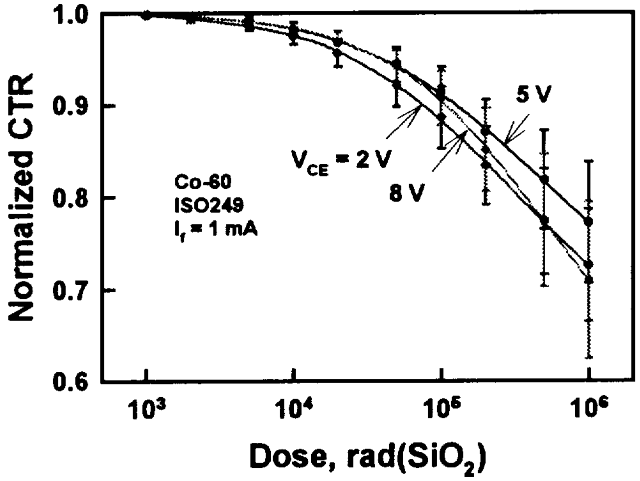

Figure 70: OLH249 Co-60 TID Induced CTR Degradation.

VII. APPLICATION OF TEST DATA

A radiation data point on an optocoupler, as such, is simply a data point. Interpretation of that data for an actual space flight application becomes more complex. In this section, we will provide several lessons learned in this arena.

A. Damage Issues

For damage issues, determining CTR degradation for a specific application has been shown to be a function of proton test energy, circuit parameters (V_{CC}, V_{CE}, I_f, I_C, Load), and the mission-specific mapping of the test energy to the transported mission environment.

Some devices may have significant device to device variance [7]. In the case of the 3C91C presented here, the initial CTR varied by as much as 44 in the same lot. This produced curves with very different slopes for the CTR degradation.

There can be a strong dependence of circuit operating parameters on the test results. If the initial V_{CE} for a particular device is very low (resulting in saturation of collector current), the forward current will have little effect on the output (nearly constant CTR with increasing dose) until a large enough fluence is reached to cause significant degradation in the output of the LED. The degradation then picks up its more traditional exponentially decreasing curve. If V_{CE} were high to begin with, small changes in forward current produce much larger changes in CTR, resulting in a more typical degradation plot.

We strongly recommend determining CTR degradation as a function of proton energy. In lieu of that, attempts have been made to utilize non-ionizing energy loss (NIEL) function. However, the risks are quite high due to the uncertainty in the dominant mechanism in the hybrid optocoupler (Si PIN diode or GaAlAs LED) [4].

B. SET Issues

For SETs, it's important to understand not only if transients are possible, but also whether the SETs are able to propagate further in their application. Should the transient propagate as false data, a false signal, etc., numerous problems could result similar to those seen on-orbit in HST and Iridium [14]. The end result of a transient will depend greatly on the pulse width and height, coupled with the speed of the device. For slower devices, the transient may be filtered out by virtue of the duration being much less than the clock speed. In faster devices, it may be necessary to provide passive filtering, active filtering or multiple channel voting by follow-on circuitry to remove the transient and prevent data corruption or loss [1].

There is a significant angular and energy dependence on cross section in several devices. The increased angle of incidence creates a longer path length for the particle to interact with the diode. This condition increases the probability of depositing a significant enough charge to cause a transient in the device. Often the cross section can be an order of magnitude or greater than what would be found if only normal incidence data were taken into account.

Prediction methods for SETs, accounting for potential direct and indirect ionization components, are currently being developed at NASA [15].

VIII. OTHER RECOMMENDATIONS

1. Application-specific testing on a large sample size is, as always, recommended whether performing tests for damage or SET, especially if the optocoupler is performing a mission critical function.
2. When interpreting a proton damage set, it is important to have application-specific data or failing that, have generic data that bounds (high and low) the actual application.
3. SET tests should be performed over a range of proton energies and angles in order to perform proper rate calculations. Heavy ion contributions must also be quantified.
4. Items such as sample-to-sample variance, interpolation of data to a specific application, the application of NIEL, annealing, and aging drive recommendations for significant pre-mission radiation design margins to be used for degradation issues.
5. Linear stability versus absolute CTR must be considered for device selection. A designer may have to review data from two different parts that provide the same function. One may degrade only very slightly with increasing fluence, the other, significantly. However, the device that degrades significantly may still have a higher CTR after degradation than the less sensitive device, making it the choice of the designer. On the other hand, if CTR stability is desired, the less radiation sensitive device might be the proper choice.

IX. ACKNOWLEDGMENT

The authors would like to thank the NASA/Electronics Radiation Characterization Project and the Defense Threat Reduction Agency, Radiation Tolerant Microelectronics Program (Contract Number 00-3001) for supporting this work.

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