Radiation Challenges for Electronics in the Vision for Space Exploration*

Kenneth A. LaBel
ken.label@nasa.gov
Co-Manager, NASA Electronic Parts and Packaging (NEPP) Program
Project Technologist, Living With a Star Space Environment Testbed (LWS SET)
Group Leader, Radiation Effects and Analysis Group, NASA/GSFC

* Radiation effects are the prime consideration in this talk. Reliability must ALSO be considered.

Outline

- Background – Radiation Effects on Electronics
- Uniqueness of Exploration Systems Missions
  - Types of missions
  - Comparison to traditional missions
- Electronic Parts and Exploration
- Radiation Effects and the Scaling of Electronics
- Simple Trade Study: The Cost of Radiation Effects Testing
- Final Comments
Critical areas for design in the natural space radiation environment

- Long-term effects causing parametric and/or functional failures
  - Total ionizing dose (TID)
  - Displacement damage
- Transient or single particle effects (Single event effects or SEE)
  - Soft or hard errors caused by proton (through nuclear interactions) or heavy ion (direct deposition) passing through the semiconductor material and depositing energy

Total Ionizing Dose (TID)

- Cumulative long term ionizing damage due to protons & electrons
  - keV to MeV range
- Electronic Effects
  - Threshold Shifts
  - Leakage Current
  - Timing Changes
  - Functional Failures
- Unit of interest is krads(material)
- Can partially mitigate with shielding
  - Reduces low energy protons and electrons

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Displacement Damage (DD)

- Cumulative long term non-ionizing damage due to protons, electrons, and neutrons
  - keV to MeV range
- Electronic Effects
  - Production of defects which results in device degradation
  - May be similar to TID effects
  - Optocouplers, solar cells, charge coupled devices (CCDs), linear bipolar devices
    - Lesser issue for digital CMOS
- Unit of interest is particle fluence for each energy mapped to test energy
  - Non-ionizing energy loss (NIEL) is one means of discussing
- Can partially mitigate with shielding
  - Reduces low energy protons and electrons

Single Event Effects (SEEs)

- An SEE is caused by a single charged particle as it passes through a semiconductor material
  - Heavy ions (cosmic rays and solar)
    - Direct ionization
  - Protons (trapped and solar)/neutrons (secondary or nuclear) for sensitive devices
    - Nuclear reactions for electronics
    - Optical systems, etc are sensitive to direct ionization
- Unit of interest: linear energy transfer (LET). The amount of energy deposited/lost as a particle passes through a material.
- Effects on electronics
  - If the LET of the particle (or reaction) is greater than the amount of energy or critical charge required, an effect may be seen
    - Soft errors such as upset (SEUs) or transients (SETs), or
    - Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)
- Severity of effect is dependent on
  - type of effect
  - system criticality

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Uniqueness of Exploration Systems Missions

- The Vision for Space Exploration creates a new paradigm for NASA missions
  - Transport (Crew Exploration Vehicle – CEV), and
  - Lunar and Mars Exploration and Human Presence
- If one considers the additional hazards faced by these concepts versus more traditional NASA missions, multiple challenges surface for reliable utilization of electronic parts.
  - The true challenge is to provide a risk as low as reasonably achievable (ALARA – a traditional biological radiation exposure term), while still providing cost effective solutions.
- The following chart tabulates the exploration environmental challenges for electronic parts relative to traditional NASA missions.

---

Summary of Environment Hazards for Electronic Parts in NASA Missions

<table>
<thead>
<tr>
<th>Environment</th>
<th>Plasma (High-E)</th>
<th>Trapped Protons</th>
<th>Trapped Electrons</th>
<th>Solar Particles</th>
<th>Cosmic Rays</th>
<th>Human Radiation</th>
<th>Long Lifespan (~10 years)</th>
<th>Nuclear Exposure</th>
<th>Repeated Launch</th>
<th>Extreme Temperatures</th>
<th>Flexibility Contaminants (Dust, etc.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEO</td>
<td>Yes</td>
<td>No</td>
<td>Severe</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>LEO (low-incl)</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>No</td>
<td>No</td>
<td>Not usual</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>LEO Polar</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>Yes</td>
<td>No</td>
<td>Not usual</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Shuttle</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Rocket Motors</td>
<td>No</td>
</tr>
<tr>
<td>International</td>
<td>No</td>
<td>Yes</td>
<td>Moderate</td>
<td>Yes</td>
<td>No</td>
<td>Partial</td>
<td>Minimal</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Interplanetary</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>During phasing orbits; Possible Other Planet</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Maybe</td>
<td>No</td>
<td>Yes</td>
<td>Rocket Motors</td>
<td>No</td>
</tr>
<tr>
<td>Exploration - CEV</td>
<td>Phasing orbits</td>
<td>During phasing orbits</td>
<td>During phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Exploration - Lunar, Mars</td>
<td>Phasing orbits</td>
<td>During phasing orbits</td>
<td>During phasing orbits</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Maybe</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
</tbody>
</table>

Yellow indicates significant Exploration hazards

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Discussion of the Hazard for Electronic Parts and Exploration

As can be observed from the previous chart, Exploration Systems faces a unique electronic parts challenge not only for radiation exposure, but for reliability challenges as well.

- Harsher environment than recent human presence missions (ISS, Shuttle)
- Potentially, the combined hazard of traditional earth science (LEO) and space science (interplanetary) missions

Cost effectiveness may drive use of innovative commercial electronics usage to meet performance constraints

- Is this unique to Exploration? No, but with the hazard faced, one must be careful to plan for radiation and electronic parts reliability

Types of Electronic Parts for Exploration

- One may view electronic parts for Exploration as meeting needs in three categories
  - Standard electronics
    - E.g., capacitors
      - Basic components
  - Standard building blocks
    - E.g., Field Programmable Gate Arrays (FPGAs)
      - Widespread usage in most systems
  - Custom devices not available as “off-the-shelf”
    - E.g., nuclear power or EVA
      - Needed for a specific application

- Note: Commercial-of-the-shelf (COTS) assemblies (e.g., commercial electronic cards or instruments) also may be considered
  - Screening is more complicated than with ISS in this approach due to more extreme environment faced
  - In any case, coordination of the parts needs and parts management can be daunting for such a program
    - Infrastructure required to provide a cost-effective basis for electronic parts for Exploration
A Critical Juncture for Space Usage – Commercial Changes in the Electronics World

Over the past decade plus, much has changed in the semiconductor world. Among the rapid changes are:

- **Scaling of technology**
  - Increased gate/cell density per unit area (as well as power and thermal densities)
  - Changes in power supply and logic voltages (<1V)
    - Reduced electrical margins within a single IC
  - Increased device complexity, # of gates, and hidden features
  - Speeds to >> GHz (CMOS, SiGe, InP…)

- **Changes in materials**
  - Use of antifuse structures, phase-change materials, alternative K dielectrics, Cu interconnects (previous – Al), insulating substrates, ultra-thin oxides, etc...
  - Increased input/output (I/O) in packaging
  - Use of flip-chip, area array packages, etc
  - Increased importance of application specific usage to reliability/radiation performance

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Implications for Electronics in Space

- With all these changes in the semiconductor world, what are the implications for usage in space? Implications for test, usage, qualification and more
  - Speed, power, thermal, packaging, geometry, materials, and fault/failure isolation are just a few for emerging challenges for radiation test and modeling.
    - Reliability challenges are equally as great
  - The following chart (courtesy of Vanderbilt University) looks at some of the recent examples of test data that imply shortfalls in existing radiation performance models.
    - Technology assumptions in tools such as CREME96 are no longer valid

Sample Modeling Shortfalls

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Sample Cost Drivers for Radiation Testing from 1996 to 2006 - Example

- **Device under test (DUTs):**
  - Commercial Memories
    - Used in solid state recorder (SSR) applications

- **1996**
  - SRAM memory
    - 4 Mbits per device
    - <50 MHz bus speed
    - Ceramic packaged DIP or LCC or QFP

- **2006**
  - DUT: DDR2 SDRAM
    - 1 Gbit per device
    - >500 MHz bus speed
    - Plastic FBGA or TSOP
    - Hidden registers and modes
    - Built-in microcontroller

- **Issues**
  - Size of memory
    - Drives complexity on tester side for amount of storage, real time processing, and length of test runs
  - Speed
    - Difficult to test at high-speeds reliably
      - Need low-noise and high-speed test fixtures
      - Classic bit flips (memory cell) extended to include transient propagation (used to be too slow a device to respond)
    - Thermal and mechanical issues (testing in air/vacuum)
  - Packaging
    - Modern device present problems for reliable test board fixture, die access (heavy ion tests) requiring expensive facility usage or device repackaging/placing
    - Difficulty in high-temp testing (worst-case)
  - Hidden registers and modes
    - Functional interrupts driving "anomalous data"
      - Not just arrows to memory call
  - Microcontroller
    - Not just a memory

Sample Cost for SEE Testing: 1996 vs 2006 a 3X Cost Delta

<table>
<thead>
<tr>
<th>1996 SEE Test of a 4M SRAM</th>
<th>2006 SEE Test of SDRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Man-hours or units</td>
</tr>
<tr>
<td>Test plan</td>
<td>0.25</td>
</tr>
<tr>
<td>Device procurements</td>
<td>7.00</td>
</tr>
<tr>
<td>Test site</td>
<td>0.50</td>
</tr>
<tr>
<td>Test board design - electrical and layout</td>
<td></td>
</tr>
<tr>
<td>Board life and population</td>
<td>1.50</td>
</tr>
<tr>
<td>Board test and performance - contracts</td>
<td>2.50</td>
</tr>
<tr>
<td>Data analysis</td>
<td>2.00</td>
</tr>
<tr>
<td>Test report (eng, red, expert, lead)</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>1996 SEE Test of a 4M SRAM</th>
<th>2006 SEE Test of SDRAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>Man-hours or units</td>
</tr>
<tr>
<td>Device procurements</td>
<td>7.00</td>
</tr>
<tr>
<td>Test site</td>
<td>0.50</td>
</tr>
<tr>
<td>Test board design - electrical and layout</td>
<td></td>
</tr>
<tr>
<td>Board life and population</td>
<td>1.50</td>
</tr>
<tr>
<td>Board test and performance - contracts</td>
<td>2.50</td>
</tr>
<tr>
<td>Data analysis</td>
<td>2.00</td>
</tr>
<tr>
<td>Test report (eng, red, expert, lead)</td>
<td>0.50</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
</tr>
</tbody>
</table>

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.
Cost to “Radiation Qualify” – Trade Study for Exploration

- Expectation is to use lots of devices NOT specifically designed for the radiation environment
  - Qualification/testing of commercial devices and boards likely required
    - Expect >1000 device types requiring lot-specific tests
- Biggest driver: SEE (heavy ion)
  - ISS used protons (different hazard faced)
  - Exploration needs heavy ions
    - Use of expensive test facilities or risky device/package manipulations required
- Estimated cost delta from ISS to Exploration
  - Assumes fewer devices need testing (each more complex) and no nuclear testing

<table>
<thead>
<tr>
<th>Program</th>
<th>Number of components for testing</th>
<th>Average “qual” cost</th>
<th>Total</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>500</td>
<td>10000</td>
<td>$5,000,000.00</td>
<td>Proton only tests</td>
</tr>
<tr>
<td>Exploration</td>
<td>300</td>
<td>60000</td>
<td>$18,000,000.00</td>
<td>TID and Heavy Ion SEE required; NSCL required for some devices/boards</td>
</tr>
<tr>
<td><strong>Cost Delta</strong></td>
<td></td>
<td></td>
<td><strong>$13,000,000.00</strong></td>
<td></td>
</tr>
</tbody>
</table>

Bottom Line

- This presentation has been a brief snapshot discussing electronics and Exploration-related challenges.
  - Radiation effects have been the prime target, however, electronic parts reliability issues must also be considered.
    - Modern electronics are designed with a 3-5 year lifetime typical.
      - “Upscreening” does not improve reliability, merely determine inherent levels.
  - Testing costs are driven by device complexity
    - Increases tester complexity, beam requirements, and facility choices
  - Commercial devices may improve performance, but are no cost panacea
    - Big need is for a more cost-effective access to high energy heavy ion facilities (NSCL and NSRL)
      - NSCL is ~$2500/hr with a 24-hour minimum
  - Cost for test equipment is not discussed, but capable testers can run >>$1M for full testing
    - Niche technology (wireless, for example) would also require infrastructure test equipment

To be presented by Kenneth A. LaBel at Space Weather Week, Boulder CO, April 27-28, 2006.