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Table 2: Test Facilities and Particles

Facility	Particle
University of California at Davis (UCD)	Proton
TRI-University Meson Facility (TRIUMF)	Proton
Indiana University Cyclotron Facility (IUCF)	Proton
Brookhaven National Laboratories (BNL)	Heavy Ion
Michigan State University National Superconducting Cyclotron Laboratory (MSU/NSCL)	Heavy Ion
Tandem Accelerator Superconducting Cyclotron (TASCC)	Heavy Ion

Proton SEE and damage tests were performed at three facilities, the University of California at Davis (UCD), TRI-University Meson Facility (TRIUMF), and the Indiana University Cyclotron Facility (IUCF). Proton test energies ranged from 26.6 to 63 MeV at UCD, 50 to 500 MeV at TRIUMF, and 54 to 197 MeV at IUCF. Typically, fluence was $1x10^{10}$ to $1x10^{11}$ particles/cm^2, and flux was $1x10^8$ particles/cm^2/s.

B. Test Method

Three SEE test modes were typically used, depending on the device under test (DUT) and the test objectives:

Dynamic - actively exercise a DUT during beam exposure while counting errors, generally by comparing DUT output with a reference device or other expected output. Devices may have several dynamic test modes, such as Read/Write or Program-Only, depending on their function. Clock speeds may also affect SEE results.

Static - load device prior to beam irradiation, then retrieve data post-run, counting errors.

Biased (SEL only) - DUT is biased and clocked while ICC (power consumption) is monitored for latch-up or other destructive conditions.

SEE DUTs were monitored for soft errors such as SEUs and hard errors such as SELs. Detailed descriptions of the types of errors observed will be noted in individual test results. Proton damage tests were preformed on biased devices with functionality and parametrics being measured either continuously during irradiation or after step irradiations (e.g., measurements every 10 krad(Si)).

Heavy ion SEE testing was performed with LET values ranging from 1.1-120 MeV•cm^2/mg.

All tests were performed at room temperature and nominal power supply voltages, unless otherwise noted.

III. Test Results and Discussion

Table 3 summarizes the devices tested and the test results, using the following conventions:

H = heavy ion test
P = proton test (SEE)
N = neutron test
SEU = SEU LET_{th} (MeV•cm^2/mg)
SEL = SEL LET_{th} (MeV•cm^2/mg)
SET = Single Event Transient
Destructive = Any destructive SEE LET_{th}
< = SEE observed at lowest tested LET
> = No SEE observed at highest tested LET
PD = Proton Damage (actually a mix of damage and ionizing dose)
TID = Total Ionizing Dose
σ = cross-section (cm^2/device, unless specified as cm^2/bit)
LDC = Lot Date Code
APL = Johns Hopkins Applied Physics Laboratory

All LET_{th}s discussed are in units of MeV•cm^2/mg; all σ_{sat}s discussed are in units of cm^2/device, unless otherwise noted.

Descriptions of test procedures for individual devices and results are summarized in Table 3. This paper is a summary of results, complete test reports are available online at:
http://flick.gsfc.nasa.gov/radhome.htm [1]

Table 3: Summary of Test Results

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Memories				
Not Available	4Mbit SRAM	SEI	H: SEU: LET_{th} <3	Low cross-section
AS5C4008DJ	4Mbit SRAM	Austin Semi w/ Samsung Die	H: SEU: LET_{th} <3	Low cross-section
WS512K8-XCX	4Mbit SRAM	White	H: SEU: LET_{th} <3	MBUs observed
Not Available	4Mbit SRAM	Electronic Designs Inc.	H: SEU: LET_{th} <3	Low cross-section
AM29LV800	Flash Memory	AMD	H: SEL: LETth > 37 SET: LET th <5, σ_{sat} ~$2x10^{-6}$	SETs are high current transients, possibly upset producing events

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Memories (Cont.)				
HM65656	SRAM	Matra	H: SEU: LET_{th} <3	No energy dependence
ISC DRAM Stack	DRAM	Irvine Sensor Corp/IBM	P; See Text (Section D)	
AT17C256	EEPROM	Atmel	H: SEL	
LMRH4Kx9 FIFO	4Kx9 FIFO	Lockheed-Martin	H: SEU: LET_{th} ~25-30	
Programmable Devices				
A1280A	FPGA	Actel	P: $\sigma \sim 1.3E^{-14}$ cm^2	S module
A1020	FPGA	Actel	H: SEU: LET_{th} >18	No energy dependence
DL5256	FPGA	Dynachip	H: SEU: LET_{th} <<37	
Processors				
RH21020	DSP	Lockheed-Martin	H: SEU: LET_{th} ~3	
Optocouplers				
3C91	Optocoupler	Mitel	PD: CTR degradation	
OLH5601	Optocoupler	Isolink	H: SET	
OLH249	Optocoupler	Isolink	H: SET	
4N48	Optocoupler	Optek	PD: CTR degradation	
4N49	Optocoupler	TI	PD: CTR degradation	
66088	Optocoupler	Micropac	PD: CTR degradation	
6651	Optocoupler	HP	H: SET	
66123	Optocoupler	Micropac	H: SET	
Converters				
M3G2805D	DC-DC Converter	Magnitude-3	H: SEL/SET LETth >82	
MHF2805S	DC-DC Converter	Interpoint	PD: functional failure	
MHF2815S	DC-DC Converter	Interpoint	PD: functional failure	
MHF2815d	DC-DC Converter	Interpoint	PD: functional failure	
MTR2805SF	DC-DC Converter	Interpoint	H: SEL: LET_{th} ~ 37.4 σ_{sat} ~1-2 x 10^{-7} cm^2 SET: LET_{th} > 82	
MTR2815SF	DC-DC Converter	Interpoint	H: SE destructive noted at worst-case condition @37.4 < LET <59.8	
ADC/DAC				
AD1672	ADC	Analog Devices	H: SEU LET_{th} <3	
MAX494	Op-Amp	MAXIM	H: SEL LET_{th} >59	
SPT7760	Analog to Digital Converter	Signal Processing Technology	P: See text (Section N)	Frequency and input sensitive
Analog				
AD780	Voltage Reference	Analog Devices	PD: 3 x 10^{11} p/cm^2	Majority of DUTs out of spec
CLC502	Op-Amp	COMLINEAR	H: SEL LET_{th} >59	
LT1021CCN8-5	Voltage Reference	Linear Technology	PD: 3 x 10^{11} p/cm^2	All of DUTs out of spec
LT1021CCN8-10	Voltage Reference	Linear Technology	PD: 3 x 10^{11} p/cm^2	All of DUTs out of spec
LT1153	Digital Circuit Breaker	Linear Technology	H: SEL LETth > 37	Heavy ion testing indicated a possible TID problem.

DEVICE #	FUNCTION	MANUF.	RESULTS	NOTES
Board Tests				
ZT-6500	CPCI Pentium Processor	Ziatech	P: SEU, SEL observed	
CPCI-100	Dual IP 3U Carrier	Greenspring	P: No events	
IP 1553	MIL-STD-1553 Interface	Greenspring	P: SEL	
Unknown	3U IP Carrier	Alphi	P: No events	
Unknown	3U IP Carrier	Alphi	P: No events	
CPCI-200	6U IP Carrier	Greenspring	P: No events	
CPCI-3603	CPCI PowerPC Processor	Force	P: SEU	
Unknown	IP Optocoupler Driver	Greenspring	P: SEU, displacement damage on optocoupler	
Unknown	HV-Unidig Driver	Greenspring	P: SEU	
Unknown	IP Serial Driver	Greenspring	P: SEU	
SCC-04	IP Serial Driver	Actis	P: SEU	
Unknown	GPS Correlator/Front-end	Plessey	P: SEU	
CMA-401A	STRONGARM Processor	Cogent Computers Inc	P: SEU	
Miscellaneous				
Honeywell ESN	ESN	Honeywell	H: op amp sensitivity	See text (Section T)
AD536	RMS-DC Converter	Analog Devices	H: SEL: $LET_{eff}th > 75$ SET: LET th <1.4, σ_{sat} ~$5x10^{-3}$	
AMP01	Amplifier	Analog Devices	H: Destructive event noted	See text (Section V)
NYTEK 8002	Delay Line	NYTEK	H: SEL LET_{th} >59	
DAC8222	12-bit DAC	Analog Devices	H: SEL: $LET_{eff}th > 85$ SET: LET $_{th}$ ~40 hi inputs LET $_{th}$ ~10 lo inputs σ_{sat} ~$1x10^{-3}$	
HI-509	Analog Mux/demux	Harris	H: SEL/SET: $LET_{th} > 60$	

A. Commercial 4Mbit SRAM

Four vendors of commercial 4 Mbit SRAMs were evaluated for SEE heavy ion characteristics. These four vendors are companies that repackage other die manufacturers' products for military and aerospace applications.

Testing was performed in a dynamic mode (1 Mhz operating rate) of read-modify-write using a logical checkerboard pattern. SEL was determined by a trip of device current limiting protection set at maximum operating current for the device. No single event functional interrupts (SEFIs) were noted.

Figure 1 compares the SEU response of two of the device types tested. It is clear that the die utilized by these two vendors are from different manufacturers. This figure shows the results for total bit errors observed. Figure 2 illustrates the multiple bit upset (MBU) results for this device. MBU counts are important input for determining the effectiveness of error detection and correction (EDAC) schemes in reliable system designs.

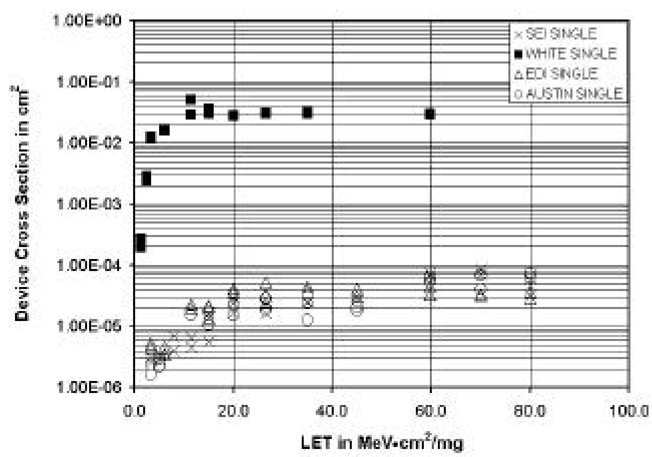

Figure 1: Commercial 4 Mbit SRAM Heavy Ion SEU comparison.

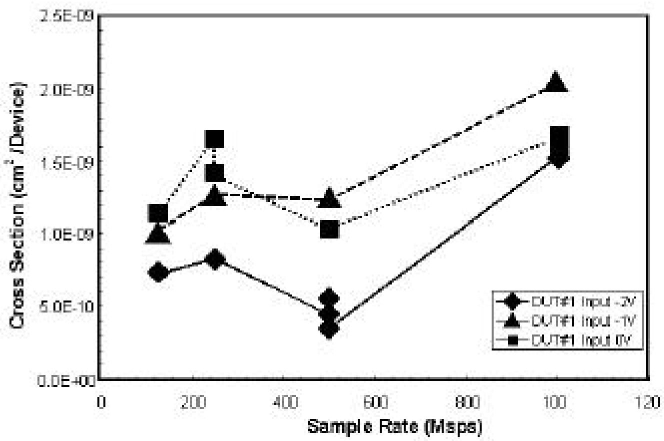

Figure 13: Cross section as a function of sample rate for various input levels.

O. AD780

The AD-780AN precision voltage references were monitored for displacement damage and total ionizing dose. The devices were exposed to a 193 MeV proton beam with a flux from 2.5 x 10^8 to 5 x 10^8 $p^+/cm^2/s$ at the Indiana University Cyclotron Facility. Five devices were exposed to a fluence of 3 x 10^{11} p^+/cm^2 with an output voltage of 2.5 ± 0.005 Volts. While the output current was not much affected, the reference voltage level did show change. With a ± 5 mV range, all but one of the devices indicated an end of life performance and the average reference voltage change of 4.6mV and a standard deviation of 4.8 mV. Annealing data were taken over the course of an hour with only random fluctuations about the end-of-exposure readings. Table 6 shows voltage reference sensitivity to 193 MeV Proton Fluence of 3.0 E+11 cm^{-2} Post-radiation Shifts in mV.

Table 6: Voltage Reference Sensitivity to 193 MeV Proton Fluence of 3.0 E+11 cm^{-2} Post-radiation Shifts in mV.

Manufacturer	Analog Devices	Linear Technology	Linear Technology
Device	AD-780AN	LT-1021CCN8-5	LT-1021CCN8-10
Output Accuracy	2.5000 V ± 0.005 V	5.000 V ± 0.0025 V	10.000 V ± 0.005 V
Run 1	0.4 mV	2.5 mV	-7.2 mV
Run 2	0 mV	3.8 mV	-11.5 mV
Run 3	0.1 mV	4.4 mV	-7.8 mV
Run 4	1.2 mV	4.6 mV	-10.4 mV
Run 5	0.6 mV	4.7 mV	-10.8 mV
Mean (1-5)	0.46 mV	4 mV	-9.5 mV
Std. Dev. (1-5)	0.48 mV	0.9 mV	1.9 mV

- AD-780 uses a compensated bandgap reference
- Both Linear Technology Devices use buried zener references

Here the compensated bandgap performed better, but the opposite was seen in: B.G. Rax, et al., [12] "Degradation of Precision Reference Devices in Space Environments, IEEE TNS, 44 (6), 1997.

P. COMLINEAR CLC502 Op Amp

The COMLINEAR CLC502 was monitored for SELs when exposed to a number of heavy ion beams at the Brookhaven National Laboratory SEE Facility. The device was exposed to Ni, Br, and I. The LET were 27, 37 and 59 MeV•cm^2/mg. The devices where tested at room temperature. No SELs were observed on two devices tested under bias conditions of 7 volts at all ion LETs to a fluence of 1x10^7 p/cm^2.

Q. LT1021CCN8-5 and LT1021CCN8-10

The LT-1021CCN8-5/10 precision voltage feferences were monitored for displacement damage and total ionizing dose. The devices were exposed to a 193 MeV proton beam with a flux from 2.5 x 10^8 to 5 x 10^8 $p^+/cm^2/s$ at the Indiana University Cyclotron Facility. Five devices of each type were exposed to a fluence of 3 x 10^{11} p^+/cm^2 with an output voltage of 5 ± 0.0025 Volts and 10 ± 0.005 Volts. While the output current was not much affected, the reference voltage level did show change. For the LT-1021CCN8-5 with a ± 2.5 mV range, all devices indicated an end of life performance and the average reference voltage change of 4.0 mV and a standard deviation of 0.9 mV. For the LT-1021CCN8-10 with a ± 5 mV range, all devices indicated an end of life performance and the average reference voltage change of –9.5 mV and a standard deviation of 1.9 mV. Annealing data was taken over the course of an hour with only random fluctuations about the end-of-exposure readings. Table 6 shows voltage reference sensitivity. Figure 14 shows voltage reference test results for LT-1021CCN8-10.

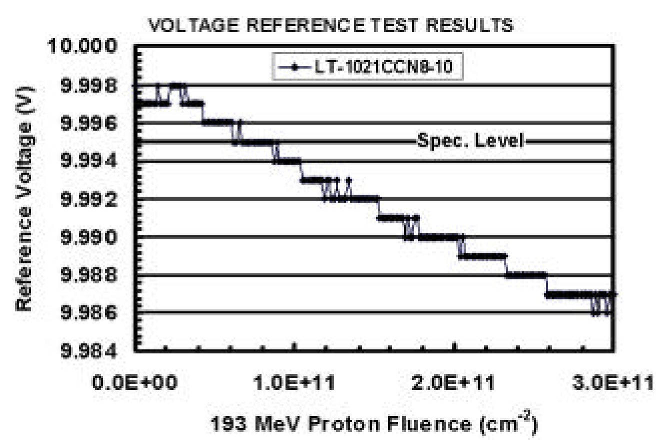

Figure 14: Voltage reference test results for LT-1021CCN8-10.

R. Linear Technology LTC1153 Electronic Circuit Breaker (ECB)

The LTC1153 ECBs were monitored for latchup induced high power supply currents at the MSU SEE Test Facility. Testing began with an LET of 11 MeV•cm^2/mg obtained with 2.4 GeV Kr-40. Following this, the Kr-40 beam was degraded in energy with a 0.037 inch thick Al foil with a resulting LET at the DUT of 30.6 MeV•cm^2/mg. The Xe-129 beam at 7.74 GeV provided an incident LET of 27 MeV•cm^2/mg, and then a 0.020 inch Al foil was used to increase the LET at the DUT to 37 MeV•cm^2/mg. The ECBs were tested under the bias conditions of +12 and +1 8 volts. There was no evidence of latchup at an LET of 37 MeV•cm^2/mg and fluence of 10^{07} ions/cm^2. An anomalous bimodal behavior in supply current was measured, but the circumstantial evidence suggests that DUT functionality may have been compromised by TID effects. TID testing with properly controlled conditions is strongly advised.

S. BOARD TESTS

Several commercial off-the-shelf (COTS) boards were proton irradiated to observed proton-induced SEEs as well as TID and displacement damage. Instead of performing Radiation Hardness Assurance (RHA) or Radiation Lot Acceptance Tests (RLATs) on piecepart devices, we are providing a "confidence" gathering process to increase the likelihood of mission success for COTS boards. Assuming that multiple copies of each board is being procured, the following test philosophy is utilized:

1. Perform proton irradiations on boards
2. Consider issues including particle, energy , fluence, flux, etc.
3. Attempt to isolate individual ICs during irradiations in order to determine sensitive components. This is difficult due to beam spread, double-sided boards, tight board layouts, etc.
4. Define a "martyr" board. Irradiate this board to a proton fluence N times greater than predicted mission fluence (mapping a multi-energy spectrum into a monoenergetic test) monitoring SEE and TID performance. If the "martyr" board passes, irradiate flight hardware boards to a low-level ("non-destructive") of proton fluence.

The martyr board is used for three reasons. These are:

- to pre-screen whether to irradiate flight hardware or not based on SELs, TID failure, etc.,
- to gain limited TID and displacement damage knowledge, and
- to gain confidence for flight SEU performance. For example, assuming a test fluence of 10X mission predicted levels and similarity between martyr and flight hardware, if no "events" were noted during martyr test, then the flight hardware has only a 1 in 10 chance of having an event during mission lifetime.

Table 7 summarizes the results observed in a qualitative manner. Full details on the test results as well as descriptions of the limitations of this method will be available in [13].

Table 7: Summary of Board Test Results.

Manufacturer	**Mfr. Part Number**	**Board Description**	**Test Date**	**Test Facility**	**Brief Results**	**Note**
Ziatech	ZT-6500	CPCI Pentium Processor	Sep-97	IUCF	SEU, SEL observed	
Greenspring	CPCI-100	Dual IP 3U Carrier	Sep-97	IUCF	No events	
Greenspring	IP 1553	MIL-STD-1553 Interface	Sep-97	IUCF	SEL	
Alphi	Unknown	3U IP Carrier	May-98	UCD CNL	No events	Martyr test
Alphi	Unknown	3U IP Carrier	Jun-98	IUCF	No events	Flight hardware test
Greenspring	CPCI-200	6U IP Carrier	May-98	UCD CNL	No events	
Force	CPCI-3603	CPCI PowerPC Processor	May-98	UCD-CNL	SEU	Flight hardware had different results than martyr
Force	CPCI-3603	CPCI PowerPC Processor	Jun-98	IUCF	SEU	Flight hardware had different results than martyr
Greenspring	Unknown	IP Optocoupler Driver	Jun-98	IUCF	SEU, Displacement damage on optocoupler	
Greenspring	Unknown	HV-Unidig Driver	Jun-98	IUCF	SEU	
Greenspring	Unknown	IP Serial Driver	Jun-98	IUCF	SEU	
Actis	SCC-04	IP Serial Driver	Jun-98	IUCF	SEU	
Plessey	Unknown	GPS Correlator/Front-end	Sep-98	UCD CNL	SEU	Loss of lock and SEFI
Cogent Computers Inc	CMA-401A	STRONGARM Processor	Sep-98	UCD CNL	SEU	Only 2 events in ~ 20 krad(Si) of protons

Table 8: ESN SEE Piecepart Summary.

Part Number	Manufac.	Description	LET_{th}** for SEL, SEGR, SEB	LET_{th}** for SEU or SET
UT75ER	UTMC	ASIC	No	~37
AMP01NBC	Analog Devices	Instrumentation Amp	>26	>4
AD574S	Analog Devices	12 Bit A/D Converter (resolution 60 mV)	>37	>37
OP77NBC	Analog Devices	Voltage Operational Amplifier	>59	>59
RH1009	Linear Tech.	2.5 V Shunt Regulator Diode	>55	>55
HSO-1840RH-Q	Harris	16 Ch. CMOS Analog Multiplexer	No	>120
HX6256	Honeywell SSEC	Static RAM CMOS 32K x 8	No	>120
HX6656	Honeywell SSEC	ROM	No	>120
MUX-28	Analog Devices	Dual 8 Ch. JFET Analog Multiplexer	No	> 85
FRC913OR	Harris	P-Ch. MOSFET	>37	N/A
FRC13OR	Harris	N-Ch MOSFET	>37***	N/A

** LETth is the threshold LET and is given in MeV•cm^2/mg

*** Derated

A. OP77NBC (U19), MUX-28 (U13), and AD574 (U15)

The Honeywell ESN was tested for SEU, SET, and single event parametric or functional failure, (e.g., single event latchup (SEL), single event gate rupture (SEGR), single event burnout (SEB)). The Honeywell Essential Services Node (ESN) contains several microelectronic devices. Table 8 gives the results for testing done at Brookhaven National Laboratory. The AMP01 instrumentation amplifier fails destructively below LETth of 37 MeV•cm^2/mg (see the section on the AMP01). The failure mechanism is unknown. The characteristics of the failure is a high current state of near 40 mA that is not recoverable on power cycle. The AMP01 also experiences SETs for LETs > 4 MeV•cm^2/mg.

B. AD536

The AD536 RMS-DC converters were monitored for transient interruptions in the output signal and for latchup induced high power supply currents. They were exposed to C, F, Cl, Ti, Br, and I heavy ion beams (normal incident LETs of 1.4, 3.4, 11.4, 18.7, 37.4, and 59.8 MeV•cm^2/mg, respectively) at the BNL SEE Test Facility. The converters were tested under bias conditions of +/- 8 volts. The devices had an input voltage source of a sine wave with frequency of 318 kHz and 10 volts peak-to-peak. For this condition, no single event induced latchups were observed in the part to an effective LET of 75 MeV•cm^2/mg. The device, however, did experience SETs. [14]

For the SETs, the cross section data shows a spread as a function of the ion species and its effective LET but a saturation cross section level was estimated at 5 x 10^{-3} cm^2. The LET threshold was never measured as transients were observed with an ion that has a normal-incidence LET of 1.4 MeV•cm^2/mg. The transients are mainly noise around the output signal of 3.3 volts with a sharp positive spike. The shape of the spike is a pulse of approximately few microseconds with peak heights of up to 2.5 volts above nominal. The noise surrounding this spike is approximately 200 mV on either side of the nominal output voltage. The AD536 is considered to have an LET threshold for latchup greater than 75 MeV•cm^2/mg. It has single event transients threshold of less than 1.4 MeV•cm^2/mg and a saturation cross section of 5 x 10^{-3} cm^2. It should be noted that for LET_{th} of 10 MeV•cm^2/mg or less, the possibility of sensitivity to proton-induced events exists. With a threshold of 1.4, this possibility is very likely but it is not addressed by this testing.

C. Analog Devices AMP01 Instrumentation Amplifier

Destructive Failure Testing:

Single Event Effects (SEEs) experimental data at Brookhaven National Laboratory has shown that the AMP01 can have a destructive failure when exposed to a heavy ion radiation environment. Test groups from GSFC and Sandia National Laboratory [15] have observed this failure independently. Table 9 describes the experimental results obtained by NASA/GSFC.

1. Notice that for DUTs 4 and 26 the failure occurred at LET = 59.8 MeV•cm^2/mg (I normal incident). Failure did not occur when testing these DUTs at effective LETs greater than 59 MeV•cm^2/mg (e.g., LET_{eff} = 73.0 MeV•cm^2/mg - Br at 60 degrees where the LET is 36.5 MeV•cm^2/mg).
2. For DUT 27 the effective cross section for failure is 1.74x10^{-6} cm^2/device for an LET_{eff} of 83.4 MeV•cm^2/mg (I at 45 degrees). Compare this to DUTs 3,4, and 26 where the cross section is greater than 1.3x10^{-5} cm^2/device at LET = 59.8 MeV•cm^2/mg (I at 0 degrees). The effective cross section for failure for DUT 27 is an order of magnitude lower that other DUTs when measure at a lower effective LET.