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CONTRACT REPORT

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The work described in this report was done under ESA contract.
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Title

Radiation Characterization and Test Methodology Study of Optocoupler Devices for Space Applications

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ESA/ESTEC Contract No. 11755/95/NL/PB-WO01/CO03

Summary :

This report presents Protons, neutrons and TID irradiation results obtained for several optocoupler devices.

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1. INTRODUCTION

The object of this document is to present an analysis of optocoupler degradation under proton, neutron and Co^{60} irradiations in the frame of ESA “Radiation Characterization and Test Methodology Study of Optocoupler Devices for Space Applications” study.

Neutron irradiations were performed in July 2000 (6^{th}-7^{th}) at CEA Valduc, proton irradiations were performed in August/September (30^{st}-2^{nd}), at PSI (OPTIS and PIF beam lines) and Co^{60} irradiation at CEA Saclay (06/08) and at Astrium Space (06/16 – 07/18) , according to the procedures referenced in the following paragraph.

The study focuses on several points:

- Primarily, neutrons and protons cause displacement damage. However, protons deposit dose too. Our purpose is to correlate {neutron + dose} and proton effects relatively to optocoupleur degradation (CTR).

- Calculation of equivalent monoenergetic proton fluences is based on the assumption that the relationship between CTR (Current Transfer Ratio) degradation and NIEL (Non Ionizing Energy Loss) (function of proton energy) is linear. Existing data shows that this is usually true in the medium energy range (30 to 100 MeV) but it is not formally demonstrated for higher energy (200 MeV).

- Optocoupler devices have been tested with different bias conditions in order to investigate the bias influence on the CTR.

This work was performed in the frame of the WO01/CO03 for ESTEC Contract n°11755/95/NL/PB.

2. REFERENCE DOCUMENTS

[1] ESA/SCC Basic Specification 25100

[2] ESA/SCC Basic Specification 22900-3

[3] ISOLINK Manufacturer Data Sheet

[4] MICROPAC Manufacturer Data Sheet

[5] OPTEK Manufacturer Data Sheet

[6] Proposal “Radiation Characterization and Test Methodology Study of Optocoupler Devices for Space Applications” ESA/ESTEC Contract No. 11755/95/NL/PB-WO01/CO03

[7] Test Plan ref No. AIN.PL.BD.3792.00

[8] K.A. LaBel et al : « A compendium of recent optocoupler radiation test data » presented at IEEE NSREC Reno July 2000.

[9] Isolink Application Note 1001 « Radiation immunity of Isolink Optocouplers »

[10] Isolink Application Note 1003 « Gamma total dose radiation performance of Isolink photocouplers »

[11] H. Johnston « Optoelectronic devices with complex failure modes » IEEE NSREC short course Reno July 2000.

[12] H. Johnston « Proton degradation of light-emitting diodes » IEEE Trans. Nuclear Science Vol 46 N° 6 Dec 99 pp 1781-1789.

[13] B.G. RAX and al « Total dose and proton damage in optoisolators » IEEE Trans. Nuclear Science Vol 43 N° 6 Dec 96 p 3167.

[14] D.W. Emily “Total Dose Response Of Bipolar Microcircuits”, IEEE NSREC Short Course 1996

[15] A.H. Johnston et al. “Proton Damage in Linear and Digital Optocouplers”, IEEE IEEE Trans. Nuclear Science, vol. 47, n° 3, june 2000.

3. PART DETAILS

Optocouplers are 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 photodiode or phototransmitter receiver.

Tests have been performed on two types of devices, standard devices and radiation tolerant devices. 4N49 type, from 3 different manufacturers (Isolink, Optek and Micropac) and 66163 from Micropac belong to the unhardened category whereas 66168/66099 (Micropac) and OLH249 (Isolink) belong to the radiation tolerant type. 4 to 6 parts of each type were used for each experimental condition.

3.1. GENERAL INFORMATION

Name **Manufacturer**	**4N49** **Isolink**	**4N49** **Micropac (Mii)**	**4N49** **Optek**	**66099** **Micropac (Mii)**	**OLH249** **Isolink**	**66163** **Micropac (Mii)**	**66168** **Micropac (Mii)**
Date Code	S 0013	M9952	M9951	9826	9837	M0012	0017
Marking	S 0013	M9952	M9951	-003 9826	SX 9837	31757 66163-001 Δ3C91C M0012	-001 0017
Package	standard TO-5	standard TO-5	standard TO-78	standard TO-5	standard TO-5	standard TO-46	standard TO-5
Level	standard	standard	standard	hardened to displacement damage and TID	hardened to displacement damage	standard	hardened to displacement damage
Temperature range	-55°C to 100°C	-55°C to 125°C	-55°C to 125°C	-55°C to 125°C	-55°C to 125°C	-55°C to 125°C	-55°C to 125°C
Technology	LED (III-V) NPN Silicon phototransistor	LED: GaAlAs NPN silicon phototransistor	No information	LED: GaAlAs photodiode	LED (III-V) NPN silicon phototransistor	LED: GaAs NPN silicon phototransistor	LED (III-V) NPN Silicon phototransistor
Detail specification	Manufacturer Data Sheet	Manufacturer Data Sheet	Manufacturer Data Sheet 07/96	Manufacturer Data Sheet 12/23/99	Manufacturer Data Sheet	Manufacturer Data Sheet	Manufacturer Data Sheet 4/25/00

Table 1: Devices General Information

3.2. PART TYPE SAMPLING FOR TESTING

Device type	Version	Manuf.	Total sample size	Proton sample size (per proton energy)	Neutron+TID sample size	TID sample size
4N49	Standard	Optek	120	15	18	18(HDR*)+ 18(LDR**)
4N49	Standard	Isolink	120	15	18	18(HDR)+18(LDR)
4N49	Standard	Micropac (Mii)	120	15	18	18(HDR)+18(LDR)
66099	Hardened to displacement damage and TID	Micropac (Mii)	70	12	12	9(HDR)+9(LDR)
66168	Hardened to displacement damage	Micropac (Mii)	120	15	18	18(HDR)+18(LDR)
66163	Standard	Micropac (Mii)	120	15	18	18(HDR)+18(LDR)
OLH249	Hardened to displacement damage	Isolink	50	12 @ 60 MeV 9 @ 200 MeV	9	9(HDR)+9(LDR)

Table 2: References and Sample Size of the selected parts

* HDR = High dose rate testing , as defined in §4.1

** LDR = Low dose rate testing, as defined in §4.1

3.3. DEVICE PHOTOGRAPHS

The device photographs are shown in annex 2.

4. TEST DESCRIPTION

The main objective of this study is to set up a radiation test methodology applicable for any optocoupler type and for any space application. In order to cover both displacement and ionization effects, different irradiation facilities were used and test conditions have been chosen accordingly to space mission requirements in terms of particle energies, fluences and total dose.

4.1. CO^{60} TEST

Ionization is one of the degradation mechanisms that may affect an optocoupler exposed to space radiation. In order to investigate total dose as well as dose rate effects, ^{60}Co testing have been performed for two distinct dose rates : “low dose rate” (LDR) and “high dose rate” (HDR). Electrical measurement test set-up and biasing conditions during irradiation are common for both LDR and HDR testing while irradiation facility, dose steps and test sequences are specific.

4.1.1. Co^{60} electrical measurements

Test set-up used for electrical measurements in the frame of ^{60}Co testing is presented here below, *Figure 1*.

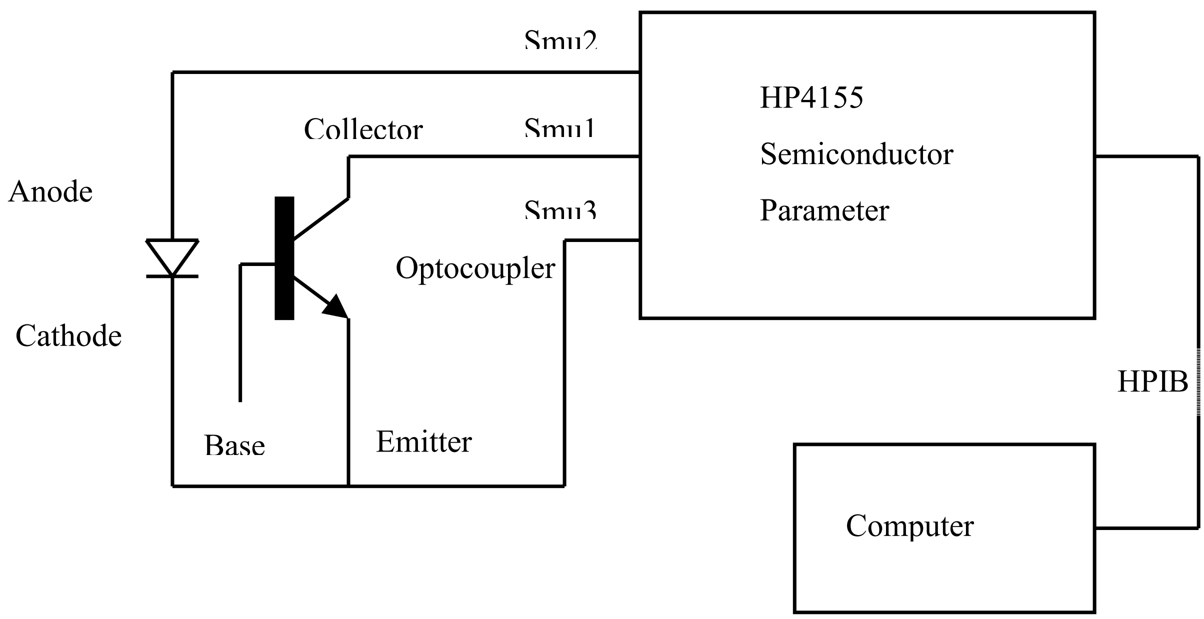

Figure 1: Description of the TID electrical measurements set-up

Optocouplers are characterized by a HP4155A analyser. We find in the HP4155A 4 channels which are used in a current mode or a voltage mode. For our application:

- SMU1 is used as a voltage supply and measurements are performed on Ic
- SMU2 is used as a current channel
- SMU3 is a reference voltage (GND)

Test set-up is the same for both LDR and HDR irradiation testing.

Electrical measurement conditions of monitored parameters are described in *Table 3*.

Symbol	Test Conditions
CTR1	Ifwd=1mA, Vce=5V, Ib=0
CTR2	Ifwd=2mA, Vce=5V, Ib=0
CTR3	Ifwd=5mA, Vce=5V, Ib=0
CTR4	Ifwd=10mA, Vce=5V, Ib=0
CTR5	Ifwd=10mA, Vce=10V, Ib=0
CTR6	Ifwd=20mA, Vce=10V, Ib=0
CTR7	Ifwd=20mA, Vce=5V, Ib=0
V_{cesat1}	Ifwd=30mA, Ic=1mA, Ib=0
V_{cesat2}	Ifwd=6mA, Ic=1mA, Ib=0
V_{fwd}	Ifwd=10mA
I_r	Vr=-2V

Table 3: Parameter Test Conditions

4.1.2. Bias conditions during irradiations

Figure 2 presents how parts are biased during irradiations in static ON mode and figure 3 how devices are biased in static OFF mode with all pins grounded.

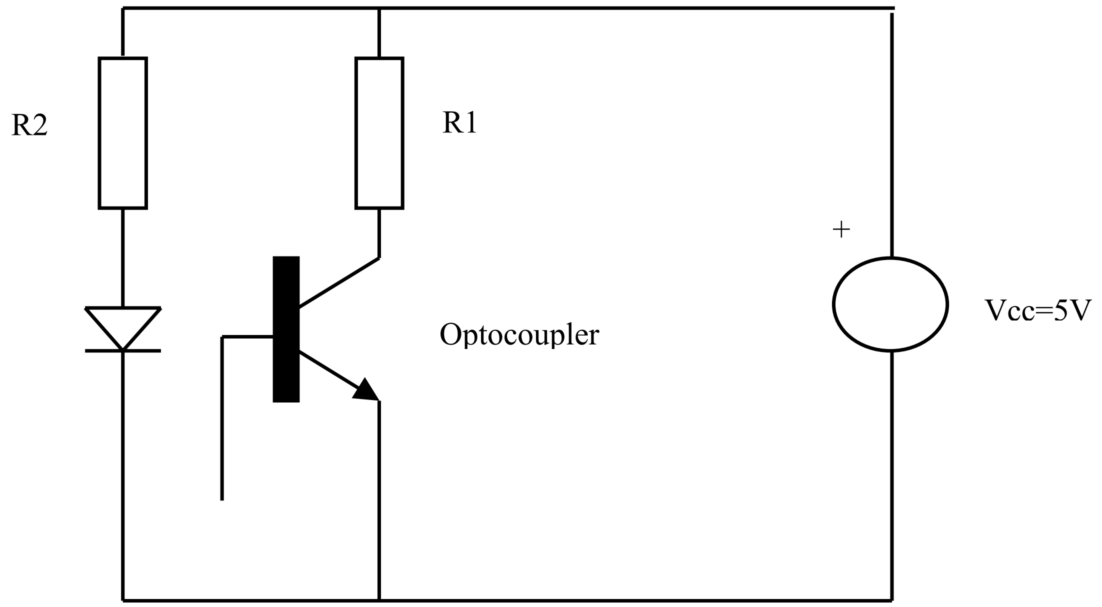

Figure 2: Biasing conditions in Static On Mode

Note : R1 = 470 Ω ; R2 = 4.7 kΩ (I_{fwd} = 1 mA) or 470 Ω (I_{fwd} = 10 mA)

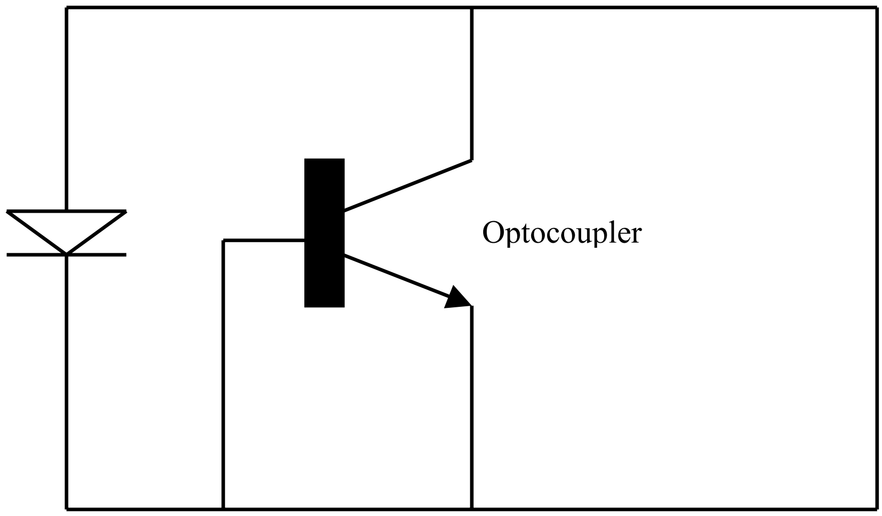

Figure 3: Biasing conditions in Static Off Mode

The following table gives the sample sizes, per bias condition and optocoupler type, for TID irradiations.

4N49 (Mii, Isolink, Optek), **66168** Mii, **66163** Mii				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	6	6	6	LDR
Samp.size ⇒	6	6	6	HDR
66099 Mii				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	3	3	3	LDR
Samp.size ⇒	3	3	3	HDR
OLH249 Isolink				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	3	3	3	LDR
Samp.size ⇒	3	3	3	HDR

Table 4: TID sample size and biasing conditions

4.1.3. Co^{60} Irradiation Facility

	"low dose rate" testing	**"high dose rate" testing**
Dose rate	<140 Rad(Si)/h	50 kRad(Si)/h
Name	Co^{60} Shepherd 484 source	Co^{60} Pagure facility
Location	ASTRIUM SAS, Vélizy, France	Cis Bio International, CEA Saclay, France

4.1.4. Low dose rate testing

Table 5 present the steps that have been followed for LDR irradiation while *Table 6* presents the irradiation test sequence :

0 kRad	**10 kRad**	**22 kRad**	**39 kRad**	**56 kRad**	**66 kRad**	**75 kRad**	**102 kRad**

Table 5: Steps of LDR Co^{60} irradiation in krad(Si)

Date (dd/mm/aa)	Beginning (hh:mn)	End (hh:mn)	Duration (h)	Dose rate (rad/h)	Dose Step (krad)	Total Dose (krad)
16/06/00	9:00					
19/06/00		8:50	72	140	10	10
19/06/00	11:30					
23/06/00		9:10	94	124	12	22
23/06/00	11:15					
28/06/00		11:50	121	140	17	39
28/06/00	12:00					
04/07/00		9:20	141	124	18	56
04/07/00	11:40					
07/07/00		9:00	69	140	10	66
07/07/00	9:10					
10/07/00		9:05	72	124	9	75
10/07/00	10:30					
18/07/00		14:10	196	140	27	102

Table 6: LowDose Rate Irradiation Test Sequence

4.1.5. High dose rate testing

Table 7 present the steps that have been followed for HDR irradiation while *Table 8* presents the irradiation test sequence :

0 kRad	20 kRad	50 kRad	100 kRad

Table 7: Steps of HDR Co^{60} irradiation in krad(Si)

Date (dd/mm/aa)	Beginning (hh:mn)	End (hh:mn)	Duration (h)	Dose rate (rad/h)	Dose Step (krad)	Total Dose (krad)
08/06/00	9:30					
08/06/00		9:54	0,4	50000	20	20
08/06/00	12:00					
08/06/00		12:36	0,6	50000	30	50
08/06/00	14:40					
08/06/00		15:40	1,0	50000	50	100

Table 8: High Dose Rate Irradiation Test Sequence

4.2. PROTON TEST

Proton irradiations were performed in August/September (31^{st}-2^{nd}), at the Paul Scherrer Institut (PSI) . In order to cover space proton energy spectrum, tests at three different energies (15, 60 and 200 MeV) have been performed with the optocouplers biased under the same conditions as for the neutron test.

Proton energies available at the OPTIS Line of PSI are ranging from 10 to 60 MeV. Lower energies are obtained by degrading the 60 MeV beam. For 200 MeV proton irradiation, tests were performed at the PIF beam Line.

4.2.1. Proton test : electrical measurements

Test set-up used for electrical measurements in the frame of proton testing is presented in *Figure 4*.

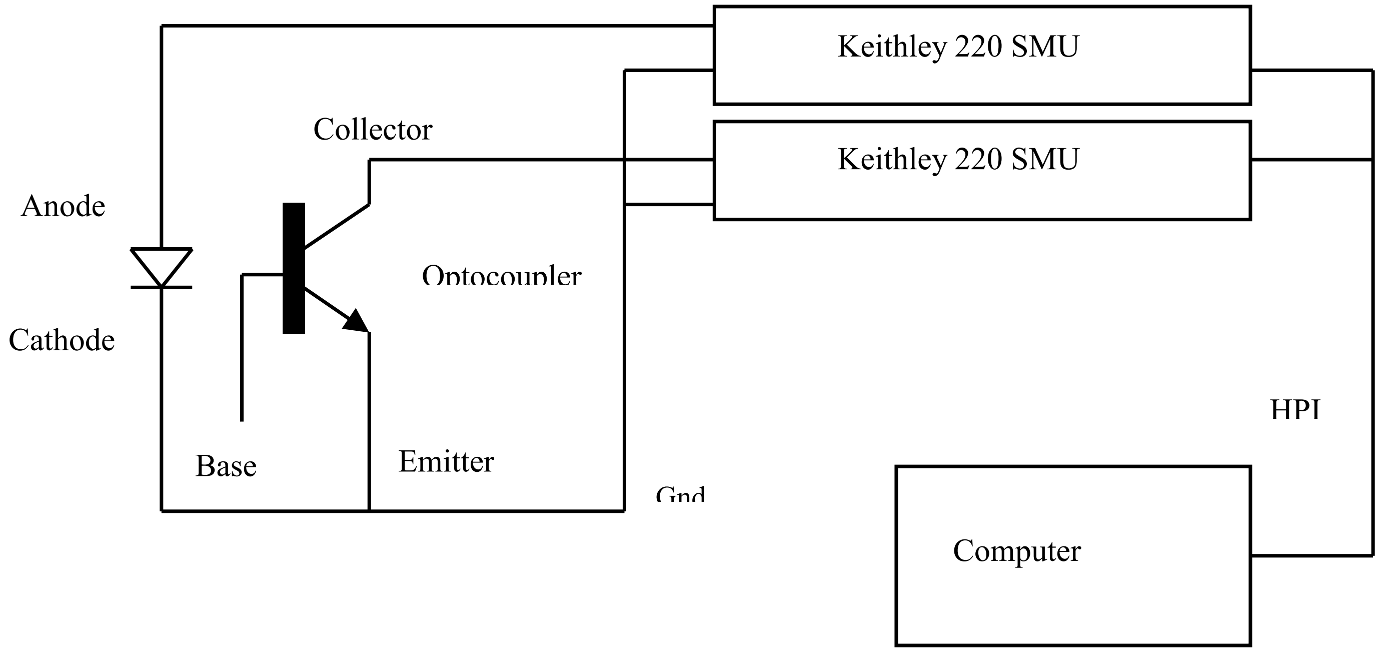

Figure 4: Description of electrical measurements set-up for proton irradiations

Optocouplers are characterized by two SMU 220 Keithley. One SMU is used as current generator (If current). The other is used as a voltage generator and perform Ic measurement. CTR is the ratio Ic/ If.

Electrical measurement conditions of monitored parameters are described in *Table 9*.

Symbol	Test Conditions
CTR1	Ifwd=1mA, Vce=5V, Ib=0
CTR2	Ifwd=2mA, Vce=5V, Ib=0
CTR3	Ifwd=5mA, Vce=5V, Ib=0
CTR4	Ifwd=10mA, Vce=5V, Ib=0
CTR5	Ifwd=10mA, Vce=10V, Ib=0
CTR6	Ifwd=20mA, Vce=10V, Ib=0
CTR7	Ifwd=20mA, Vce=5V, Ib=0
Vcesat1	Ifwd=30mA, Ic=1mA, Ib=0
Vcesat2	Ifwd=6mA, Ic=1mA, Ib=0
Vfwd	Ifwd=10mA
Ir	Vr=-2V

Table 9: Parameter test Conditions

4.2.2. Bias Conditions during irradiations :

The biasing conditions during irradiations are the same as for the TID test (*Figure 2* and *Figure 3*).

The following table gives the sample size for each of the 3 bias conditions and for each optocoupler type (the sample size depends on the number of parts available).

4N49 (Mii, Isolink, Optek), **66168** Mii, **66163** Mii				
If ⇒	1mA	10mA	Off	**Ep**
Samp.size ⇒	5	5	5	**15 MeV**
Samp.size ⇒	5	5	5	**60 MeV**
Samp.size ⇒	5	5	5	**200 MeV**
66099 Mii				
If ⇒	1mA	10mA	Off	**Ep**
Samp.size ⇒	4	4	4	**15 MeV**
Samp.size ⇒	4	4	4	**60 MeV**
Samp.size ⇒	4	4	4	**200 MeV**
OLH249 Isolink				
If ⇒	1mA	10mA	Off	**Ep**
Samp.size ⇒	4	4	4	**60 MeV**
Samp.size ⇒	3	3	3	**200 MeV**

Table 10: Proton sample size and biasing conditions

4.2.3. Proton Irradiation Facility

Name : Paul Scherrer Institut (PSI), OPTIS/PIF beam lines

Location : CH-5323, Villigen, PSI, Switzerland.

4.2.4. Proton Test condition

4.2.4.1. Fluxes and fluences used for proton tests

Table 11 Presents proton fluxes while *Table 12* provides fluence steps followed during proton experiment, for each proton energy. Dose deposited by 15 MeV protons is also indicated in *Table 12*.

Energy	Fluxes (p/cm²/s)
15 MeV	$7\ 10^{7}$
60 MeV	$1.5\ 10^{8}$
200 MeV	$4\ 10^{8}$

Table 11: experimental proton fluxes (p/cm²/s) for the 3 energy

	STEP0	STEP1	STEP2	STEP3	STEP4	STEP5	STEP6	STEP7
15 MeV	0		1.24e+10	2.48e+10	4.9e+10	1.2e+11	1.8e+11	2.42e+11
Dose deposited by 15MeV protons (krad(Si))	0	1	5	10	20	50	75	100
60 MeV	0	7.26e+9	3.63e+10	7.26e+10	1.5e+11	3.63e+11	5.45e+11	7.27e+11
200 MeV	0	1.74e+10	8.59e+10	1.72e+11	3.44e+11	8.6e+11	1.27e12	1.72e+12

Table 12: Fluence steps in p/cm²

60 MeV and 200 MeV proton fluences are evaluated from 15 MeV fluences with damage equivalent fluence coefficient calculated with NIEL.

Note : in order to keep the optocouplers undelidded, we have validated that during the 15 MeV experiment, and taking into account the loss of energy after passing the package; proton energy remains very close from 15 MeV at die level,.

4.2.4.2. Specific information related to 15 MeV proton testing

Schedule : Week 35 (30/08-02/09/00)

Date: 30/08/00-31/08/00

Energy: 15 MeV

For 15 MeV experiment, the optocoupler devices are located on test frames A and B as presented in *Figure 5* and in *figure 6*.

Note : OLH249 have not been irradiated with 15MeV protons.

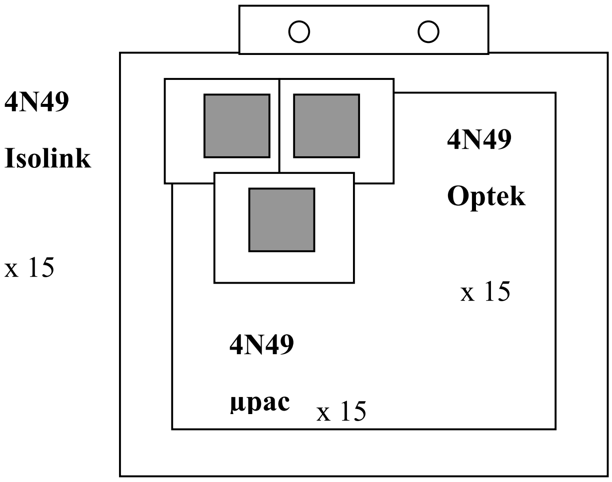

Figure 5:Device position on frame N° A

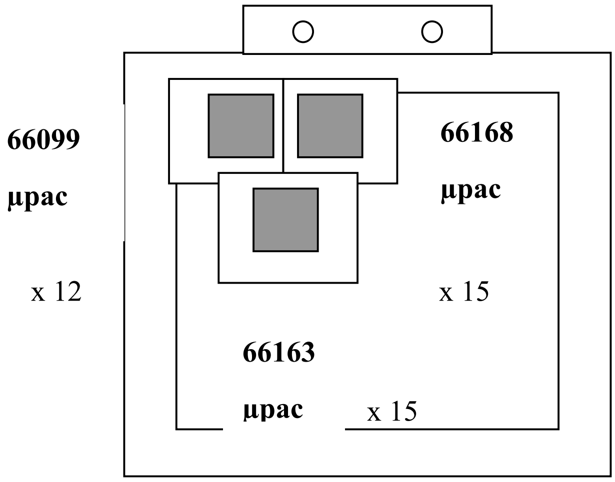

Figure 6 : Device position on frame N° B

The 15 MeV proton test sequence is reported in the following table.

Run	Time	Frame	Total Fluence (p/cm²)	Total dose kRad(Si)	Remarks
1	23h15	A	$1.24^{e}10$	5	
2	23.h29	B	$1.24^{e}10$	5	
3	00h15	A	$2.48^{e}10$	10	
4	00h32	B	$2.48^{e}10$	10	
5	02h00	B	$4.96^{e}10$	20	
6	02h08	A	$4.96^{e}10$	20	Board rotated 90° for smaller irradiation area.
7	02h50	B	$1.2^{e}11$	50	
8	03h30	A	$1.2^{e}11$	50	
9	03h49	B	$1.8^{e}11$	75	
10	04h10	A	$1.8^{e}11$	75	No further test for A carried out CTR<1%
11	04h37	B	$2.4^{e}11$	100	µpac parts removed (having CTR< 1%)
	05h00				Stop Beam

Table 13:15 MeV Proton Test Sequence

4.2.4.3. Specific information related to 60 MeV proton testing

Date: 31/08/00-01/09/00

Energy: 60 MeV

For 60 MeV experiment, the optocoupler devices are located on test frames A and C as presented in *Figure 7* and in *Figure 8*, frame B being the same as for 15 MeV experiment.

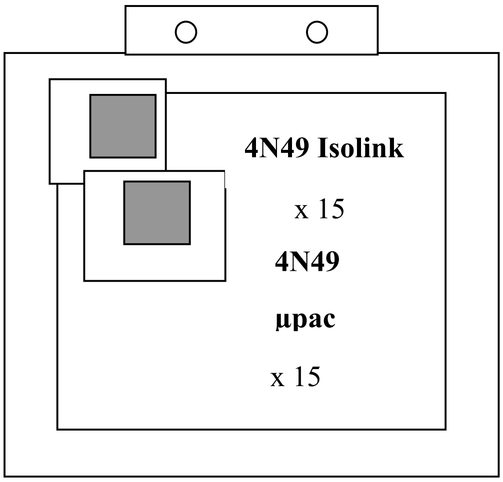

Figure 7: Device position on frame N° A

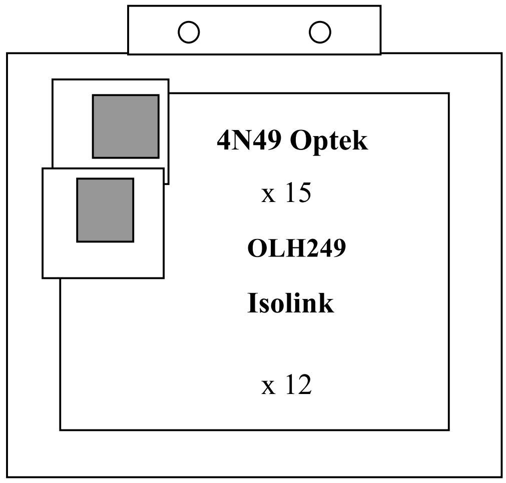

Figure 8: Device position on frame N° C

The 60 MeV proton test sequence is reported in the following table.

Run	Time	Frame	Total Fluence (p/cm²)	Total dose kRad(Si)	Remarks
12	20h25	B	7.26^{e}9	1	
13	20h35	A	7.26^{e}9	1	
14	20h42	C	7.26^{e}9	1	
15	22h35	B	3.63^{e}10	5	
16	22h46	A	3.63^{e}10	5	
17	22h58	C	3.63^{e}10	5	
18	23h41	B	7.26^{e}10	10	
19	23h48	A	7.26^{e}10	10	
20	23h58	C	7.26^{e}10	10	
21	00h45	B	1.5^{e}11	20	
22	00h54	A	1.5^{e}11	20	
23	01h05	C	1.5^{e}11	20	
24	01h22	B	3.63^{e}11	50	66163 µpac removed from Frame
25	01h54	A	3.63^{e}11	50	
26	02h22	C	3.63^{e}11	50	
27	02h50	B	5.45^{e}11	75	
28	03h15	A	5.45^{e}11	75	End of test
29	03h42	C	5.45^{e}11	75	4N49 Optek: end of the test
30	04h05	B	7.27^{e}11	100	
31	04h20	C	7.27^{e}11	100	
	05h50				Stop test

Table 14: 60 MeV Proton Test Sequence

4.2.4.4. Specific information related to 200 MeV proton testing

Date: 01/09/00-02/09/00

Energy: 200 MeV

For 200 MeV experiment, the optocoupler devices are located on test frames A1, A2 and B as presented in *Figure 9* and in *Figure 10.*

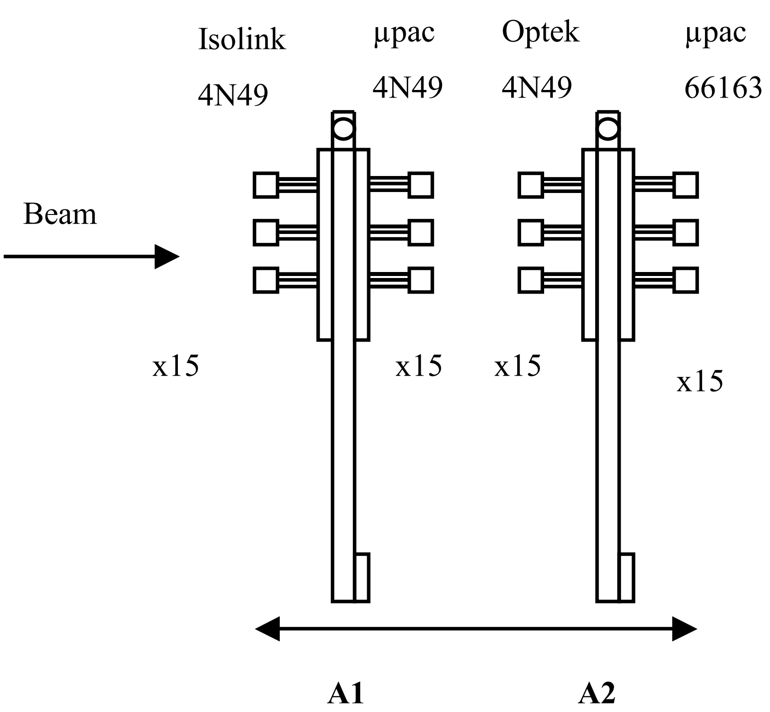

Figure 9: Devices positions on frames

N° A1 and N° A2

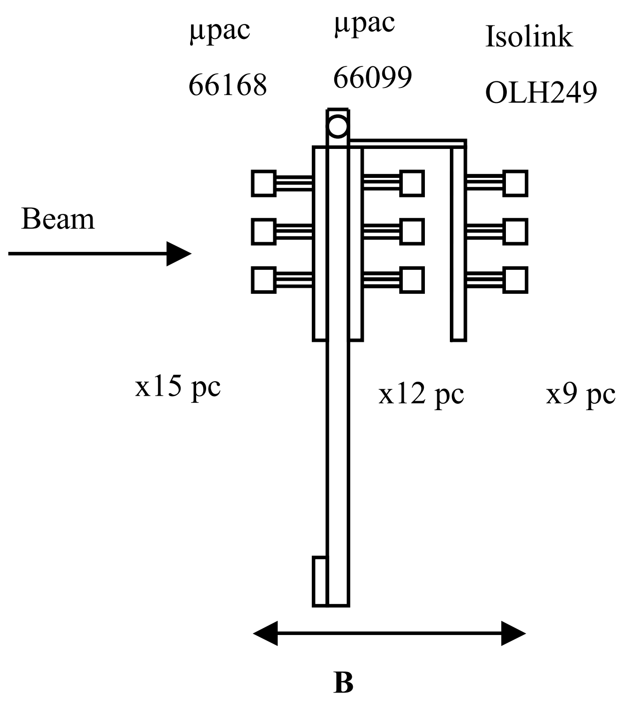

Figure 10: Devices positions on frames

N° B

This test configuration is allowed as protons are high energy ones. The energy does not decrease significantly when they go through the successive boards.

Table 15 Present the 200 MeV proton test sequence

Run	Time	Frame	Total Fluence (p/cm²)	Total dose kRad(Si)	Remarks
32	23h40	B	1.74^E10	1	
33	23h59	A1/A2	1.74^E10	1	
34	00h35	B	8.59^E10	5	
35	01h00	A1/A2	8.59^E10	5	
36	01h26	B	1.72^E11	10	
37	02h00	A2/A1	1.72^E11	10	
38	02h25	B	3.44^E11	20	
39	02h48	A1/A2	3.44^E11	20	
40	03h26	B	8.6^E11	50	
41	04h08	A2/A1	8.6^E11	50	
42	04h50	B	1.29^E12	75	
43	05h24	A1/A2	1.29^E12	75	
44	05h57	B	1.72^E12	100	
					Stop test

Table 15: 200 MeV Proton Test sequence

4.3. NEUTRON TEST

Neutron irradiations were performed (July 2000 (6^{th}-7^{th})) at CEA Valduc with an equivalent energy of 1 MeV (in silicon).

4.3.1. Neutron test : electrical measurements

Electrical measurements are the same as for proton tests (*Figure 4*, *Table 9*)

4.3.2. Bias conditions during irradiations:

The biasing conditions during irradiations are the same as for the TID test (*Figure 2* and *Figure 3*).

The following table gives the sample size for each of the 3 bias conditions and for each optocoupler type (the sample size depends on the number of parts available).

4N49 (Mii, Isolink, Optek), 66168 Mii, 66163 Mii				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	6	6	6	
66099 Mii				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	4	4	4	
OLH249, Isolink				
If ⇒	1mA	10mA	Off	
Samp.size ⇒	3	3	3	

Table 16: neutron sample size and biasing conditions.

4.3.3. Neutron Irradiation Facility

Name : Prospero neutron accelerator from CEA Valduc

Location : DAM/CEA centre de Valduc 21120 Is-sur-Tille, France

4.3.4. Neutron Test Conditions

- Electrical Measurements were performed for neutron fluences as defined in *Table 17*. The neutron fluence corresponds to 15 MeV proton equivalent fluence calculated by the help of NIEL in GaAs.

Prot. Eq. Dose (krad(Si))	**0**	**10 kRad**	**20 kRad**	**50 kRad**	**75 kRad**	**100 kRad**
Prot. 15 MeV (p/cm²)	0	2.4e+10	4.8e+10	1.2e+11	1.8e+11	2.4e+11
Neut. 1 MeV(n/cm²)	0	1.84e+11	3.7e+11	9.24e+11	1.38e+12	1.84e+12

Table 17: neutron equivalent damage fluence (n/cm²) for each step

The total dose deposited by neutrons is assumed to be negligible.

Fluxes and test sequence are described in *Table 18*.

Step	Date	Time of Irradiation and Measurements	1 MeV equivalent fluence (Si) (n.cm²)	Irradiation time (s)	Flux rate ($n.cm^2.s^{-1}.w^{-1}$)
1 run	06/07/00	In/Out: 8h50-10h00 End of Meas:10h55	$1.84\ 10^{11}$	900	$9.99.10^{5}$
2 run		In/Out:11h00-12h30 End of Meas:13h20	$3.7\ 10^{11}$	900	$9.99.10^{5}$
3 run		In/Out: 13h25-14h45 End of Meas:15h35	$9.24.10^{11}$	900	$9.99.10^{5}$
4 run	07/07/00	In/Out: 8h55-10h10 End of Meas:10h55	$13.8.10^{11}$	900	$9.99.10^{5}$
5 run		In/Out: 11h00-12h40 End of Meas:13h30	18.410^{11}	900	$9.99.10^{5}$

Table 18: Neutron fluxes and Test Sequence

5. EXPERIMENTAL RESULTS

5.1. INTRODUCTION

This paragraph will present experimental measurements obtained during ^{60}Co, proton and neutron irradiation. Experimental description has been provided in previous chapter (§4.1, §4.2 and §4.3) while monitored parameters are reminded in *Table 19*.

Experimental results will focus on CTR degradation, the most important parameter to consider in radiation design tolerance. Influence of test and biasing conditions, manufacturer and type ("hardened" vs "unhardened") will be presented for each irradiation type (^{60}Co, proton and neutron) and dose rate effects will be studied for ^{60}Co.

Up to the end of this report, CTRi (%) is defined as:

$$CTRi\ (\%) = 100 \times (CTRi / CTRi_0)$$

Symbol	Test Conditions
CTR1	Ifwd=1mA, Vce=5V, Ib=0
CTR2	Ifwd=2mA, Vce=5V, Ib=0
CTR3	Ifwd=5mA, Vce=5V, Ib=0
CTR4	Ifwd=10mA, Vce=5V, Ib=0
CTR5	Ifwd=10mA, Vce=10V, Ib=0
CTR6	Ifwd=20mA, Vce=10V, Ib=0
CTR7	Ifwd=20mA, Vce=5V, Ib=0
Vcesat1	Ifwd=30mA, Ic=1mA, Ib=0
Vcesat2	Ifwd=6mA, Ic=1mA, Ib=0
Vfwd	Ifwd=10mA
Ir	Vr=-2V

Table 19: Test Conditions

5.2. CTR DEGRADATION WITH TOTAL IONIZING DOSE (TID)

5.2.1. Influence of the test conditions

Figures 11 and 12 present the CTR degradations for the 66163 (standard) and 66168 (hardened) parts respectively at Low Dose Rate (LDR) and for If=0mA during irradiation. These data are mean values for all the parts tested under identical experimental conditions.

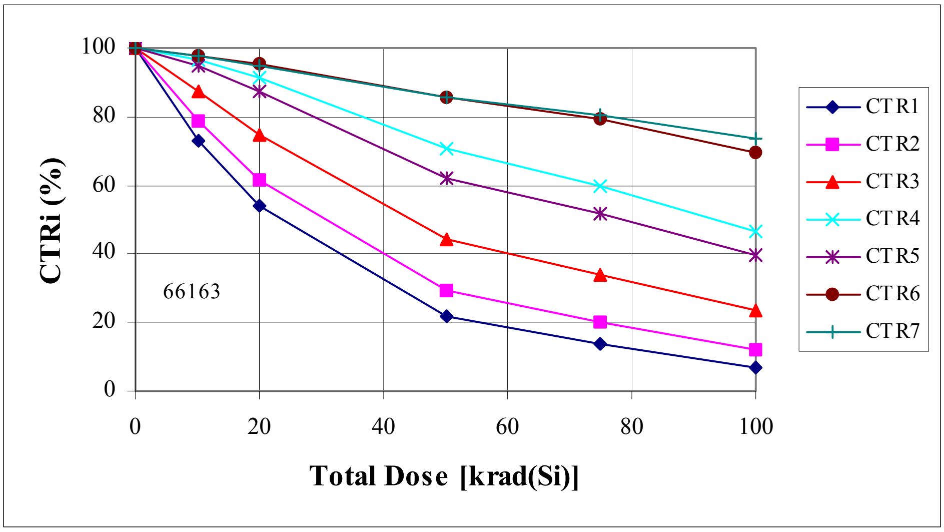

Figure 11: CTRi @ LDR, If=0mA during irradiation, for 66163 Mii parts

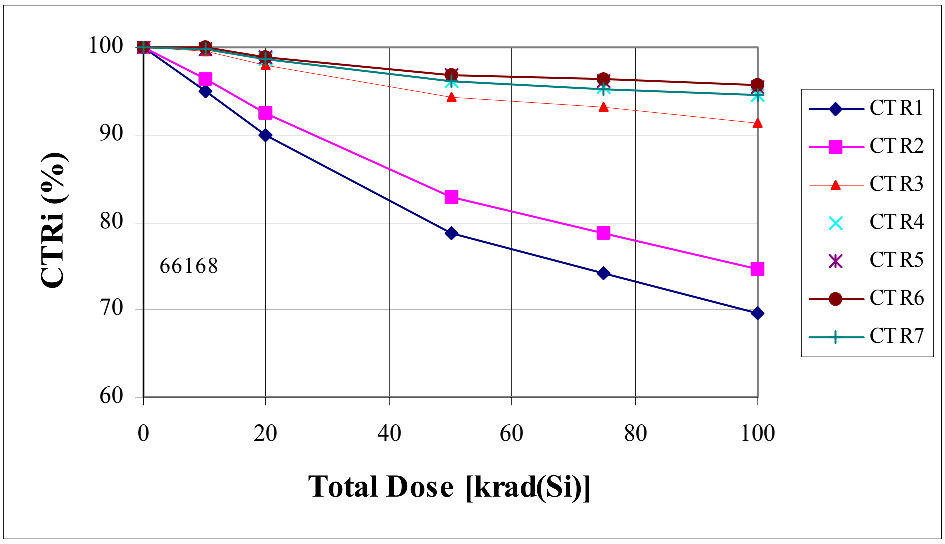

Figure 12: CTRi @ LDR, If=0mA during irradiations, for 66168 Mii parts

In both cases, we observe that CTR1 (I_f = 1 mA/V_{CE} = 5.0 V) corresponds to a worst case. This behavior can also be noticed for the other optocoupler types (standard and hardened) and for other experimental conditions (high dose rate and various bias conditions). The low current in the diode generates a low current in the phototransistor (typically a bipolar transistor) and this low injection level configuration is known to be very sensitive to radiation damage due to significant surface recombination[14]. So, this report will mainly focus on CTR1 results, the complete set of test data being provided in annex 1.

5.2.2. Effects of the different bias conditions during irradiation

Most of the studied parts (hardened or standard) present a clear irradiation biasing dependence at low and high dose rate. The OLH249 is an exception, no irradiation biasing influence appearing under fixed dose rate. A significant device to device degradation variation under identical experimental conditions does not allow a clear conclusion for the 66099.

The following *figures (13, 14, 15)* present the CTR1 degradation for irradiations performed with various If (0, 1 or 10 mA), at Low Dose Rate (LDR = 130 rad(Si)/h), for 66163, 4N49 (standard parts) and 66168 (hardened).

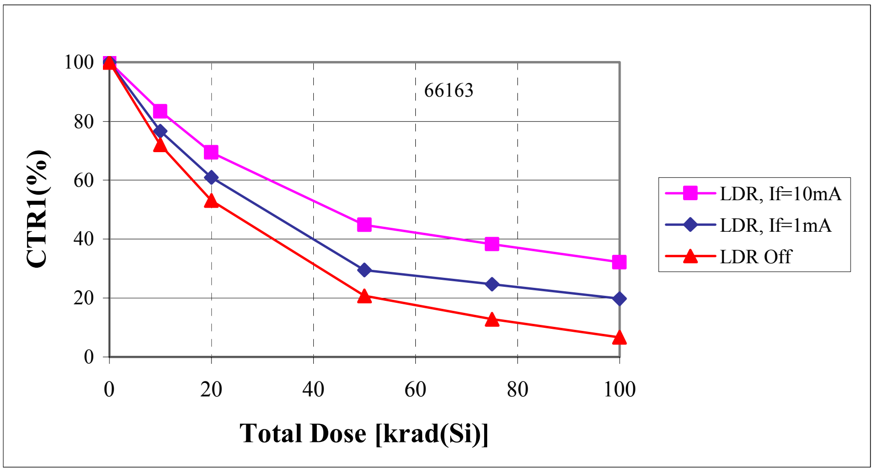

Figure 13: 66163 Mii irradiated under different If

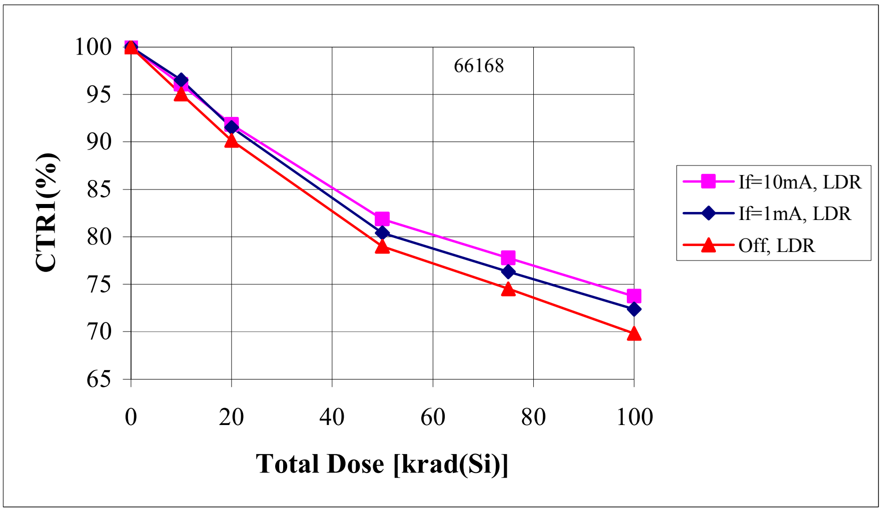

Figure 14: 66168 Mii irradiated under different If

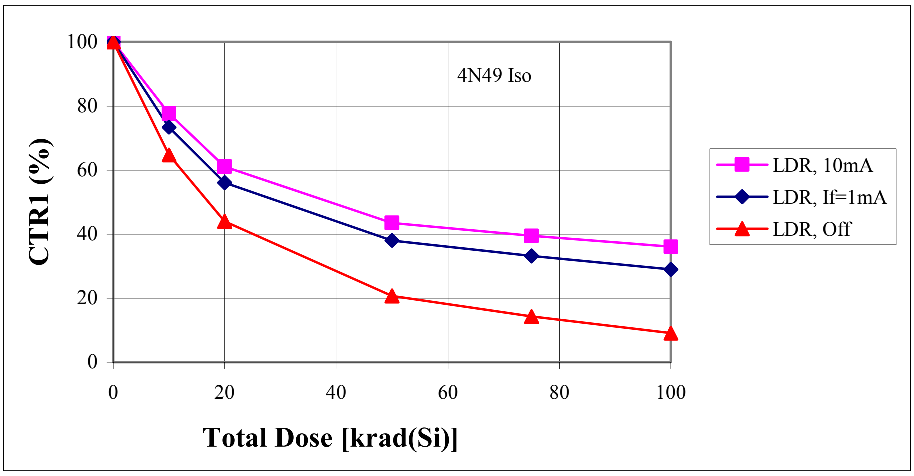

Figure 15: 4N49 Isolink irradiated under different If

This irradiation biasing dependence can be linked to the transistor sensitivity. A bipolar transistor is known to be usually more degraded when irradiated with all pins grounded than under forward bias conditions, due to be higher electrical fields in non-forward biased junctions[14].

5.2.3. Comparison between manufacturers

Figure 16 presents the CTR1 degradation of all studied parts. These results correspond to experiments performed at low dose rate (130 rad(Si)/h) without bias i.e. the worst bias condition.

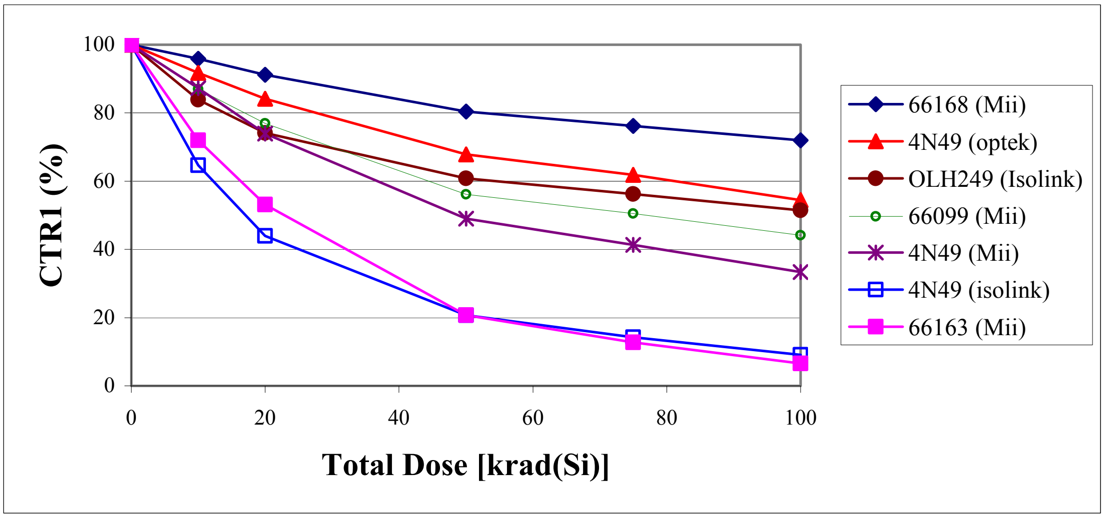

Figure 16: Comparison, at Low Dose Rate, between parts

The same types of sensitivities between types appear at high dose rate or under different bias conditions.

Wide differences appear between devices and manufacturers. Hardened (to displacement damage) devices seem to be more TID tolerant than unhardened ones. One can also notice than the 4N49 from Optek, a standard device, has a surprisingly good total dose tolerance.

5.2.4. Dose Rate Effects

Two dose rates were used : a High Dose Rate (HDR) of 50 krad(Si)/h and a Low Dose Rate (LDR) of 130 rad(Si)/h. The LDR is expected to cause more damage than HDR. The enhancement of surface recombination is more important in the LDR case and affects more significantly the photo-response (1st order) and the current gain (2nd order) of the transistor.

Figures 17 and 18 exhibit that all the parts and types (hardened or not) are subjects, at various levels, to enhanced low dose rate degradations.

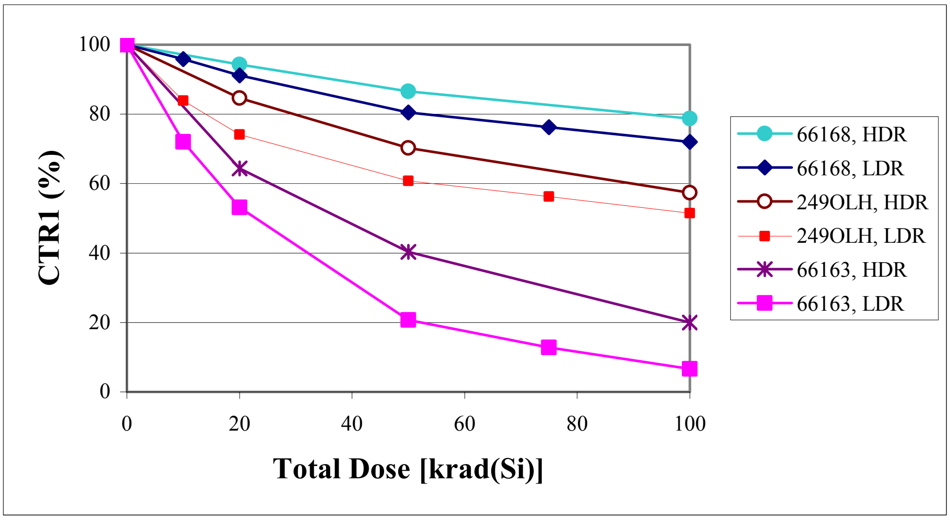

Figure 17: Comparison LDR-HDR for 3 types

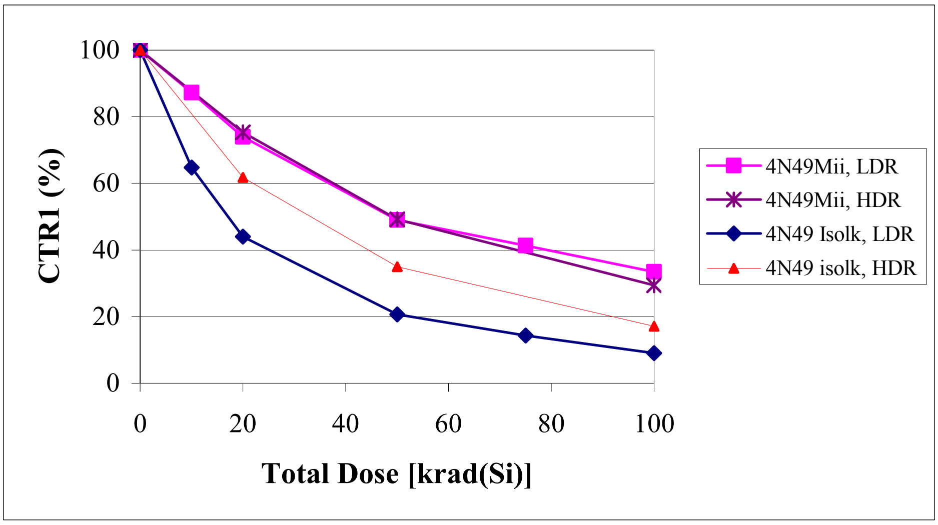

Figure 18: Comparison LDR-HDR for 4N49 (Isolink and Mii)

Results of 4N49 Optek are not presented because no clear dose rate effect have been seen (parts slightly more degraded at high dose rate whereas no important variations between parts can be noticed). These different behaviors, for same references but different manufacturers, are probably linked to transistor dies which are not systematically the same between manufacturers.

66099 also presents a higher degradation at high dose rate, but in that case, a lack of results homogeneity under the same experimental conditions, may be due to process variations, require a careful examination of the results. Besides, some structure differences between 66099 devices and other ones, i.e.

photodiode and transistor instead of phototransistor for the output stage, may also be an explanation for these differences.

5.2.5. Conclusion

All the studied parts are degraded by total dose and, as expected, standard optocouplers are more damaged than hardened ones. Most of devices from both family also present a dose rate dependence, low dose rate irradiations being a worst case. This can be linked to the silicon bipolar transistor sensitivity.

Following tables present:

- a summary of CTR1 (%) Low Dose Rate results for parts unbiased during irradiations (worst case) (*Table 20*)
- a summary of CTR1 (%) High Dose Rate results for parts unbiased during irradiations (*Table 21*)
- CTRi degradations at Low Dose rate for the 66163 Mii (*Table 22*).

dose (krad(Si))	66168 Mii	66163 Mii	4N49 Optek	4N49 Isolink	4N49 Mii	OLH249 Isolink	66099 Mii
0	100	100	100	100	100	100	100
10	96	72	92	65	87	84	87
20	91	53	84	44	74	74	77
50	80	21	68	21	49	61	56
75	76	13	62	14	41	56	51
100	72	7	54	9	33	51	44

Table 20: Summary of CTR1 (%) LDR results for parts unbiased (OFF) during irradiations (worst case)

dose (krad(Si))	66168 Mii	66163 Mii	4N49 Optek	4N49 Isolink	4N49 Mii	OLH249 Isolink	66099 Mii
0	100	100	100	100	100	100	100
20	94	64	82	62	75	85	65
50	87	40	61	35	49	70	43
100	79	20	40	17	29	57	28

Table 21: Summary of CTR1 (%) HDR results for parts unbiased (OFF) during irradiations (usual worst case)

CTRi %	1	2	3	4	5	6	7
Dose (krad(Si))							
0	100	100	100	100	100	100	100
10	73	79	87	96	95	98	98
20	54	62	75	91	87	95	95
50	22	29	44	70	62	86	85
75	14	20	34	60	52	79	81
100	7	12	24	47	40	69	74

Table 22: Summary of CTRi (%) LDR results for the 66163 Mii (unbiased (OFF) parts)

5.3. CTR DEGRADATION WITH PROTON FLUENCE

5.3.1. Influence of the test conditions

Figures 19 and 20 present all the CTR degradations for 66163 (standard) and 66168 (hardened) parts submitted to 15 MeV proton irradiation (mean value for all bias conditions). CTRi (CTRi (%) = 100 x (CTRi / $CTRi_0$)). Test conditions are identical to the one detailed in *table 19*.

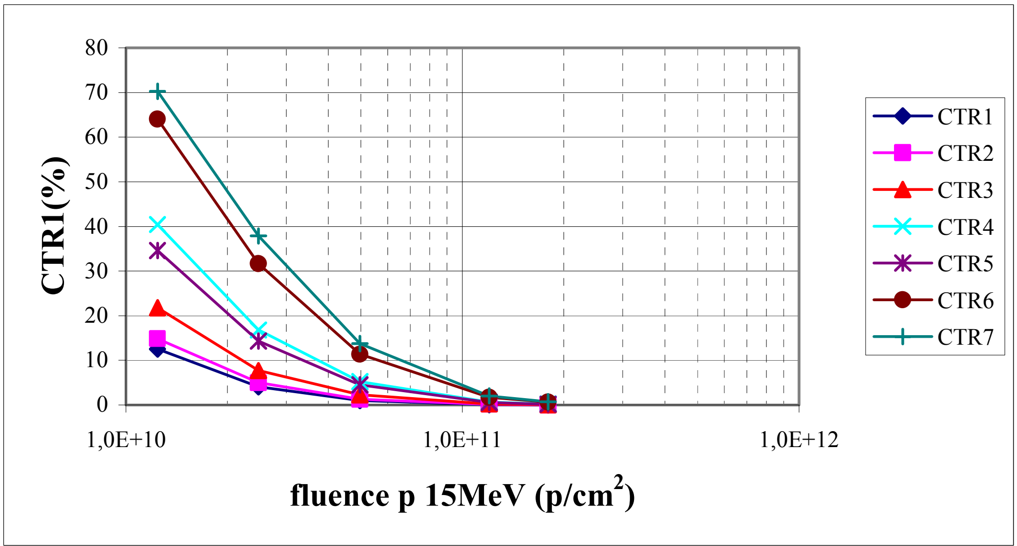

Figure 19: CTRi degradations for 66163 Mii unhardened parts

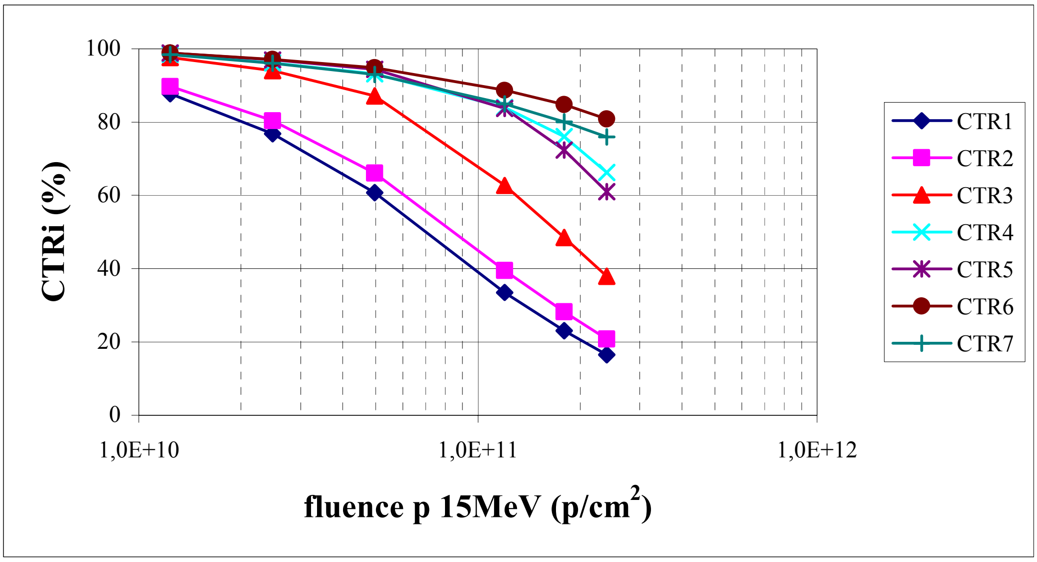

Figure 20: CTRi degradations for 66168 Mii hardened parts

In both cases, we observe that CTR1 (I_f = 1 mA/V_{CE} = 5.0 V) corresponds to a worst case, as previously observed in ^{60}Co experiment. This behavior can also be noticed for the other optocouplers types and for other experimental conditions (different proton energy and various bias conditions).

Types hardened to displacement damage are, as expected, significantly more tolerant than unhardened ones.

5.3.2. Effects of the different bias conditions during irradiation

Following figures present the CTR1 evolution for the 4N49, 66163, 66168 and OLH249, when submitted to 15/60/200 MeV proton irradiation with various If values during irradiations.

5.3.2.1. Stantard optocoupleurs

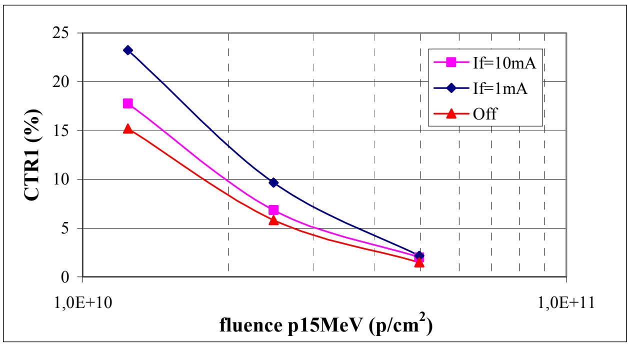

Figure 21: 4N49 Mii irradiated with 15 MeV protons and different If

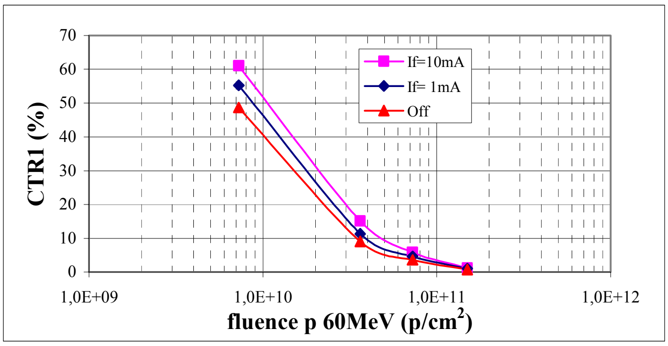

Figure 22: 4N49 Mii irradiated with 60 MeV protons and different If

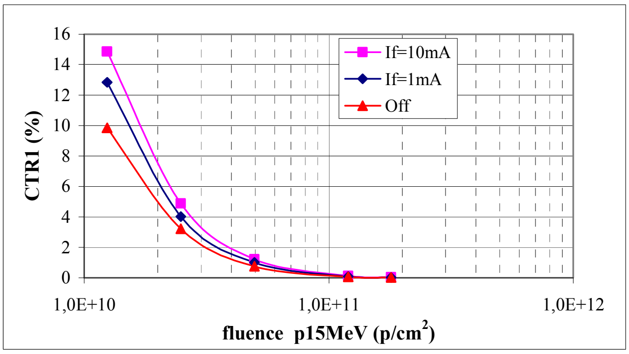

Figure 23: 66163 Mii irradiated with 15 MeV protons and different If

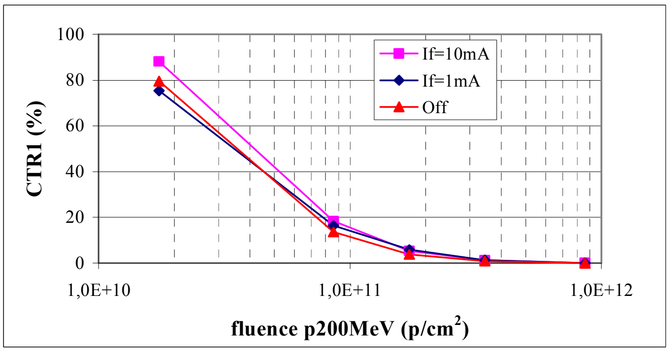

Figure 24: 66163 Mii irradiated with 200 MeV protons and different If

These figures evidence the influence of biasing conditions during irradiation. For unhardened optocouplers, unbiased (OFF) condition is a worst case (15 MeV results is marginal and has not yet been explained). The other point is that biasing influence is present independently of the proton energy.

5.3.2.2. Hardened optocoupleurs

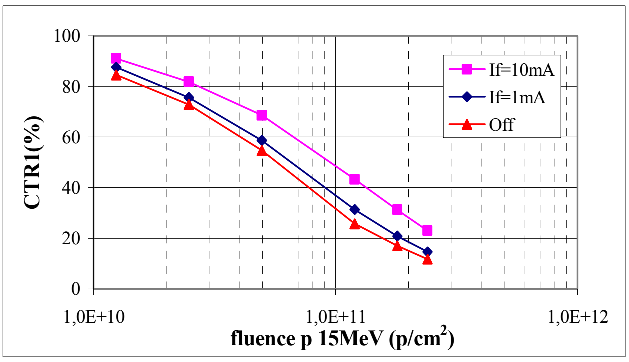

Figure 25: 66168 Mii irradiated with 15 MeV protons and different If.

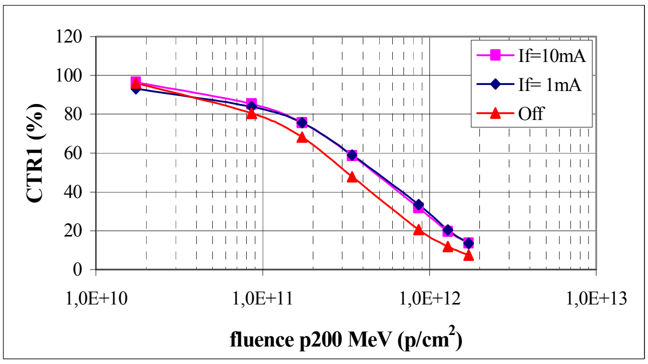

Figure 26: 66168 Mii irradiated with 200 MeV protons and different If

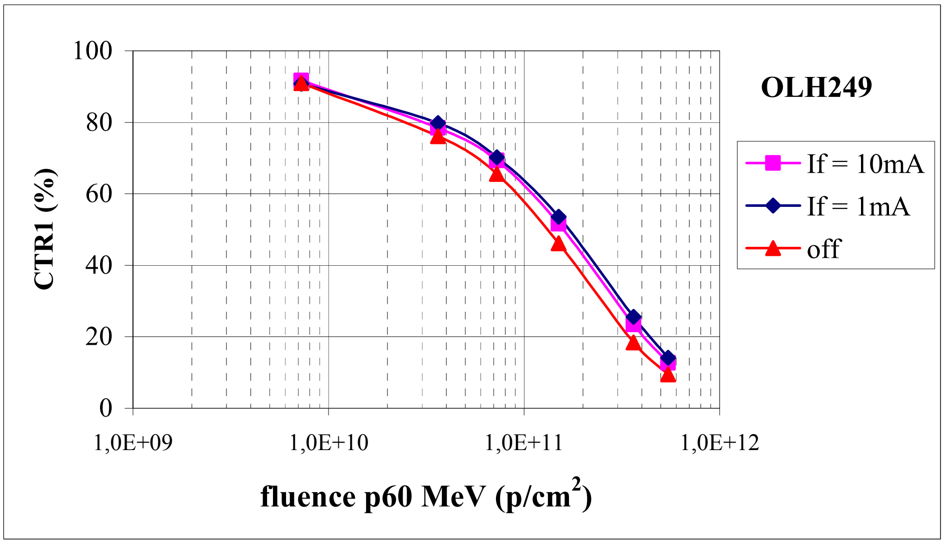

Figure 27: OLH249 Mii irradiated with 60 MeV protons and different If.

The Off condition appears to be the worst case (same as for standard optocoupler) for protons whereas parts irradiated with If=10mA are, generally, the less degraded.

Then, biasing influence turns out to be of the same nature for both proton and ^{60}Co irradiation.

5.3.3. Comparison between manufacturers

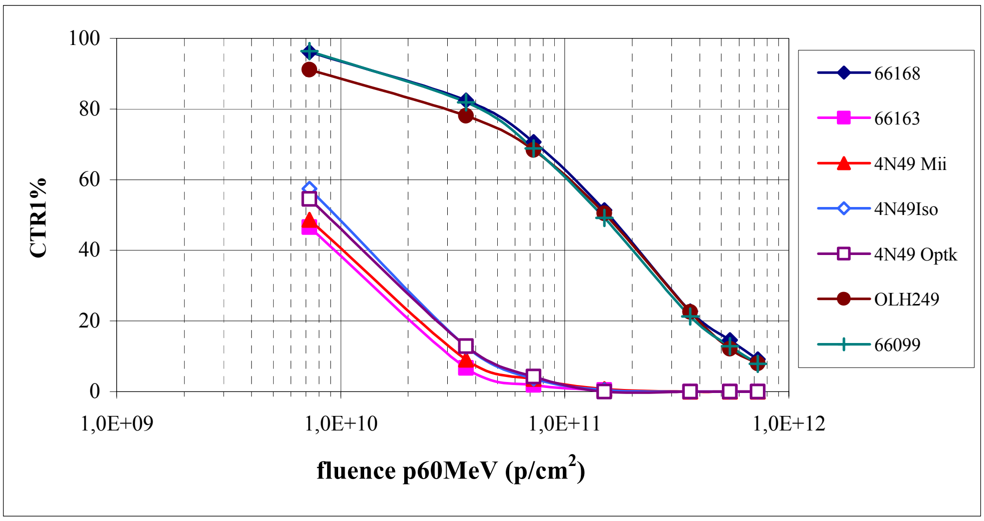

Figure 28: Comparison between parts type under 60 MeV proton irradiations (off during irradiations)

Figure 28 presents the CTR1 degradation of all studied parts type, submitted to 60 MeV proton irradiation (the same behaviors can be observed with other proton energies). Parts were remained off during exposures (worst case). As expected, wide differences appear between hardened and unhardened devices. As an example, when considering a fluence of about 3 10^{10} p60 MeV/cm² that roughly corresponds to 15 years in geosynchronous orbit behind 6 to 7 mm of Aluminum, CTR1 (($I_f = 1$ mA/$V_{CE} = 5.0$ V) degradation is less than 20% for an hardened product while the degradation of an unhardened part is above 80%.

Some differences also appear between identical types from different manufacturers (4N49). That is to say that concerned types are not so identical… at least from a radiation point of view.

5.3.4. Conclusion

All the studied parts are degraded by protons and, as expected, standard optocoupleurs are far more damaged than hardened ones (cf *Table 23*). Most of devices from both family also present a bias dependence, unbiased (OFF) mode being a worst case. We also observed that CTR1 ($I_f = 1$ mA/$V_{CE} = 5.0$ V) corresponds to a worst case test condition (cf *Table 24*), as previously observed in ^{60}Co experiment.

CTR1 %	**66168 Mii**	**66163 Mii**	**4N49 Mii**	**4N49 Isolink**	**4N49 Optek**	**OLH249 Isolink**	**66099 Mii**
fluence 60MeV							
7,26E+09	96	47	49	57	55	91	96
3,63E+10	83	7	9	13	13	78	82
7,26E+10	71	2	4	4	4	69	69
1,50E+11	51	1	1	1	1	51	49
3,63E+11	23	0	0	0	0	23	21
5,45E+11	15	0	0	0	0	12	13
7,27E+11	9	0	0	0	0	0	8

Table 23: Summary of 60 MeV proton irradiation results on CTR1 (%) unbiased (OFF) during irradiations

CTRi (%)	1	2	3	4	5	6	7
fluence p15MeV							
1,24E+10	10	12	19	38	33	62	69
2,48E+10	3	4	7	15	13	30	36
4,96E+10	1	1	2	5	4	10	13
1,20E+11	0	0	1	1	1	2	2
1,80E+11	0	0	0	0	0	1	1

Table 24: Summary of 15 MeV proton irradiation results on CTRi (%), 66163 Mii parts, unbiased (OFF) mode

5.4. CTR DEGRADATION WITH NEUTRON FLUENCE

5.4.1. Influence of the test conditions

Figure 29 presents the CTRi degradations (same test conditions as for protons and TID, see *table 19*) for the 66163 parts submitted to 1 MeV neutron irradiation (mean value for all bias conditions).

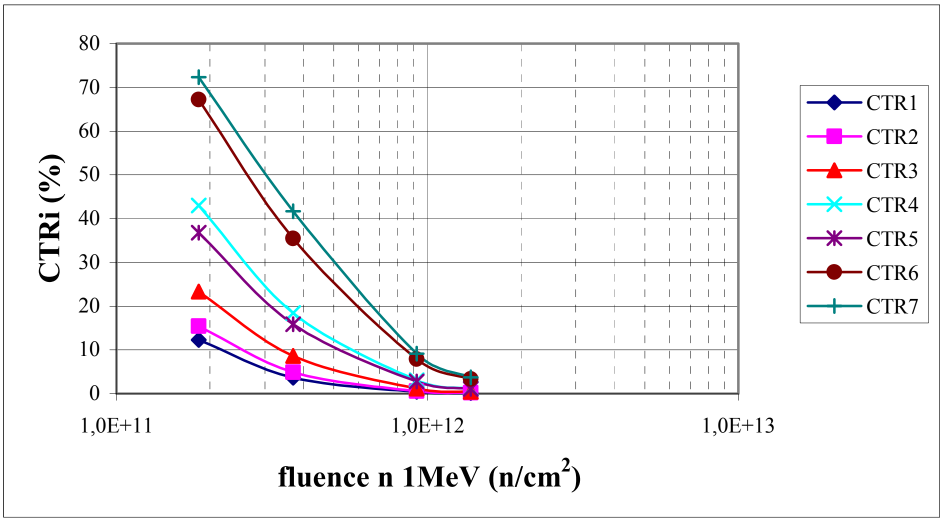

Figure 29: CTRi for 66163 Mii unhardened parts

Once more, CTR1 (I_f = 1 mA/V_{CE} = 5.0 V) is the worst case test condition ; this result is also valid for other biasing conditions and optocoupler types. Complete set of neutron data is provided in annex 1.

5.4.2. Effects of the different bias conditions during irradiation

Following figures (*Figure 30* to *Figure 34*) present the CTR1 evolution for the unhardened 4N49 (Isolink, Optek) and 66163 (Mii) and for the hardened 66168 and OLH249 optocouplers, when submitted to 1 MeV neutron irradiation with various If values during irradiations.

5.4.2.1. Standard types

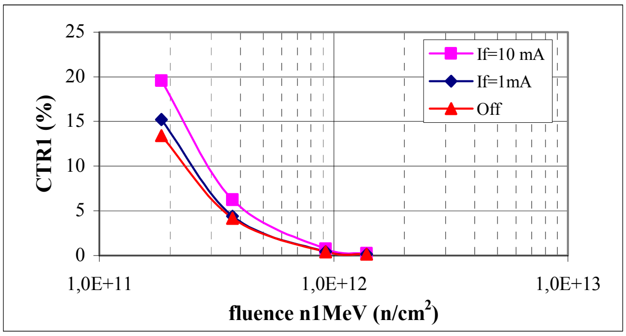

Figure 30: 4N49 Optek irradiated with 1 MeV neutrons and different If

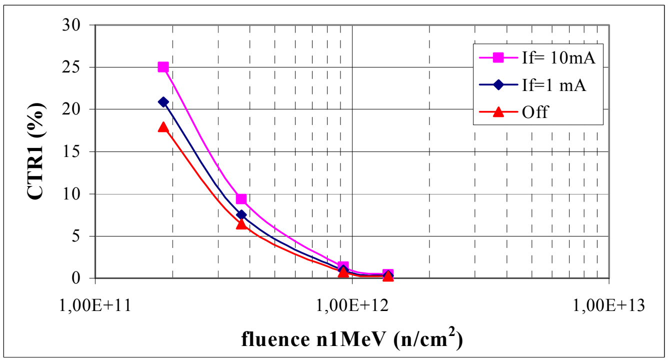

Figure 31: 4N49 Isolink irradiated with 1 MeV neutrons and different If

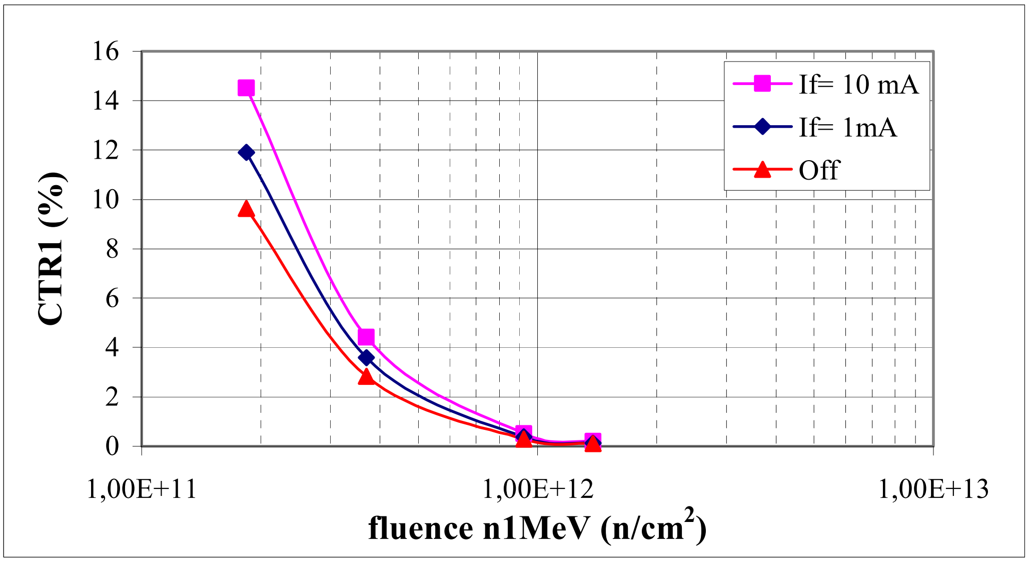

Figure 32: 66163 Mii irradiated with 1 MeV neutrons and different If

These figures evidence the influence of biasing conditions during irradiation. For unhardened optocouplers, unbiased (OFF) condition is a worst case.

5.4.2.2. Hardened types

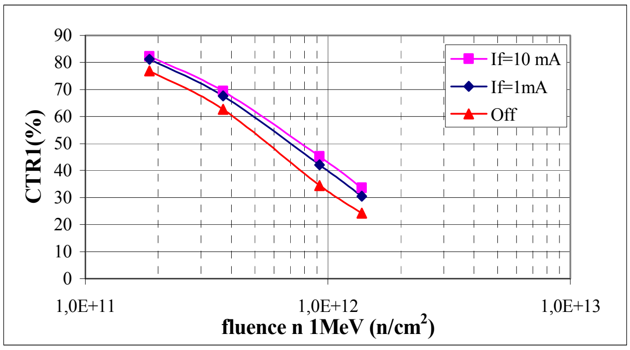

Figure 33: 66168 Mii irradiated with 1 MeV neutrons and different If

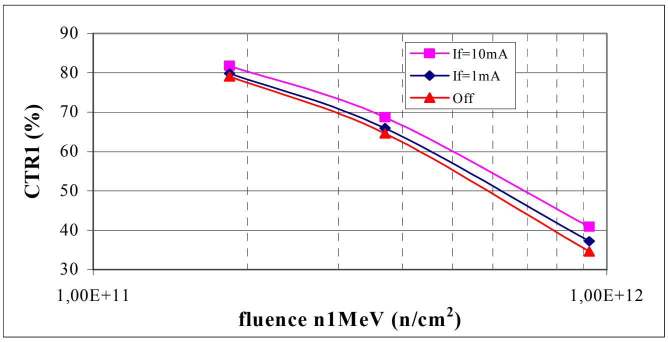

Figure 34: OLH249 irradiated with 1 MeV neutrons and different If.

The unbiased (OFF) condition appears to be the worst case (same as for standard optocoupler) for neutron irradiation. This is consistent with both proton and ^{60}Co irradiation results.

5.4.3. Comparison between manufacturers

Figure 35 presents the CTR1 degradation of all studied parts submitted to 1 MeV neutron irradiation. Parts were remained off during exposures (maximum degradation). Wide differences appear first between hardened and unhardened devices, as expected, and also between identical types from different manufacturers (4N49). Hardened (to displacement damage) devices are significantly more tolerant than unhardened ones.

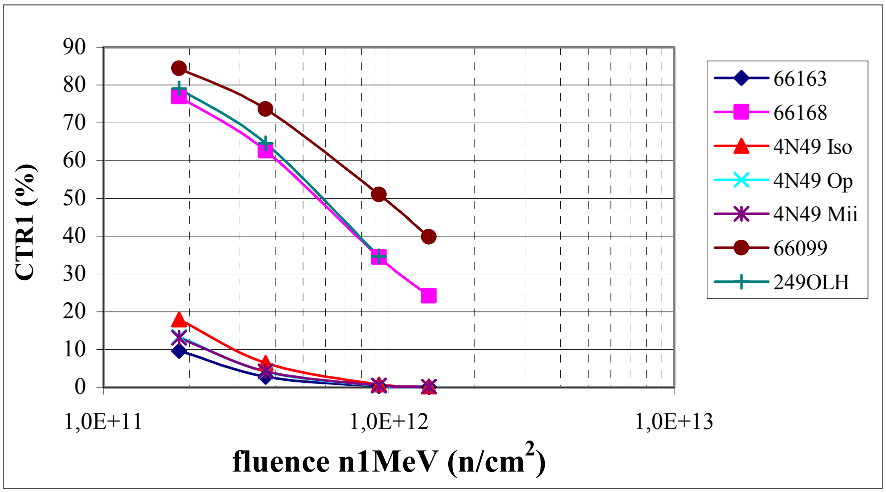

Figure 35: Comparison between parts under 1 MeV neutron irradiation

5.4.4. Conclusion

All the studied parts are degraded by neutrons and, as expected, standard optocoupleurs are far more damaged than hardened ones. Most of devices from both family also present a bias dependence, the Off configuration being the worst case.

	66163 Mii	66168 Mii	4N49 Isolink	4N49 Optek	4N49 Mii	66099 Mii	OLH249 Isolink
fluence n1MeV							
1,84E+11	9,64	76,92	17,94	13,40	13,11	84,42	79,08
3,70E+11	2,84	62,67	6,44	4,16	4,26	73,67	64,6
9,24E+11	0,30	34,53	0,73	0,40	0,51	50,99	34,63
1,38E+12	0,11	24,23	0,26	0,14	0,21	39,86	N/A

Table 25: Summary of 1 MeV neutron irradiation results on CTR1 (%) unbiased (OFF) during irradiations

CTRi (%)	1	2	3	4	5	6	7
fluence n1MeV							
0,00E+00	100	100	100	100	100	100	100
1,84E+11	12	15	23	43	37	67	72
3,70E+11	4	5	9	18	16	35	42
9,24E+11	0	1	1	3	3	8	9
1,38E+12	0	0	0	1	1	3	4

Table 26: Summary of 1 MeV neutron irradiation results on CTRi (%), 66163 Mii parts, unbiased (OFF) mode

5.5. DEGRADATION OBSERVED ON OTHER PARAMETERS

CTR is the more affected parameter, but not the only one. If V_{fwd} and I_R changes are negligible after any type of irradiation, Vce_{sat} presents significant degradations. No noticeable differences appeared between results for the various biasing conditions during irradiations.

Thus, the following figures (*Figure 36*, *Figure 37* and *Figure 38*) present the V_{cesat1} increases ($V_{cesat1}/V_{cesat1(prerad)}$) under various particle exposures for 66168 and 66163 (mean values for all bias conditions during irradiations).

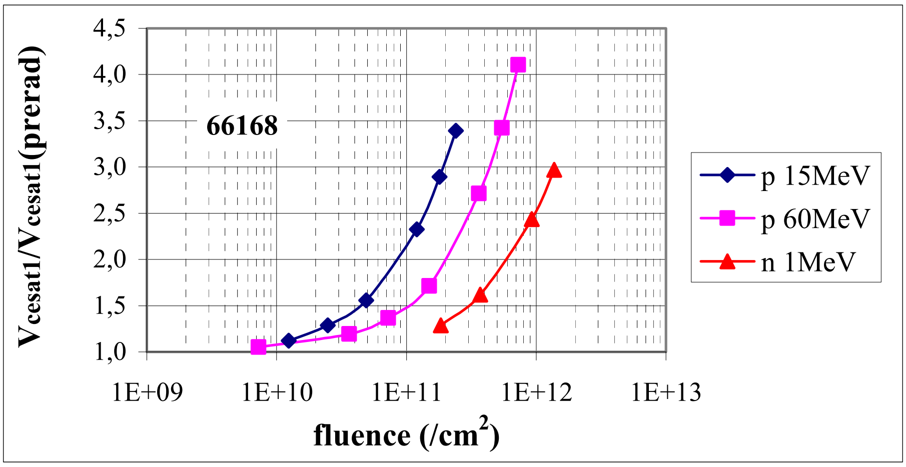

Figure 36: Vcesat$_1$ changes for 66168 Mii under proton/neutron irradiation

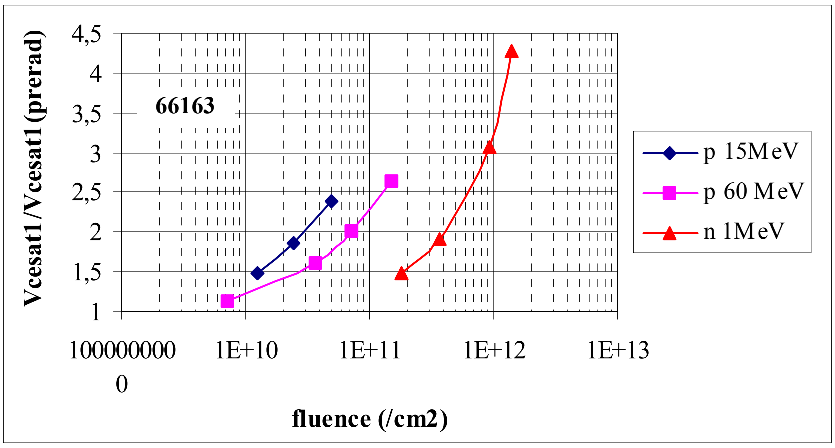

Figure 37: Vcesat$_1$ changes for 66163 Mii under proton/neutron irradiation

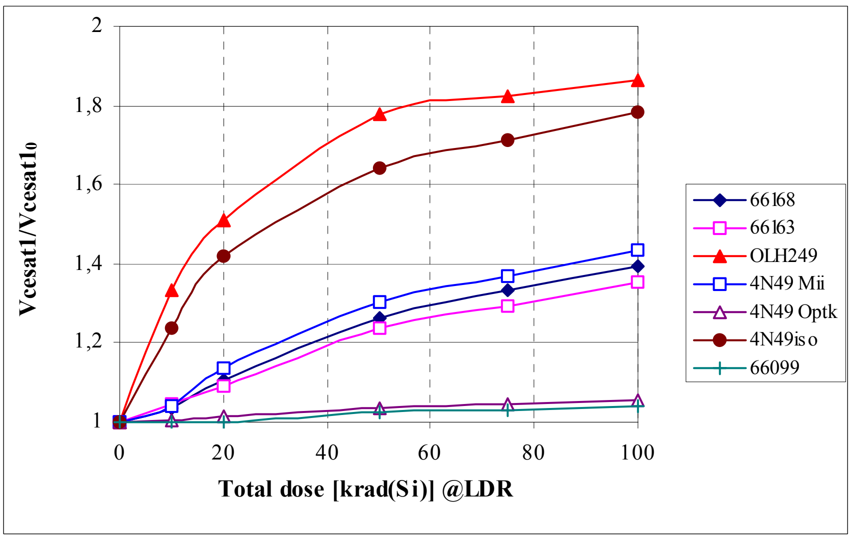

Figure 38 : Vcesat$_1$ changes for all types, ^{60}Co irradiation

6. ANALYSIS

Four major points will be analysed in the following :

- The validity of the NIEL concept to normalise the degradation for different proton energies and for neutrons
- Comparison between different optocouplers degradation factor
- The influence of bias during irradiation on the CTR degradation
- The validity of the test procedure for proton degradation by {neutron + dose } and Co^{60} irradiation

6.1. OPTOCOUPLER DEGRADATION MECHANISMS

Each tested optocoupler consists of a light emitting diode (LED) electrically isolated but optically coupled to a NPN silicon phototransistor (or a photodiode and a NPN transistor (66099)).

Radiation effects on these two parts are briefly reviewed hereafter [11-13, 15].

According to many authors, the basic LED structure should be insensitive to total ionising dose as built in III-V materials. Its sensitivity to displacement damage comes from the creation of non-radiative centres within the bulk of the material.

These centres compete with radiative centres and band-band recombination and the result is a reduction of optical power at a given diode direct current value as some recombination become non-radiative.

The variation of the output optical power with fluence can be described by the following relation:

$$(P/P_0)^{\alpha} = 1 + \tau_0 K \phi$$

where P and P_0 are the output power after and before irradiation, α a coefficient depending on the construction and mode of operation, ϕ the particle fluence, the minority carrier lifetime and K.

Usually LEDs are operated in constant current mode and α =2/3 for linearly graded junctions or α=1 for abrupt junction devices.

An important feature of this equation is that reduction in output power is only significant when $\tau_0 K \phi >> 1$. When τ_0 is small then the LED will be insensitive to radiation.

The NPN Phototransistor :

The structure consists of a an extended base region surrounded by a narrow emitter ring.

Photocarriers are generated in the base, the collector-base space charge layer and the neutral collector region. The collection is made by drift in the space charge region and by diffusion in the neutral regions.

The minority carrier diffusion length is reduced by irradiation at constant carrier generation, the photocurrent diminishes with fluence. The current gain of the phototransistor is also reduced by irradiation but this is generally considered as a second order effect.

For the 4N49, widely used in space applications, the different contributions to the observed degradation were separated by making complementary tests of the LED optical power output, collected photocurrent and transistor gain. The CTR degrades more severely at low currents than that would be estimated by the product of the optical power and the photoresponse. This is because the transistor operates at lower and lower current when the LED optical output power and the base-collector photocurrent degrade. For these values of the collector current the current gain of the phototransistor becomes smaller and smaller.

6.2. COMPARISON BETWEEN DIFFERENT OPTOCOUPLERS DEGRADATION FACTORS

The same doses and fluences were used for the different optocouplers. Some are unhardened (or standard), others are radiation tolerant or radiation hardened (note that radiation tolerant or radiation hardened is not a "standard" denomination). The main difference between the two types lies in a shorter LED wavelength for the hardened ones.

To establish a rough comparison between the different behaviour we will show below a summary of the results for only one test condition of bias and measurement : CTR1 for devices biased at If=0mA.

6.2.1. Ionisation (Co^{60}, Low Dose rate) :

	Standard devices				**Hardened devices**		
Dose (krad)	**4N49 Iso.**	**4N49 optek**	**4N49 Mii**	**66163 Mii**	**66099 Mii**	**66168 Mii**	**OLH249 Iso.**
0	100	100	100	100	100	100	100
10	65	92	87	72	87	96	84
20	44	84	74	53	77	91	74
50	21	68	49	21	56	80	61
75	14	62	41	13	51	76	56
100	9	54	33	7	44	72	51

Table 27: CTR1 values for if=0mA under Low Dose Rate irradiations

As already mentioned in §5.2 and shown in *Table 27* large variations in CTR1 values can be reported towards the end but depend on optocoupler type ; Note that if the general trend confirm that hardened device perform generally better than unhardened ones, the best unhardened type (4N49 Optek) perform better that the worst hardened one (66099 Mii).

Note also that all types could be used at 100 krad(Si) if a degradation by a factor of about five is accepted by the designer, considering ionisation as the only degradation mechanism (knowing that it is not the case for space environment).

6.2.2. Comparison for displacement damage :

This comparison is made based on 1 MeV neutrons results :

	Standard devices				Hardened devices		
Fluence ($x10^{11}$ n/cm^2)	**4N49 Isolink**	**4N49 optek**	**4N49 Mii**	**66163 Mii**	**66099 Mii**	**66168 Mii**	**OLH249 Isolink**
0	100	100	100	100	100	100	100
1.84	18	13	13	10	84	77	79
3.7	6	4	4	3	74	63	65
9.24	1	0	1	0	51	35	35
13.8	0	0	0	0	40	24	N/A

Table 28: CTR1 values for If= 0mA under 1 MeV neutrons irradiation

Here we clearly see a marked difference between standard (4N49 and 66163) and hardened devices.

At a fluence $\Phi = 3,7\ 10^{11}$ n/cm2, unhardened devices show a remaining CTR of only 3 to 6% of the initial value. Hardened devices show a remaining CTR of more than 60% the initial value.

6.3. INFLUENCE OF BIASING CONDITIONS ON CTR TEST CONDITION:

Three different bias where used during irradiation. The LED current was fixed at three different values (0, 1mA, 10mA) while the collector-emitter voltage was fixed at 5V.

6.3.1. Dose (Co^{60})

For dose the comparison is made on 4N49 Isolink which shows the strongest sensitivity (*Table 29* to *Table 31*). This is also valid for other optocoupler types.

Dose (krad)	Bias If=0 mA	Bias If=1mA	Bias If=10mA
0	100	100	100
10	65	73	78
20	44	56	61
50	21	38	44
75	14	33	39
100	9	29	36

Table 29 : summary of CTR1 measurements to TID (LDR, Co^{60}), 4N49 Isolink

Dose (krad)	Bias If=0 mA	Bias If=1mA	Bias If=10mA
0	100	100	100
10	90	92	94
20	80	85	88
50	57	73	78
75	48	68	74
100	38	63	71

Table 30: summary of CTR3 measurements to TID (LDR, Co^{60}), 4N49 Isolink

Dose (krad)	Bias If=0 mA	Bias If=1mA	Bias If=10mA
0	100	100	100
10	93	94	95
20	87	89	90
50	72	81	83
75	65	78	81
100	56	75	78

Table 31: summary of CTR5 measurements to TID (LDR, Co^{60}), 4N49 Isolink

We clearly see that the worst case is obtained for If=0mA and the best case is obtained for If=10mA.

So when we will compare degradation at different proton energies it will be necessary to compare degradation for the same bias condition for CTR1.

For CTR3 or CTR5 a mean on all devices will often be used as the influence of bias is less important and also the degradation due to dose is far less.

6.3.2. Influence of bias for neutrons :

The biasing influence is first studied as a standard device (4N49 isolink), for CTR1 measurement.

Fluence (x1 E11 n/cm2)	Bias If=0 mA	Bias If=1mA	Bias If=10mA
0	**100**	**100**	**100**
1,84	**18**	**21**	**25**
3,70	**6**	**8**	**9**
9,24	**1**	**1**	**1**
13,80	**0**	**0**	**0**

Table 32: CTR1 measurements for neutrons,4N49 Isolink

We note first that biasing conditions have an impact on CTR measurement. The worst case corresponds to If = 0mA while the best case corresponds to If = 10mA. As we expect that neutrons induce only displacement damage, it seems that bias influence displacement degradation in the LED.

The influence of bias conditions is then studied for a “radhard” device 66168 Mii for CTR1

Fluence (x1 E11 n/cm2)	Bias If=0mA	Bias If=1mA	Bias If=10 mA
0	**100**	**100**	**100**
1,84	**77**	**81**	**82**
3,70	**63**	**68**	**69**
9,24	**35**	**42**	**45**
13,80	**24**	**31**	**34**

Table 33: summary of CTR1 measurements , 66168 Mii

There, the worst case is still for If = 0mA and the best case is If = 10mA. However influence of bias is reduced comparatively to standard devices.

6.3.3. Influence of bias for protons :

It has been shown in previous paragraph that both ionisation (results with ^{60}Co testing) and displacement damage (results with neutron testing) are influenced by bias condition ; then, the same behaviour is also expected with protons, due to the fact that CTR degradation is in this case related to both ionisation and displacement damage. Analysis is presented here below on 4N49isolink and 66168 Mii, for a proton energy Ep=60 MeV :

Fluence (p/cm2)	Bias If=0 mA	Bias If=1mA	Bias If=10mA
0	**100**	**100**	**100**
7,26E+09	**57**	**65**	**68**
3,63E+10	**13**	**19**	**19**
7,26E+10	**4**	**6**	**6**
1,50E+11	**0**	**1**	**1**

Table 34: CTR1 degradation under 60 MeV proton exposures, 4N49 Isolink

Fluence (p/cm2)	Bias If=0mA	Bias If=1mA	Bias If=10 mA
0,00E+00	**100**	**100**	**100**
7,26E+09	**96**	**97**	**98**
3,63E+10	**82**	**84**	**91**
7,26E+10	**71**	**72**	**83**
1,50E+11	**51**	**54**	**69**
3,63E+11	**23**	**27**	**44**
5,45E+11	**15**	**16**	**29**
7,27E+11	**9**	**11**	**22**

Table 35: CTR degradation under 60 MeV proton exposures, 66168 Mii

Once again, the best configuration is obtained with If = 10mA and the worst case with If=0 mA. Furthermore, We can notice the same behaviour for all CTR conditions.

6.4. DISPLACEMENT DAMAGE AND IONISATION CONTRIBUTIONS TO OVERALL CTR DEGRADATION.

Figures 39 and 40 present a comparison between CTR degradation due to Co^{60} and due to protons based on deposited dose, for "hardened" (66168 Mii) and standard (66163 Mii) devices.

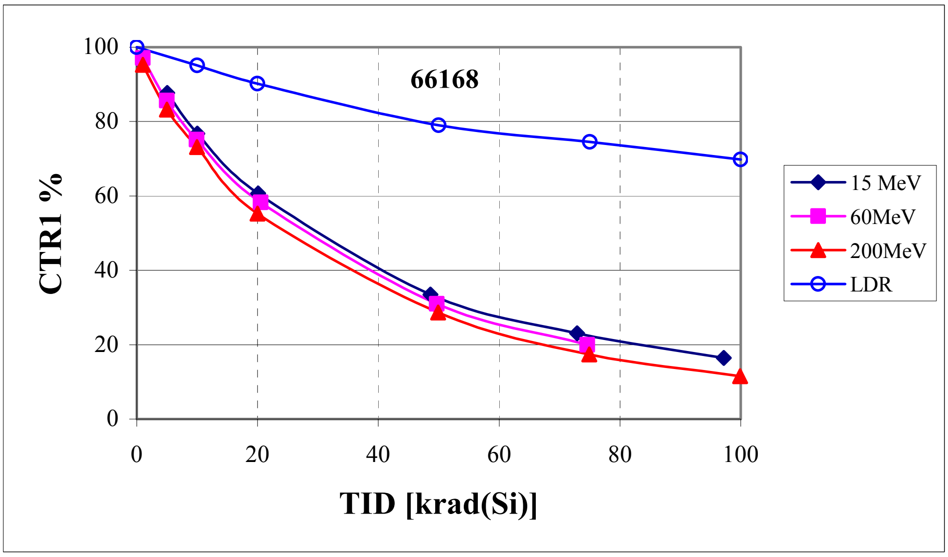

Figure 39: 66168 degradation under the real experimental proton fluences for their respective equivalent TIDs

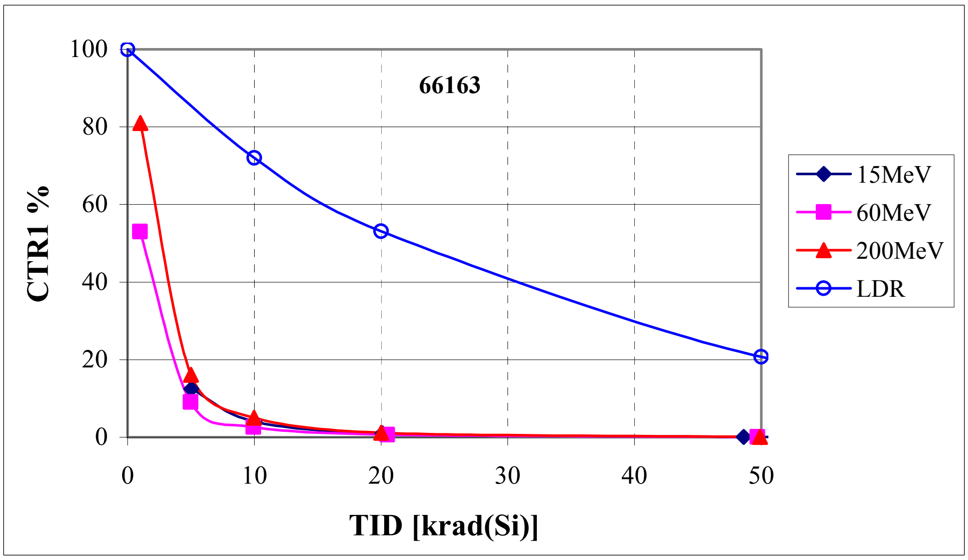

Figure 40: 66163 degradation under the real experimental proton fluences for their respective equivalent TIDs

It can clearly be noticed that CTR decrease is far more important in the case of proton irradiations, at equivalent deposited dose level. We know that Co^{60} only produces γ photons (1.17 and 1.33 MeV) ;

then, the CTR degradation is only due to ionisation mechanism. As protons generate both ionising and displacement damage, the increased degradation may be attributed to displacement effects. Then, both graphs clearly demonstrate that displacement damages can be considered as the dominant effect.

6.5. NEED FOR NORMALISATION

6.5.1. CTR degradation under real experimental proton fluences

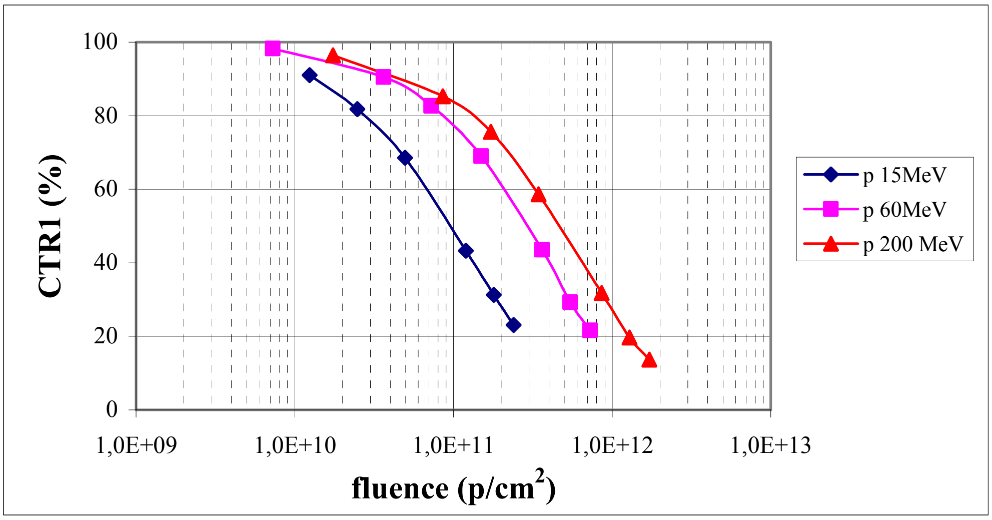

Figure 41: Comparison based on real proton fluences for 66168 Mii

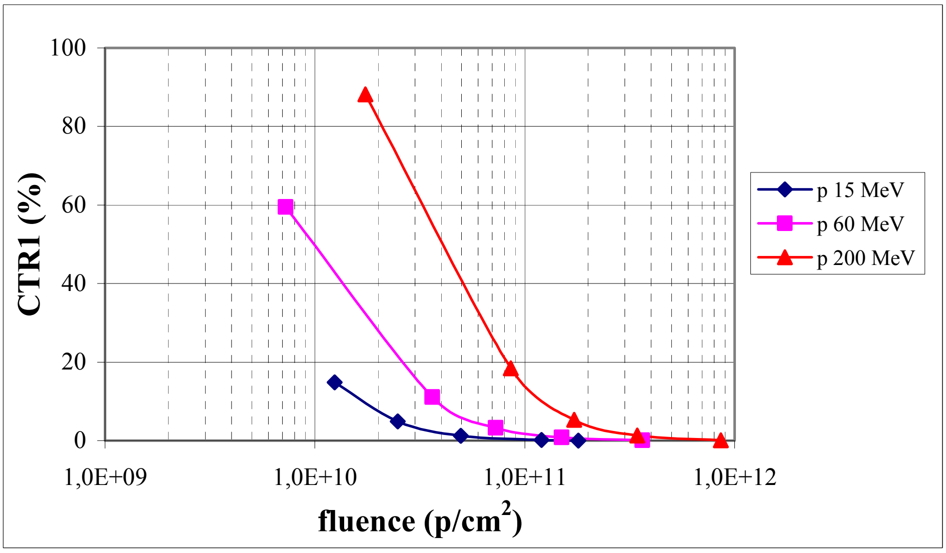

Figure 42: Comparison based on real proton fluences for 66163 Mii

As it can be noticed, no direct correlation is possible between degradations for a given proton fluence, the CTR deterioration being strongly related to the proton energy. The energy transfer is far more important for low energy particles and this behaviour affects both standard and hardened types.

6.5.2. Fluences normalisation as a function of ionising dose

The different fluence steps were chosen to deliver the same ionising dose at the three energies used for proton testing (15, 60 and 200 MeV) by applying the LET value in SiO2. This fluence ratio between different energies is not exactly the NIEL ratio because LET/NIEL is not exactly constant (cf *Table 36* and *Table 37*) in that energy range. However, the variation of the NIEL/LET ratio (from 5,6 10^6 to 4,3 10^6) being relatively small, we can expect that normalisation to dose will give nearly equal degradation.

Ep (MeV)	**NIELGaAs (Barry)**	**NIELGaAs (Summers)**	**LET SiO_2 ($MeV.cm^2/mg$)**
15	4,5 E-03	4,60E-03	2,53E-02
60	1,8 E-03	3,70E-03	8,56E-03
200	8,5 E-04	3,93E-03	3,63E-03

Table 36: NIEL and LET values for relevant proton energies.

Ep (MeV)	**LET (MeV.cm2/mg)**	**NIEL (Barry) KeV.cm2/g**	**LET/NIEL X 1 E6**
15	2,53E-02	4,5 E-3	5,62
60	8,56E-03	1,8 E-3	4,75
200	3,63E-03	8,5 E-4	4,27

Table 37: Ratio LET/NIEL for 3 energies

Note that the NIEL calculation found by Summers et al. [*"Damage correlations in semiconductors exposed to gamma, electron and proton radiations", G.P. Summers et al, IEEE Trans. Nuc. Sc. Vol 40, n°6, Dec. 1993*] was usually used for NIEL applications. In 1995 Barry [*"The Energy Dependence of Lifetime Damage Constants in GaAs LEDs for 1 to 500 MeV Protons", A. L. Barry et al., IEEE Trans. Nuc. Sc. Vol 42, n°6, Dec. 1995*] reported the energy dependence of proton damage constants for protons of energies up to 500 MeV, as measured by lifetime degradation in light-emitting diodes. In his work, the energy dependence of these damage constants is compared with the NIEL vs. energy calculations of Summers et al. A major deviation in the shape of the energy dependence from calculated values of NIEL vs. energy is observed in the range 150-500 MeV. It should be noted that the prime interest of his work is to propose a measured NIEL constant. So we decided to choose the NIEL constant found by Barry instead of Summer NIEL value.

The following table presents the fluence steps used during the test and the equivalent dose in SiO_2 :

Fluence Ep=15	Dose krad	Fluence Ep=60	Dose krad	Fluence Ep=200	Dose krad
0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
-	-	7,26E+09	9,94^{E}-01	1,74E+10	1,01E+00
1,24E+10	5,02E+00	3,63E+10	4,97E+00	8,59E+10	4,99E+00
2,48E+10	1,00E+01	7,26E+10	9,94E+00	1,72E+11	9,99E+00
4,96E+10	2,01E+01	1,50E+11	2,05E+01	3,44E+11	2,00E+01
1,20E+11	4,86E+01	3,63E+11	4,97E+01	8,60E+11	4,99E+01
1,80E+11	7,29E+01	5,45E+11	7,46E+01	1,29E+12	7,49E+01
2,40E+11	9,72E+01	7,27E+11	9,96E+01	1,72E+12	9,99E+01

Table 38: fluence steps and related deposited dose

Then, based on *Table 38*, the following table presents, for standard 4N49 Isolink biased with I_F =1mA during irradiations, the CTR1(%) degradation at each dose step deposited by protons of each energies.

Dose krad (LET x fluence)	15 MeV	60 MeV	200 MeV
0	**100**	-	-
1	**-**	**65**	**94**
5	**24**	**19**	**20**
10	**9**	**6**	**8**
20	**2**	**1**	**2**
50	**0,19**	**0**	**0**
75	**0**	**0**	**0**

Table 39: Summary of CTR1(%) degradation under dose deposited by protons for 4N49 Isolink

At low fluence a strong difference between 60 MeV and 200 MeV is observed but for other fluences results are quite near each other.

This approach is also applied to a hardened device (66168 Mii) and presented *Table 40* :

Dose krad (LET x fluence)	15 MeV	60 MeV	200 MeV
0	**100,00**	**100,00**	**100,00**
1	**-**	**96,78**	**93,20**
5	**87,56**	**83,85**	**83,84**
10	**75,66**	**72,00**	**75,61**
20	**58,73**	**54,41**	**59,09**
50	**31,39**	**26,81**	**33,56**
75	**20,88**	**16,01**	**20,50**
100	**14,63**	**10,58**	**13,49**

Table 40: Summary of CTR degradation by TID, 66168 Mii

So, at the first order, we can notice that, for fluence values that give the same ionising dose at different proton energies, the observed degradation is nearly the same. But this result happens only because in the proton energy range used in the test, the ratio between LET (SiO_2) and NIEL (GaAs) (Barry values) does not vary too much. Then, a more precise methodology is required to perform the normalisation.

6.5.3. NIEL Normalisation

6.5.3.1. Between proton of different energies

In the previous paragraph we have seen that dose equivalence coefficient between fluences of different proton energies will give relatively close CTR degradation values. This agreement is obtained, as explained earlier because the ratio LET/NIEL(GaAs) does not vary very much between 15 MeV and 200 MeV.

However, it was also shown that if displacement damage is the dominant damage mechanism, ionising dose also provides some contribution to overall degradation. Then, in order to obtain a more precise equivalence between energies and particles a more complex procedure is needed.

For a given proton energy fluence (for example 15 MeV), we calculate first the deposited ionising dose. Secondly, we determine the equivalent fluence at the two other energies (e.g. 60 and 200 MeV) by using the NIEL concept. Lastly, we calculate the dose deposited at these two fluences (for 60 and 200

MeV protons). We can then evaluate the difference of deposited dose between the three energies and a dose correction can then be done when calculating CTR degradation.

This is illustrated below when we calculate equivalences to 15 MeV proton energy.

Columns:

1 Fluence steps used in the experiment for Ep=15 MeV

2 Dose in krad : Fluence x LET (at Ep=15 MeV)

3 Equivalent fluence at E= 60 MeV by applying the NIEL ratio : NIEL(60)/NIEL(15)

4 Dose in krad deposited at this fluence of 60 MeV protons. (Equivalent fluence x LET (60MeV)

5 Difference of dose between Ep=15 MeV and Ep=60 MeV for the NIEL equivalent fluence

6 Equivalent fluence at E=200 MeV by applying the NIEL ratio NIEL(200)/NIEL(15)

7 Dose in krad deposited by fluence obtained in column 6 : Equivalent fluence x LET(200 MeV)

8 Difference of dose between equivalent fluences for Ep=15 MeV and Ep=200 MeV

9 Equivalent fluence for neutrons of 1 MeV equivalent energy.

fluences	**Dose [krad(Si)]**	**equiv p60 MeV**		**Δdose [krad(Si)]**	**equiv p200 MeV**	**deposited dose [krad(Si)]**	**Δdose [krad(Si)]**	**equiv n1 MeV**
1,24E+10	5,02E+00	3,36E+10	4,60E+00	4,24E-01	6,71E+10	3,90E+00	1,12E+00	8,51E+10
2,48E+10	1,00E+01	6,71E+10	9,19E+00	8,48E-01	1,34E+11	7,80E+00	2,24E+00	1,70E+11
4,96E+10	2,01E+01	1,34E+11	1,84E+01	1,70E+00	2,68E+11	1,56E+01	4,49E+00	3,41E+11
1,20E+11	4,86E+01	3,25E+11	4,45E+01	4,10E+00	6,49E+11	3,77E+01	1,09E+01	8,24E+11
1,80E+11	7,29E+01	4,87E+11	6,67E+01	6,16E+00	9,74E+11	5,66E+01	1,63E+01	1,24E+12
2,40E+11	9,72E+01	6,49E+11	8,89E+01	8,21E+00	1,30E+12	7,54E+01	2,17E+01	1,65E+12
P60 MeV fluences	**Dose [krad(Si)]**		**deposited dose [krad(Si)]**	**Δdose [krad(Si)]**	**equiv p200 MeV**	**deposited dose [krad(Si)]**	**Δdose [krad(Si)]**	**equiv n1 MeV**
7,26E+09	9,94E-01	2,68E+09	1,09E+00	-9,18E-02	1,45E+10	8,43E-01	1,51E-01	1,84E+10
3,63E+10	4,97E+00	1,34E+10	5,43E+00	-4,59E-01	7,26E+10	4,22E+00	7,55E-01	9,21E+10
7,26E+10	9,94E+00	2,68E+10	1,09E+01	-9,18E-01	1,45E+11	8,43E+00	1,51E+00	1,84E+11
1,50E+11	2,05E+01	5,54E+10	2,24E+01	-1,90E+00	3,00E+11	1,74E+01	3,12E+00	3,81E+11
3,63E+11	4,97E+01	1,34E+11	5,43E+01	-4,59E+00	7,26E+11	4,22E+01	7,55E+00	9,21E+11
5,45E+11	7,46E+01	2,01E+11	8,15E+01	-6,89E+00	1,09E+12	6,33E+01	1,13E+01	1,38E+12
7,27E+11	9,96E+01	2,69E+11	1,09E+02	-9,19E+00	1,45E+12	8,44E+01	1,51E+01	1,84E+12

Table 41: Example of equivalent dose calculation

We recall that the fluence steps used in the experiment were normalised in order to obtain an equal value of the ionising dose for the three proton energies. When we use NIEL equivalence, we have no measurement at the equivalent fluence found by NIEL ratio. We need an interpolation. This interpolation is obtained by using a polynomial fitting function.

6.5.3.2. Between [Neutron + ionising dose] and protons

The same normalization method is applied for fluence calculation (NIEL). Then, corresponding dose is taken into account, based on ^{60}Co Low Dose Rate experiment.

6.6. RESULTS OVERVIEW

6.6.1. Hardened types

Table 42 and *Figure 43* present here the synthesis of CTR1 behaviour of an "hardened" device (66168 Mii), for the three proton energies in *Table 42* and also for [neutron + dose] in *Figure 43* :

Fluences (based on 15MeV protons)	Ep=15 MeV	Ep=60 MeV	Ep=200 MeV
1,24E+10	87,71	85,7	86,1
2,48E+10	76,78	75,6	76,4
4,96E+10	60,67	61,4	60,1
1,20E+11	33,47	33,3	33,3
1,80E+11	23,06	23,1	16,5
2,40E+11	16,47	14,3	10,8

Table 42: Summary of CTR1 values for 3 proton energies, 66168 Mii

This table exhibit an excellent agreement between CTR degradation calculated the three proton energies. Note that for the highest fluence values this agreement is slightly affected. This may be explained by coming back to the degradation mechanisms in the optocoupler.

When we apply the NIEL ratio for GaAs we consider that the LED is the most sensitive part of the device. However, at high fluences, the degradation contribution from the phototransistor (reduction of the diffusion length in the collector and reduction of the current gain of the phototransistor) may become non negligible.

This means that we can normalise the dominant degradation mechanism and obtain a good equivalence (here NIEL in GaAs) but if contributions from the silicon part become as important as those from the LED, a different model should be used.

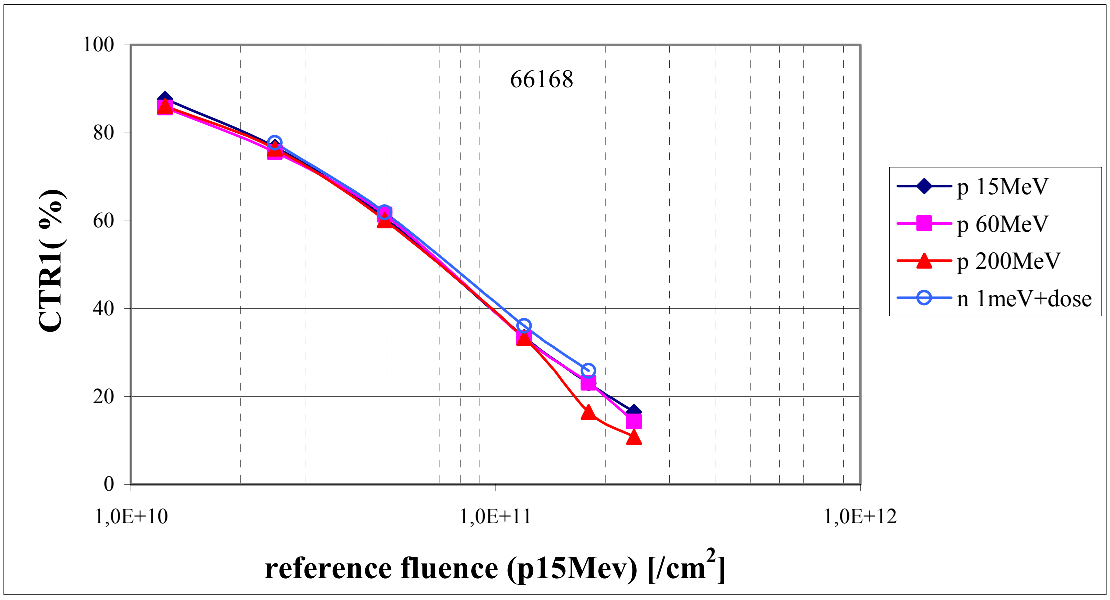

Figure 43 : Comparison based on equivalent 15MeV proton fluence for 66168

Results presented in *Table 42* are confirmed in *Figure 43* which also evidences that the equivalence between protons and [neutron + dose] is verified. This is also true for the other "hardened" types (OLH249 Isolink presented in *Figure 44,* and 66099 Mii presented in *Table 43).*

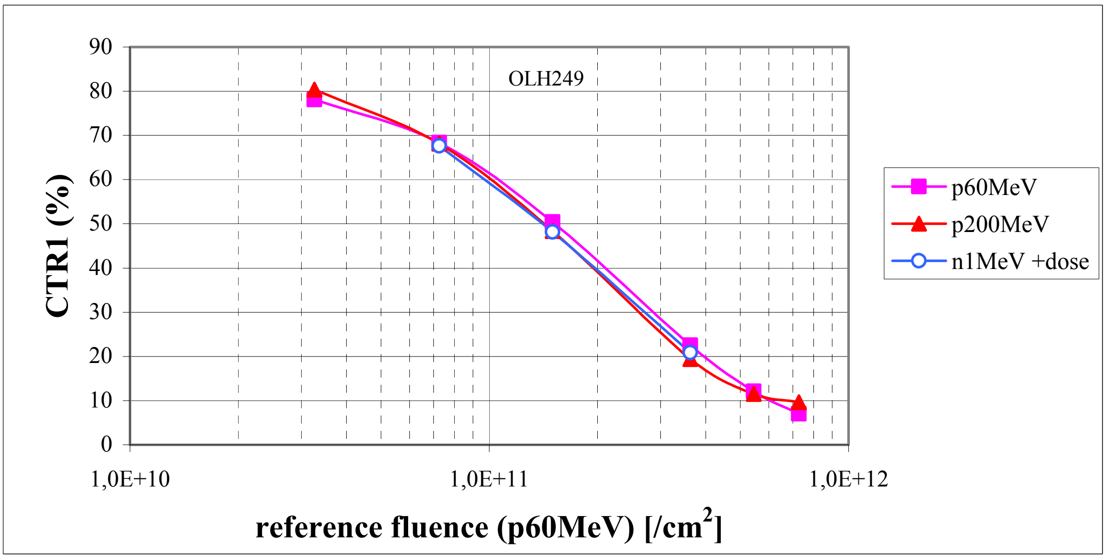

Figure 44: Comparison based on equivalent 60MeV proton fluence for OLH249

EXP.	15 MeV		60 MeV			
	CTR1	CTR1		CTR1	CTR1	CTR1
fluence n1 MeV	prot	neut+dos	prot	neut+dos	prot	neut+dos
(p/cm2)	%	%	%	%	%	%
1,84E+11	71,0	72,6	68,9	73,4	70,0	75,1
3,70E+11	51,2	55,0	49,2	56,2	50,4	58,4
9,24E+11	22,0	28,3	21,3	29,1	23,3	30,9
1,38E+12	12,2	19,4	12,9	20,0	14,5	20,9

Table 43 : Comparison based on equivalent 1 MeV neutron fluence for 66099 Mii

Detailed results are given in annex 1.

6.6.2. Standard types

Figure 45 and *Figure 46* provide for standard types the same information as the one given for "hardened" parts in the previous paragraph..

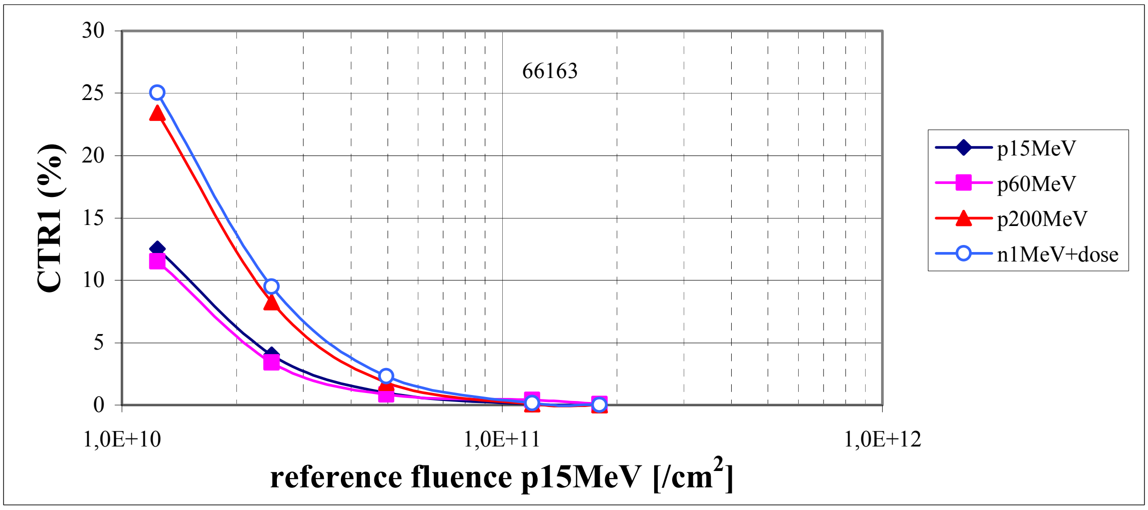

Figure 45: Comparison based on equivalent 15MeV proton fluence for 66163

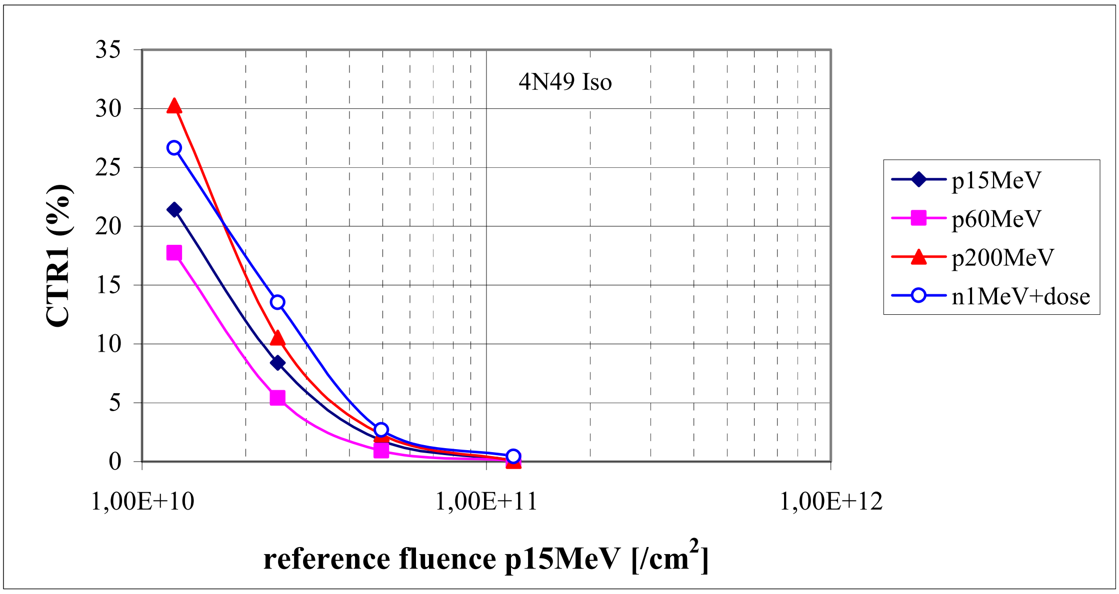

Figure 46: Comparison based on equivalent 15MeV proton fluence for the 4N49 Isolink

The close agreement demonstrated in the case of "hardened" devices is not so clear for standard devices, especially at low fluences. Some explanations may be proposed :

- when we apply the NIEL ratio for GaAs we consider that the LED is the most sensitive part of the device. However, when increasing the fluence, the degradation contribution from the phototransistor (reduction of the diffusion length in the collector and reduction of the current gain of the phototransistor) may become non negligible.

- there is some uncertainties about how to compare damage at different proton energies as the energy dependence of NIEL is different for Si and III-V materials

- Maybe the main point : some unresolved issues relating to what NIEL to apply depending on device technology remain.[15, recent presentations in NSREC 2001].

7. CONCLUSION

Neutron, proton and Co^{60} tests were performed on various types of optocouplers. Experiments performed on unhardened and "rad-tolerant" optocouplers have given an important amount of results.

We have shown, for the devices studied, that displacement damage is the main degradation mechanism (vs ionisation damage). This allow us to use the NIEL concept to compare effects for different energies of protons.

For each type, the sensitivity of CTR degradation toward bias condition during irradiation was shown for ionising dose, proton and neutron irradiation. Clear tendencies have been shown whatever testing is performed : OFF is a worst case while 10 mA is a best case.

For a given type (4N49) the sensitivity to ionising dose and displacement damage depends on the manufacturer.

The main objective of this study was to establish a standard low cost test procedure. This was aimed to be done by correlating the CTR degradation for several proton energies and for the combination [neutron+dose] by the help of the NIEL normalisation. Then, an irradiation at only one energy could be used to establish the degradation expected with a given spectrum.

The NIEL normalisation has been based on Barry et al work, with an adapted dose correction if needed.

The good working of the test methodology has been shown for hardened devices. For standard devices, the validity of the applied methodology is not so clear. Several explanation are possible, for example :

- when we apply the NIEL ratio for GaAs we consider that the LED is the most sensitive part of the device. However, when increasing the fluence, the degradation contribution from the Silicon phototransistor (reduction of the diffusion length in the collector and reduction of the current gain of the phototransistor) may become non negligible.
- Maybe the main point : some unresolved issues concerning the NIEL to apply depending on device technology remain.[15, recent presentations in NSREC 2001].

Thus, considering the today knowledge, we recommend to perform protons test at an energy lower than 60 MeV for unhardened devices.