Compendium of Recent Single Event Effects for Candidate Spacecraft Electronics for NASA

Martha V. O'Bryan, Dakai Chen, Michael J. Campola, Megan C. Casey, Alyson D. Topper, Kenneth A. LaBel, Jonathan A. Pellish, Jean-Marie Lauenstein, Robert A. Gigliuto, Edward P. Wilcox, Raymond L. Ladbury, Melanie D. Berg, and Robert R. Davies

***Abstract*— We present the results of single-event effects (SEE) testing and analysis investigating the effects of radiation on electronics. This paper is a summary of test results.**

***Index Terms*—Single event effects, spacecraft electronics, digital, linear bipolar, and hybrid devices.**

I. INTRODUCTION

The performance of electronic devices in a space radiation environment is often limited by its susceptibility to SEE. Interpreting the results of SEE testing of complex devices is quite difficult. Given the rapidly changing nature of both technology and the related SEE issues being discovered, SEE test data are very application specific and adequate understanding of the test conditions is critical [1].

Given this limitation of test data (application-specific), studies discussed herein were undertaken to establish the sensitivities of candidate spacecraft electronics, as well as new electronic devices, to heavy ion induced single-event upset (SEU), single-event latchup (SEL), single-event gate rupture (SEGR), single-event burnout (SEB), and single-event transients (SET). For total ionizing dose (TID) and displacement damage dose (DDD) results, see a companion paper submitted to the 2013 Institute of Electrical and Electronics Engineers (IEEE) Nuclear and Space Radiation Effects Conference (NSREC) Radiation Effects Data Workshop entitled: "Compendium of Recent Total Ionizing Dose and Displacement Damage for Candidate Spacecraft Electronics for NASA" by A. Boutte, *et al.* [2].

II. TEST TECHNIQUES AND SETUP

A. Test Facilities

All SEE tests were performed between March 2012 and February 2013. Heavy ion experiments were conducted at Lawrence Berkeley National Laboratory (LBNL) [3] and at the Texas A&M University Cyclotron (TAMU) [4]. Both of these facilities are suitable for providing a variety of ions over a range of energies for testing. The devices under test (DUTs) were irradiated with heavy ions having linear energy transfers (LETs) ranging from 0.6 to 120 MeV•cm^2/mg. Fluxes ranged from $1x10^2$ to $1x10^5$ particles/cm^2/s, depending on device sensitivity. Representative ions used are listed in Table I. LETs in addition to the values listed were obtained by changing the angle of incidence of the ion beam with respect to the DUT, thus changing the path length of the ion through the DUT and the "effective LET" of the ion [5]. Energies and LETs available varied slightly from one test date to another.

Laser SEE tests were performed at the pulsed laser facility at the Naval Research Laboratory (NRL) [6], [7]. For single photon absorption, the laser light had a wavelength of 590 nm resulting in a skin depth (depth at which the light intensity decreased to 1/e – or about 37% – of its intensity at the surface) of 2 μm. A nominal pulse rate of 1 kHz was utilized. Pulse width and beam spot size are listed in Table II.

This work was supported in part by the NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA).

Martha V. O'Bryan is with MEI Technologies Inc., work performed for NASA Goddard Space Flight Center (GSFC), Code 561.4, Bldg. 22, Rm. 062A, Greenbelt, MD 20771 (USA), phone: 301-286-1412, fax: 301-286-4699, email: martha.v.obryan@nasa.gov.

Dakai Chen, Michael J. Campola, Megan C. Casey, Kenneth A. LaBel, Jonathan A. Pellish, Jean-Marie Lauenstein, and Raymond L. Ladbury are with NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), email: Dakai.Chen-1@nasa.gov, michael.j.campola@nasa.gov, megan.c.casey @nasa.gov, kenneth.a.label@nasa.gov, jonathan.a.pellish@nasa.gov, jean.m.lauenstein@nasa.gov, raymond.l.ladbury@nasa.gov.

Alyson D. Topper, Robert A. Gigliuto, Edward P. Wilcox, and Melanie D. Berg are with MEI Technologies, Inc., work performed for NASA/GSFC, Code 561.4, Greenbelt, MD 20771 (USA), email: Alyson.D.Topper @nasa.gov, Robert.A.Gigliuto@nasa.gov, Ted.Wilcox@nasa.gov, and Melanie.D.Berg@nasa.gov.

Robert R. Davies, is with Ball Aerospace & Technologies Corporation, P.O. Box 1062, Boulder, CO 80306-1062, email: rrdavies@ball.com.

TABLE I: HEAVY ION TEST FACILITIES AND TEST HEAVY IONS

	Ion	Energy (MeV)	Surface LET in Si (MeV•cm^2/mg) (Normal Incidence)	Range in Si (µm)
LBNL	^{18}O	183	2.2	226
	^{22}Ne	216	3.5	175
	^{40}Ar	400	9.7	130
	^{23}V	508	14.6	113
	^{65}Cu	660	21.2	108
	^{84}Kr	906	30.2	113
	^{107}Ag	1039	48.2	90
	^{124}Xe	1233	58.8	90
	10 MeV per amu tune			
TAMU	^{14}N	210	1.3	428
	^{20}Ne	300	2.5	316
	^{40}Ar	599	7.7	229
	^{63}Cu	944	17.8	172
	^{84}Kr	1259	25.4	170
	^{109}Ag	1634	38.5	156
	^{129}Xe	1934	47.3	156
	^{197}Au	2954	80.2	155
	15 MeV per amu tune			

amu = atomic mass unit

TABLE II: LASER TEST FACILITY

Naval Research Laboratory (NRL) Pulsed Laser SEE Test Facility
Laser: 590 nm, 1 ps pulse width, beam spot size ~1.2 μm

B. *Test Method*

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages. We recognize that high-temperature and worst-case power supply conditions are recommended for SEL device qualification. Testing is performed per JESD57 test procedures unless otherwise noted [8].

1) *SEE Testing - Heavy Ion:*

Depending on the DUT and the test objectives, one or more of three SEE test methods were typically used:

Dynamic – the DUT was exercised continually while being exposed to the beam. The events and/or bit errors were counted, generally by comparing the DUT output to an unirradiated reference device or other expected output (Golden chip or virtual Golden chip methods) [9]. In some cases, the effects of clock speed or device operating modes were investigated. Results of such tests should be applied with caution due to the application-specific nature of the results.

Static – the DUT was loaded prior to irradiation; data were retrieved and errors were counted after irradiation.

Biased – the DUT was biased and clocked while power consumption was monitored for SEL or other destructive effects. In most SEL tests, functionality was also monitored.

In SEE experiments, DUTs were monitored for soft errors, such as SEUs, and for hard errors, such as SEGR. Detailed descriptions of the types of errors observed are noted in the individual test reports [10], [11].

SET testing was performed using a high-speed oscilloscope controlled via LabVIEW®. Individual criteria for SETs are specific to the device being tested and the application. Please see the individual test reports for details [10], [11].

Heavy ion SEE sensitivity experiments include measurement of the linear energy transfer threshold (LET$_{th}$) and cross section at the maximum measured LET. The LET$_{th}$ is defined as the maximum LET value at which no effect was observed at an effective fluence of 1×10^7 particles/cm^2. In the case where events are observed at the smallest LET tested, LET$_{th}$ will either be reported as less than the lowest measured LET or determined approximately as the LET$_{th}$ parameter from a Weibull fit. In the case of SEGR experiments, measurements are made of the SEGR threshold V$_{ds}$ (drain-to-source voltage) as a function of LET at a fixed V$_{gs}$ (gate-to-source voltage).

2) *Pulsed Laser Facility Testing*

The DUT was mounted on an X-Y-Z stage in front of a 100x lens that produces a spot diameter of about 1.2 µm at full-width half-maximum (FWHM). The X-Y-Z stage can be moved in steps of 0.1 μm for accurate positioning of SEU sensitive regions in front of the focused beam. An illuminator, together with a charge coupled device (CCD) camera and monitor were used to image the area of interest thereby facilitating accurate positioning of the device in the beam. The pulse energy was varied in a continuous manner using a polarizer/half-waveplate combination and the energy was monitored by splitting off a portion of the beam and directing it at a calibrated energy meter.

III. TEST RESULTS OVERVIEW

Principal investigators are listed in Table III. Abbreviations and conventions are listed in Table IV. SEE results are summarized in Table V. Unless otherwise noted, all LETs are in MeV•cm^2/mg and all cross sections are in cm^2/device. All SEL tests are performed to a fluence of 1×10^7 particles/cm^2 unless otherwise noted.

TABLE III: LIST OF PRINCIPAL INVESTIGATORS

Principal Investigator (PI)	Abbreviation
Melanie D. Berg	MB
Megan C. Casey	MC
Michael J. Campola	MJC
Dakai Chen	DC
Robert A. Gigliuto	RG
Raymond L. Ladbury	RL
Jean-Marie Lauenstein	JML
Jonathan A. Pellish	JP
Edward (Ted) P. Wilcox	TW

TABLE IV: ABBREVIATIONS AND CONVENTIONS

LET = linear energy transfer (MeV•cm^2/mg)
LET$_{th}$ = linear energy transfer threshold (the maximum LET value at which no effect was observed at an effective fluence of 1x10^7 particles/cm^2 – in MeV•cm^2/mg)
< = SEE observed at lowest tested LET
> = no SEE observed at highest tested LET
σ = cross section (cm^2/device, unless specified as cm^2/bit)
σ$_{maxm}$ = cross section at maximum measured LET (cm^2/device, unless specified as cm^2/bit)
BiCMOS = bipolar complementary metal oxide semiconductor
BJT = bipolar junction transistor
CCD = charge coupled device
CMOS = complementary metal oxide semiconductor
C$_{out}$ = output capacitance
DDR2 SDRAM = 2nd generation double data rate synchronous dynamic random access memory
DFF = D flip-flop
DUT = device under test
JFET = junction field-effect transistor
H = heavy ion test
I$_{out}$ = output current
L = laser test
LBNL = Lawrence Berkeley National Laboratory
LDC = lot date code
LDMOS = lateral diffused metal-oxide semiconductor
MOSFET = metal oxide semiconductor field effect transistor
N/A = not available
NRL = Naval Research Laboratory

TABLE IV: ABBREVIATIONS AND CONVENTIONS (CONT).

Op-Amp = operational amplifier
PI = principal investigator
REAG = Radiation Effects and Analysis Group
PRBS = Pseudorandom Binary Sequence
SCD = source control drawing
SEB = single -event burnout
SEE = single-event effect
SEFI = single-event functional interrupt
SEGR = single-event gate rupture
SEL = single-event latchup
SET = single-event transient
SEU = single-event upset
Si = silicon
SiC = silicon carbide
SiGe = silicon germanium
SMT = surface mount technology
SOI = silicon-on-insulator
TAMU = Texas A&M University Cyclotron Facility
TRIP = test report in progress
VDMOS = vertical double-diffused metal-oxide semiconductor
V$_{be}$ = base-emitter voltage
V$_{cc}$ = core voltage
V$_{ce}$ = collector-emitter voltage
V$_{ds}$ = drain-source voltage
V$_{gs}$ = gate-source voltage
V$_{in}$ = input voltage
V$_{IO}$ = input/output voltage
V$_{out}$ = output voltage
V$_{R}$ = reverse voltage
WC = worst case

TABLE V: SUMMARY OF SEE TEST RESULTS

Part Number	Manufacturer	LDC	Device Function	Technology	Particle: (Facility/Year/Month) P.I./REAG ID #	Test Results: LET in MeV•cm^2/mg, σ in cm^2/device, unless otherwise specified	Supply Voltage	Sample Size (Number Tested)	Reference
Voltage Regulators / Low Dropout Regulators:									
MSK5978RH	M. S. Kennedy	1217 LBNL; 1138 NRL	Voltage Regulator	Bipolar	H: (LBNL12Sep) DC; 12-077; L: (NRL12Dec) MJC; 13-025	H: SET LET$_{th}$ ~ 3.5 and σ$_{maxm}$ = 1 × 10^{-3} cm^{-2} at LET = 58.8, for 1.5V output. SET amplitude = ±200 mV and width = 2 µs, for 1.5 and 3.3 V output. L: WC SET observed of pulse width 5µs, pulse height -0.2 V with application filter.	5-10 V LNBL; 5 V NRL	2	[12], [13]
VRG8660	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-053	WC SET observed of pulse width 2.5 µs, pulse height -2.5 V	5 V	2	TRIP
VRG8661	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-040	WC SET observed of pulse width 8 µs, pulse height 1.9 V	-5 V	2	TRIP
VRG8662	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-041, 12-053	WC SET observed of pulse width 70 µs, pulse height 1.2 V	5 V	2	TRIP
VRG8663	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-041, 12-053	WC SET observed of pulse width 0.7 µs, pulse height -1.5 V	-5 V	2	TRIP
VRG8666	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-041, 12-053	WC SET observed of pulse width 20 µs, pulse height -0.25 V	5 V	2	TRIP
VRG8684	Aeroflex	N/A	Voltage Regulator	Bipolar	L: (NRL13Feb) MJC; 12-053	WC SET observed of pulse width 97 µs, pulse height 1.87 V	5 V	2	TRIP
IRUH330	International Rectifier	1138	Low dropout regulator	SOI	H: (LBNL12May) DC; 12-012	No SET observed with trigger settings of +60 mV and -200 mV. (Facility noise determined the trigger levels)	5 V	2	TRIP
MSK5058RH	M. S. Kennedy	1049	Low dropout regulator	Bipolar	H: (LBNL12Mar; LBNL12May) DC; 12-021	9.7 < SET LET$_{th}$ ≤ 19.5 and σ$_{maxm}$ = 2.21 × 10^{-4} cm^2 at LET = 58.8. Amplitude = - 0.7 V and width = 100 µs. C$_{out}$ = 2 × 47 µF and V$_{out}$ = 1.5 V.	5 V	1	[14], [15], [16]
Amplifiers:									
LMP2012	National Semiconductor	H9B1150A	Op-Amp	Bipolar	L: (NRL12Dec) MJC; 12-085	WC SET observed of pulse width 5 µs, pulse height -3.3 V	3.3 V	2	TRIP
SMA1031	M/A-COM	1218	Cascadable Amplifier	Hybrid	H: (LBNL12Nov) MJC; 12-051	SEL LET$_{th}$ > 67.9; SET LET$_{th}$ < 58.8; SETs were < 5 ns	5 V; 7 V; 10 V	3	[17]

Part Number	Manufacturer	LDC	Device Function	Tech-nology	Particle: (Facility/Year/Month) P.I./REAG ID #	Test Results: LET in MeV•cm^2/mg, σ in cm^2/device, unless otherwise specified	Supply Voltage	Sample Size (Number Tested)	Reference
Logic Device:									
NBSG53AMNG	On Semiconductor	0951	DFF	SiGe	H: (LBNL12Sep) MJC; 12-007	SEL LET$_{th}$ > 58.8	3.3 V	3	[18]
54LVTH16244	Texas Instruments	1117C	Buffer	BiCMOS	H: (LBNL13Jan) DC; 13-008	SEL $\sigma_{maxm} = 2.56 \times 10^{-6}$ cm^2 and LET$_{th}$ = 62 for the 90% confidence level upper bound worst case rate. Tested with case temperature = 93±3 ^{o}C.	3.5 V	3	[19]
54LVTH16245	Texas Instruments	1037D	Bus Transceiver	BiCMOS	H: (LBNL13Jan) DC; 13-007	SEL LET$_{th}$ > 75, with case temperature = 93±3 ^{o}C.	3.5 V	2	[20]
DC-DC Converters:									
SA50-28	Microsemi	1140	DC-DC Converter	SMT (CMOS, BiCMOS, and Bipolar)	H: (LBNL12May) DC; 12-019	Contact PI for test results.	28 V	1	none
M3G280515T	International Rectifier	0943; 1036	DC-DC Converter	Bipolar/ MOSFET	H: (TAMU12Mar) RG; A635	SEB of MBR20200 diode in output filter at LET = 51.5 Load = max conditions (80%/25%/25%)	36 V	4	[21]
Memory Devices:									
M470T6464QZ3-CE6 (K4T1G084QF-BCE7DDR2)	Samsung	N/A	DDR2 SDRAM	CMOS	H: (TAMU12Nov) RL; 12-036	SEL LET$_{th}$ > 81 SEU LET$_{th}$ < 0.6; SEUs observed for all test ions including Nitrogen; SEU $\sigma_{maxm} \sim 2.1 \times 10^{-3}$ cm^2	1.8 V	3	[22]
K9FAG08U0M	Samsung	1043	16 Gbit NAND Flash	32nm CMOS NAND	H: (LBNL12May) TO; A456	SEL LET$_{th}$ > 82; SEU LET$_{th}$ < 3.5; SEFI LET$_{th}$ ~ 30	3.3 V	2	[23]
MOSFET / Power Diodes / Transistors:									
CMF20120D	CREE	N/A	Power MOSFET	SiC	H: (TAMU12Aug; LBNL12Nov) MC; 12-030 and A554	SEGR LET$_{th}$ < 5.6. MOSFETs failed at V_{ds} as low as 120 V with 944 MeV Ar and as low as 60 V with 1032 MeV Kr.	0 V_{gs}	TAMU 11; LBNL 11	TRIP
CMF10120D	CREE	N/A	Power MOSFET	SiC	H: (TAMU12Aug; LBNL12Nov) MC 12-080	SEGR LET$_{th}$ < 9.7. MOSFETs failed at V_{ds} as low as 130 V with 400 MeV Ar and as low as 50 V with 1232 MeV Xe.	0 V_{gs}	18	TRIP
BT1206	TranSiC	3910	Transistor	SiC BJT	H: (LBNL12Mar; TAMU12Aug) MC; A555; 12-081	SEB LET$_{th}$ < 20.3. BJTs failed with 1914 MeV Kr at V_{ce} as low as 370 V with a 1 MΩ collector current limiting resistor, and at < 360 V with no resistor.	0 V_{be}	LBNL 4; TAMU 4	TRIP
SJEP120R100	SemiSouth	T1026	JFET	SiC	H: (TAMU12Aug) MC; A535	SEB LET$_{th}$ < 5.6. JFETs failed at V_{ds} as low as 450 V with 944 MeV Ar.	0, -5, -10 V_{gs}	7	TRIP
SJEP170R550	SemiSouth	PD90A1215 PH	JFET	SiC	H: (LBNL12Nov) MC; 12-082	SEB LET$_{th}$ < 9.7. JFETs failed at V_{ds} as low as 700 V with 400 MeV Ar.	1700 V	4	TRIP
SFR130S.5	SSDI	12012	100 V N-type MOSFET	VDMOS	H: (LBNL12Nov) JML; 12-087	Primary failure mode: SEB. 886 MeV Kr (LET = 31) max pass/first fail V_{ds}: 35/40V at 0V_{gs}, 40/45 V at -10V_{gs}, -20V_{gs}; 400 MeV Ar (LET = 9.7): 60/65 V at 0V_{gs}.	0, -10, -20 V_{gs}	11	[24]
Test Structure	Tower JAZZ	CA18HA B1230-X18	40 V MOSFET	LDMOS	H: (LBNL12Nov) JML; A613	Tests conducted on multiple process variations in support of product development.	0 V_{gs}	5	TRIP
BUY25CS54A	Infineon	1146.5	250 V N-type MOSFET	Super-junction	H: (TAMU12Aug; TAMU12Dec) JML; A624	Primary failure mode: SEGR. 1289 MeV Ag (LET = 42) & 1512 MeV Xe (LET = 52) pass 250 V_{ds} at 0 to -15 V_{gs}; 2247 MeV Au (LET = 85) pass 250 V_{ds} at 0 to -10 V_{gs}, max pass/first fail V_{ds} 130/140V at -15 V_{gs}	0, -5, -10, -15 V_{gs}	10 in Aug; 8 in Dec	[25]
JAXA R 2SK4188	Fuji	1128	500 V N-type MOSFET	VDMOS	H: (TAMU12Aug) JML; 12-038	Primary failure mode: SEGR. 1289 MeV Ag (LET = 42) first fail ~410 V_{ds} at 0 V_{gs}, max pass/first fail V_{ds} 50/60V at -13 V_{gs}	0, -13 V_{gs}	5	[26]

Part Number	Manufacturer	LDC	Device Function	Technology	Particle: (Facility/Year/Month) P.I./REAG ID #	Test Results: LET in MeV•cm^2/mg, σ in cm^2/device, unless otherwise specified	Supply Voltage	Sample Size (Number Tested)	Reference
RAD7264	Aeroflex	12-060	250 V N-type MOSFET	VDMOS	H: (TAMU12Aug) JML; 12-023	Primary failure mode: SEGR. 1348 MeV Ag (LET = 41) pass 250 V_{ds} at 0, -5 V_{gs}, max pass/first fail V_{ds} 240/250V at -10 V_{gs}, 90/100V at -15 V_{gs}; 1512 MeV Xe (LET = 52) pass 250 V_{ds} at 0 V_{gs}, max pass/first fail V_{ds} 220/240V at -5 V_{gs}, 80/90V at -10 V_{gs}	0, -5, -10, -15 V_{gs}	10	[27]
STRH100N10FSY3	STMicroelectronics	Engineering Samples	100 V N-type MOSFET	VDMOS	H: (TAMU12Dec) JML; A639	Determination of worst-case energy for SEGR. Max pass/first fail V_{ds}: 291 MeV Cu (LET = 28) 25/30 V (vs. 45/50 V at 838 MeV (LET = 19)); 320 MeV – 509 MeV Kr (LET 39 – 35) 20/25 V (vs. 25/30 V at 1108 MeV (LET = 27))	-10 V_{gs}	16	TRIP
SUM45N25-58	Vishay	T11HAD	250 V N-type MOSFET	Trench	H: (LBNL12Nov) JML; 12-028	Primary failure mode likely SEB. 1039 MeV Ag (LET = 48) max pass/first fail V_{ds} 80/90 V at 0, -5, -10 V_{gs}	0, -5, -10 V_{gs}	9	TRIP
Miscellaneous:									
CDCM7005	Texas Instruments	0826A; 0831A	Clock Synthesizer	CMOS	H: (LBNL12Sep) MJC; 12-027 and 12-031 and/or 12-032	SEU LET_{th} > 4.9	3.3 V	2	TRIP
HMC6416USLC3	Hittite	300889	Comparator	SiGe	H (LBNL13Jan) MJC; 12-083	SEL LET_{th} > 58.8	3.3 V	3	TRIP
NB7L14MNG	ON Semiconductor	0934	Fanout Buffer	SiGe	H: (LBNL12Nov) MJC; 12-051	SEL LET_{th} > 58.8	3.3 V	3	[28]
MBRC20200CT	ON Semiconductor	N/A	Schottky Diode	Si	H: (LBNL12May; TAMU12Aug; LBNL12Sep; LBNL12Nov) MC/RG; 12-034	SEB LET_{th} > 2.2. Diodes failed at V_R = 200 V with 216 MeV Ne and at V_R = 110 V with 1232 MeV Xe.	V_R	14 in May; 6 in Aug; 16 in Sept; 12 in Nov	TRIP
120720A	Crane Aerospace & Engineering (Sensitron)	Wafer #: 1-T33	Schottky Diode	Si	H: (LBNL12Nov; TAMU13May) MC; 12-078	SEB LET_{th} > 77 at V_R = 45 V	V_R	7	TRIP
53111	Micropac	1105	Solid State Relay	Power MOSFET Optocoupler	(TAMU12Mar) JP/TW; A626	SEL LET_{th} > 84	3.3V	3	[29]
TLK2711-SP	Texas Instruments	0627A	Transceiver	0.25 μm CMOS	H: (LBNL12May) TW; 12-015	SEL LET_{th} > 67.9; SETs observed with internal PRBS test circuitry disabled; SEU σ_{maxm} = 9.25 x10^{-5} at an LET of 67.9.	2.5 V	2	[30]
A3PE3000L	Actel/Microsemi	1108 (2012 testing); 0832; 1031 (2011 testing)	ProASIC FPGA	CMOS	H: (LBNL12Mar; TAMU11SEP) MB; 12-052	Ongoing research investigating combined radiation effects; SEL LET_{th} > 75; SEU LET_{th} < 2.8 at 120 MHz; and < 2.8 at 2KHz.	V_{cc} = 1.5 V, V_{IO} = 3.3 V	2 tested in 2012; 6 tested in 2011	[31], [32], [33], [34]

IV. TEST RESULTS AND DISCUSSION

As in our past workshop compendia of NASA Goddard Space Flight Center (GSFC) test results, each DUT has a detailed test report available online at http://radhome.gsfc.nasa.gov [10] describing the test method, SEE conditions/parameters, and test results. Graphs of data are also provided.

This section contains summaries of testing performed on a selection of featured parts.

A. M.S. Kennedy MSK5978RH

The MSK5978RH is a radiation hardened low-dropout voltage regulator. The part is designed and packaged by M.S. Kennedy, using the RH3080 die from Linear Technology, Inc. We evaluated the SEE susceptibility at LBNL with 10 MeV/amu cocktail of heavy ions. The ion species included: Ne, Ar, Kr, and Xe. We tested the part with V_{in} = 5 V or 10 V, V_{out} = 1.5 V or 3.3 V, and I_{out} from 0.1 A to 0.5 A (0.7 A maximum rated). The test circuit included a 220 μF capacitor in parallel with a 330 kΩ resistor (1.5 V), or a 330 kΩ and 265 kΩ (3.3 V) resistor. A cooling plate kept at 5 ^{o}C managed the heat dissipation of the part inside the vacuum chamber. Proper heat sinking is critical during SEE testing of linear and switching regulators.

We found that the parts were susceptible to heavy-ion-induced glitches and perturbations. The SETs showed characteristics of output rippling. The output oscillations varied from 1.2 V to 1.7 V for the 1.5 V output and from 3.1 V to 3.5 V for the 3.3 V output. The duration of the oscillations lasted approximately 2 μs. Fig. 1 shows an example of a SET with V_{in} = 5 V, V_{out} = 1.5 V, and I_{out} = 0.1 A. The SET cross section showed dependence on the output voltage. The SET cross section was approximately one order of magnitude higher for the 1.5 V output than for the 3.3 V output at LET =

58.9 MeV•cm^2/mg. We also observed a higher cross section for the lower output load. Fig. 2 shows the SET cross section as a function of effective LET for various device conditions. Appropriate output filtering for ripple rejection may be required for space applications.

We did not observe any destructive events or functional interrupts for irradiations with Xe at normal incidence with LET = 58.9 MeV•cm^2/mg, and at a 30^o tilt angle with effective LET = 68 MeV•cm^2/mg. We note that the angular irradiation, especially at a 45^o incident angle, may have induced beam shadowing effects. The complete test report can be accessed via the web [11].

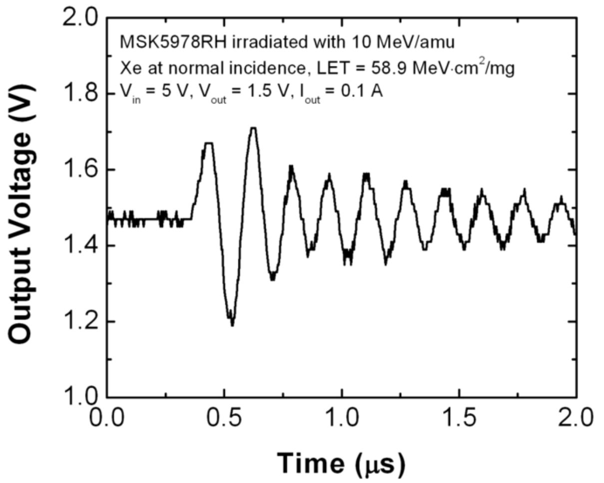

Fig. 1. Output voltage vs. time during an SET for the MSK5978RH irradiated with Xe at normal incidence at LET = 58.9 MeV•cm^2/mg, for V_{in} = 5 V, V_{out} = 1.5 V, and I_{out} = 0.1 A.

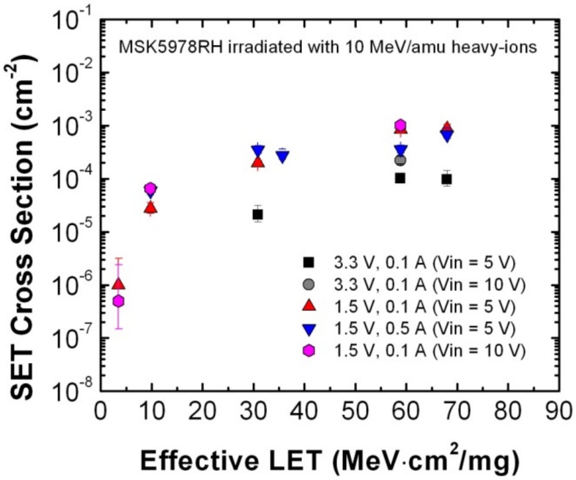

Fig. 2. SET cross section vs. effective LET for the MSK5978RH irradiated with 10 MeV/amu heavy ions, for various circuit conditions. Data set from one part only

B. *Crane Aerospace & Engineering and ON Semiconductor Schottky Diodes*

In the 2012 SEE Compendium [15], destructive SEE failures in two different DC-DC converters are discussed. After further failure analysis, it was discovered that both suffered similar destructive failures in the output Schottky diodes. The diodes internal to these converters were a 200 V Schottky manufactured by ON Semiconductor and a 45 V Schottky manufactured to the converter manufacturer's source control drawing (SCD), but is equivalent to a Crane Aerospace & Engineering diode. These diodes have been tested independently of the converters at TAMU using both the 15 MeV/amu and 25 MeV/amu beam tunes, and at LBNL using the 10 MeV/amu tune. The full results of these tests can be found in [35].

A distinct threshold LET was discovered for the ON Semiconductor diodes: when irradiated with 216 MeV Ne (LET = 3 MeV•cm^2/mg), they failed at a reverse voltage of 195 V, but no failures were observed when irradiated with 183 MeV O (LET = 2 MeV•cm^2/mg), even at the full-rated reverse voltage of 200 V. The heaviest ion with which they were irradiated was 1232 MeV Xe (LET = 59 MeV•cm^2/mg), and they failed at a reverse voltages as low as 115 V, which is well below the 75% derating required by NASA Technical Publication EEE-INST-002 [36]. After irradiation, the parts were visually examined and several showed displaced metal due to the high current when the diodes failed, which manifests as a short between the anode and cathode. When the displaced metal was apparent, it was always along the guard ring.

Interestingly, the Crane Aerospace & Engineering diodes were irradiated with 1232 MeV Xe and 2076 MeV Ta (LET = 77 MeV•cm^2/mg) and did not fail, even at the full-rated reverse voltage of 45 V. The diode in the original converter irradiation failed towards the center of the diode, and not along the guard ring like the ON Semiconductor parts. This may indicate a different source for the failure in the Crane Aerospace & Engineering diodes, such as latent electrostatic discharge damage.

Fig. 3 shows the last passing voltage at which the ON Semiconductor MBR20200CT diodes did not fail during irradiation.

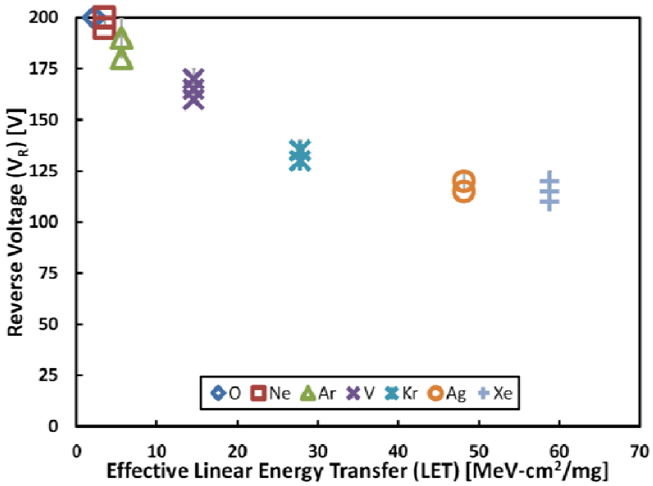

Fig. 3. The last passing voltage at which the MBR20200CT diodes did not fail during irradiation. The errors bars show the voltage at which the diode did fail.

V. ACKNOWLEDGMENT

The authors thank members of the Radiation Effects and Analysis Group who contributed to the test results presented here: Hak Kim, Alvin J. Boutte, Anthony M. Phan, Mark R. Friendlich, Donald K. Hawkins, James D. Forney, Donna J. Cochran, Christina M. Seidleck, Stephen R. Cox, and Martin A. Carts. Special thanks go to Cheryl J. Marshall, Paul W. Marshall, and Anthony B. Sanders for technical and editorial support.

VI. SUMMARY

We have presented current data from SEE testing on a variety of mainly commercial devices. It is the authors' recommendation that these data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

VII. REFERENCES

[1] Kenneth A. LaBel, Lewis M. Cohn, and Ray Ladbury,"Are Current SEE Test Procedures Adequate for Modern Devices and Electronics Technologies?," http://radhome.gsfc.nasa.gov/ radhome/ papers/ HEART08_LaBel.pdf

[2] Alvin J. Boutte, Donna J. Cochran, Dakai Chen, Michael J. Campola, Jonathan A. Pellish, Raymond L. Ladbury, Ted Wilcox, Jean-Marie Lauenstein, Robert A. Gigliuto, Kenneth A. LaBel, and Martha V. O'Bryan, "Compendium of Recent Total Ionizing Dose and Displacement Damage for Candidate Spacecraft Electronics for NASA," submitted for publication in IEEE Radiation Effects Data Workshop, Jul. 2013.

[3] Michael B. Johnson, Berkeley Lawrence Berkeley National Laboratory (LBNL), 88-Inch Cyclotron Accelerator, Accelerator Space Effects (BASE) Facility http://cyclotron.lbl.gov.

[4] B. Hyman, "Texas A&M University Cyclotron Institute, K500 Superconducting Cyclotron Facility," http://cyclotron.tamu.edu/ facilities.htm, Jul. 2003.

[5] W.J. Stapor, "Single-Event Effects Qualification," IEEE NSREC95 Short Course, sec. II, pp 1-68, Jul. 1995.

[6] J. S. Melinger, S. Buchner, D. McMorrow, T. R. Weatherford, A. B. Campbell, and H. Eisen, "Critical evaluation of the pulsed laser method for single event effects testing and fundamental studies," IEEE Trans. Nucl. Sci., vol 41, pp. 2574-2584, Dec. 1994.

[7] D. McMorrow, J. S. Melinger, and S. Buchner, "Application of a Pulsed Laser for Evaluation and Optimization of SEU-Hard Designs," IEEE Trans. Nucl. Sci., vol 47, no. 3, pp. 559-565, Jun. 2000.

[8] JEDEC Government Liaison Committee, Test Procedure for the Management of Single-Event Effects in Semiconductor Devices from Heavy Ion Irradiation," JESD57, http://www.jedec.org/standards-documents/docs/jesd-57, Dec. 1996.

[9] R. Koga and W. A. Kolasinski, "Heavy Ion-Induced Single Event Upsets of Microcircuits; A Summary of the Aerospace Corporation Test Data," IEEE Trans. Nucl. Sci., vol. 31, pp. 1190 – 1195, Dec. 1984.

[10] NASA/GSFC Radiation Effects and Analysis home page, http://radhome.gsfc.nasa.gov

[11] NASA Electronic Parts and Packaging (NEPP) web site, http://nepp.nasa.gov/.

[12] Dakai Chen, Paul Musil, Sana Rezgui, and Anthony Phan, "Heavy-ion Test Report for the MSK5978RH Low Dropout Voltage Regulator," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL090912_MSK5978RH.pdf, Sept. 2012.

[13] A. J. Boutte, M. Campola, J. Forney, "Single Event Transient Testing of the MSK5978RH Voltage Regulator," http://radhome. gsfc.nasa.gov/radhome/papers/NRL121912_MSK5978RH.pdf, Dec. 2012.

[14] Dakai Chen, Megan Casey, and Paul Musil, "Heavy-ion Test Report for the MSK5058RH Buck Regulator," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL032312_MSK5058RH, Mar. 2012.

[15] Martha V. O'Bryan, Kenneth A. LaBel, Jonathan A. Pellish, Jean-Marie Lauenstein, Dakai Chen, C.J. Marshall, M.C. Casey, R.A. Gigliuto, A.B. Sanders, T.R. Oldham, H.S. Kim, A.M.Phan, M.D. Berg, P.W. Marshall, R. L. Ladbury, E. P. Wilcox, A.J. Boutte, P.L. Musil and G.A. Overend, "Compendium of Single Event Effects for Candidate Spacecraft Electronics for NASA," NSREC 2012 IEEE Radiation Effects Data Workshop, pp. 22-30, Jul. 2012.

[16] Dakai Chen and Ted Wilcox, "Pulsed-laser Test Report of the MSK5058RH Switching Regulator," http://radhome.gsfc.nasa. gov/ radhome/ papers/ NRL082411_MSK5058RH.pdf, Aug. 2011.

[17] Michael Campola, Ted Wilcox, and Hak Kim, "Heavy Ion Test Results of the M/A-COM SMA1031 Amplifier," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL111412_SMA1031.pdf, Nov. 2012.

[18] Michael Campola and Ted Wilcox, "Heavy Ion Test Results of the On Semiconductor NBSG53AMN D-Flip Flop," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL090812_NBSG53AMN.pdf, Sept. 2012.

[19] Dakai Chen, Megan Casey, Anthony Phan, Hak Kim, and Rob Davies, "Heavy-ion Test Report for the 54LVTH16244 Buffer," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL013113_ 54LVTH16244.pdf, Jan. 2013.

[20] Dakai Chen, Megan Casey, Anthony Phan, Hak Kim, and Rob Davies, "Heavy-ion Test Report for the 54LVTH16245 Bus Transceiver," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL013113_54LVTH16245.pdf, Jan. 2013.

[21] Robert Gigliuto and Megan Casey, "Observed Diode Failures in DC-DC Converters," NEPP Electronic Technology Workshop, http://nepp.nasa.gov/workshops/etw2012/talks/Tuesday/T15_Gigliuto_Observed_Diode_Failures.pdf, Jun. 2012.

[22] Raymond Ladbury, Melanie Berg, Ted Wilcox, Anthony Phan and Hak Kim "Samsung K4T1G084QF-BCE7DDR2 SDRAM Heavy-Ion Single-Event Effects Characterization Report," note: the M470T2863FB3-CE6 DDR2 die are components on K4T1G084QF-BCE7DDR2, http://radhome. gsfc.nasa.gov/ radhome/ papers/ TAMU12Nov_M470T2863FB3.pdf, Nov. 2012.

[23] Timothy Oldham, "Samsung 16G NAND Flash Memory SEE Test Report," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL051812_K9FAG08U0M.pdf, A456, May 2012.

[24] J.-M. Lauenstein, A. M. Phan, A. D. Topper, and E. P. Wilcox, "Single-Event Effect Testing of the Solid State Devices, Inc. SFR130S.5 n-Type Power MOSFET," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL111512_SFR130S5.pdf, Nov. 2012.

[25] J.-M. Lauenstein, M.C. Casey, A.D. Topper, A.M. Phan, and E.P. Wilcox, "Single-Event Effect Testing of the Infineon Technologies BUY25CS54A (ESCC 5205/027) n-Type Power MOSFET," http://radhome. gsfc.nasa.gov/ radhome/ papers/ T082112_ BUY25CS54A.pdf, Aug. 2012.

[26] Jean-Marie Lauenstein, Megan Casey, Alyson Topper, Anthony Phan, and Ted Wilcox, "Preliminary SEE Test Report (V2) Single-Event Effects Testing of the Fuji JAXA R2SK4188 n-Type Power MOSFET," http://radhome. gsfc.nasa.gov/ radhome/ papers/ T082112_JAXAR2SK4188.pdf, Aug. 2012.

[27] J.-M. Lauenstein, M.C. Casey, A.M. Phan, E.P. Wilcox, and A.D. Topper, "Single-Event Effect Testing of the Aeroflex Corporation RAD7264 n-Type Power MOSFET," http://radhome. gsfc.nasa.gov/ radhome/ papers/ T082112_RAD7264.pdf, Aug. 2012.

[28] Michael Campola "Single Event Effects testing of the On Semiconductor NB7L14MNG Fanout Buffer," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL013113_NB7L14MNG.pdf, Jan. 2013.

[29] Jonathan A. Pellish, Ted Wilcox, and Alvin Boutte, "Heavy Ion Test Results of the Micropac 53111 Power MOSFET Optocoupler," http://radhome. gsfc.nasa.gov/ radhome/ papers/ T031112_53111.pdf, A626, Mar. 2012.

[30] Ted Wilcox, "Heavy Ion Test Results of the Texas Instruments TLK2711-SP Transceiver," http://radhome. gsfc.nasa.gov/ radhome/ papers/ LBNL051812_TLK2711.pdf, May 2012.

[31] M. Berg, M. Friendlich, C. Perez, H. Kim, and Ken LaBel, "Taming the Single Event Upset (SEU) Beast - Approaches and Results for Field Programmable Gate Array (FPGA) Devices and How to Apply Them," NEPP Elec. Tech. Workshop, http://radhome.gsfc.nasa.gov/ radhome/ papers/NEPP_ETW2011_Berg.pdf, Jun. 2011.

[32] M. Berg, M. Friendlich, J. Lakeman, T. Wilcox, H. Kim, K. LaBel, and J. Pellish, "Single Event Effects in Field Programmable Gate Array (FPGA) Devices: Update 2012," NEPP Elec. Tech. Workshop, http://radhome. gsfc. nasa. gov/ radhome/ papers/ NEPP_ETW2012_ Berg.pdf, Jun. 2012.

[33] Melanie Berg, Hak Kim, Mark Friendlich, Chris Perez, Christina Seidlick, and Ken LaBel, "Actel ProASIC A3PE3000L-PQ208 Field Programmable Gate Array Single Event Effects (SEE) High-Speed Test Plan- Phase II," http://radhome. gsfc.nasa.gov/ radhome/ papers/ T091011_A3PE3000L.pdf, Sept. 2011.

[34] Melanie Berg, Hak Kim, Mark Friendlich, Chris Perez, Christina Seidlick, and Ken Label, "Actel ProASIC Field Programmable Gate Array Single Event Effects (SEE) High-Speed Test - Phase I," http://radhome.gsfc.nasa.gov/ radhome/ papers/ T052110_A3PE 3000.pdf, Mar. 2010.

[35] M. C. Casey, J.-M. Lauenstein, D. Chen, K. A. Label, R. A. Gigliuto, E. P. Wilcox, H. S. Kim, A. M. Phan, "Destructive Single-Event Failures in Diodes," to be presented at the IEEE NSREC, July 2013 and published in IEEE Tran. Nucl. Sci., Dec. 2013.

[36] Dr. Kusum Sahu, "EEE-INST-002: Instructions for EEE Parts Selection, Screening, Qualification, and Derating," http://nepp.nasa. gov/DocUploads/FFB52B88-36AE-4378-A05B2C084B5EE2CC/ EEE-INST-002_add1.pdf, Apr. 2008.