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 data on neutron, proton and heavy ion Displacement Damage (DD), Single Event Transients (SET) and degradation due to Total Ionizing Dose (TID). Proton data includes ionizing and non-ionizing damage mechanisms.

I. Introduction

Optocouplers, also known as optoisolators, are hybrid devices typically used by spaceflight designers to provide electrical isolation between circuits such as subsystem-to-subsystem interfaces. These devices consist of a transmitter [light emitting diode (LED)] coupled to a receiver equipped with a photo-intrinsic-n (PIN) photodiode or phototransistor detector. Many devices also have additional support 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 several government and industry test organizations testing at several facilities and using various test methods.

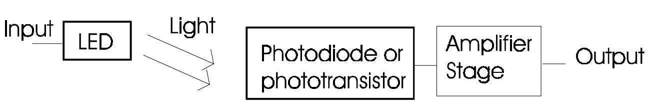

Figure 1: Typical Optocoupler Block Diagram

II. Radiation Issues

There are three major radiation issues affecting optocouplers for space flight applications: displacement damage, single event transients and total ionizing dose.

A. Displacement Damage

Primarily neutrons and protons cause DD. Protons predominate the natural space environment and contribute to both TID and DD. Thus, depending on a device's primary degradation mode, proton tests can yield results that are either nearly identical to Co-60 TID tests or can show substantially more degradation than would be expected from TID alone. Neutrons are important primarily for avionics and manmade nuclear environments and contribute almost exclusively to DD. Although many optical components degrade from DD, the optocoupler devices most susceptible to such degradation are amphoterically doped or single heterojunction LEDs [2,3,4]. Double heterojunction LEDs appear to be substantially less sensitive to DD [4,5,6]. Concerns about DD issues in optocouplers were first noted when in-flight degradation of optocouplers on the TOPEX/Poseidon satellite led to the failure of several non-critical status signal data paths. Rax, et al. [2], first described this radiation issue. Further investigations to characterize DD effects in optocouplers are discussed in [4,6,7,8,9]. DD affects the current transfer ratio (CTR) of optocouplers and may also affect other performance parameters such as timing. CTR is defined as the ratio of collector current (I_C) in the phototransistor or photodiode to the LED forward current (I_F).

$$CTR = \frac{I_C}{I_F} \qquad \text{[Eq. 1]}$$

Issues such as particle energy, mapping of test results to in-flight predictions, proper interpretation of application-specific test data, initial device CTR, sample-to-sample variation, 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 for optocouplers to the forefront was a series of 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 and subsequent proton testing that found SET sensitivity in certain optocouplers [1]. Further work has since explored the mechanisms of these transients, their magnitude, duration, and SET cross sections as a function of device performance, incident particle, incident beam angle, and a variety of application-specific conditions [7,10,11].

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 testing typically utilizes Co-60 sources (ionizing radiation). However, in some cases proton damage testing, which allows measurement of the combined effects of TID and DD, has been used in place of Co-60. The parameter most sensitive to TID is usually the CTR. In some applications, derating the part sufficiently to compensate for the expected CTR loss during the mission lifetime can mitigate the CTR degradation [5].

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 Laboratory (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 the 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

Eight 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 unless otherwise indicated (some results were at 125°C). Table 2 presents an overview of the test methods used by each organization. All methods, results and data use the following abbreviation or acronym conventions:

CTR = I_C/I_F
CTR_O = Initial (pre-rad) CTR
CTR/CTR_O = Normalized CTR
DUT = Device Under Test
GSFC = NASA Goddard Space Flight Center
HP = Hewlett Packard (now Agilent)
I_C = Output current of the photodiode or phototransistor
I_D = Photovoltaic MOSFET Relay Drain Current
I_F = Forward current of the LED
JPL = Jet Propulsion Laboratories
kbps = kilobits per second
LDC = Lot Date Code
LED = Light-Emitting Diode
LMSSC MSO = Lockheed Martin Space Systems Company, Missiles and Space Operation
Mbps = megabits per second
Mfg = Manufacturer
Mii = Micropac
MOSFET = Metal-Oxide-Semiconductor Field-Effect Transistor
NRL = Naval Research Laboratories
PV Relay = Photo Voltaic relay
R_C = Load applied as input feedback
R_F, C_F = Passive filter (resistor/capacitor combination) for SET testing
R_L = The forward load applied to the input to vary I_F for a constant V_{CC}
RT = Room Temperature
SN = Serial Number
SNL = Sandia National Laboratories
TI = Texas Instruments
V_{CC} = Voltage drop across the load and LED
V_{CE} = Voltage drop across the collector/emitter of the photodiode or phototransistor (receiver)
V_D = Photovoltaic MOSFET Relay Drain Voltage
V_O = Voltage drop across the collector of the photodiode or phototransistor (receiver)

A. Displacement Damage Testing

In displacement damage testing, CTR, is typically the parameter of interest. The device is typically set up as shown in Figure 2. Testing is usually done in step irradiations either biased or unbiased. Electrical measurements are generally made after each step of the irradiation procedure, concentrating on certain parameters (I_F, I_C, V_{CE}, and V_{CC}). Usually, one parameter is varied while the others are held constant. Some measurements have been made in-situ with one bias condition being maintained during the testing (no sweep). See Table 2 for test conditions used by each test organization.

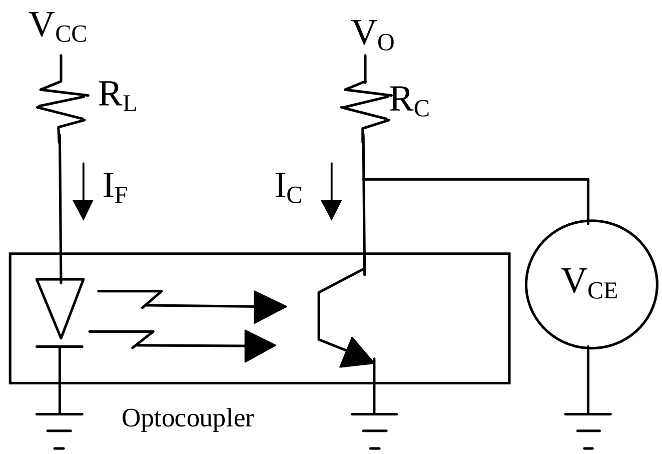

Figure 2: Schematic of experimental setup to measure CTR degradation [7].

B. SET Testing

SET testing is generally performed using a setup similar to that illustrated 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 (analog SET), the output of a follow-on TTL device (digital SET), or some other filtering device. Note that any RC filter must be addressed in the transient data assessment as it directly affects the transient pulse shape.

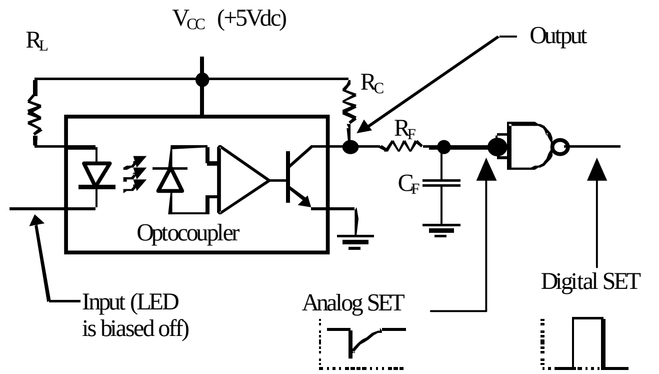

Figure 3: Schematic representation of a SET test circuit showing a filter network and two probe locations for analog and digital transient capture [7].

C. Total Ionizing Dose Testing

The devices tested for TID by SNL were unbiased and irradiated with Co-60 gamma rays stepwise to 1Mrad(Si). The electrical performance of these parts was tested between steps.

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 the fluence (particles/cm^2) of the particle indicated. If the part degraded, the fluence given represents the level where degradation was first noted. 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 (particles/cm^2) given to the device. Table 5 summarizes the TID results. The "Results/Notes" section gives the onset of degradation.

Table 2. Test Methods

Displacement Damage						
Organization	**Input**	**V_{CE}**	**R_C (Load)**	**Note**	**Parameters Measured**	**Particles**
Aerospace	Sweep I_F	Constant	Variable	step irradiation	CTR	Protons, Helium
Ball Aero	Sweep I_F	Constant	Variable	step irradiation	CTR	Protons
Boeing	Sweep I_F	Sweep	Constant	step irradiation	CTR	Protons
	Off	Sweep	Constant	step irradiation	Leakage	
GSFC	Sweep I_F, Fixed V_{CC}	Constant	Constant	in situ	CTR, Switching, Leakage	Protons, Neutrons, Heavy Ions
	Sweep I_F, Fixed V_{CC}	Sweep	Variable	step irradiation		
JPL	Sweep I_F	Constant	Constant	step irradiation	CTR	Protons
LMSSC MSO	Constant	Constant	Constant	step irradiation	CTR	Protons
NRL	Sweep I_F	Constant	Constant	step irradiation	CTR	Protons
SRL	Sweep I_F	Sweep	Constant	step irradiation	CTR	Neutrons
SET						
Organization	**Note:**				**Parameters Measured**	**Particles**
GSFC	The part should be biased in such a way that the LED is off. If the LED is on, SET sensitivity is negligible [1].				SET	Protons, Heavy Ions
JPL					SET	Protons, Heavy Ions
LMSSC MSO					SET	Protons
NRL					SET	Protons
Total Ionizing Dose						
Organization	**Input**	**V_{CE}**	**R_C (Load)**	**Note**	**Parameters Measured**	**Particles**
SNL	Constant	Sweep	Constant	step irradiation	CTR	Co-60 Gamma Rays

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

Device	Mfg	LDC	Device Speed	Test Organization	Test Facility	Energy/Particles Used	Results/Notes (particles/cm^2)
4N24	TI	8850	400kbps	Aerospace	LBL	45MeV Protons, 48MeV He	CTR Degradation at $5.8x10^{10}$ p+, 5.2E8 He
4N49	TI	9408	400kbps	Aerospace	LBL	35, 55MeV Protons	CTR Degradation at $4.8x10^{9}$ 35MeV, $6.8x10^{10}$ 55MeV
4N49	TI	9408	400kbps	Aerospace	LBL	55MeV Protons, 48MeV He	CTR Degradation at $6.8x10^{10}$ p+, $5.2x10^{8}$ He
OLF400	Isolink	9713	400kbps	Aerospace	LBL	55MeV Protons	No CTR degradation at $8.1x10^{11}$
4N49	Mii	9518	400kbps	Ball	UCD/CNL	63MeV Protons	CTR Degradation at $4.5x10^{10}$
OMT1062	Optek	9628	50kbps	Ball	UCD/CNL	63MeV Protons	CTR Degradation at $4.5x10^{10}$
66092	Mii	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation at $3x10^{10}$
66099	Mii	9650	50kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at $3x10^{10}$
4N48	Mii	9550	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N48	Mii	9618	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	TI	8646	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9327	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9329	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	TRW	9439	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $3x10^{10}$
4N49	Mii	9504	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9511	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $3x10^{10}$
4N49	Mii	9529	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9550	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N49	Mii	9648	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $1x10^{10}$
4N55	HP	9337	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
4N55	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at $3x10^{10}$
6N134	Mii	9645	10Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at $3x10^{10}$
6N140	HP	9711, 15, 16	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
6N140 (66058)	Mii	9623	400kbps	Boeing	UCD/CNL	63MeV Protons	Degradation of CTR at $3x10^{10}$
DIH126	Dionics	9521	N/A	Boeing	UCD/CNL	63MeV Protons	Degradation of Relay (PV MOSFET Relay) at $9x10^{9}$
FB00KBY	Teledyne	9531	N/A	Boeing	UCD/CNL	63MeV Protons	Degradation of Relay (PV MOSFET Relay) at $9x10^{9}$
HCPL-5231	HP	9632, 9633	2Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at $3x10^{10}$
HCPL-5430	HP	9644	40Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at $3x10^{10}$
HCPL-5431	HP	9618	40Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at $3x10^{10}$
HCPL-5530 (4N55)	HP	9642	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
HCPL-5531 (4N55)	HP	9632, 9633	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
HCPL-5630 (6N134)	HP	9716	10Mbps	Boeing	UCD/CNL	63MeV Protons	No Parametric degradation at $3x10^{10}$
HCPL-5701 (6N140A)	HP	9315	400kbps	Boeing	UCD/CNL	63MeV Protons	Some CTR degradation at $3x10^{10}$
HCPL-5730 (6N140A)	HP	9701	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
OLH149	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
OLH249	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
OLH304	Isolink	Unknown	1Mbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
OLH349	Isolink	Unknown	1Mbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$
OLH400	Isolink	Unknown	400kbps	Boeing	UCD/CNL	63MeV Protons	No CTR degradation to $3x10^{10}$

Device	Mfg	LDC	Device Speed	Test Organization	Test Facility	Energy/Particles Used	Results/Notes (particles/cm^2)
66088	Mii	Unknown	625kbps	GSFC	UCD/CNL	63MeV Protons	No CTR degradation to $1x10^9$
66088	Mii	Unknown	625kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $2x10^{10}$
66099	Mii	Unknown	50kbps	GSFC	TRIUMF	58MeV Protons	No CTR degradation to $2x10^{10}$
66099	Mii	Unknown	50kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $5x10^{11}$
66123	Mii	Unknown	10Mbps	GSFC	TRIUMF	58MeV Protons	No Parametric degradation to $2x10^{10}$
3C91C	Mitel	Unknown	200kbps	GSFC	UCD/CNL	63, 31, 21, 14MeV Protons	Degradation of CTR at $<1x10^{10}$ for all energies
4N48	Mii	Unknown	400kbps	GSFC	SPR	Neutrons	Degradation of CTR at $2x10^{11}$
4N48	Optek	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $2x10^{10}$
4N49	Mii	Unknown	400kbps	GSFC	TRIUMF	58MeV Protons	No CTR degradation to $2x10^{10}$
4N49	TI	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $2x10^{10}$
6N134	HP	Unknown	10Mbps	GSFC	SPR	Neutrons	No Parametric degradation to $8x10^{11}$ 1MeV equiv.
6N140	Mii	Unknown	400kbps	GSFC	TRIUMF	58MeV Protons	No CTR degradation to $2x10^{10}$
HCPL-6651 (6N134)	HP	Unknown	10Mbps	GSFC	TRIUMF	Various Protons	No Parametric degradation at $2x10^{10}$
HSSR-7110	HP	9637	N/A	GSFC	UCD/CNL	63MeV Protons	Leakage and On/Off Time degradation at $2.3x10^{11}$ (Part is a Power MOSFET PV Relay)
OLH249	Isolink	Unknown	400kbps	GSFC	IUCF	195MeV Protons	Degradation of CTR at $6x10^{11}$
OLH400	Isolink	Unknown	400kbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $4x10^{11}$
OLS700	Isolink	Unknown	1Mbps	GSFC	UCD/CNL	63MeV Protons	Degradation of CTR at $3.8x10^{11}$
P2824	Hamamatsu	Unknown	333kbps	GSFC	TRIUMF, LLUMC, IUCF, SPR	Various Protons, Neutrons	Degradation of CTR at $2x10^{10}$ (TRIUMF 58MeV p+), $1.7x10^{10}$ (LLUMC 52MeV p+), $2.5x10^{10}$ (IUCF 195MeV p+), $5.4x10^{10}$ (SPR 1MeV equiv. Neutrons)
4N49	Mii	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR at $5x10^{10}$
4N49	Optek	Unknown	400kbps	JPL	IUCF	192MeV Protons	Degradation of CTR at $5x10^{10}$
OLH1049	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at $1x10^{10}$
OLH1049.0002	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at $1x10^{10}$
OLH1049.0003	Optek	Special Process	Unknown	JPL	UCD/CNL	50MeV Protons	Degradation of CTR at $1x10^{10}$
4N35	Mii	Unknown	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at $5x10^{11}$
4N49	Mii	CEJG M9628	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at $1x10^{11}$
4N49	Mii	66092-101S special process	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at $4x10^{11}$
6N140	Mii	8836 8302401EC 31757	400kbps	LMSSC MSO	IUCF	192MeV Protons	Degradation of CTR at $1x10^{11}$
HCPL-2201	HP	9538	20Mbps	LMSSC MSO	IUCF	192MeV Protons	No CTR degradation at $6x10^{11}$
HCPL-2430	HP	9630	5Mbps	LMSSC MSO	IUCF	192MeV Protons	No CTR degradation at $6x10^{11}$
61082-300 photodiode	Mii	9827	~1Mbps	LMSSC MSO	HCL	73MeV Protons	Ic degradation at $2x10^{10}$
62017 GS3040-3 LED	Mii	Unknown	~1Mbps	LMSSC MSO	HCL	73MeV Protons	If degradation at $2x10^{10}$
OP224 LED	Optek	GaAlAs IR, 890nm	~1Mbps	LMSSC MSO	HCL	73MeV Protons	If degradation at $2x10^{10}$
OP604 phototransistor	Optek	npn silicon	~1Mbps	LMSSC MSO	HCL	73MeV Protons	Ic degradation at $2x10^{10}$
MC099	Mii	Unknown	50kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at $3.8x10^{10}$
OLI400	Isolink	9841	400kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at $1.5x10^{11}$
QCPL-5729	HP	Unknown	400kbps	NRL	UCD/CNL	63MeV Protons	Degradation of CTR at $3.8x10^{10}$
OLH249	Isolink	400kbps	400kbps	SNL	SPR	Neutrons	Degradation of CTR at $1x10^{12}$
S4N49	Mii	400kbps	400kbps	SNL	SPR	Neutrons	Degradation of CTR at $1x10^{12}$

Table 4: Proton and Heavy Ion SET Summary

Device	Mfg	LDC	Device Speed	Test Org.	Test Facility	Energy/Particles Used	Results/Notes (particles/cm^2)
66099	Mii	Unknown	50kbps	GSFC	TRIUMF	58MeV Protons	No SET to $2x10^{10}$
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 $1x10^{9}$
4N49	Mii	9628 + Special Process	400kbps	GSFC	TRIUMF	63, 58MeV Protons	No SET to $2x10^{10}$
4N55	HP	9702	400kbps	GSFC	UCD/CNL	38MeV Protons	No SET to $1x10^{9}$
6N134	Mii	Unknown	10Mbps	GSFC	TRIUMF	58MeV Protons	SETs observed
6N136	Mii	9624	400kbps	GSFC	UCD/CNL	38MeV Protons	No SET to $1x10^{9}$
6N140A	HP	9707	400kbps	GSFC	UCD/CNL	38MeV Protons	No SET to $1x10^{9}$
6N140	Mii	Unknown	400kbps	GSFC	TRIUMF	58MeV Protons	SETs observed
HCPL-5401	HP	9642	40Mbps	GSFC/Ball	UCD/CNL	38MeV Protons	SETs observed
HCPL-5631 (6N134)	HP	9427, 9707	10Mbps	GSFC/Ball	UCD/CNL	38MeV Protons	SETs observed
HCPL-6651 (6N134)	HP	Unknown	10Mbps	GSFC	UCD/CNL,	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
OLH5601	Isolink	Unknown	10Mbps	GSFC	TRIUMF		SETs observed
P2824	Hamamatsu	Unknown	333kbps	GSFC	TRIUMF	58MeV Protons	No SET to $2x10^{10}$
6N134	HP	Unknown	10Mbps	JPL	BNL	Various Heavy Ions	SETs observed
6N140	HP	Unknown	400kbps	JPL	BNL	Various Heavy Ions	SETs observed
4N35	Mii	Unknown	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to $5x10^{11}$
4N49	Mii	CEJG M9628	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to $4x10^{11}$
4N49	Mii	66092-101S special process	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to $4x10^{11}$
6N140	Mii	8836 8302401EC 31757	400 kbps	LMSSC MSO	IUCF	44 to 192MeV Protons	No SET to 810^{11}
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	~1Mbps	LMSSC MSO	HCL	73, 145MeV Protons	SETs observed
OP604 phototransistor	Optek	Unknown	~1Mbps	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(SiO_2)
4N49	Mii	Unknown	400kbps	SNL	Sandia RHA	Co-60 gammas	Degradation of CTR at 100krads(SiO_2)

VI. Test Data

A. Proton, Neutron and Heavy Ion Displacement Damage Effects

1) The Aerospace Corporation

a. 4N24 (TI)

The 4N24 was irradiated with 45MeV protons and 48MeV He ions at LBL. The parts were irradiated under bias and tested after each step. Test parameters were set at I_F = 5mA, with V_{CC} = 1.5V, V_{CE} = 8V. CTR degradation was noted in both cases. See Figures 4 and 5.

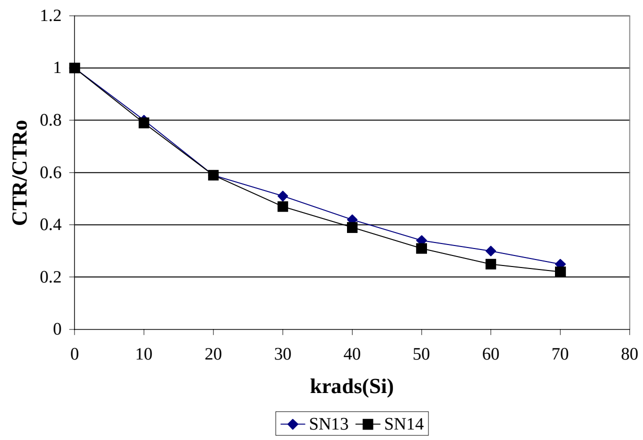

Figure 4: 45MeVProton Induced CTR Degradation in TI 4N24.

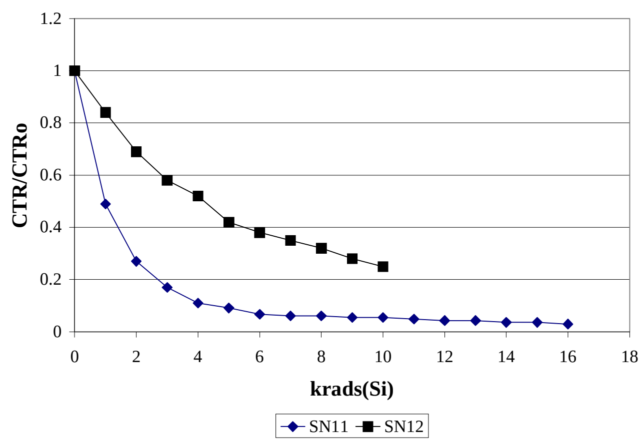

Figure 5: 48MeV He Induced CTR Degradation in TI 4N24.

b. 4N49 (TI) Multiple Tests

The 4N49 was irradiated with 35 and 55MeV protons at LBL. The devices were irradiated under bias and tested after each step. Test parameters were set at V_{CC} = 5V and V_{CE} = 5V. Series resistors were chosen to set I_F to 1, 2, 5, and 10mA. CTR degradation was noted in all cases, see Figures 6-9. In Figure 8, all points after 8krads(Si) show the results of exposure with the bias off. The bias was turned on for a short time while reading data after each irradiation step.

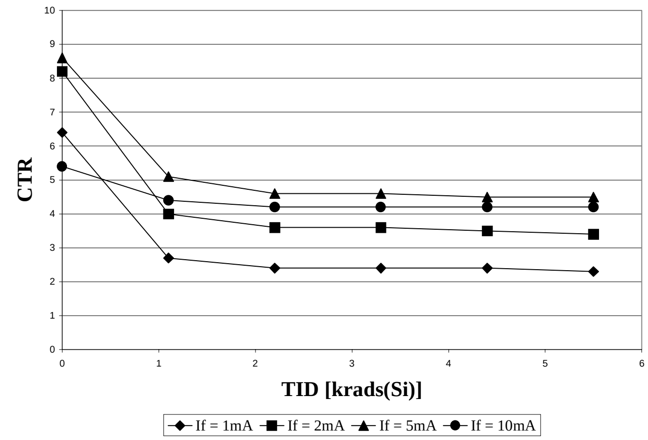

Figure 6: 35MeV Proton Induced CTR Degradation in TI 4N49 (SN2).

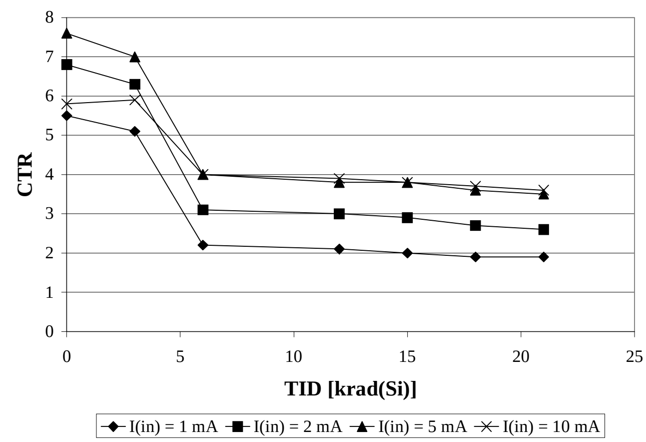

Figure 7: 35MeV Proton Induced CTR Degradation in TI 4N49 (SN3).

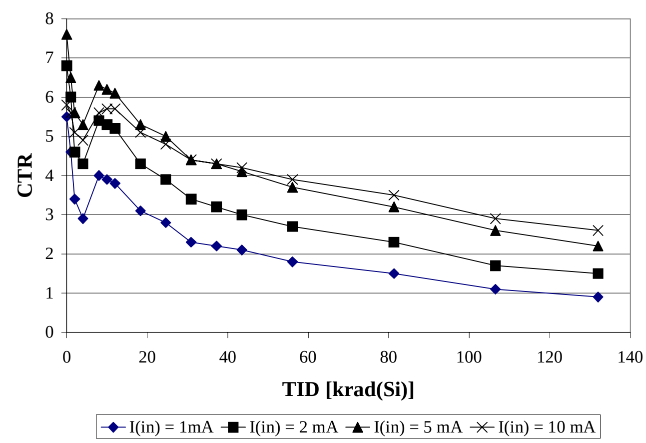

Figure 8: 55MeV Proton Induced CTR Degradation in TI 4N49 (SN1).

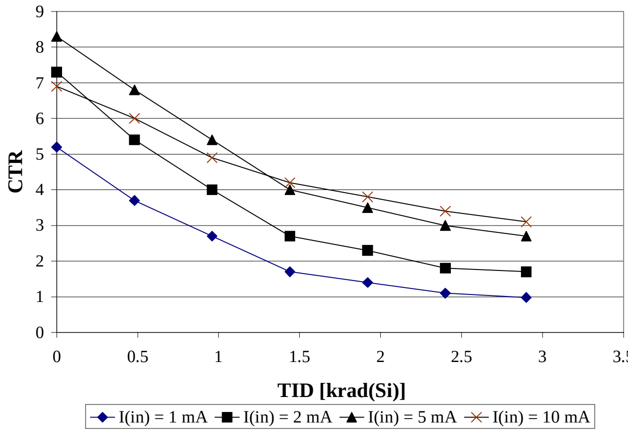

Figure 9: 55MeV Proton Induced CTR Degradation in TI 4N49 (SN4).

The 4N49 was irradiated with 55MeV protons and 48MeV Helium ions at LBL. The parts were irradiated under bias and tested after each step. Test parameters were set at I_F = 2mA, V_{CC} = 5V, V_{CE} = 5V. CTR degradation was noted in both cases. See Figures 10 and 11.

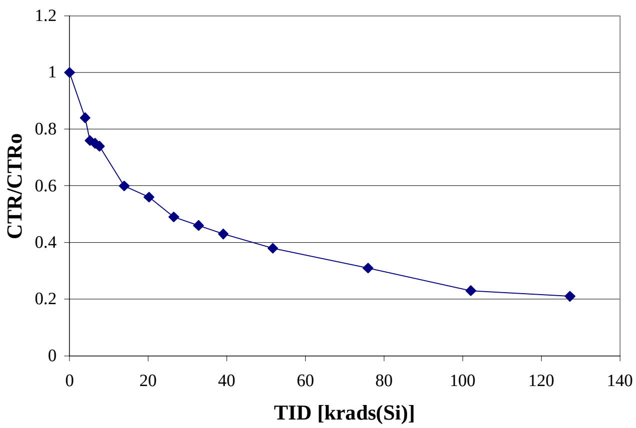

Figure 10: 55MeV Proton Induced CTR Degradation in TI 4N49.

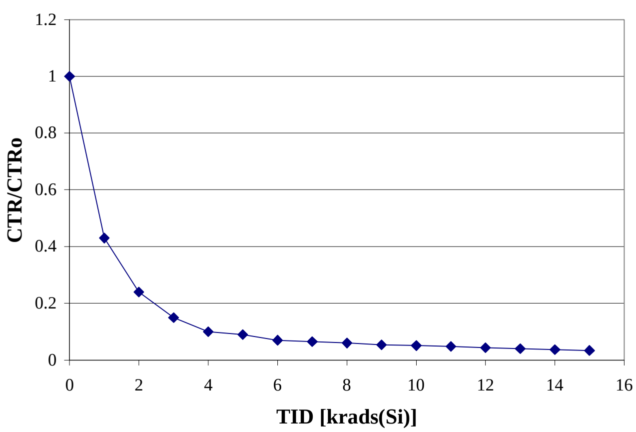

Figure 11: 48MeV Helium Induced CTR Degradation in TI 4N49.

c. OLF400 (Isolink)

The OLF400 was irradiated with 55MeV protons at LBL. Test parameters were set at V_{CC} = 5V, V_{CE} = 5V and the output resistance was 300Ω. The input resistance was varied (R_L = 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 for each of the resistors. The results show a decrease in output current with increasing proton dose, that is, CTR degradation. Results are presented in Figure 12.

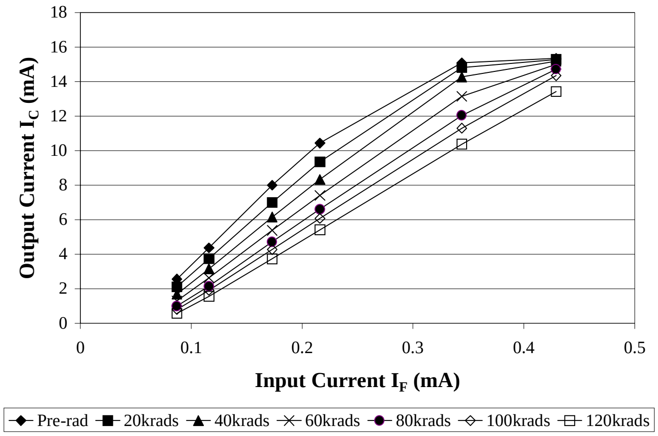

Figure 12: 55MeV Proton Induced I_C Degradation in Isolink OLF400.

2) Ball Aerospace NASA/JPL

a. 4N49 (Mii)

The 4N49 was irradiated with 63MeV protons at UCD/CNL. The ten samples were divided into two groups. Five samples were irradiated with the LED off (I_F = 0mA, V_{CE} = 5V) and the other five samples were irradiated with the LED on (I_F = 5mA, V_{CE} = 28V). The parts were tested after each irradiation step. In both groups, the input resistance was varied to give I_F = 1, 3, 5, and 8mA. These bias conditions are representative of a proposed space application. For proton fluences less than $1x10^{11}p/cm^2$, there is only a slight difference in the radiation response between the two 4N49 groups. However, at the highest proton fluence tested ($4.2x10^{11}p/cm^2$), the normalized CTR for the group irradiated with the LED off was 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 [8].

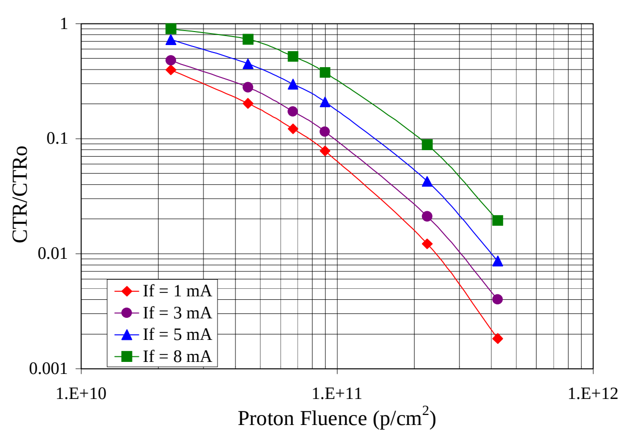

Figure 13: 63MeV Proton Induced CTR Degradation in Mii 4N49 (Bias Conditions during Irradiation: If = 0 mA, Vce = 5V.)

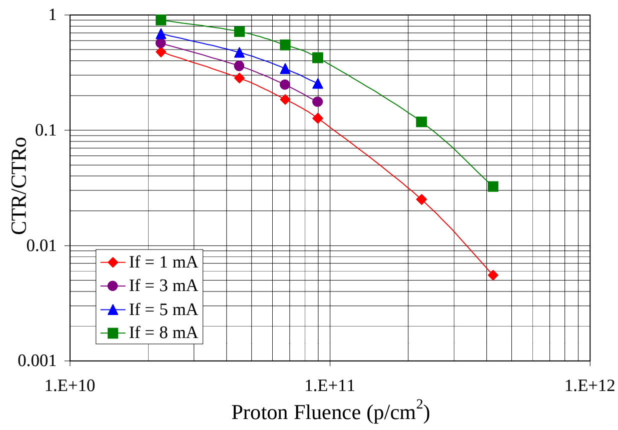

Figure 14: 63MeV Proton Induced CTR Degradation in Mii 4N49 (Bias Conditions during Irradiation: If = 5 mA, Vce = 28V.)

b. OMT1062 (Optek)

The OMT1062 slotted optical switch was irradiated with 63MeV protons at UCD/CNL. Six samples were step irradiated with the LED biased on (I_F = 15mA, V_{CE} = 5V) which reflects the particular application of interest. The parts were tested after each step irradiation. 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 7.4x10^{9}p/cm^2 (63MeV protons) imparts a total ionizing dose of ~1.0krad(Si). This data suggests that ionizing dose damage constitutes about 2% of the combined ionizing dose and displacement damage (at 2.2x10^{11}p/cm2) [8].

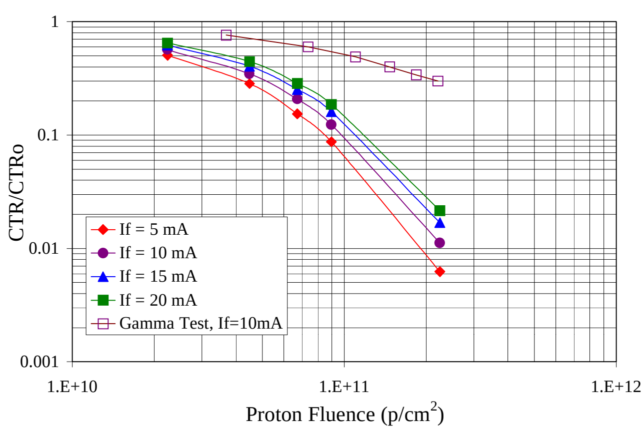

Figure 15: 63MeV Proton Induced CTR Degradation in Optek OMT1062 (Bias Conditions during Irradiation: If = 15 mA, Vce = 10V.)

3) Boeing

a. 66092 (Mii)

The 66092 was irradiated 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 3x10^{10}p/cm^2.

b. 66099 (Mii)

The 66099 was irradiated 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 3x10^{10}p/cm^2.

c. 4N48 (Mii) Multiple Tests

The 4N48 (LDC9550) was irradiated 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.

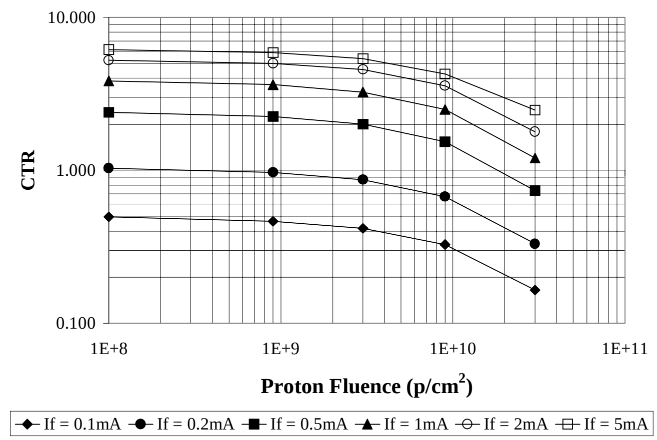

Figure 16: 63MeV Proton Induced CTR Degradation in Mii 4N48 (LDC9550).

The 4N48 (LDC9618) was irradiated 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.

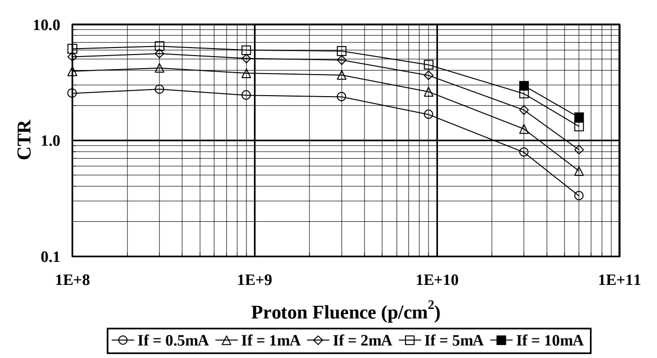

Figure 17: 63MeV Proton Induced CTR Degradation in Mii 4N48 (LDC9618).

d. 4N49 Multiple Tests, Multiple Vendors

The TI 4N49 (LDC8646) was irradiated 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).

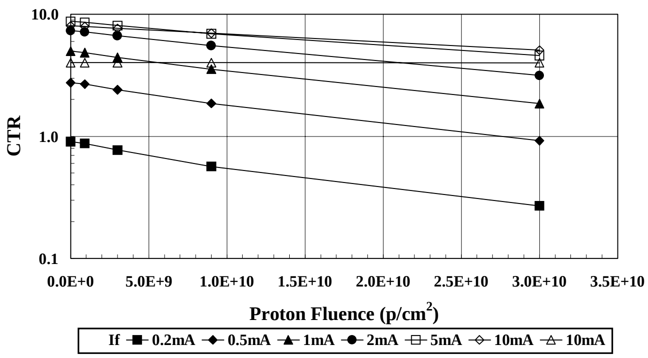

Figure 18: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC8646).

The Mii 4N49 (LDC9327) was irradiated 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.

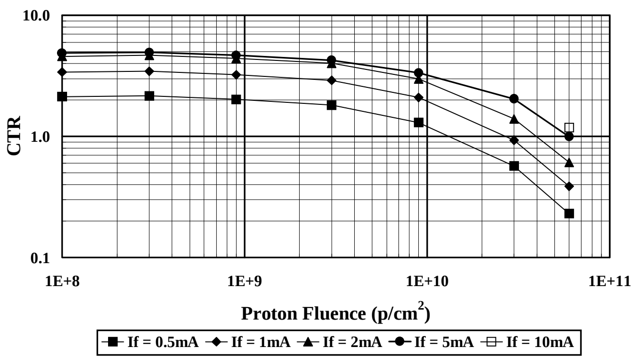

Figure 19: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9327).

The Mii 4N49 (LDC9329) was irradiated 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.

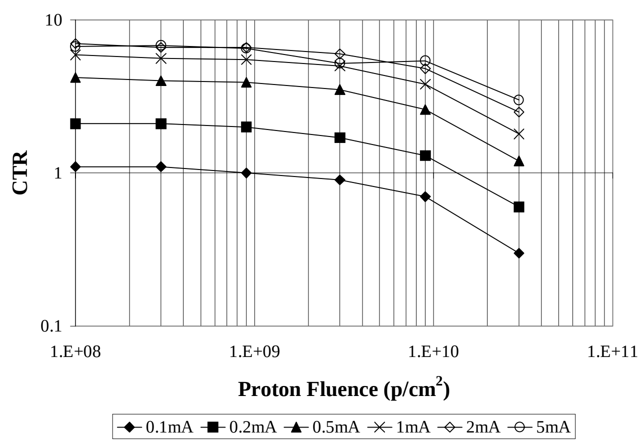

Figure 20: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9329).

The TRW 4N49 (LDC9439) was irradiated 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.

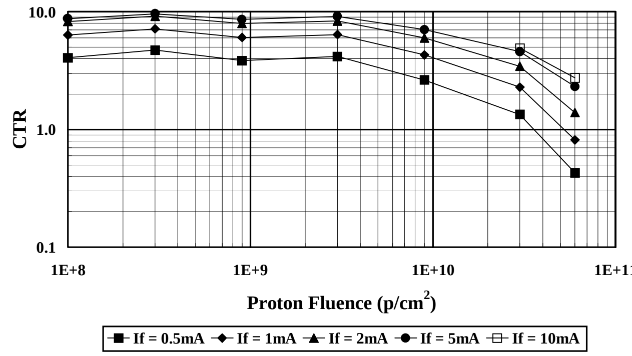

Figure 21: 63MeV Proton Induced CTR Degradation in TRW 4N49 (LDC9439).

The Mii 4N49 (LDC9504) was irradiated 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.

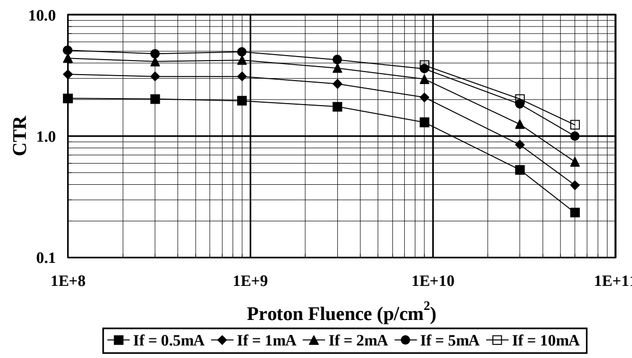

Figure 22: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9504).

The Mii 4N49 (LDC9511) was irradiated 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.

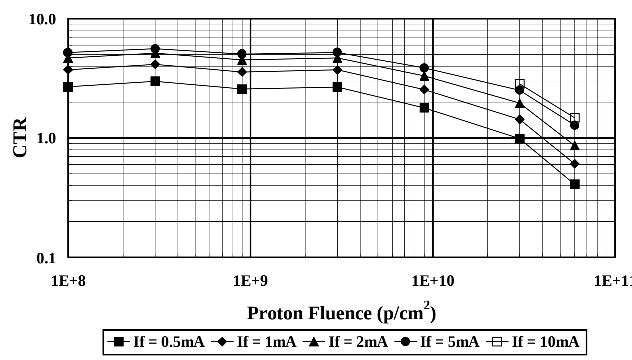

Figure 23: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9511).

The Mii 4N49 (LDC9529) was irradiated 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).

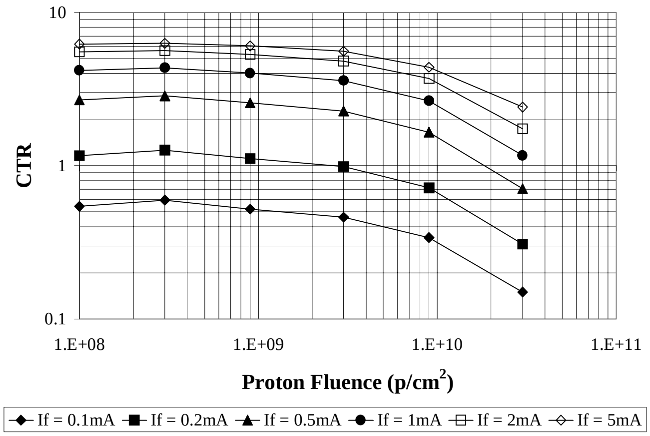

Figure 24: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9529).

The Mii 4N49 (LDC9550) was irradiated 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.

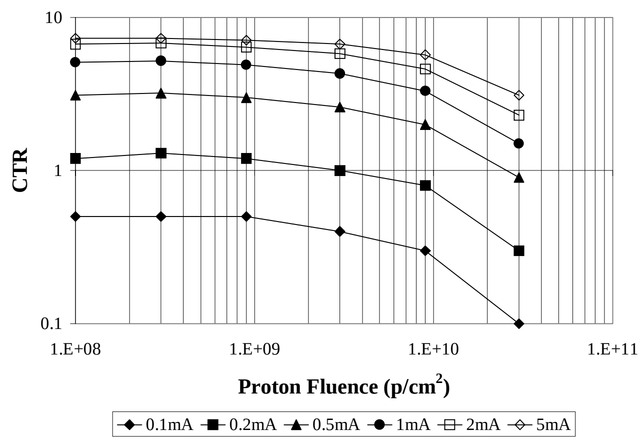

Figure 25: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9550).

The Mii 4N49 (LDC9623) was irradiated 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.

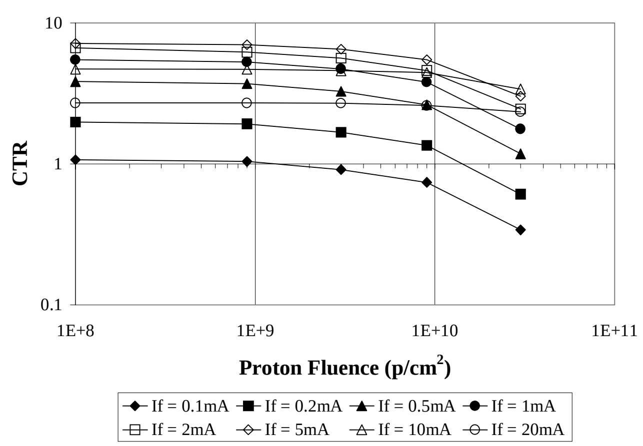

Figure 26: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9623).

The Mii 4N49 (LDC9648) was irradiated 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.

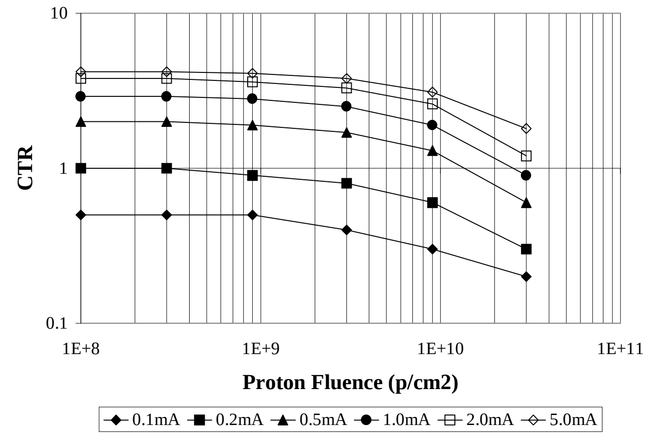

Figure 27: 63MeV Proton Induced CTR Degradation in Mii 4N49 (LDC9648).

e. 4N55 Multiple Tests, Multiple Vendors

The HP 4N55 was irradiated with 63MeV protons at UCD/CNL. I_C was measured for V_{CE} = 0.4V and 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 $3x10^{10}p/cm^2$.

The Mii 4N55 was irradiated with 63MeV protons at UCD/CNL. I_C was measured for V_{CE} = 0.4V and V_{CC} = 5V for I_F = 5.0, 10, and 20mA. There was no CTR degradation to $3x10^{10}p/cm^2$.

f. 6N134 (Mii)

The 6N134 was irradiated with 63MeV protons at UCD/CNL. I_C was measured for V_{CE} = 0.6V and V_{CC} = 5.5V with continuous I_F sweep from 0 to 10mA. There was no parametric degradation to $3x10^{10}p/cm^2$.

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

The 6N140 was irradiated with 63MeV protons at UCD/CNL. I_C was measured at V_{CE} = 5V and V_{CC} = 5V with continuous I_F sweep from 0 to 1mA. There was no CTR degradation to $3x10^{10}p/cm^2$.

h. 6N140 (Mii) (66058 type)

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

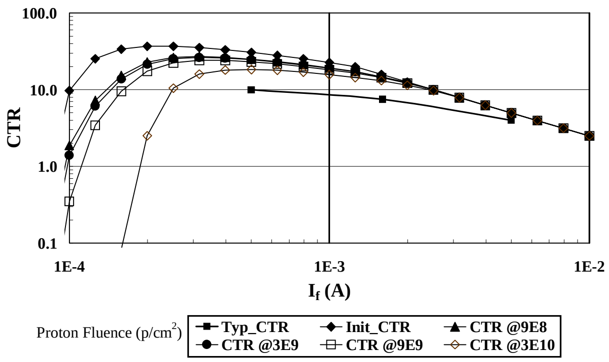

Figure 28: 63MeV Proton Induced CTR Degradation in 6N140 (LDC9623).

i. DIH126 (Dionics)

The DIH126 PV Relay was irradiated 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 degradation of V_D was very similar to that of the degradation of I_D in both the forward and reverse directions as seen in Figure 29.

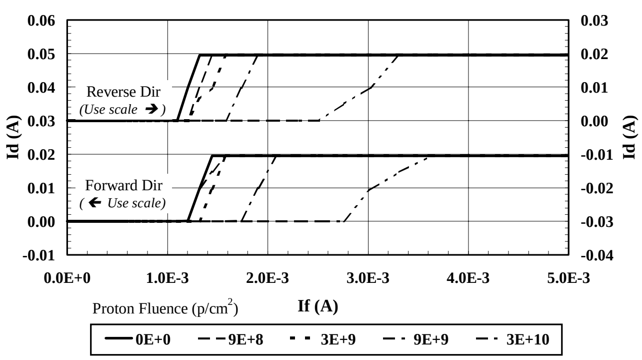

Figure 29: 63MeV Proton Induced Forward/Reverse Relay Degradation Measurements for DIH126.

j. FB00KBY (Teledyne)

The FB00KBY PV Relay was irradiated 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 degradation of V_D was very similar to that of the degradation of I_D in both the forward and reverse directions as seen in Figure 30.

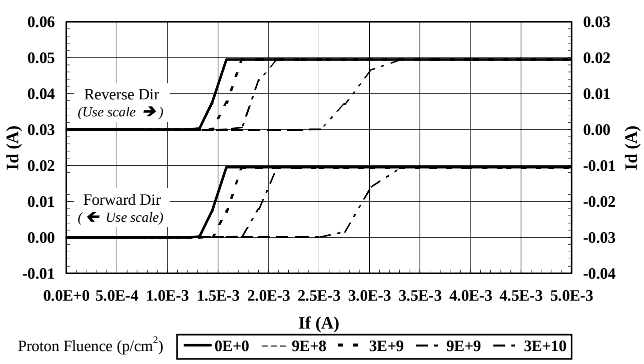

Figure 30: 63MeV Proton Induced Relay Degradation in FB00KBY.

k. HCPL-5231 (HP)

The HCPL-5231 Logic Gate Optocoupler was irradiated with 63MeV protons at UCD/CNL. There was some leakage degradation 125°C. The bias conditions were I_F = 8mA and V_{CC} = 4.5V. See Figure 31 for test results. I_O and V_O are the logic output current and voltage respectively. There was no significant change in output voltage for V_{CC} = 5V or 15V and I_F = 7 to 8mA to a fluence of $3x10^{10}$p/cm^2 at either temperature.

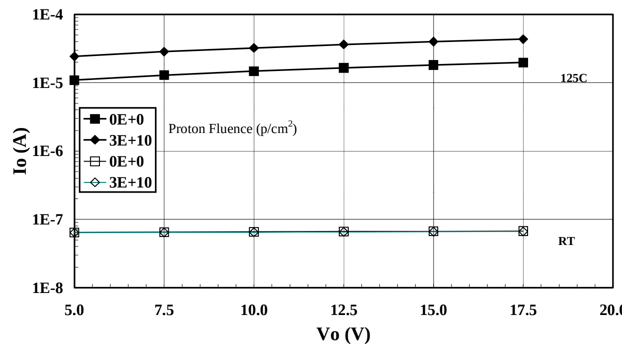

Figure 31: 63MeV Proton Induced Leakage Degradation at 125°C in HCPL-5231.

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

The HCPL-5430 and HCPL-5431 were irradiated 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 part types to a fluence of $3x10^{10}$p/cm^2.

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

The HCPL-5530 and HCPL-5531 were irradiated 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 $3x10^{10}$p/cm^2.

n. HCPL-5630 (HP)

The HCPL-5630 was irradiated 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 $3x10^{10}$p/cm^2.

o. HCPL-5701 (HP)

The HCPL-5701 was irradiated 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 $3x10^{10}$p/cm^2. Data was obtained at both room temperature and 125°C. See Figures 32 and 33.

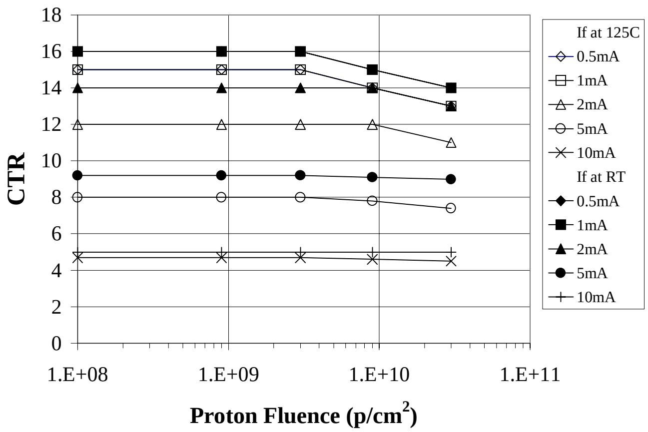

Figure 32: 63MeV Proton Induced CTR Degradation in HCPL-5701 at Room Temperature and 125°C for V_{CC} = 5V.

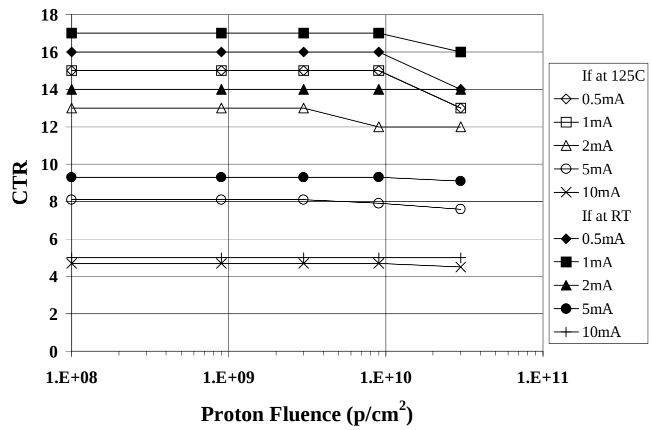

Figure 33: 63MeV Proton Induced CTR Degradation in HCPL-5701 at Room Temperature and 125°C for V_{CC} = 10V.

p. HCPL-5730 (HP)

The HCPL-5730 was irradiated 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 $3x10^{10}$p/cm^2. Data was obtained at both room temperature and 125°C. See Figure 34.

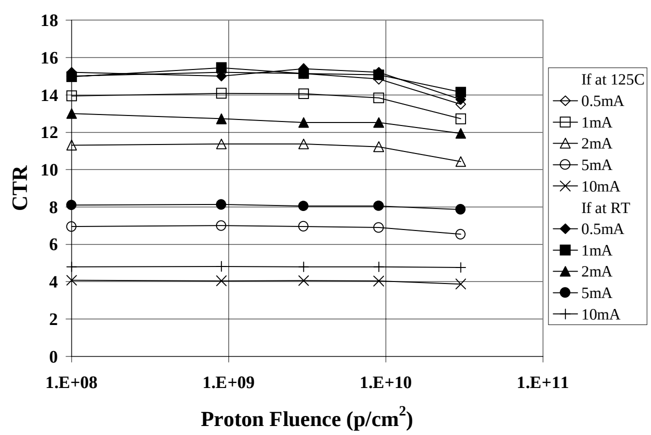

Figure 34: 63MeV Proton Induced CTR Degradation in HCPL-5730.

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

These Isolink parts were irradiated with 63MeV protons at UCD/CNL. There was no significant degradation in CTR for any of the parts irradiated. The bias conditions were V_{CC} = 5V and I_F = 0.5, 1, 2, and 5mA. The parts were irradiated to a fluence of $3x10^{10}$p/cm^2.

r. OLH400 (Isolink)

The OLH400 was irradiated 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 $3x10^{10}$p/cm^2 at both room temperature and 125°C.

4) Goddard Space Flight Center, NASA

a. 66088 (Mii) Multiple Tests

The 66088 was irradiated at UCD/CNL with 63MeV protons. CTR degradation measurements were taken for I_F = 10, 15 and 20mA, V_{CE} = 5V. No degradation of CTR was observed to $1x10^9$p/cm^2 [6].

The 66088 was irradiated at UCD/CNL with 63MeV protons. The tests conditions were I_F = 4.1, 10, 15.4, and 19.7mA with constant V_{CE} = 5V [9]. See Figure 35.

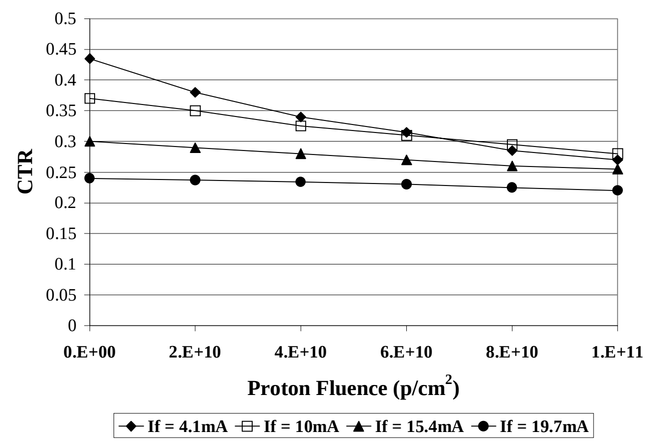

Figure 35: 63MeV Proton Induced CTR Degradation in 66088.

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. Mii's 66099 was tested and showed no CTR degradation [6].

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

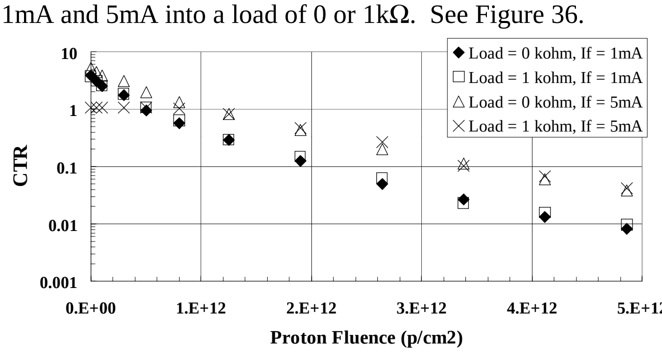

Figure 36: 63MeV Proton Induced CTR Degradation in 66099.

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. Mii's 66123 was tested and showed no parametric degradation [6].

d. 3C91C (Mitel)

Several 3C91C devices were irradiated 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 during irradiation with 63 and 31MeV protons. The test parameters were IF = 5mA and Vce = 5V. As expected, 31MeV protons induce more degradation than 63MeV protons for an equivalent fluence. Results from the 21 and 14MeV protons are similar to the results for the 31MeV protons. Significant part-to-part variability was also observed (See Figure 38). Annealing measurements were not made [9].

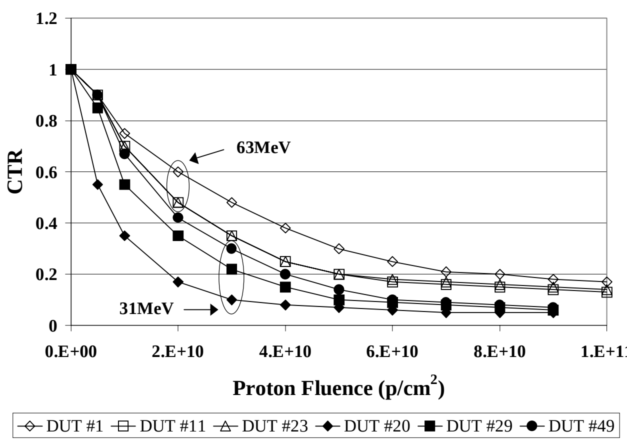

Figure 37: 63 and 31MeV Proton Induced CTR Degradation in 3C91C.

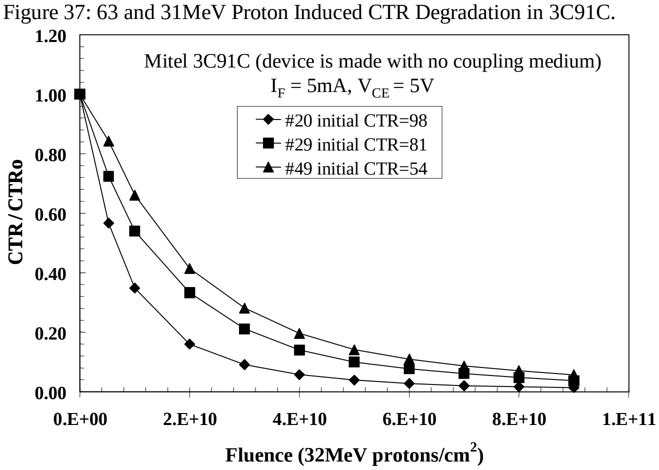

Figure 38: Part to Part Variability in CTR Degradation in 3C91C.

e. 4N48 Multiple Tests, Multiple Vendors

The Mii 4N48 was irradiated 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 [6,12].

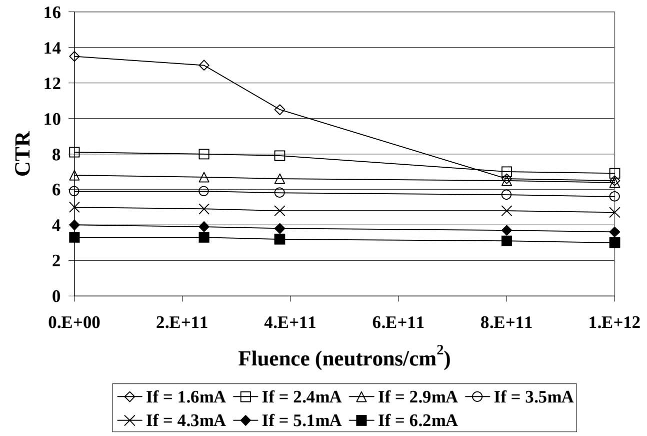

Figure 39: 1 MeV Equivalent Neutron Induced CTR Degradation in Mii 4N48.

The Optek 4N48 was irradiated at UCD/CNL with 63MeV protons. The Optek 4N48 contains an amphoterically doped LED. Figure 40 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 was saturated for drive currents greater than 2.5mA. Operating a device in this mode leads to a more radiation tolerant application [9]. See Figure 40.

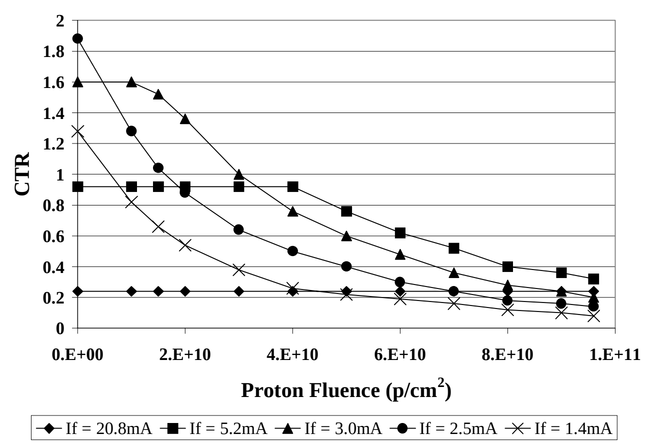

Figure 40: 63MeV Proton Induced CTR Degradation in Optec 4N48.

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. Mii's 4N49 was irradiated and there was no CTR degradation [6].

The TI 4N49 was irradiated at UCD/CNL with 63MeV protons. Figure 41 gives in situ measurements of CTR. I_F was varied between 1.2 and 11mA and V_{CE} = 6V [6].

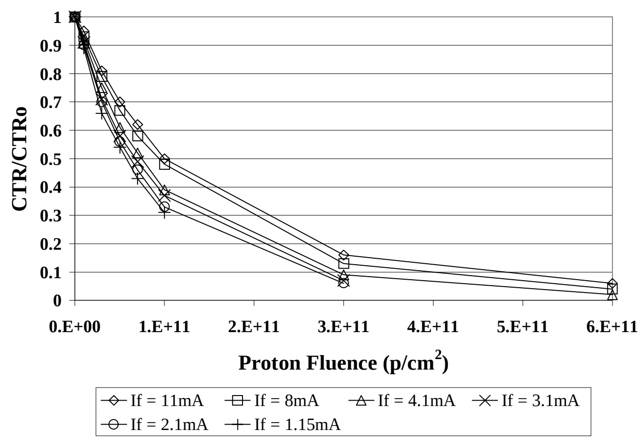

Figure 41: 63MeV Proton Induced CTR Degradation in TI 4N49.

g. 6N134 (HP)

The 6N134 was irradiated 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_{CE} = 5V. No parametric degradation was observed [12].

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. Mii's 6N140 was tested and there was no CTR degradation [6].

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 [6].

j. HSSR-7110 (HP)

The HP HSSR-7110 Power MOSFET that contains an optocoupler was irradiated with 63MeV protons at UCD/CNL. The test conditions were I_F = 10mA, V_{CE} = 28V, input square wave of 1Hz to 1kHz was applied. The parts were irradiated to a total dose of 50krads(Si) and annealed for two weeks. After 30krads(Si), the part was well above the specification of 250µA for output leakage and by 50krads(Si), 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 [13]. See Figures 42-44 for further details.

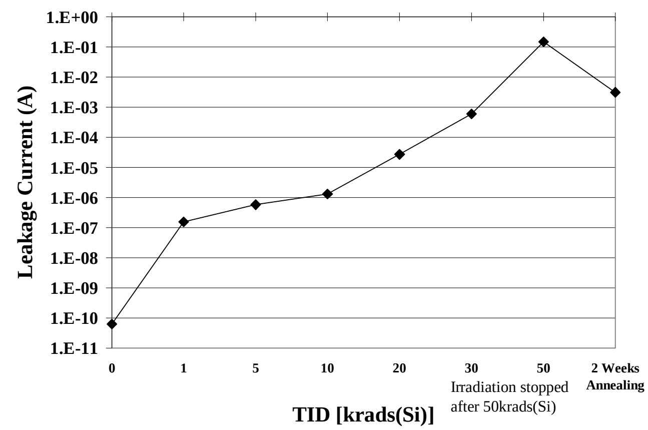

Figure 42: 63MeV Proton Induced Output Leakage Current Degradation in HSSR-7110.

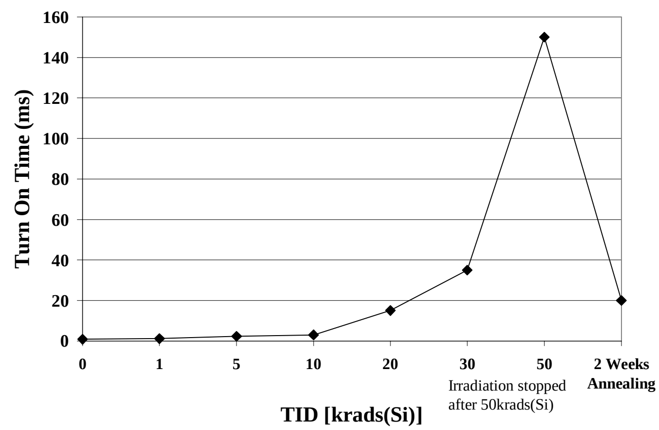

Figure 43: 63MeV Proton Induced Turn-On Time Degradation in HSSR-7110.

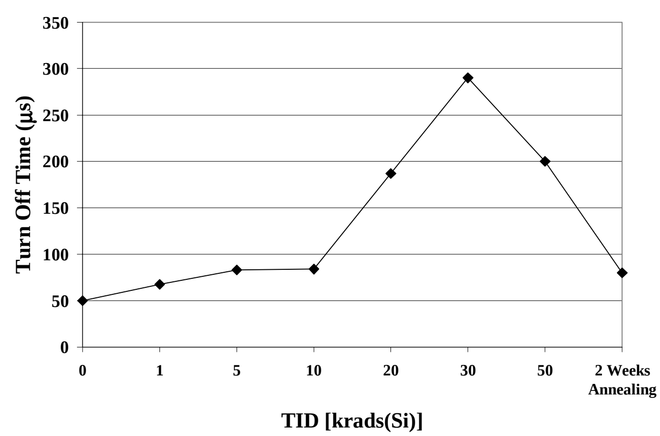

Figure 44: 63MeV Proton Induced Turn-Off Time Degradation in HSSR-7110.

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 $6x10^{11}$p/cm^2.

l. OLF400 (Isolink)

The OLF400 was irradiated with 63MeV protons at UCD/CNL. Some degradation of CTR was noted at 1.3×10^{12}p/cm^2 at low I_F [14]. I_F was set as several values from 0.3 to 18.1mA. Above 3.6mA, the device is in saturation and the CTR at each new I_F remains constant with increasing fluence. See Figure 45 for test results.

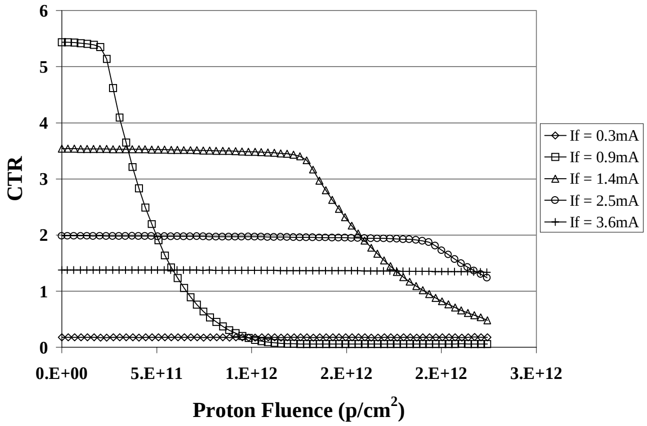

Figure 45: 63MeV Proton Induced CTR Degradation in OLF400.

m. OLS700 (Isolink)

The OLS 700 was irradiated with 63MeV protons at UCD/CNL. Significant degradation was observed at 2×10^{11}p/cm^2 [14].

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 2×10^{10}p/cm^2. The Hamamatsu P2824 was tested and CTR degradation was observed [6].

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. Proton and neutron step irradiations of the P2824 optocouplers were performed at LLUMC, SPR, and IUCF.

The results from exposing these optocouplers to a 51.8 MeV proton beam at LLUMC are shown in Figure 46. Results from neutron exposures of this device performed 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 [6,12].

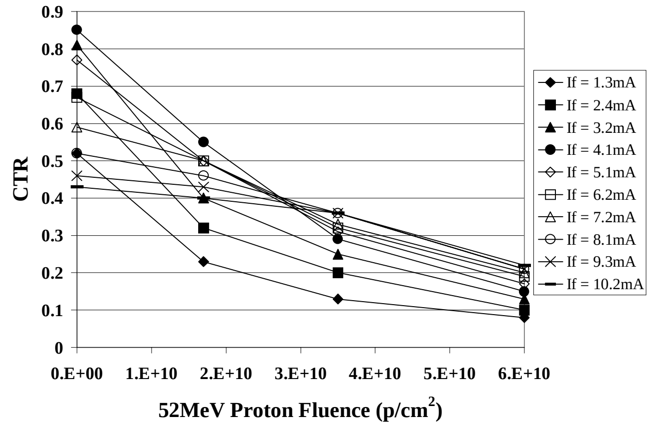

Figure 46: Proton Induced CTR Degradation in P2824 (Testing at LLUMC).

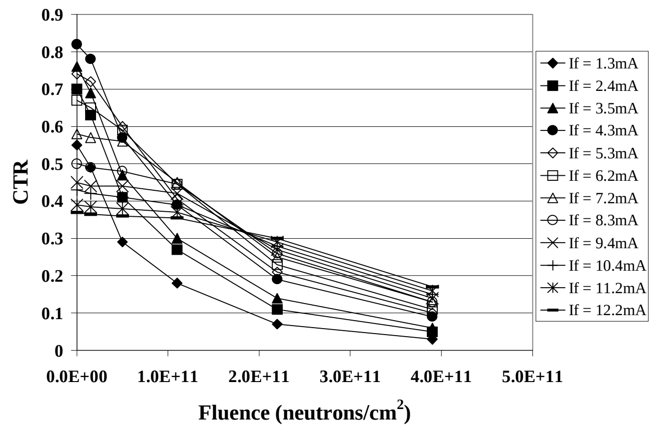

Figure 47: 1MeV-Equivalent Neutron Induced CTR Degradation in P2824 (Testing at SPR).

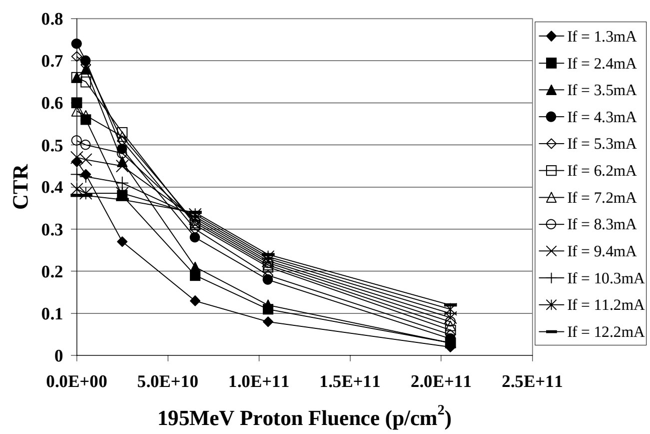

Figure 48: Proton Induced CTR Degradation in P2824 (Testing at IUCF).

5) Jet Propulsion Laboratories, NASA

a. 4N49 Multiple Tests, Multiple Vendors

The Mii and Optek 4N49 were irradiated with 192MeV protons at IUCF. The devices were irradiated intact (not delidded). The devices were tested after each step irradiation with I_F = 0.5, 1 and 8mA. See Figure 49 for more details.

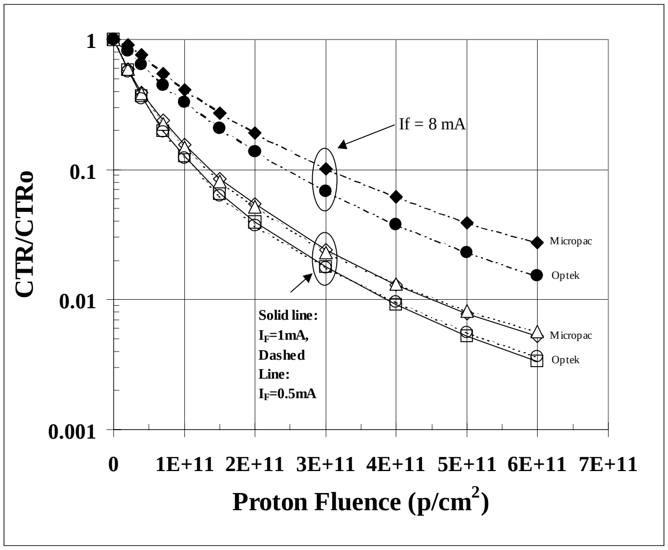

Figure 49: 192MeV Proton Induced CTR Degradation in Mii and Optek 4N49.

b. OLH1049 (Optek) Multiple Tests

Three different device styles of the Optek OLH1049 were irradiated with 50MeV protons at UCD/CNL. The parts were irradiated with three different bias conditions: (1) I_F = 0V and V_{CE} = 5V, (2) I_F = 0.5mA, V_{CE} = 0V, and (3) I_F = 3mA, V_{CE} = 0V. Electrical measurements were made with V_{CE} = 5V and I_F = 0.1, 0.2, 0.5, and 1mA. The parts showed some CTR degradation beginning at $1x10^{10}$p/cm^2 and end results at $8x10^{10}$p/cm^2 were slightly more than an order of magnitude less than initial values. It is interesting to note that diagnostic tests revealed that displacement damage in the LED is the dominant mechanism, rather than displacement damage in the photodiode.

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

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

The Mii 4N35, 4N49 and 6N140 optocouplers were irradiated with 192MeV protons at IUCF. CTR degradation was noticeable in these Mii devices with I_F = 1mA and V_{CC} = 5V at $1x10^{11}$p/cm^2 as shown in Figure 50. A special process Mii 4N35 was tested that showed improvement in the hardness against CTR degradation.

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

HP HCPL-2201 and HCPL-2430 optocouplers were irradiated 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 $6x10^{11}$p/cm^2. Also see Figure 50.

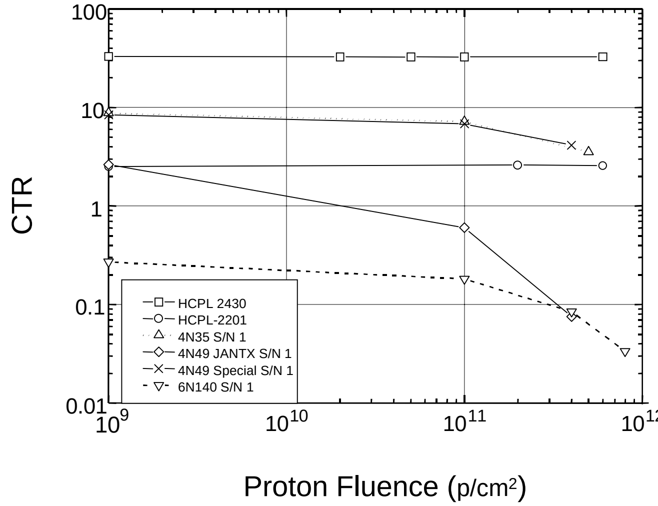

Figure 50: 192MeV Proton Induced CTR Degradation in Mii 4N35, 4N49, 6N140 and HP HCPL 2430, HCPL 2201 optocouplers.

c. 81082-300 photodiode (Mii)

The Mii 81082 photodiode was irradiated with 73MeV protons at HCL. The photodiode showed degradation with increasing fluence. (Pre irradiation I_C = 3.0μA, $2x10^{10}$p/cm^2 = 2.1μA, $1.2x10^{11}$p/cm^2 = 0.6μA, $4.2x10^{11}$p/cm^2 = 0.2μA.)

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

The Mii 62017 (GS3040-3 LED) was irradiated with 73MeV protons at HCL. The LED showed little change with increasing fluence. (Pre irradiation I_F = 15 mA, $2x10^{10}$p/cm^2 = 15.4 mA, $1.2x10^{11}$p/cm^2 = 15.3 mA, $4.2x10^{11}$p/cm^2 = 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 irradiated with 73MeV protons at HCL. Displacement damage was observed in the OP604 with V_{CE} = 15V at a fluence of $2x10^{10}$p/cm^2. See Figures 51 and 52.

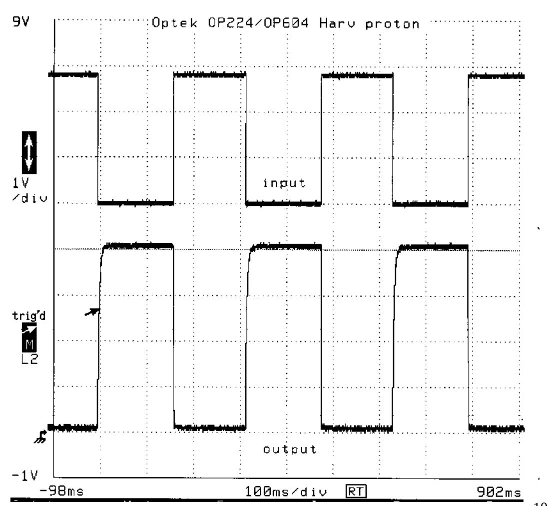

Figure 51: Proton Damage observed in the OP604 after $2x10^{10}$ protons/cm^2 at 73.3MeV. The bottom trace shows the device output that has risen by at least 1.7V.

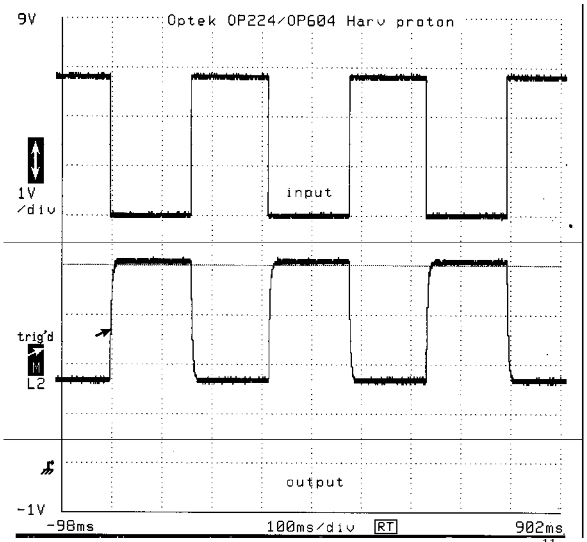

Figure 52: Proton Damage observed in the OP604 after $1.2x10^{11}$ $protons/cm^2$ at 73.3MeV. The bottom trace shows device output degradation. Similar results were observed at 148MeV.

7) Naval Research Laboratory

a. MC099 (Mii)

The MC099 was irradiated 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 53 shows CTR degradation.

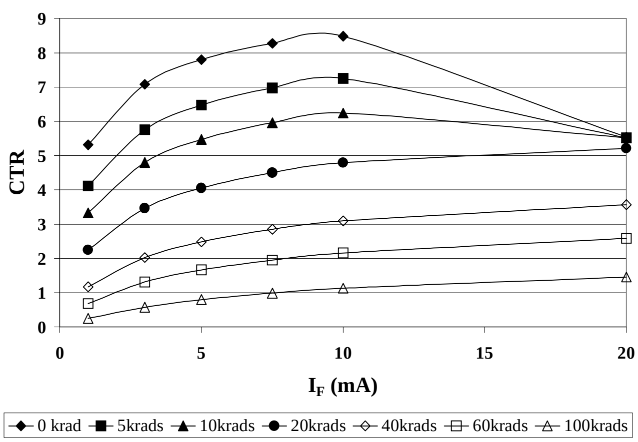

Figure 53: 63MeV Proton Induced CTR Degradation in MC0099.

b. OLI400 (Isolink)

The OLI 400 was irradiated 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 54 shows CTR degradation.

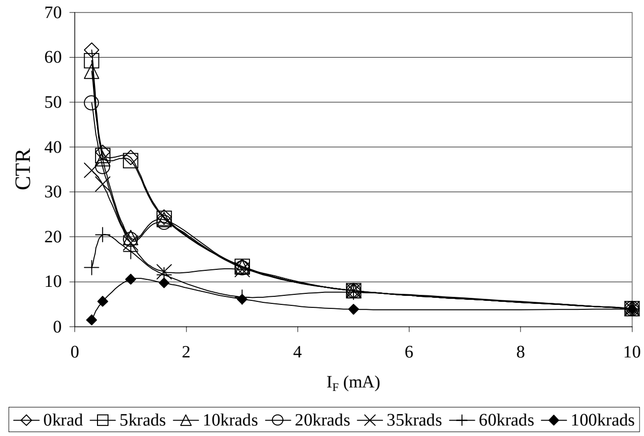

Figure 54: 63MeV Proton Induced CTR Degradation in OLI400.

c. QCPL-5729 (HP)

The QCPL-5729 was irradiated 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 55 shows CTR degradation.

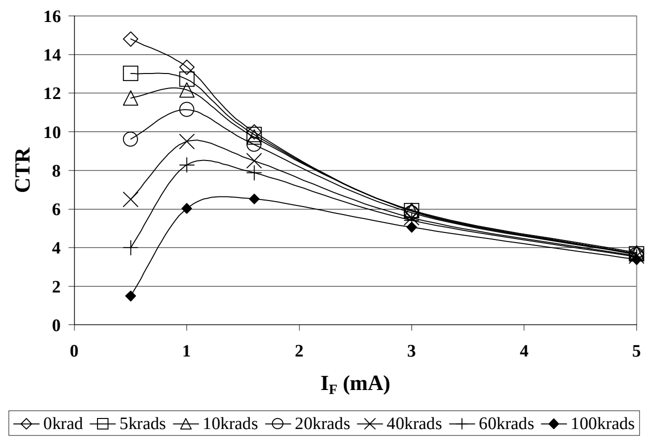

Figure 55: 63MeV Proton Induced CTR Degradation in QCPL-5729.

8) Sandia National Laboratories

Five Mii 4N49 and five Isolink OLH249 optocouplers were irradiated with neutrons at SPR. After each irradiation step, 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 56 and 57 show CTR degradation with irradiation conditions of I_F = 1 mA and V_{CE} = 2, 5, and 8V.

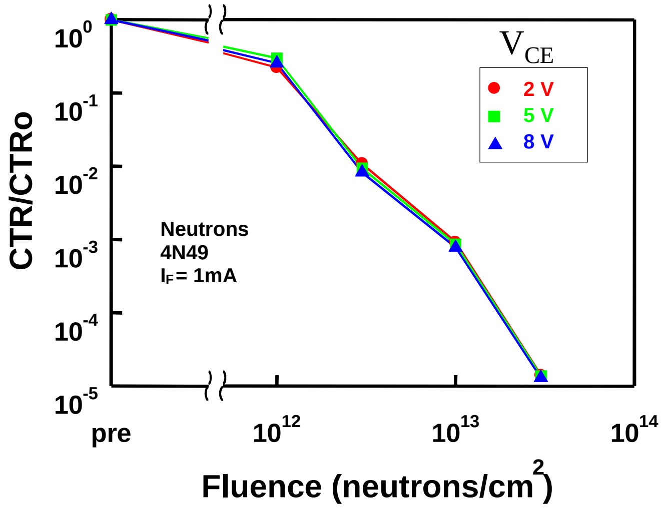

Figure 56: 1MeV-Equivalent Neutron Induced CTR Degradation in 4N49.

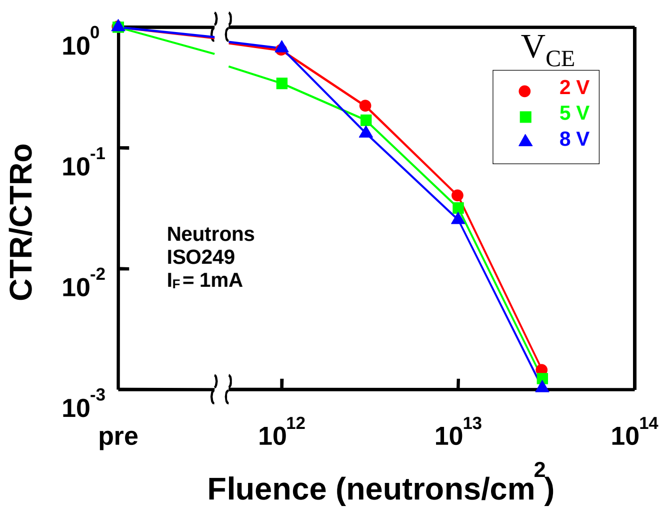

Figure 57: 1MeV-Equivalent Neutron Induced CTR Degradation in OLH249.

B. Proton and Heavy Ion Induced 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. Mii's 66099 was tested and no SETs were observed [6].

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. Mii's 66123 was tested and SETs were observed [6].

The Mii 66123 was irradiated with 68 to 225MeV protons at TRIUMF [9]. SETs were observed for several angles and energies [7]. See Figure 58.

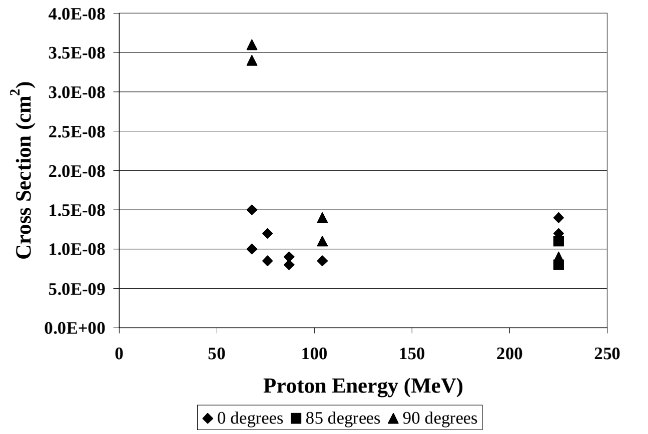

Figure 58: SET Measurements vs. Proton Energy and Angle of Incidence on the Output of the Mii 66123.

c. 4N48 (Optek)

The Optek 4N48 was irradiated with 38.2MeV protons at UCD/CNL. No SETs were observed with the bias off, up to 1x10^9p/cm^2. Complete technical data, along with test procedures and results are available [6,15].

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. Mii's 4N49 was tested and no SETs were observed [6].

e. 4N55 (HP) [Tested with Ball Aerospace]

The HP 4N55 was irradiated with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off up to 1x10^9p/cm^2. Complete technical data, along with test procedures and results are available [1,6,15].

f. 6N134 (Mii)

The 6N134 was irradiated with 68, 103, 159 and 225MeV protons at TRIUMF. Transients were observed with the bias off for all proton energies. See Figure 59.

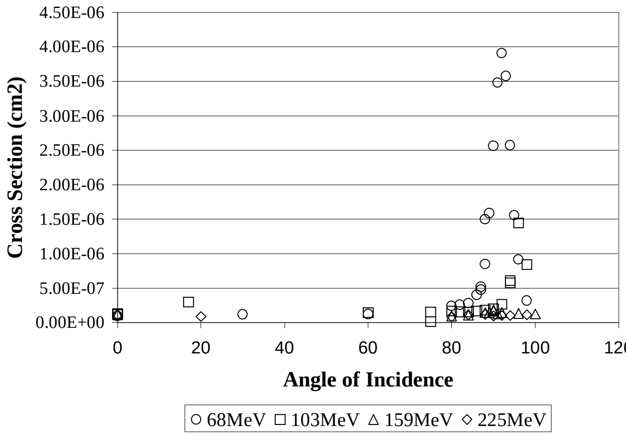

Figure 59: SET Cross Section vs. Angle of Incidence for Various Proton Energies in 6N134.

g. 6N136 (Mii)

The Mii 6N136 was irradiated with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off, up to $1x10^9 p/cm^2$. Complete technical data, along with test procedures and results are available [1,6,15].

h. 6N140A (HP)

The HP 6N140A was irradiated with 38.2MeV protons at UCD/CNL. No transients were observed with the bias off, up to $1x10^9 p/cm^2$. Complete technical data, along with test procedures and results are available [1,6,15].

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 $2x10^{10} p/cm^2$. Mii's 6N140 was tested and no SETs were observed [6].

j. HCPL-5401 (HP) [Tested with Ball Aerospace]

The HP HCPL-5401 was irradiated 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 [1,6,15]. Figure 60 shows the cross sections for 0° and 90° angle of incidence and Figure 61 shows an oscilloscope trace of an actual output transient. The channel two (bottom) trace is 50ns per division at 2.0V per division.

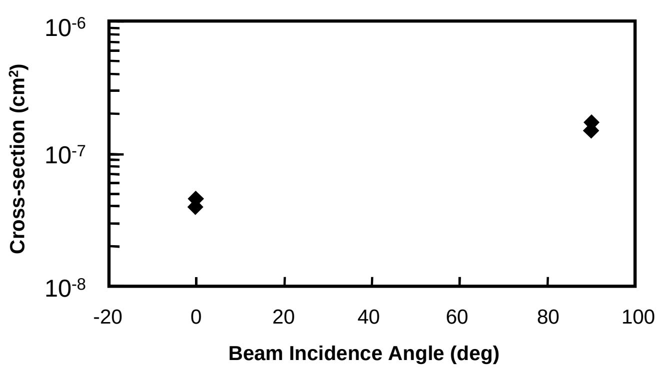

Figure 60: 38MeV Proton Induced SET Cross Section vs. Angle of Incidence in HP5401.

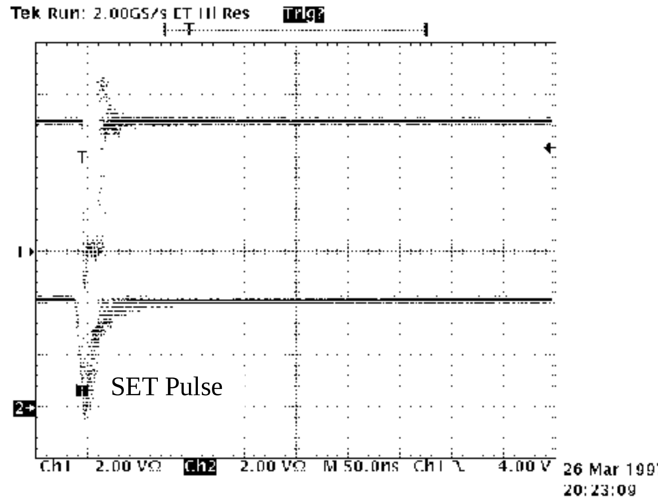

Figure 61: Oscilloscope Trace of a SET in an HP5401.

k. HCPL-5631 (HP) [Tested with Ball Aerospace]

The HP HCPL-5631 was irradiated 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 duration with a channel error cross section of $\sim 5x10^{-8} cm^2$ 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 [6,15]. See Figures 62 and 63 for more information.

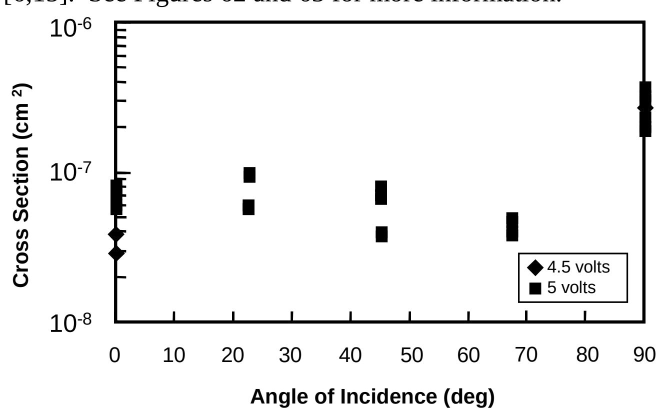

Figure 62: 38MeV Proton Induced SET Cross Sections for V_{CE} = 4.5 and 5V in HCPL5631.

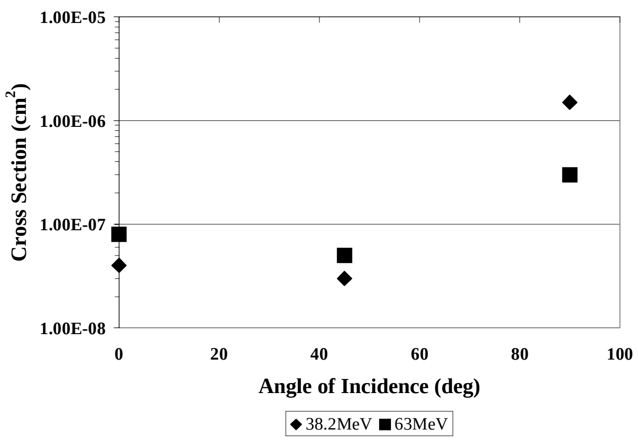

Figure 63: HCPL5631 Cross Section Data for Various Angles of Incidence at 38 and 63MeV.

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. Tests with passive and active filters showed no SETs [6]. Some angle of incidence data was taken as well. See Figure 64.

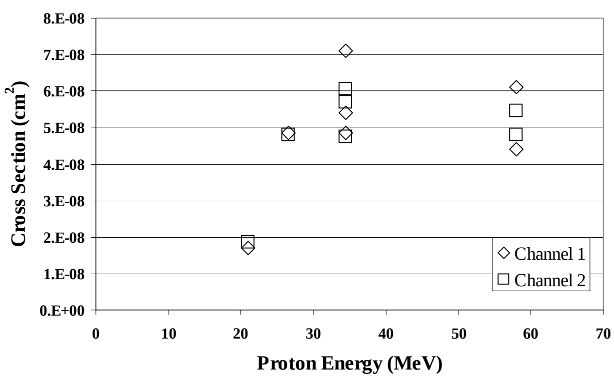

Figure 64: SET Cross Section vs. Proton Energy for HCPL6651.

Proton-induced SETs were observed for several angles and proton energies at TRIUMF. SETs were also observed during irradiation with 240MeV He ions at various angles at MSU/NSCL. A complete description is given in [1,7]. 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.

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 [7,9].

n. OLH5601(Isolink)

Proton SET testing was performed at TRIUMF. The devices were irradiated with 68, 103, 159, and 225MeV protons. See Figure 65.

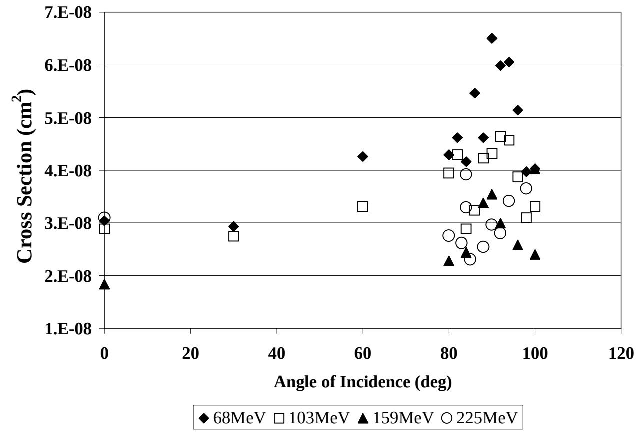

Figure 65: OLH5601 Cross Section vs. Angle of Incidence for Various Proton Energies.

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 [6].

2) Jet Propulsion Lab, NASA

a. 6N134 (HP)

The HP 6N134 was irradiated with various heavy ions at BNL [10]. The cross section results are presented in Figure 66.

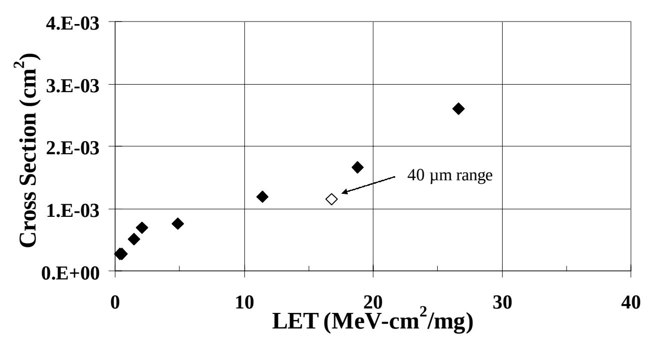

Figure 66: Heavy ion SET cross section results for 6N134.

b. 6N140 (HP)

The HP 6N140 was irradiated with various heavy ions at BNL [10]. The cross section results are presented in Figure 67.

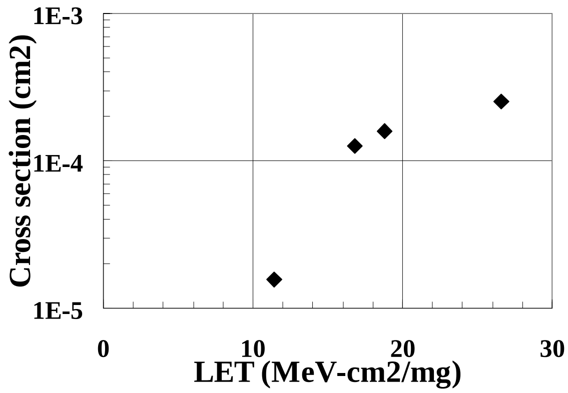

Figure 67: Heavy ion SET cross section results for 6N140.

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

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

The Mii 4N35, 4N49, 6N140 optocouplers were irradiated 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 $5x10^{11}p/cm^2$, both 4N49s showed no SETs to $4x10^{11}p/cm^2$ and the 6N140 showed no SETs to $8x10^{11}p/cm^2$.

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

The HCPL-2201 and HCPL-2430 were irradiated 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 68.

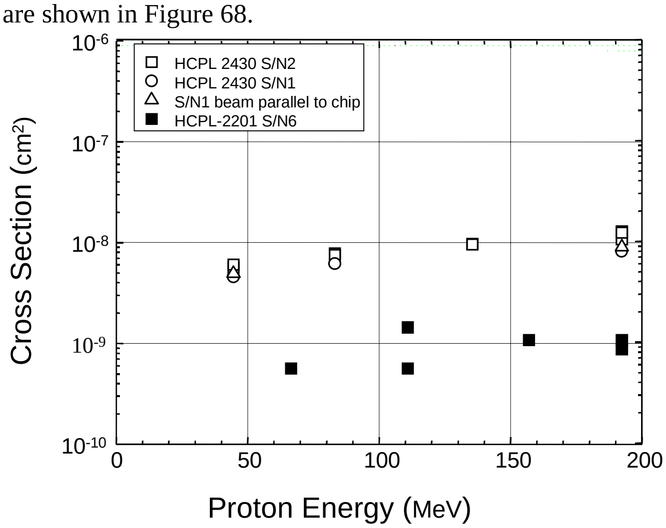

Figure 68: HCPL2201 and HCPL2430 Cross Sections for Various Proton Energies.

c. 61082-300 photodiode (Mii)

The 61082-300 photodiode was irradiated with 73 and 145MeV protons at HCL. Figures 69 and 70 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 by 5x), is the output signal from the photodiode. Quantitative measurements of the frequency of these glitches as a function of incident angle and proton energy were not performed.

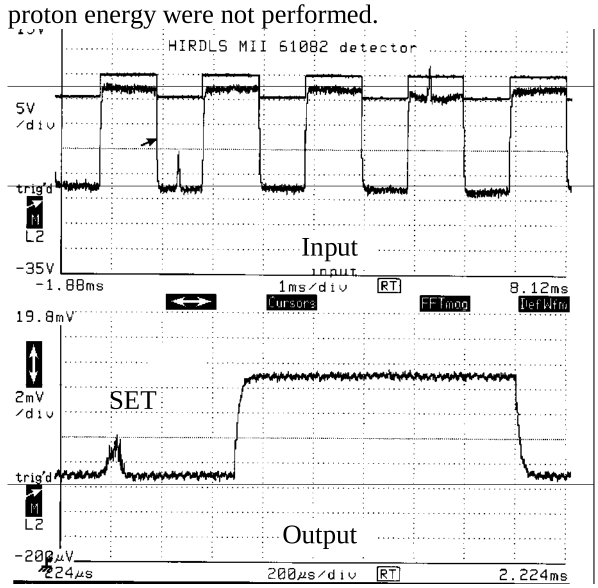

Figure 69: 61082 SET Observed on Output Low.

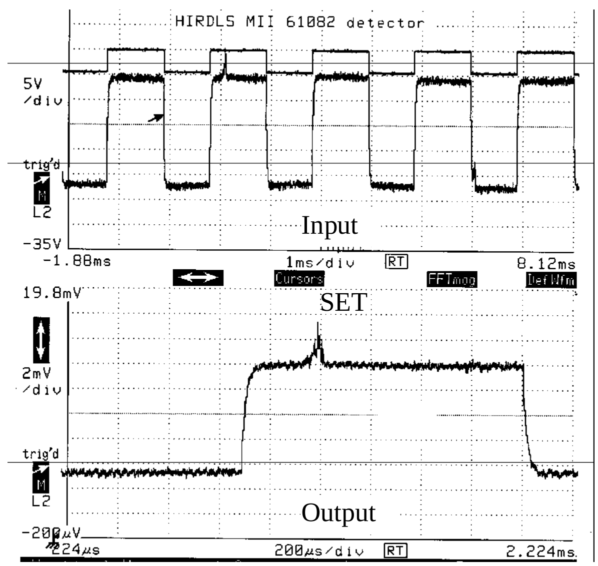

Figure 70: 81082 SET Observed on Output High.

d. OP604 phototransistor (Optek)

The OP604 phototransistor was irradiated 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 irradiated with 63MeV protons at UCD/CNL. The protons were normally incident and V_{CE} = 5V. With a 20pf capacitor, $\sigma = 3.7x10^{-8}cm^2$/channel and with a 100pf capacitor, $\sigma = 2.8x10^{-8}cm^2$/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 TID irradiation. Optocouplers were irradiated to a TID of 1Mrad(SiO_2) in logarithmic steps with Co-60 gamma rays with zero input and output bias (all pins shorted together) at a dose rate of 50rad(SiO_2)/s. After each radiation step, 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 71 and 72 show degradation of CTR for I_F = 1mA and for 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 TID than the OLH249 optocouplers.

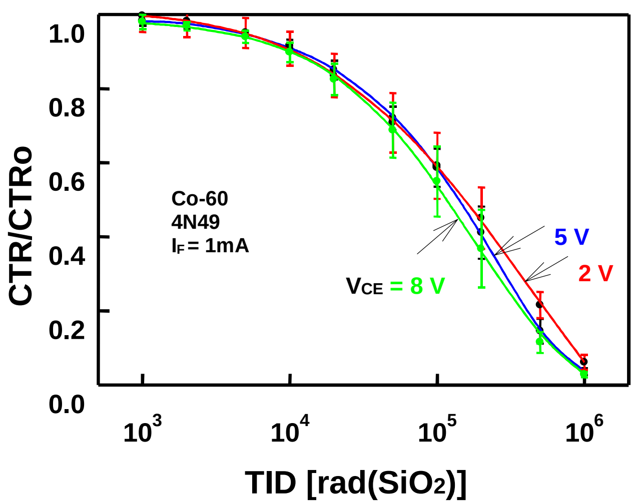

Figure 71: 4N49 Co-60 TID Induced CTR Degradation.

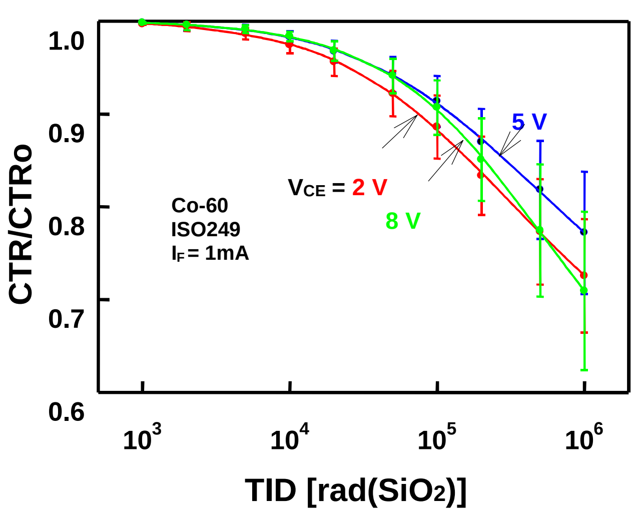

Figure 72: OLH249 Co-60 TID Induced CTR Degradation.

VII. Application of Test Data

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

A. Damage Issues

Predicting CTR degradation for a specific application involves obtaining damage test data for appropriate test particle energies for devices operating with appropriate circuit parameters ($V_{CC,}$ V_{CE}, I_f, I_C, Load). These results must be mapped over to the mission-specific transported radiation environment.

Some devices may have significant part to part variance [9]. In the case of the 3C91C presented here, the initial CTR varied by as much as 44 (absolute value) in the same lot. The resulting CTR degradation curves had very different slopes.

Operating parameters can also affect the level of degradation of degradation an optocoupler exhibits in a given application. If a device's collector current is saturated (for example, for V_{CE} sufficiently low), radiation-induced changes in LED output will have little effect on the optocoupler output. This results in nearly constant CTR with increasing dose until the fluence is large enough to significantly degrade the LED output. The degradation vs. fluence curve then assumes its more characteristic exponentially decreasing form. If V_{CE} were high to begin with, small changes in forward current would produce much larger changes in CTR, resulting in a more typical degradation plot even for low fluences.

When significant CTR degradation is expected for a specific mission application, the effects of the degradation can be mitigated in some cases. This can be done by derating the CTR or by adjusting the application bias conditions to reduce the severity of the degradation.

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

B. SET Issues

For SETs, it is important to understand not only whether transients are possible, but also whether the SETs can propagate downstream of the optocoupler to produce system-level data errors. Such errors can result in problems similar to those seen on-orbit in HST and Iridium [16]. The end result of a transient will depend on the pulse width and height, the speed of the device and the characteristics of the circuitry downstream. For slower devices, the transient may be filtered out because its duration is less than a clock cycle. In faster devices, one may need 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 dependence of SET cross section on angle and energy. Increasing the angle of incidence results in a longer path length for the particle to generate charge in the diode. The increase in path length increases the probability that the deposited charge will be sufficient to cause a transient in the device. Often the cross section can increase by an order of magnitude or more compared to the cross section at normal incidence.

NASA is currently developing SET prediction methods that account for the contributions of both direct and indirect ionization [17].

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, extrapolation of generic test data to a specific application, the application of NIEL, annealing, and the effects of 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 serve 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 better choice for 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.

X. References

[1] K.A. LaBel, et al. “Proton-Induced Transients in Optocouplers: In-Flight Anomalies, Ground Irradiation Test, Mitigation and Implications.” *IEEE Trans. Nuc. Sci.* 44(6), December 1997: 1885-1892.

[2] C.E. Barnes, et al. “Radiation Effects in Optoelectronic Devices.” Sandia Report, SAND84-0771, 1994.

[3] A.H. Johnston, et al. “Proton Degradation of Light-Emitting Diodes.” *IEEE Trans. Nuc. Sci.*, 46(6), December 1999: 1781-1789.

[4] R.A. Reed, et al. “Energy Dependence of Proton Damage in AlGaAs Light-Emitting Diodes.” Paper to be presented at 2000 IEEE NSREC Conference.

[5] B.G, Rax, et al. “Total Dose and Proton Damage in Optocouplers.” *IEEE Trans. Nuc. Sci.*, 43(6), December 1996: 3167-3173.

[6] M.V. O’Bryan, et al. “Single Event Effect and Radiation Damage Results for Candidate Spacecraft Electronics.” *IEEE Radiation Effects Data Workshop*, July 1998: 39-50.

[7] R.A. Reed, et al. “Emerging Optocoupler Issues with Energetic Particle-Induced Transients and Permanent Radiation Degradation.” *IEEE Trans. Nuc. Sci.*, 45(6), December 1998: 2833-2841.

[8] M. D’Ordine. “Proton Displacement Damage in Optocouplers.” *IEEE Radiation Effects Data Workshop*, July 1997: 122-124.

[9] M.V. O’Bryan, et al. “Recent Radiation Damage and Single Event Effect Results for Microelectronics.” *IEEE Radiation Effects Data Workshop*, July 1999: 1-14.

[10] A.H. Johnston, et al. “Single-Event Upset Effects in Optocouplers.” *IEEE Trans. Nuc. Sci.*, 45(6), December 1998: 2867-2875.

[11] A.H. Johnston, et al. “Angular and Energy Dependence of Proton Upset in Optocouplers.” *IEEE Trans. Nuc. Sci.*, 46(6), December 1999: 1335-1341.

[12] R.A. Reed, et al. “Test Report of Proton and Neutron Exposures of Devices That Utilize Optical Components an are Contained in the CIRS Instrument.” http://radhome.gsfc.nasa.gov/radhome/papers/i090397.html

[13] G. Jackson. “Radiation Test Results for the Hewlett Packard HSSR-7110 Optocoupler.” http://radhome.gsfc.nasa.gov/radhome/papers/d121696.htm

[14] Unpublished GSFC test report, 3/26/98.

[15] R.A. Reed. “Test Report for Proton Induced Single Event Transients in Optocouplers.” http://radhome.gsfc.nasa.gov/radhome/papers/d031997.htm

[16] B. Heidergott. “Iridium and Celestri Constellation Update.” *11th SEE Symposium*, April 1998.

[17] K.A. LaBel, NASA/GSFC, personal communication, 2000.