Compendium of Single Event Effects Test Results for Commercial Off-The-Shelf and Standard Electronics for Low Earth Orbit and Deep Space Applications

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***Abstract*—We present the results of Single Event Effects (SEE) testing with high energy protons and with low and high energy heavy ions for electrical components considered for Low Earth Orbit (LEO) and for deep space applications.**

INTRODUCTION

The human space exploration program at NASA is focused on destinations in cis-lunar space and eventually to Mars with the Orion Multi-purpose Crew Vehicle being developed by the Lockheed Martin Corporation. Additionally, smaller-scale projects such as small satellites, robotic rovers, and various science payloads will be exposed to similar environments. For all of these missions, the hardware will be exposed to Galactic Cosmic Radiation (GCR) and possibly Solar Particle Events (SPE). For these missions, program performance and reliability requirements necessitate the need for heavy ion certification. To date, this has been carried out by traditional (low energy) heavy ion testing as well as using the Variable Depth Bragg Peak (VDBP) method for part characterization and for destructive screening. Often times, a proton screening test is performed prior to heavy ion testing.

PROTON TESTING

NASA JSC uses 200 MeV protons to test for destructive and nondestructive errors for hardware intended for LEO, i.e. for the International Space Station (ISS) [6]-[7]. This test exposes most known failure modes that have a Mean Time Before Failure (MTBF) <= 10 years in the LEO environment. Proton testing replicates approximately 6-10 years of the heavy ion linear energy transfer (LET) environment up to an LET of approximately 10-14 MeV-cm²/mg in silicon. The typical test exposes the device under test to a fluence of ≥ 1E+10 protons/cm2 which accomplishes two goals. The first is to find single event effects caused by heavy ions up to LET of ~10 MeV-cm²/mg. Secondly, the test produces a total ionizing dose (TID) of at least 600 rads (Si), which corresponds to about 10 years of total ionizing dose exposure in LEO. This NASA method does not fully characterize the part, but it intends to screen for hard failures and provides very conservative estimates up to a 10 year MTBF in LEO [6]-[8]. This test is typically performed at the board or box level which provides a means to reduce the cost of testing, especially with modern Commercial Off-The-Shelf (COTS) units.

TRADITIONAL HEAVY ION TESTING

NASA uses traditional methods to perform heavy ion testing and requires each part be characterized to high LET (depending on mission) or failure. Traditional methods require the parts to be de-lidded for single piece part testing and characterization because the beam energies are too low to penetrate through the packaging. Often times, components with specific application voltages representative of flight like conditions are tested to understand transient radiation induced responses to these devices or test for the effectiveness of mitigation strategies. Analyses of the SEE signatures at the system level are required to determine the system effects and what mitigations are necessary.

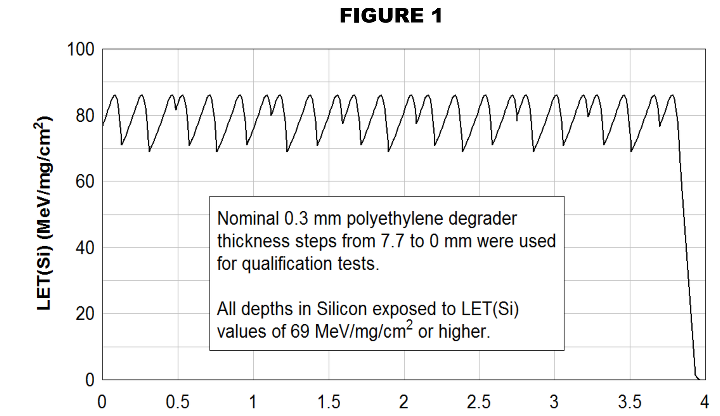
HIGH ENERGY HEAVY ION TESTING

Increasingly, the human rated missions are incorporating complex parts that are too difficult (or costly) to de-lid or have sensitive volume depths unreachable by low energy heavy ion beams. This problem has been encountered on the Orion Multi-purpose Crewed Vehicle program [9]. Additionally, designs include more Commercial Off-The-Shelf (COTS) units to support crew activities for which there are no rad-hard versions available. In these cases, the traditional test facilities at TAMU and LBNL cannot provide beams with enough energy to penetrate these devices. Furthermore, NASA JSC is seeing a trend towards screening flight boards to certain LET levels for destructive effects while also using the high energy beams to evaluate flight circuits for evaluation of system level soft errors. For individual parts characterization we employ the Variable Depth Bragg Peak (VDBP) method [3]-[5] and for screening, a modified VDBP method which uses various degrader steps to ensure all locations in the board are exposed to a certain LET level desired by the program. All VDBP testing reported in this report was accomplished using the ion beams listed in Table 1 and the testing was performed at the NASA Space Radiation Laboratory (NSRL).

Table1
LET (Si) for Ion Beams Used For VDBP Testing

	Max Energy (MeV/n)	LET at Max E (MeV-cm2/mg)	Peak LET (MeV-cm2/mg)**	Range in Si (mm)
H^1	2500	0.00171	0.51	5470
C^{12}	1500	0.06227	5.2	972
Fe^{56}	1470	1.171	29.3	235
Kr^{84}	383	3.28	41	26.5
Xe^{132}	350	7.7	69.2	16.3
Ta^{181}	342	14.8	87.5	12.1
Au^{197}	165	24.7	94.2	3.7

FIGURE 1



For VDBP destructive screening, a series of degrader steps are used to slide the Bragg curve through the whole device. Where the Bragg curves intersect will define a minimum LET exposure at all locations in that device and this value is a function of the degrader step size used. Figure 1 shows the 165 MeV/n Au beam with 0.3 mm of degrader will expose the whole part to an LET of 69 MeV-cm²/mg or higher.

(References Available in Paper)

RESULTS: TABLE 2A: SUMMARY OF SEE TEST RESULTS

Part #	LDC**	Part type	Manufacturer	Facility	Weibull Parameters***
RH1016MW	1011A	High Speed Comp	LT	LBNL	SET: L_0=12.5, σ_{sat}=6E-5, W=50, S=2.5 SET= +/- 0.5V, Max LET=75.7
HYSE-117RH-Q	Proto	Adj Pos volt reg	Intersil	LBNL	SET: Vin=15V, Vout=5V, Max SET=6.88V, 15 usec L_0=7, σ_{sat}=1.2E-4, W=40, S=3, Max LET=75
OLI249	114814	Opto	Isolink	LBNL	SET: L_0=25, σ_{sat}=6.0E-3, W=50, S=4, SET>= 2.2V, Vsup and Vout=3.3V, 60 usec duration maximum, Max LET=75.7
RH1014MW	1101A	Quad op amp	LT	TAMU	SET: L_0=8.6, σ_{sat}=8.4E-4, W=32, S=3, Max POS SET=8V/22 usec, SET: L_0=1.8, σ_{sat}=7.0E-3, W=26, S=1.7, Max NEG SET=-9V/60 usec Max LET=87.1
LMC6484	1043	Quad op amp	National Semiconductor	TAMU	No SEL, SET < 10 usec, Max LET=87.1
HS-4423BRH	X1006A	Dual Inv MOSFET Driver	Intersil	TAMU	SET: L_0 = 19, σ_{sat}= 2.94E-05, W = 16.03, S=1.926 80 nsec transients, Max LET=85.4
54LVC08A	1217A	Quadruple 2-input AND Gate	TI	IUCF	No SEE with 1E10 protons/cm² at 200 MeV
SG7805AT	7C1143P	5V Voltage Regulator	Microsemi	IUCF	No SEE with 5E10 protons/cm² at 200 MeV
IS705RH	1113AC	Power-up/down Microprocessor Reset Circuit	Intersil	NSRL	SET: σ_{sat}=7.47E-5, L_0=22, W=26.85, S=3.09 No SEL to LET=60 with 1E6 ions/cm²
IRHM7360SE	542	400V N-Channel MOSFET	International Rectifier	TAMU	176V at 40 LET pass voltage (9 kOhm load)
AD589	231	Volt Reference	AD	LBNL	SET1: Short positive (less than 50ns) followed by 8 usec neg 400mV Weibull: L_0=2, σ_{sat} =4.0E-4, W=2, S=1.1 SET 2: 1us, 500mV: Weibull: L_0=24, σ_{sat} =2.0E-4, W=20, S=1 both tested to LET=75, No DSEE
OP27	145	Op-amp	AD	LBNL	SET1: 1V, 150 usec, Weibull: L_0=3.4, σ_{sat} =8.0E-4, W=15, S=2 SET2: -500mV, 150 usec, Weibull: L_0=25, σ_{sat} =1.0E-4, W=20, S=4, 12V bias, output=2V No DSEE, Max LET=75.6
HS-4423	**	FET driver	Intersil	LNBL	No SET, Bias at 13V, Max LET=75.7
VRG8662	1002	LDO reg	Aeroflex	TAMU	SET at high LET (56>SET≥87.1), No DSEE
IS-1009RH	451	2.5V Reference	Intersil	TAMU	Vsupply=13V, Vout=2.5V SET1: 0.5, -2V, 5 usec: Weibull: L_0=5.7, σ_{sat} =8.1E-4, W=14.6, S=1 SET2: same as 1 but 45 usec: Weibull: L_0=5, σ_{sat} =7.4E-5, W=17.7, S=1.226 No DSEE, Max LET=87.1
IRHLG77214	1126	250V Quad N-Channel MOSFET	IR	TAMU	No SEB at 182V at LET= 87.1, gate leakage noted on 2 units
GoPro Hero 3	**	Camera	GoPro	IUCF	Camera survived 1E10/cm² 200 MeV protons with many SEE
MKD25PA128IO-672A	**	Solid State Drive Assy	Memkor	IUCF	DSEE: Unit failed to respond to power cycle Bendel A = 13.08, 200 MeV protons
IRHF7330SE	1406	N-Channel MOSFET	IR	TAMU	Degradation observed at 1E5 ions/cm², Max LET=77.3
IR2110L4	1146	FET driver	IR	TAMU	SET: State changes and transients, No DSEE, Max LET=77.3
HERO4		Camera	GoPro	IUCF	Numerous SEE, no DSEE to 1E10/cm² 200 MeV protons
IRHQ57214SE	1436	250V N-Channel MOSFET	IR	TAMU	Pass at Vds=171V, LET=77.3, SET=+/-4V on the drain, +/- 1.75V on the source. <0.5 usec duration
IRHYS67234T3	1439	250V, N-Channel MOSFET	IR	TAMU	Vds=240V, No DSEE or degradation to LET=75
2N3439	1148	350V, NPN BJT	Microsemi	TAMU	SET=1.8V, <0.5 usec, σ_{sat}= 2.33E-3 Vce=166V, No DSEE to LET=77.3
OP27AL	0936A	Linear Bipolar	AD	LBNL	DSEE: Above LET=45.6
Hero3	**	Camera and associated electronics	GoPro	NSRL	DSEE at LET=4.2
MACQ-500E-2	**	Overhead module	TTC	MGH	Unit failed in less than 1E10/cm² with 200 MeV protons
RH1013MW	1320A	Precision Op-amp	Linear Technology	LBNL	largest SET: 5.7V, 13 usec, No DSEE to LET=75
IRHF7110SCS	1130	N-Channel 100V MOSFET	International Rectifier	TAMU	No DSEE or degradation, Vds=20V Max LET=75
88E1111-NDC2	1307	PHY	Marvell	TAMU	SEU "Packet Errors" Weibull: L0=0.1, σ_{sat} =1.3E-3, W=70, S=1.3 SEFI Weibull: L_0=0.1, σ_{sat}=9.0E-6, W=70, S=0.7 cleared with RESET or power cycle, Max LET=77
WIL6120	**	Radio controller	Wilocity	NSRL	SEE σ=3.65E-4 at LET=4.2 (upper limit for self-recovering SEE) SEE σ=5.58E-4 at LET=4.2 (upper limit for SEE requiring intervention)
NSW-12GT-1	**	12 bit Ethernet Switch	TTC	MGH	SEFI requiring power cycle: Bendel A=13.07 DSEE: Bendel A=18.03, 1E10/cm² 200 MeV protons
SN54AC14W	1131A	Hex inverter/Schmitt trigger	TI	LBNL	SET=+/-200mV, No SET at LET=48 Upper limit σ=3.85E-6 at LET=75
NSW-12GT-1 (power supply only)	**	28V to 5V converter	TTC	NSRL	DSEE σ=1.00E-5 at LET=14.2
Hero4 Black	**	Portable HD Digital Video Camera	GoPro	NSRL	DSEE σ=1.36E-6 at LET=14.2
D54250WYK1	**	SBC	NUC Intel	NSRL	DSEE σ=9.04E-5 at LET=14.2
MAGBES-21HS	**	5 Port Ethernet Switch	MPLAG Elektronikuntern ehmen	NSRL	DSEE σ=1.87E-6 at LET=14.2
PIP37-1	**	Ruggedized SBC	MPLAG Elektronikuntern ehmen	NSRL	DSEE σ=5.06E-4 at LET=14.2
GoPro Htr 6/8/2015 DSS	**	Heater board	Deep Space Systems	NSRL	DSEE σ=5.05E-7 at LET=14.2
NSW-8GT-TG-D-1	**	8 Port Network Switch	TTC	MGH	SEE: Bendel A=14.81
175-0600-0103L	**	5 Port Ethernet Switch	Gadget Smyth	MGH	SEE Bendel A=12.73 (self-recovering SEE) SEE Bendel A=14.33 (SEE requiring intervention) DSEE: Bendel A=15.01, 1E10/cm² 200 MeV protons
ATXMEGA128A1U	1504	Microcontroller	Atmel	TAMU	Stuck bits – stuck at 0. Weibull: L_0=16.2, σ_{sat}=7.9E-5, W=101.3, S=2.3 tested powered to LET=77
JANSF2N7484T3	**	MOSFET	IR	NSRL	No SEE to LET=60 with fluence=1E6 ions/cm²
QT625LBM-25.8 MHZ	**	Oscillator	Q-Tech	NSRL	SEFI: Weibull: L_0=1.0, σ_{sat}=7.9E-6, W=5.9, S=5.01 Max LET=60 using VDBP method
IS9-139ASRH	**	Voltage Comparitor	Intersil	NSRL	No DSEE to LET=60 with fluence=1E6/cm²

LDC of ** - available upon request, Units*** 1) cross sections in cm²/device, 2) LET in MeV- cm²/mg, 3) usec=microsec, nsec=nanosec, msec=millisec

RESULTS: TABLE 2B: SUMMARY OF SEE TEST RESULTS

Part #	LDC**	Part type	Manufacturer	Facility	Weibull Parameters***
IS9-1825ASRH	**	PWM Controller	Intersil	NSRL	No DSEE to LET=60 with fluence=1E6 ions/cm²
SPT6235M-NPN	**	Transistor	SSDI	NSRL	No SEE to LET=60 with fluence=1E6 ions/cm²
4011BEDIE2HR	**	NAND Gate	ST-Micro	LBNL	Worst case SET: -370 mV, 20 nsecs, Max LET=77.5
RIC7113A4SCS	1424	High/Low side Gate Driver	IR	TAMU	Longest Dropout 550 msecs, No DSEE, Max LET=77
74AC00	1507	Quad 2-inout NAND Gate	Fairchild Semi	LBNL	Worst SET =+/- 300 mV, 58 nsecs, No DSEE, Max LET=75
HCPL-523K #300	1314	Dual Logic Opto	Avago Technologies	LBNL	No DSEE, Max LET=75
OLH249	1548	Opto - Hybrid	Isolink	LBNL	Worst case SET: 1.28V, 70 usecs, Max LET=75
RH6105	**	Current Sense Amp	Linear Tech	LBNL	Worst case SET: 3V / -1V, < 9 usecs, Max LET=75
SN54AHC244W	726	Octal Buffer	TI	TAMU	High Temp No DSEE, Max LET=77
IS42S16400J-5BL	**	SDRAM	ISSI	NSRL	Bitflip Error: Weibull: L_0=1.0, σ_{sat}=4.6E-1, W=110, S=2.9 No DSEE to fluence=7.68E4 ions/cm² at LET=39
SI7415DN-T1-GE3	**	P Channel MOSFET	Vishay	NSRL	No DSEE at LET=29, at 12V, to fluence=1E6 ions/cm²
DS2411R+T&R	**	SCSI terminator	Maxim	NSRL	No DSEE at LET=39 to fluence=7.79E4 ions/cm²
TMP006AIYZFR	**	Thermopile	TI	NSRL	Local temp error: Weibull: L_0=10, σ_{sat}=2.5E-5, W=14, S=4 Obj temp error: Weibull: L_0=5, σ_{sat} =3.2E-5 No DSEE at LET=29 to fluence=7.37E4 ions/cm²
74AUP1G157GW	**	Analog Mux	NXP	NSRL	No SEE to LET=39 with fluence=1.61E5 ions/cm²
ASDMPC-10.000MHZ-RT-T	**	Oscillator	Abracon	NSRL	Failed immediately
DS1339A	**	Clock	Maxim Integrated	NSRL	Soft Errors: Weibull: L_0=12, σ_{sat}=9E-5 No DSEE at LET=29 with fluence=7.54E4 ions/cm²
N25Q128	**	Flash memory	Micron	NSRL	Read Error: Weibull: L_0=1, σ_{sat}=4E-5, W=27, S=2 No DSEE to LET=29 with fluence=7.5E4 ions/cm²
CB3LV-3C-25MHZ	**	Oscillator		NSRL	No SEE to LET=39 with fluence=7.55E4 ions/cm²
FDMC86139	**	P-Channel MOSFET, 100V	Fairchild/ON semi	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
TLV70133	**	Linear Regulator	TI	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
TPS22929	**	Single Load Switch	TI	NSRL	No DSEE to LET=15 with fluence=1E5 ions/cm²
CB3LV	**	Oscillator	CTS-Frequency controls	NSRL	No DSEE to LET=15 with fluence=1E5 ions/cm²
TPS73601	**	Linear Voltage Regulator	TI	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
DP83640	**	Precision PHYTERTM IEEE 1588 Transceiver	TI	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
OPA2209	**	Precision Op Amps	TI	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
LM4040	**	Voltage Reference	ON-Semi	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
LT3092	**	200mA 2-Terminal Programmable Current Source	Linear Technology	NSRL	No DSEE to LET=11.75 with fluence=1E5 ions/cm²
OMAP L138	**	ARM/DSP Processor	TI	NSRL	L2 Error: Weibull: L_0=1, σ_{sat}=2.23E-2, W=57, S=1.04 Overcurrent Weibull: L_0 = 24, σ_{sat}=3E-4 L3 Error: Weibull: L_0=1, σ_{sat} =2.88E-4, W=16.6, S=1.166 L1D Error: Weibull: L_0=1, σ_{sat}=8.57E-3, W=120.8, S=1.2 CPU Functional Interrupt: Weibull: L_0=1, σ_{sat}=4.15E-4, W=55.2, S=1.2 PRU Functional Interrupt Weibull: L_0=3, σ_{sat}=2E-4 Software error Weibull: L_0=3, σ_{sat}=2.1E-4, W=19.5, S=1.628 No DSEE to LET=73 with fluence=1E4 ions/cm²
FRO15L3EZ	**	Reverse Polarity Device	ON Semiconductor	NSRL	No DSEE to LET=39 with fluence=1E6 ions/cm²
TPS62142	**	Temperature Sensor	TI	NSRL	No DSEE to LET=39 with fluence=1E6 ions/cm²
TPS73601	**	Remote Power Regulator	TI	NSRL	No DSEE to LET=39 with electronics=1E6 ions/cm²
RM48L950	**	16/32 BIT RISC Flash Microcontroller	TI	NSRL	RAM single bit error: Weibull: L_0=3, σ_{sat}=1.44E-2, W=19.5, S=1.628 Software error: Weibull: L_0=1, σ_{sat}=2.1E-4, W=27.3, S=0.869 Flash error: Weibull: L_0=2.7, σ_{sat}= 5.5E-4, SEFI: Weibull: L_0=1, σ_{sat}=6.0E-4 No DSEE: LET=39, 9E3 ions/cm²
KSZ8895	**	Ethernet Switch	Microchip Tech.	NSRL	DSEE: Weibull: L_0=12, σ_{sat}=1.59E-3, W=5.4, S=2.376
MT29F32G08	**	NAND flash	Micron	NSRL	MTD2 Byte error Weibull : L_0=3, σ_{sat}=1.3E-1, W=66.15, S=2.38 ECC was very effective at lower LET Erase Failed Error: Weibull: L_0=4, σ_{sat}=1.3E-4, W=23.8, S=0.462 MTD2 Bad Block Error: Weibull L_0=2, σ_{sat}=1.0E-4 No DSEE to LET=51 with fluence=5E4 ions/cm²
NVH0505	**	DC/DC converter		NSRL	No DSEE to LET=51 with fluence=1E4 ions/cm²
AD5622	**	Bias converter DAC	Analog Devices	NSRL	No SEE to LET=24 with fluence=1E4 ions/cm²
AD7991	**	Bias converter ADC	Analog Devices	NSRL	No SEE to LET=24 with fluence=1E4 ions/cm²
AGLN250V2-VQG100	**	Flash FPGA	Microsemi	NSRL	SEFI: L_0=18, σ=3E-5 No DSEE to LET=51 with fluence=9E3 ions/cm²
MT46H64M16LFB	**	DDR memory	Micron	NSRL	Single bit error Weibull: L_0=9, σ_{sat}=9E-3, W=10, S=1.274 Multiple bit error Weibull L_0=9, σ_{sat}=1E-4 No DSEE to LET=51 with fluence=1E4 ions/cm²
LAN8710A-EZC	**	Ethernet PHY	Microchip Tech	NSRL	SEFI: L_0=2, σ_{sat}=1E-4 No DSEE to LET=39 with fluence=1E5 ions/cm²
DS90LV047/48	**	Quad Line Driver/receiver	TI	NSRL	No SEE to LET=39 with fluence=1E5 ions/cm²
TIMEPIX	**	Radiation sensor	Timepix	NSRL	No SEE to LET=39 with fluence=1E5 ions/cm²
TPS54295RSAT	**	Switching Regulator	TI	NSRL	SEFI: Weibull: L_0=4, σ_{sat}=4.5E-5, W=3, S=2 DSEE at LET=19
LTC3646	**	Step down regulator	Linear Technology	NSRL	Trigger: Weibull: L_0=3, σ_{sat}=2.65E-4, W=44, S=1.38 SEFI: Weibull: L_0=39, σ=9E-5 No DSEE to LET=39 to fluence=9E4 ions/cm²
LM3880Q	**	Power Sequencer	TI	NSRL	No SEE to LET=24 with fluence=9E3 ions/cm² No DSEE to LET=39
INA230	**	Bidirectional current/power monitor	TI	NSRL	Trigger error: Weibull: L_0=24, σ_{sat}=7E-5, W=35, S=1 Register error: Weibull: L_0=24, σ_{sat}=6E-5, W=15, S=1 No DSEE to LET=51 with fluence=1E4 ions/cm²
OMH3040 OMH3005S	1523	Hall-effect Sensor	TT Electronics / Optek	LBNL	Worst case SET: 15V to ground, 4 usecs, No DSEE at LET= 77.5
RIC7113A4SCS	1424	High/Low side Gate Driver	IR	TAMU	Longest Dropout 550 msecs, No DSEE at 77
JANTXV2N3439UA	1447	High V Transistor	Microsemi	TAMU	Worst case SET: 2V and -2.4V, < 100 nsecs, No DSEE at LET=77
OMH3075	_0043	Hall-effect Sensor	TT Electronics / Optek	TAMU	Worst case SET: 15V to ground, 5 usecs, No DSEE at LET=75

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