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

Commercial and emerging technology devices have established themselves in the space flight community as a means to meet the needs for higher performance, cost savings, and scheduling demands. With this dramatic increase in the use of these devices, the importance of ground testing for the effects of total ionizing dose (TID) and proton-induced degradation (also known as displacement damage (DD)) to qualify the devices for flight, has increased due to the often uncertain nature of such devices.

The results of testing presented here were done to establish the sensitivity of the devices selected as candidate spacecraft electronics to TID and proton damage (both ionizing and non-ionizing). This testing serves to determine the limit to which a candidate device may be used or if it may not be used at all.

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.

Testing performed at Naval Surface Warfare Center Division (NAVSEA) used the Shepherd Model 484 Cobalt-60 Tunnel Irradiator Test Facility. The source is capable of delivering dose rates between 0.8 rads(Si)/s and 49.5 rads(Si)/s.

Testing performed by JAYCOR was done at four facilities: The Salk Institute (Salk Inst.) Gammabeam 150-C CO-60 Irradiator, the Sandia National Laboratories (SNL) Gamma Irradiation Facility (GIF), the Defense Microelectronics Activity (DMEA) Science and Engineering Gamma Irradiation Test (SEGIT) Facility using a J.L. Shepherd & Assoc. Model 81 Co-60 irradiator, and Titan Corp. Pulse Sciences Division (PSD) Cs-137 irradiator. TID facilities are summarized in Table I.
Table I: Gamma Ray TID Test Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton Energy, (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Goddard Space Flight Center Radiation Effects Facility (GSFC REF) Co-60</td>
<td></td>
</tr>
<tr>
<td>Naval Surface Warfare Center Division (NAVSEA) Shepherd Model 484</td>
<td></td>
</tr>
<tr>
<td>Cobalt-60 Tunnel Irradiator Test Facility</td>
<td></td>
</tr>
<tr>
<td>JAYCOR: Salk Institute, Sandia National Laboratories, Defense Microelectronics Activity, (Co-60), Titan Corp. (Cs-137)</td>
<td></td>
</tr>
</tbody>
</table>

B. Test Facilities – Proton Damage

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). The proton damage test facilities and energies used on the devices are shown in Table II.

Table II: Proton Damage Test Facilities

<table>
<thead>
<tr>
<th>Facility</th>
<th>Proton Energy, (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>University of California at Davis (UCD) Crocker Nuclear Laboratory (CNL)</td>
<td>26.6-63</td>
</tr>
<tr>
<td>Indiana University Cyclotron Facility (IUCF)</td>
<td>54-197</td>
</tr>
</tbody>
</table>

C. Test Method

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

1) TID Testing

TID testing was performed to the MIL-STD-883 1019.5 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 $1 \times 10^{10}$ protons).

III. Test Results Overview

Abbreviations and conventions are listed in Table III. Abbreviations for principal investigators (PIs) and test engineers are listed in Table IV. Definitions for the categories are listed in Table V. TID results are summarized in Table VI. Displacement Damage testing results are presented in Table VII. Unless otherwise noted, all LETs are in MeV·cm²/mg and all cross sections are in cm²/device. 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>
<thead>
<tr>
<th>Part Number</th>
<th>Manufacturer</th>
<th>LDC</th>
<th>Function</th>
<th>Facility Date/Ref. (Co-60 source unless otherwise noted)</th>
<th>Dose Rate (rads(Si)/s)</th>
<th>Summary of Results</th>
<th>Degradation Level (kрадs(Si))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>SG7805</td>
<td>Linfinity (Microsemi)</td>
<td>9439</td>
<td>Positive Linear Voltage Regulator</td>
<td>GSFC02OCT – SB</td>
<td>~0.28</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[4]</td>
</tr>
<tr>
<td>SG7815</td>
<td>Linfinity (Microsemi)</td>
<td>0039</td>
<td>Positive Linear Voltage Regulator</td>
<td>GSFC02SEP – SB</td>
<td>~0.28</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[5]</td>
</tr>
<tr>
<td>SG7915</td>
<td>Linfinity (Microsemi)</td>
<td>0207</td>
<td>Negative Linear Voltage Regulator</td>
<td>GSFC02OCT – SB</td>
<td>~0.28</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[6]</td>
</tr>
<tr>
<td>LP2953</td>
<td>National Semicondor</td>
<td>0208A</td>
<td>Voltage regulator</td>
<td>GSFC02DEC – CP</td>
<td>0.1 to 0.47</td>
<td>Voltage output and dropout out of specification limits after 2.5 kрадs(Si)</td>
<td>&lt;2.5</td>
<td>[7]</td>
</tr>
<tr>
<td>LM193</td>
<td>National Semicondor</td>
<td>Flight Lot</td>
<td>Dual voltage comparator</td>
<td>GSFC02OCT – CP</td>
<td>0.06 to 0.4</td>
<td>V_{th} out of specification limits after 7 kрадs(Si) V_{o} out of specification limits after 15 kрадs(Si) Functional after 65 kрадs(Si) (maximum test dose)</td>
<td>&lt;7</td>
<td>[8]</td>
</tr>
<tr>
<td>OP27ARC</td>
<td>Analog Devices</td>
<td>0128A</td>
<td>Op amp</td>
<td>GSFC031AN – CP</td>
<td>0.08 to 0.14</td>
<td>All parameters within specification limits up to 25 kрадs(Si)</td>
<td>&gt;25</td>
<td>[9]</td>
</tr>
<tr>
<td>OP97</td>
<td>Analog Devices</td>
<td>0133A</td>
<td>Op amp</td>
<td>GSFC02OCT – SB</td>
<td>~0.15</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[10]</td>
</tr>
<tr>
<td>OP221</td>
<td>Analog Devices</td>
<td>0127</td>
<td>Op amp</td>
<td>GSFC02SEP – SB</td>
<td>~0.08</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[11]</td>
</tr>
<tr>
<td>OP296</td>
<td>Analog Devices</td>
<td>0048</td>
<td>Op amp</td>
<td>GSFC02SEP – SK</td>
<td>~0.01</td>
<td>Devices failed functionally at 1.8 kрадs(Si)</td>
<td>&lt;1.8</td>
<td>[12]</td>
</tr>
<tr>
<td>AD743</td>
<td>Analog Devices</td>
<td>0110</td>
<td>Op amp</td>
<td>GSFC02SEP – SB</td>
<td>~0.28</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[13]</td>
</tr>
<tr>
<td>AD822</td>
<td>Analog Devices</td>
<td>0211</td>
<td>Op amp</td>
<td>GSFC02SEP – SB</td>
<td>~0.28</td>
<td>No parametric failures were observed up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[14]</td>
</tr>
<tr>
<td>AD625</td>
<td>Analog Devices</td>
<td>0204</td>
<td>Instrument Amplifier</td>
<td>GSFC02OCT – SB</td>
<td>~0.28</td>
<td>No parametric degradation up to 20 kрадs(Si)</td>
<td>&gt;20</td>
<td>[15],[16]</td>
</tr>
<tr>
<td>AD5334</td>
<td>Analog Devices</td>
<td>0011</td>
<td>Quad 8-bit DAC</td>
<td>GSFC02SEP – JH</td>
<td>~0.11</td>
<td>Parametric and functional failure at 20 kрадs(Si)</td>
<td>15 &lt; x &lt; 20</td>
<td>[17]</td>
</tr>
<tr>
<td>Part Number</td>
<td>LDC</td>
<td>Manufacturer</td>
<td>Function</td>
<td>Facility Date/P.I.</td>
<td>Summary of Results</td>
<td>Degradation Level (krad(Si))</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>-----</td>
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<td>----------</td>
<td>-------------------</td>
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<td></td>
</tr>
<tr>
<td>P40</td>
<td>L40</td>
<td>Texas Instruments</td>
<td>Power Supply for GaAs power amplifier</td>
<td>OSFOC0102 - SB</td>
<td>Functional failure between 20 and 40 krad(Si)</td>
<td>&lt;9</td>
<td>[18]</td>
<td></td>
</tr>
<tr>
<td>TP59103</td>
<td>N4</td>
<td>Texas Instruments</td>
<td>Power Supply for GaAs power amplifier</td>
<td>OSFOC0102 - SB</td>
<td>Functional failure between 20 and 40 krad(Si)</td>
<td>&lt;9</td>
<td>[19]</td>
<td></td>
</tr>
<tr>
<td>CULTR1 RS Encoder</td>
<td>N4</td>
<td>Texas Instruments</td>
<td>Voltage regulator</td>
<td>OSFOC0102 - MX</td>
<td>No degradation of performance at 100 krad(Si)</td>
<td>&lt;5</td>
<td>[20], [21]</td>
<td></td>
</tr>
<tr>
<td>LM139</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Voltage regulator</td>
<td>NAVSEA02 - CP</td>
<td>Output saturation voltage of specification limit and significantly degraded after 5 krad(Si)</td>
<td>&lt;2.5</td>
<td>[22]</td>
<td></td>
</tr>
<tr>
<td>LTC1657/CDN</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (DME)</td>
<td>All parameters within specification limits after 2.5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&gt;50</td>
<td>[23], [24], [25]</td>
<td></td>
</tr>
<tr>
<td>LP205</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (DME)</td>
<td>Line regulation out of specification limits after 5 krad(Si)</td>
<td>&lt;5</td>
<td>[26]</td>
<td></td>
</tr>
<tr>
<td>MEC02D2</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (Titan Corp.)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;10</td>
<td>[27]</td>
<td></td>
</tr>
<tr>
<td>LM16/LSM01/ADJ</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (Titan Corp.)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;5</td>
<td>[28]</td>
<td></td>
</tr>
<tr>
<td>ADG32</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (Salk Inst.)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;5</td>
<td>[29]</td>
<td></td>
</tr>
<tr>
<td>M4103</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Line regulator</td>
<td>JAYCORO2 - CP (Salk Inst.)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;5</td>
<td>[30]</td>
<td></td>
</tr>
<tr>
<td>LM16144</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Op amp</td>
<td>8-bit DAC (20 MHz)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;5</td>
<td>[31]</td>
<td></td>
</tr>
<tr>
<td>ADC1275/DM</td>
<td>M4</td>
<td>Texas Instruments</td>
<td>Op amp</td>
<td>8-bit DAC (20 MHz)</td>
<td>Line regulation out of specification limits after 5 krad(Si), significantly degraded after 10 krad(Si)</td>
<td>&lt;5</td>
<td>[32]</td>
<td></td>
</tr>
<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>Degradation Level (krads(Si))</td>
<td>Reference</td>
<td></td>
</tr>
<tr>
<td>-------------</td>
<td>--------------</td>
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<td>-------------------------------</td>
<td>-----------</td>
<td></td>
</tr>
<tr>
<td>HV583</td>
<td>Supertek</td>
<td>N/A</td>
<td>Serial to parallel converter</td>
<td>UCD02APR – SB</td>
<td>TID degradation at 50 krad(Si)</td>
<td>50</td>
<td>[33]</td>
<td></td>
</tr>
<tr>
<td>MRX8501</td>
<td>Encore</td>
<td>A1 312-12</td>
<td>Fiber Optic Receiver</td>
<td>UCD02FEB – MC</td>
<td>Not sensitive to TID/DD up to ~103 krad(Si) at fluence of 7.16 x 10^{11} p/cm²</td>
<td>&gt;103</td>
<td>[34]</td>
<td></td>
</tr>
<tr>
<td>MTX8501</td>
<td>Encore</td>
<td>A1 233-01</td>
<td>Fiber Optic Transmitter</td>
<td>UCD02FEB – SB/PM</td>
<td>Not sensitive to TID/DD up to 28.8 krad(Si)</td>
<td>&gt;28.8</td>
<td>[34]</td>
<td></td>
</tr>
<tr>
<td>M166099</td>
<td>Micropac</td>
<td>Custom</td>
<td>Optocoupler</td>
<td>UCD02APR – SB</td>
<td>Observed anomalous decay of CTR</td>
<td>&lt;5</td>
<td>[35]</td>
<td></td>
</tr>
<tr>
<td>M166099</td>
<td>Micropac</td>
<td>Custom</td>
<td>Optocoupler</td>
<td>IUCP02JUN – SB</td>
<td>Observed anomalous decay of CTR</td>
<td>&lt;5</td>
<td>[36]</td>
<td></td>
</tr>
<tr>
<td>CO-566</td>
<td>Vectron</td>
<td>0142</td>
<td>Oscillator</td>
<td>IU02JUNE – JH</td>
<td>TID: &gt; 1 Mrad(Si); DD: &gt; 3.23 x 10^{13} p/cm²</td>
<td>&gt;1000</td>
<td>[37]</td>
<td></td>
</tr>
<tr>
<td>CO-7185</td>
<td>Vectron</td>
<td>0143</td>
<td>Oscillator</td>
<td>IU02JUNE – JH</td>
<td>TID: &gt; 1 Mrad(Si); DD: &gt; 2.72 x 10^{13} p/cm²</td>
<td>&gt;1000</td>
<td>[38]</td>
<td></td>
</tr>
<tr>
<td>AD7664</td>
<td>Analog Devices</td>
<td>0110</td>
<td>16-bit ADC (570 ksp/s)</td>
<td>IU03FEB – JH</td>
<td>Devices failed due to proton TID at 21.7 ± 1.1 krad(Si)</td>
<td>21.7</td>
<td>[39]</td>
<td></td>
</tr>
<tr>
<td>ColdFire</td>
<td>Motorola</td>
<td>0120</td>
<td>Microprocessor</td>
<td>IU02JUNE – JH</td>
<td>Dose failure occurred at ~62 krad(Si).</td>
<td>-62</td>
<td>[40]</td>
<td></td>
</tr>
<tr>
<td>SH-4</td>
<td>Hitachi</td>
<td>N/A</td>
<td>Microprocessor (Commercial version of RH microprocessor)</td>
<td>IU02JUNE – JH</td>
<td>Hard failure occurred after ~11 krad(Si) (1.91 x 10^{13} p/cm²) Could not determine whether latchup or dose failure was reason for hard failure. Device also tested for SEFI and SEL.</td>
<td>11</td>
<td>[41]</td>
<td></td>
</tr>
<tr>
<td>GP2021</td>
<td>Zarlink</td>
<td>9617A</td>
<td>GPS 12-Channel correlator</td>
<td>IU02JUNE – JH</td>
<td>Hard failure occurred after ~49 krad(Si) (8.3 x 10^{15} p/cm²)</td>
<td>49</td>
<td>[42]</td>
<td></td>
</tr>
</tbody>
</table>
IV. TID TEST RESULTS AND DISCUSSION

1) AD5334

The AD5334 quad 8-bit DAC from Analog Devices was tested to 50 krads(Si) at a dose rate of ~0.11 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. The devices were biased statically. After 15 krads(Si), all devices began to deviate from the nominal values in DNL, INL, gain error, offset error, and supply current. See Figures 1 and 2 for DNL & INL results. After 20krads(Si), the above parameters began to degrade very significantly with DNL and INL having degraded to well outside 8-bit performance.

![Fig. 1. AD5334 Maximum DNL as a function of TID.](image1)

![Fig. 2. AD5334 Maximum INL as a function of TID.](image2)

After 30 krads(Si), the device lost monotonicity and the output voltage became oscillatory across the entire range of the DAC. Annealing at 100°C for one week did not provide significant recovery.

2) ADG425

The ADG425 analog switch from Analog Devices was tested to 50 krads(Si) at an average dose rate of ~0.19 rads(Si)/s. Tests were performed by JAYCOR. Six devices were statically biased and total current was monitored during testing. Two devices were unbiased during testing. After 2.5 krads(Si), the biased devices were out of specification in IDD, ISS, IS_off_+10V, and IS_off_-10V. The degradation between 10 and 20 krads(Si) was significantly enough that the timing and high/low threshold readings could not be made and the devices would not change from state to state. Annealing at room temperature for 1 week resulted in no observed recovery. The unbiased devices show some degradation at 30 and 50 krads(Si). Annealing the unbiased devices resulted in no significant recovery.

3) LM193

The LM193 quad low power voltage comparator from National Semiconductor was tested to 65 krads(Si) at an average dose rate of ~0.25 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. Four devices were statically biased and two devices were unbiased during testing. After 7 krads(Si), both I+ and I- in all devices (biased and unbiased) were well above the specification limits. After 15 krads(Si), VIO were above the specification limit for the four biased devices; one unbiased device went above the specification limit after 35 krads(Si). All other parameters stay within specification limits up to the maximum test dose level of 65 krads(Si) (see Fig. 3.). Annealing at room temperature for 1 week resulted in no significant annealing.

![Fig. 3: Variation of VIO with TID in the LM193.](image3)

4) LM139

The LM139 (M38510/11201BDA) quad low power voltage comparator from National Semiconductor was tested to 50 krads(Si) at an average dose rate of 0.295 rads(Si)/s. NAVSEA Crane Division performed the total dose testing at their Co-60 tunnel irradiator. Six devices were statically biased, two unbiased. Results of the total dose testing indicated:

- Both unbiased devices failed to operate properly between 5 krads(Si) and 10 krads(Si) as evidenced by output saturation voltage (VOL) increasing well above specification (See Fig. 4.).
- All statically biased devices failed to operate properly between 10 krads(Si) and 20 krads(Si) as evidenced by output saturation voltage (VOL) increasing well above specification (See Fig. 4.).
• All devices began showing power supply current decrease after 5.0 krads(Si).

5) **MRX8501/MTX8501**

The MTX8501/MRX8501 12 x 1.25 Gbps parallel array transmitter and receiver modules from Emcore were tested for DD and TID effects with 63 MeV protons at UC Davis, CNL cyclotron. The first receiver was exposed to a total fluence of 7.16x10^{11} protons/cm^2; equivalent to 103 krads(Si). Following this exposure, there was no change in the functioning of the device, or in the current supplied to the board. The second receiver was exposed to a TID of 30.7 krads(Si) and no change was observed. The transmitter was exposed to a fluence of 2x10^{11} protons/cm^2; equivalent to a TID of 28.8 krads(Si) and no change in error rate or operating parameters was observed. These devices were also tested for SEE, those results are also in the test report and are presented in "Single Event Effects Results for Candidate Spacecraft Electronics for NASA" accepted for publication in IEEE NSREC 2003 Data Workshop, July, 2003.

6) **OP296**

The OP296 micropower, rail-to-rail input and output operational amplifier from Analog Devices was tested to 1.8 krads(Si) at a dose rate of 0.01 rads(Si)/s. Tests were performed at the NASA GSFC REF Co-60 facility. The devices were biased statically. The devices failed functionally at 1.8 krads(Si) and no recovery was observed after annealing for one week at room temperature.

7) **AD7664**

The AD7664 16-bit ADC from Analog Devices was tested with protons at IUCF. While performing other tests, the devices were left in the beam until TID failure. The devices failed at a TID of 21.7 +/-1.1 krads(Si). The devices were also tested for proton induced SEL and heavy ion induced SEL see [1] for more details on those tests.

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

The Authors would like to acknowledge the sponsors of this effort: NASA Electronics Radiation Characterization (ERC) Project, a portion of NASA Electronic Parts and Packaging Program (NEPP), NASA Flight Projects, and the Defense Threat Reduction Agency (DTRA) under IACRO 02-40391.

VII. REFERENCES


