Current Total Ionizing Dose Results and Displacement Damage Results for Candidate Spacecraft Electronics for NASA

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Abstract—We present data on the vulnerability of a variety of candidate spacecraft electronics to total ionizing dose and displacement damage. Devices tested include optoelectronics, digital, analog, linear bipolar devices, hybrid devices, Analog-to-Digital Converters (ADCs), and Digital-to-Analog Converters (DACs), among others.

I. INTRODUCTION

The space flight community will continue to utilize commercial and emerging technology devices to meet the increasing demands for higher performance, cost savings, and delivery schedules. With the use of these devices, the importance of ground testing for the effects of total ionizing dose (TID) and proton-induced degradation to qualify the devices for flight, can not be underestimated due to the inherent vulnerability of many of these devices.

The test results presented here were gathered to establish the sensitivity of the devices selected as candidate spacecraft electronics to TID and proton damage. Proton-induced degradation is a mix of ionizing (TID) and non-ionizing damage. This non-ionizing damage is commonly referred to as displacement damage (DD). This testing serves to determine the limit to which a candidate device may be used in space applications. For single event effects (SEE) results, see a companion paper submitted to the 2004 IEEE NSREC Radiation Effects Data Workshop entitled: "Current Single Event Effects Results for Candidate Spacecraft Electronics for NASA" by M. O'Bryan, et al. [1]

II. TEST TECHNIQUES AND SETUP

A. Test Facilities - TID

TID testing was performed using a Co-60 source at the Goddard Space Flight Center Radiation Effects Facility (GSFC REF). The source is capable of delivering a dose rate of up to 0.5 rads(Si)/s, with dosimetry being performed by an ion chamber probe.

B. Test Facilities – Proton

Proton DD/TID tests were performed at two facilities: The University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL) that has a 76° cyclotron (maximum energy of 63 MeV), and the Indiana University Cyclotron Facility (IUCF) that has an 88° cyclotron (maximum energy of 205 MeV). Table I lists the proton damage test facilities and energies used on the devices.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of California at Davis (UCD)</td>
<td>26.6-63</td>
</tr>
<tr>
<td>Crocker Nuclear Laboratory (CNL)</td>
<td></td>
</tr>
<tr>
<td>Indiana University Cyclotron Facility (IUCF)</td>
<td>54-205</td>
</tr>
</tbody>
</table>

C. Test Methods

Unless otherwise noted, all tests were performed at room temperature and with nominal power supply voltages.

Presented by Donna Cochran at NSREC04 Data Workshop, Atlanta, GA, July 22, 2004
1) **TID Testing**

TID testing was performed to the MIL-STD-883 1019.6 test method [2].

2) **Proton Damage Testing**

Proton damage tests were performed on biased devices with functionality and parametrics being measured either continually during irradiation (in-situ) or after step irradiations (for example: every 10 krad(Si), or every 1x10^10 protons).

### III. Test Results Overview

Abbreviations and conventions are listed in Table II. Abbreviations for principal investigators (PIs) are listed in Table III. Definitions for the categories are listed in Table IV. This paper is a summary of results. Please note that these test results can depend on operational conditions. Complete test reports are available online at http://radhome.gsfc.nasa.gov [3].

Table II: Abbreviations and Conventions:

- ADC = analog to digital converter
- ASIC = application specific integrated circuit
- CCD = charge coupled device
- CMOS = complementary metal oxide semiconductor
- CTR = current transfer ratio
- DAC = digital to analog converter
- DD = displacement damage
- DNL = differential non-linearity
- DUT = device under test
- GSFC REF = Goddard Space Flight Center Radiation Effects Facility
- I_bias = bias current
- I_f = forward current
- I_os = offset current
- I_read = Read current
- LDC = lot date code
- I_cc = power supply current
- MeV = Mega electron volt
- N/A = not applicable
- op amp = operational amplifier
- opto = optocoupler
- p/cm^2 = protons/cm^2
- PI = Principal Investigator
- RHrFPGA = radiation hardened reprogrammable field programmable gate array
- TID = total ionizing dose
- V_il = input saturation voltage
- V_load = load voltage
- V_ok = output saturation voltage
- V_os = offset voltage

<table>
<thead>
<tr>
<th>Table III: List of Principal Investigators</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Abbreviation</strong></td>
</tr>
<tr>
<td>SB</td>
</tr>
<tr>
<td>JH</td>
</tr>
<tr>
<td>SK</td>
</tr>
<tr>
<td>KL</td>
</tr>
<tr>
<td>RL</td>
</tr>
<tr>
<td>CM</td>
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<td>PM</td>
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<tr>
<td>CP</td>
</tr>
<tr>
<td>RR</td>
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<table>
<thead>
<tr>
<th>Table IV: List of Categories</th>
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<tr>
<td>2</td>
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<td>3</td>
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<tr>
<td>4</td>
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<tr>
<td>5</td>
</tr>
</tbody>
</table>

**REV** Research Test Vehicle – Please contact the P.I. before utilizing this device for spacecraft applications.
<table>
<thead>
<tr>
<th>Part Number</th>
<th>Manufacturer</th>
<th>LDC</th>
<th>Function</th>
<th>Facility Date/P.I (Co-60 source unless otherwise noted)</th>
<th>Dose rate (rads(Si)/y)</th>
<th>Summary of Results</th>
<th>Degradation Level (krads(Si))</th>
<th>Cat.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SN74LVC16244A</td>
<td>Texas Instruments</td>
<td>No LDC available; Markings: 31AX94k</td>
<td>Buffer/Driver</td>
<td>GSFC03/SB</td>
<td>~0.2</td>
<td>No parametric degradation to 20 krad(Si)</td>
<td>&gt;20</td>
<td>1</td>
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<tr>
<td>SN74LVC16245A</td>
<td>Texas Instruments</td>
<td>No LDC available; Markings: 29E8Y5K</td>
<td>Transceiver</td>
<td>GSFC03/SB</td>
<td>~0.2</td>
<td>No parametric degradation to 20 krad(Si)</td>
<td>&gt;20</td>
<td>1</td>
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<tr>
<td>CD54HC4052</td>
<td>Texas Instruments</td>
<td>0232</td>
<td>Multiplexer/Demultiplexer</td>
<td>GSFC04/JH</td>
<td>~0.2</td>
<td>Icc exceeds specification limits after 18-25 krad(Si); Functional after 25 krad(Si) (max dose tested)</td>
<td>18-25</td>
<td>4</td>
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<tr>
<td>TC5525</td>
<td>Toshiba</td>
<td>0030</td>
<td>32kx8 SRAM</td>
<td>GSFC001JUN/SB</td>
<td>0.28</td>
<td>krad(Si) may exceed specification limits after 30 krad(Si) (max dose tested)</td>
<td>20-30</td>
<td>3</td>
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<tr>
<td>T367-GAFE7</td>
<td>Agilent</td>
<td>Nov03</td>
<td>ASIC</td>
<td>GSFC04FEB/SK</td>
<td>0.03</td>
<td>No parametric degradation to 10 krad(Si)</td>
<td>&gt;10</td>
<td>1</td>
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<tr>
<td>T367-GARC3</td>
<td>Agilent</td>
<td>Nov03</td>
<td>ASIC</td>
<td>GSFC04FEB/SK</td>
<td>0.04</td>
<td>No parametric degradation to 10 krad(Si)</td>
<td>&gt;10</td>
<td>1</td>
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<tr>
<td>ADC1175</td>
<td>National</td>
<td>Markings: EM04AB</td>
<td>8 bit ADC</td>
<td>GSFC03OCT/CP</td>
<td>~0.17</td>
<td>No parametric degradation to 48 krad(Si)</td>
<td>&gt;48</td>
<td>1</td>
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<tr>
<td>MAX145</td>
<td>Maxim</td>
<td>0310</td>
<td>ADC</td>
<td>GSFC04/SK</td>
<td>0.03</td>
<td>No parametric degradation to 10 krad(Si)</td>
<td>&gt;10</td>
<td>1</td>
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<tr>
<td>MAX494</td>
<td>Maxim</td>
<td>0229</td>
<td>Quad Op Amp</td>
<td>GSFC04/SK</td>
<td>0.03</td>
<td>One device experienced functional failure after 10 krad(Si); All others passed to 10 krad(Si)</td>
<td>10</td>
<td>4</td>
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<tr>
<td>MAX5121</td>
<td>Maxim</td>
<td>0134</td>
<td>DAC</td>
<td>GSFC04/SK</td>
<td>0.03</td>
<td>No parametric degradation to 10 krad(Si)</td>
<td>&gt;10</td>
<td>1</td>
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<tr>
<td>MAX6325</td>
<td>Maxim</td>
<td>0037</td>
<td>Voltage Reference</td>
<td>GSFC03/RL/SK</td>
<td>0.03</td>
<td>Load Regulation exceeds specification limits after 4 krad(Si); Line Regulation exceeds specification limits after 12 krad(Si); VOUT measurements fell below specification limits after 20.5 krad(Si); Devices still functional after 24 krad(Si)</td>
<td>4</td>
<td>5</td>
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<td>AD524</td>
<td>Analog Devices</td>
<td>0133</td>
<td>Instrument Amplifier</td>
<td>GSFC03JUL/SB</td>
<td>~0.46</td>
<td>*krad(Si) exceeds specification limits after 10 krad(Si); VOL exceeds specification limits after 50 krad(Si); VOUT exceeds specification limits after 60 krad(Si); Functional after 90 krad(Si) (max dose tested) *</td>
<td>10</td>
<td>4</td>
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<td>AD587</td>
<td>Analog Devices</td>
<td>0213</td>
<td>Voltage Reference</td>
<td>GSFC03/RL/SK</td>
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<td>No parametric degradation to 24 krad(Si)</td>
<td>&gt;24</td>
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<tr>
<td>OP27</td>
<td>Analog Devices</td>
<td>0215</td>
<td>Op Amp</td>
<td>GSFC03JUL/JH</td>
<td>~0.2</td>
<td>No parametric degradation to 50 krad(Si)</td>
<td>&gt;50</td>
<td>1</td>
</tr>
</tbody>
</table>

Presented by Donna Cochran at NSREC04 Data Workshop, Atlanta, GA, July 22, 2004
<table>
<thead>
<tr>
<th>Part Number</th>
<th>Manufacturer</th>
<th>LDC</th>
<th>Function</th>
<th>Facility Date/T.I (Co-60 source unless otherwise noted)</th>
<th>Dose rate (rads(Si)/s)</th>
<th>Summary of Results</th>
<th>Degradation Level (krads(Si))</th>
<th>Cat.</th>
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</thead>
<tbody>
<tr>
<td>Mixed Signal or Linear Device (continued)</td>
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<td></td>
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<tr>
<td>OP200</td>
<td>Analog Devices</td>
<td>9931</td>
<td>Op Amp</td>
<td>GSFC03AUG/JH</td>
<td>−0.2</td>
<td>No parametric degradation to 50 krads(Si)</td>
<td>&gt;50</td>
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<tr>
<td>LT1024</td>
<td>Linear Technology</td>
<td>0114</td>
<td>Op Amp</td>
<td>GSFC03OCT/JH</td>
<td>−0.2</td>
<td>Ionization parameter exceeds specification limits after 2 krads(Si); Vos exceeds specification limits after 4 krads(Si); Functional after 30 krads(Si) (max dose tested)</td>
<td>2</td>
<td>5</td>
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<tr>
<td>UCC1806</td>
<td>Unitrode</td>
<td>0126</td>
<td>Pulse Width Modulator</td>
<td>GSFC03/JH</td>
<td>0.27</td>
<td>Functional failure between 20 and 30 krads(Si); No significant parametric degradation prior to failure</td>
<td>20-30</td>
<td>3</td>
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<tr>
<td>OP420</td>
<td>Analog Devices</td>
<td>9917</td>
<td>Quad Op Amp</td>
<td>GSFC03/SH/KL</td>
<td>−0.15</td>
<td>No parametric degradation to 15 krads(Si)</td>
<td>&gt;15</td>
<td>1</td>
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<td>DAC8408</td>
<td>Analog Devices</td>
<td>0020</td>
<td>Quad 8-bit DAC</td>
<td>GSFC03/SH/KL</td>
<td>−0.42</td>
<td>DNL exceeded specification limits after 6.7 krads(Si); Devices failed functionally after 10.7 krads(Si)</td>
<td>6.7</td>
<td>4</td>
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<td>DC-DC Converter</td>
<td>International</td>
<td>0351</td>
<td>DC-DC Converter</td>
<td>GSFC04/SH/KL</td>
<td>0.03</td>
<td>No parametric degradation to 10 krads(Si)</td>
<td>&gt;10</td>
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<tr>
<td>Optical Devices</td>
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<tr>
<td>PIDS</td>
<td>Fairchild</td>
<td>N/A</td>
<td>Optocoupler</td>
<td>GSFC03JUL/JH</td>
<td>−0.15</td>
<td>No parametric degradation to 50 krads(Si)</td>
<td>&gt;50</td>
<td>1</td>
</tr>
<tr>
<td>HSDL-4420</td>
<td>Agilent</td>
<td>N/A</td>
<td>Infrared emitter</td>
<td>GSFC03/JH</td>
<td>0.2</td>
<td>No degradation in CTR at three If to 50 krads(Si) Note: HSDL-4420 and HSDL-5420 tested as a pair</td>
<td>&gt;50</td>
<td>1</td>
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<tr>
<td>HSDL-5420</td>
<td>Agilent</td>
<td>N/A</td>
<td>Infrared PIN photodiode</td>
<td>GSFC03/JH</td>
<td>0.2</td>
<td>No degradation in CTR at three If to 50 krads(Si) Note: HSDL-4420 and HSDL-5420 tested as a pair</td>
<td>&gt;50</td>
<td>1</td>
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<tr>
<td>Part Number</td>
<td>Manufacturer</td>
<td>LDC</td>
<td>Function</td>
<td>Facility Date/P.I.</td>
<td>Summary of Results</td>
<td>Cat.</td>
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<td>SN74LVC16244A</td>
<td>Texas Instruments</td>
<td>No LDC available; Markings: 31AX94K</td>
<td>Buffer/Driver</td>
<td>IU03NOV/SB</td>
<td>No degradation to 3.27x10^11 p/cm²</td>
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<tr>
<td>SN74LVC16245A</td>
<td>Texas Instruments</td>
<td>No LDC available; Markings: 29E3Y9K</td>
<td>Transceiver</td>
<td>IU03NOV/SB</td>
<td>No degradation to 3.27x10^11 p/cm²</td>
<td>1</td>
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<tr>
<td>5AM</td>
<td>IBM</td>
<td>N/A</td>
<td>SiGe 5AMSTC</td>
<td>UCD03OCT/RR/PM</td>
<td>No functional degradation after 2Mrad(Si) proton dose. [nare04_Marshall]</td>
<td>RTV</td>
<td></td>
<td></td>
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<tr>
<td>7HP</td>
<td>IBM</td>
<td>N/A</td>
<td>SiGe 12 bit SR</td>
<td>UCD03OCT/RR/PM</td>
<td>No parametric degradation after 150 krad(Si) proton dose (expect much higher) [nare04_Marshall]</td>
<td>RTV</td>
<td></td>
<td></td>
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<tr>
<td>8HP</td>
<td>IBM</td>
<td>N/A</td>
<td>SiGe</td>
<td>UCD03DEC/PM</td>
<td>No parametric degradation up to 1x10^12 63 MeV protons [nare04_Kuo]</td>
<td>RTV</td>
<td></td>
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<tr>
<td>9HP</td>
<td>IBM</td>
<td>N/A</td>
<td>SiGe</td>
<td>UCD03DEC/PM</td>
<td>No parametric degradation up to 7x10^12 63 MeV protons [nare04_Sutton]</td>
<td>RTV</td>
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<tr>
<td>UT54LVDS8217</td>
<td>Aeroflex</td>
<td>0312</td>
<td>Serializer</td>
<td>IU03OCT/SB</td>
<td>No degradation to 1.5x10^12 p/cm² (~94 krad(Si))</td>
<td>1</td>
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<tr>
<td>RHRFPGA</td>
<td>Honeywell</td>
<td>0314</td>
<td>FPGA</td>
<td>IU03OCT/TS</td>
<td>No degradation to 3.4x10^13 p/cm²</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RHRFPGA</td>
<td>Teledyne</td>
<td>0312</td>
<td>Solid-State Relay (OPTO)</td>
<td>IU03OCT/SB</td>
<td>Functional failure after 5.01x10^11 p/cm² (DUT 12) (~30 krad(Si), 6.68x10^11 p/cm² (DUT 11), (~40 krad(Si))</td>
<td>3</td>
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<tr>
<td>OMR9701</td>
<td>International Rectifier</td>
<td>0313</td>
<td>Solid-State Relay (OPTO)</td>
<td>IU03OCT/SB</td>
<td>All four devices pass all tests up to 75 krad(Si) Significant degradation in V_LOAD in one device at 100 krad(Si)</td>
<td>2</td>
<td></td>
<td></td>
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<tr>
<td>JFET</td>
<td>Interfet</td>
<td>Markings: SN194AL 16</td>
<td>JFET</td>
<td>UCD03DEC/EB</td>
<td>Noise spectra functionally failed in some devices after 1 krad(Si)</td>
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<tr>
<td>WFC IV</td>
<td>E2V</td>
<td>N/A</td>
<td>CCD</td>
<td>UCD03OCT/CM/PM</td>
<td>5x10^7 p/cm²; Best pixel annealing studied as a function of temperature. [SPIE04, Polidan]</td>
<td>RTV</td>
<td></td>
<td></td>
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<tr>
<td>P-Channel (SNAP)</td>
<td>Dalsa &amp; Berkeley</td>
<td>N/A</td>
<td>CCD</td>
<td>UCD03OCT/CM/PM</td>
<td>5.7x10^7 p/cm²; At -85°C, the charge transfer efficiency is about an order of magnitude better than observed for n-CCDx. [SPIE04, Marshall]</td>
<td>RTV</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Presented by Donna Cochran at NSREC04 Data Workshop, Atlanta, GA, July 22, 2004
IV. TEST RESULTS AND DISCUSSION

1) TC55257

The TC55257 32kx8 SRAM from Toshiba was tested to 30 krad(Si) at an average dose rate of 0.28rad(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. All parts passed all tests to 20 krad(Si), however there was significant degradation in the READ current in all three devices at 20 krad(Si). After the 30 krad(Si) exposure, the devices exceeded the specification limits for READ current, and Stand By current with readings of 3mA for both in all three. Two devices also displayed functional READ/WRITE failures after 30 krad(Si). No annealing was performed on these devices. [T032803_TC55257]

![Fig.1 TC55257 average current readings for READ and STANDBY.](image)

2) MAX494

The MAX494 quad op amp from Maxim Semiconductor was tested to 10 krad(Si) at an average dose rate of 0.03rad(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. Two sets of 7 devices were irradiated. In the first set, all devices passed all tests to 7.5 krad(Si). One device failed catastrophically after 10 krad(Si) while the remaining 6 passed all parametric tests. After annealing the devices at room temperature for one week, no significant change was noted in any parameter in the 6 remaining devices. An extensive failure analysis was unable to determine the root cause of the one catastrophic failure due to the level of thermal damage internal to the device. The second set of 7 devices passed all tests to 10 krad(Si). After annealing the devices at room temperature for one week, no significant change was noted in any parameter. [G2004_MAX494]

3) AD524

The AD524 op amp from Analog Devices was tested to 100 krad(Si) at an average dose rate of 0.46rad(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. After the 10 krad(Si) exposure, all devices exceeded the specification limits for +Ibias and -Ibias. After the 70 krad(Si) exposure, there was significant degradation in the input offset voltage and some degradation in the output offset voltage. The devices were still functional after 100 krad(Si). [G030CT_AD587]

![Fig.2 Analog Devices AD524 +/- input offset currents.](image)

4) LT1024

The LT1024 dual op amp from Linear Technology Corp. was tested to 30 krad(Si) at an average dose rate of 0.2 rad(Si)/s. Testing was performed at the NASA GSFC REF Co-60 Facility. The devices were statically biased. After the 2 krad(Si) irradiation step, all devices exceeded the specification limit for Ibias. After the 4 krad(Si) irradiation step, all devices exceeded the specification limit for Vos as well. The devices continued to function after 30 krad(Si) although with significant further degradation in Ibias and VOS. [G101503_LT1024_TID]

![Fig.3a Linear Technologies LT1024 Ibias degradation.](image)

![Fig.3b Linear Technologies LT1024 VOS degradation.](image)
V) RHrFPGA

The RHrFPGA from Honeywell is a SOI based CMOS device. The devices were tested for DD and TID effects at IUCF with proton energy of 203 MeV. Each of the three devices was exposed to a fluence of 3.4x10^{13} p/cm^2 (DD dose ~ 2 Mrad(Si)). No parametric degradation was observed in the devices. [i103003_RHrFPGA_Honeywell]

V. SUMMARY

We have presented data from recent TID and proton-induced damage tests on a variety of primarily commercial devices. It is the authors' recommendation that this data be used with caution. We also highly recommend that lot testing be performed on any suspect or commercial device.

VI. ACKNOWLEDGMENT

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VII. REFERENCES


