# Challenges for Electronics in the Vision for Space Exploration*

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

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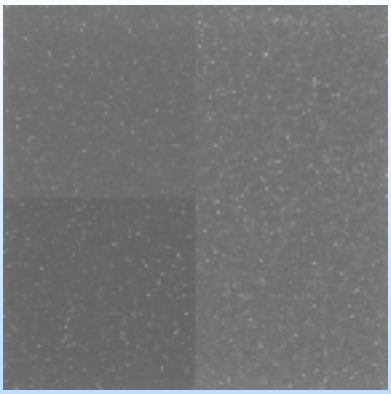
# Outline

- Background – Radiation Effects on Electronics
- Uniqueness of Exploration Systems Missions
  - Types of missions
  - Comparison to traditional missions
- Electronic Parts and Exploration
  - Sample Electronics Radiation and Reliability Issues that Impact Space Exploration
- Four-pronged Infrastructure Approach
  - Parts Management Process
  - Parts Reliability Capability
  - Radiation Effects Knowledge and Capabilities
  - Exploration-specific Technology Evaluation
- Recommended Investment Areas
- Summary Comments

# Radiation Effects and Spacecraft

- 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

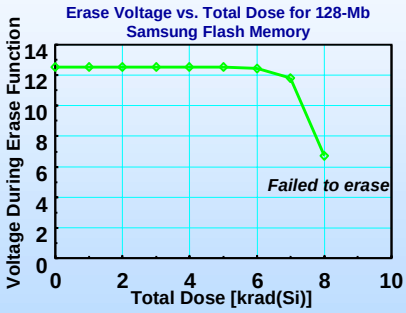


*An Active Pixel Sensor (APS) imager under irradiation with heavy ions at Texas A&M University Cyclotron*



# 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



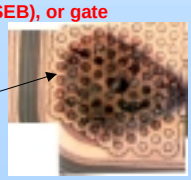
# Displacement Damage (DD)

- 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 upsets (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

*Destructive event in a COTS 120V DC-DC Converter*



# 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

| | Plasma (charging) | Trapped Protons | Trapped Electrons | Solar Particles | Cosmic Rays | Human Presence | Long Lifetime (>10 years) | Nuclear Exposure | Repeated Launch | Extreme Temperature | Planetary Contaminates (Dust, etc) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **GEO** | Yes | No | Severe | Yes | Yes | No | Yes | No | No | No | No |
| **LEO (low-incl)** | No | Yes | Moderate | No | No | No | Not usual | No | No | No | No |
| **LEO Polar** | No | Yes | Moderate | Yes | Yes | No | Not usual | No | No | No | No |
| **Shuttle** | No | Yes | Moderate | No | No | Yes | Yes | No | Yes | Rocket Motors | No |
| **ISS** | No | Yes | Moderate | Yes - partial | Minimal | Yes | Yes | No | No | No | No |
| **Interplanetary** | During phasing orbits; Possible Other Planet | During phasing orbits; Possible Other Planet | During phasing orbits; Possible Other Planet | Yes | Yes | No | Yes | Maybe | No | Yes | Maybe |
| **Exploration - CEV** | Phasing orbits | During phasing orbits | During phasing orbits | Yes | Yes | Yes | Yes | No | Yes | Rocket Motors | No |
| **Exploration – Lunar, Mars** | Phasing orbits | During phasing orbits | During phasing orbits | Yes | Yes | Yes | Yes | Maybe | No | Yes | Yes |

**Yellow indicates significant Exploration hazards**

## 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

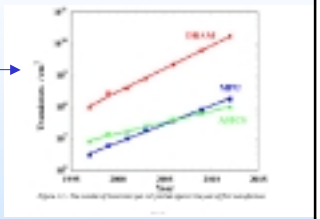


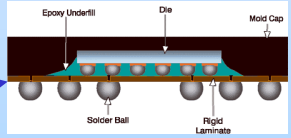
## Types of Electronic Parts for Exploration

- 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

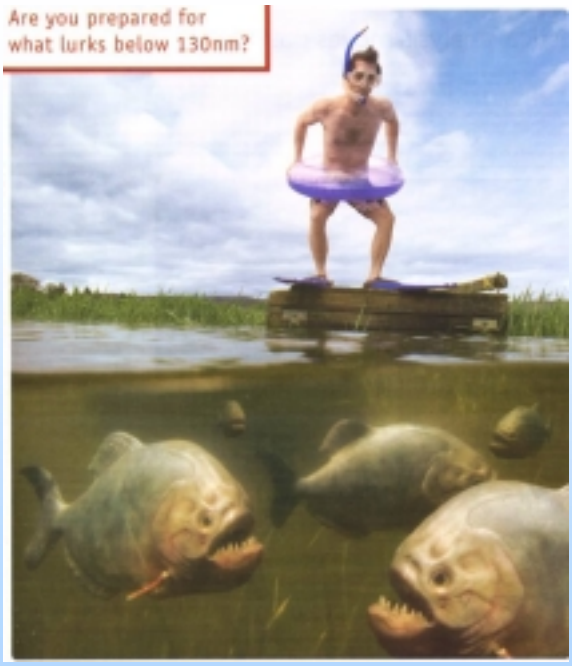
# A Critical Juncture for Space Usage – Commercial Changes in the Electronics World

- 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



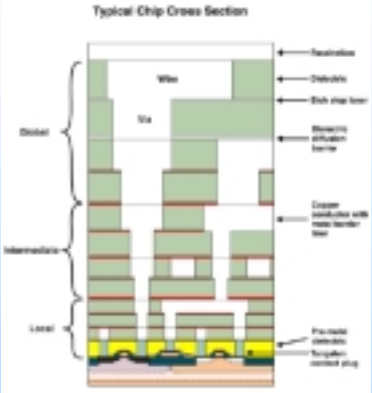




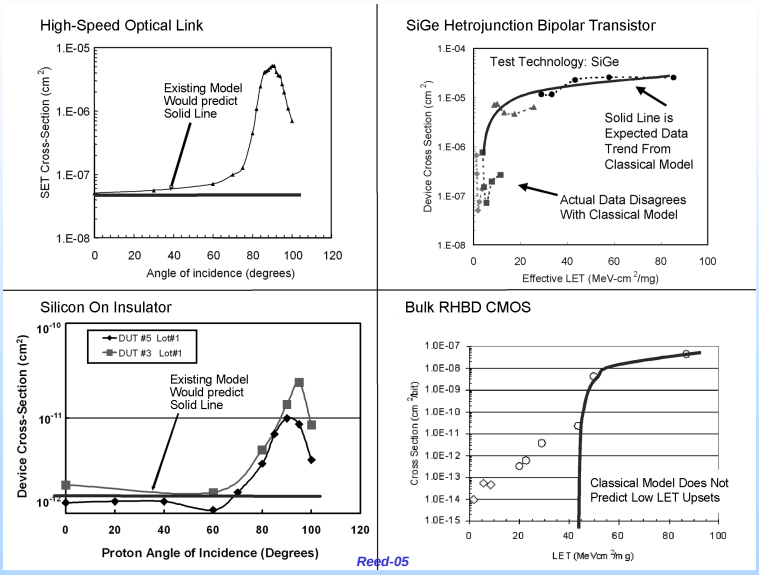
# Implications for Electronics in Space

- **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

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## Current Status of Radiation Knowledge Maturity for Electronics

| Radiation Response | Guideline Document | Test Method | Data Base | Modeling & Simulation |
|---|---|---|---|---|
| SEU/MBU | Yes | Yes | Yes | ~ mature |
| SET | No | No | No | No |
| SEL | Yes | Yes | Yes | No |
| SEGR | No | No | No | No |
| SEFI | No | No | No | No |
| TID | Yes | Yes | Yes | Yes |
| Displacement Damage | Yes | Yes | No | No |

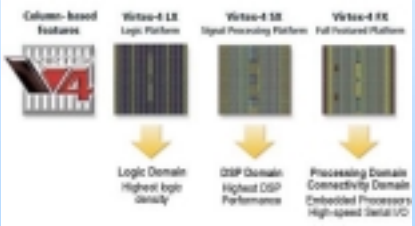


## Approach to Electronic Parts Assurance for Exploration

- What follows is a recommended four-prong approach alliances to existing programs
  - The main alliance is with the NASA Electronic Parts and Packaging (NEPP) Program (OSMA) that provides limited ground-based technology evaluation and Parts Assurance on a "One NASA" basis.
    - NEPP works generic technology issues that are NOT specific to a Program, but of general NASA interest
      - Note: NEPP budget is ~ ½ of FY2000 levels due to cuts and full-cost implementation
      - What is being recommended is complementary to NEPP
  - Other alliances with flight testbeds such as LWS SET and New Millenium are also encouraged
  - The four prongs for electronic parts assurance are
    - Parts management and control
    - Reliability test and analysis capability
    - Radiation effects test and analysis capability
    - Exploration-specific technology evaluation
- *Environment models are outside of traditional parts assurance, but recommendations will be made later in presentation*

# Parts Management and Control

- Support coordination, management, and control of electronic parts as related to Exploration Missions
- Support infrastructure issues required for successful electronic parts utilization
  - Vendor audits, standards committees, etc
- Recommendation
  - Provide parts support at each center (min. 1 FTE/WYE per)




Complex new FPGA architectures include hard-cores: processing, high-speed I/O, DSPs, programmable logic, and configuration latches



# Reliability Test and Analysis

- Goal: Provide dedicated infrastructure to support new and existing device evaluation
  - Provide a quick-turn capability for performing failure analyses on technologies of interest to Exploration
  - Keep evaluation capabilities on par with commercial technology advances
    - Allows cost-effective evaluation of space-specific issues
    - Keeps labs "state-of-the-art"
- Recommendation
  - Utilize existing strengths at GSFC, JPL, GRC, MSFC, ARC, LaRC, and JSC. Examples,
    - GSFC and JPL are MAIN strengths for parts reliability efforts for the agency
    - GRC has capability for extreme temp, power, and RF
    - MSFC and JSC have historical base for electronics for human presence missions
- *Note: the cost for the capability to evaluate "state of the art" is on a rapid upwards spiral. Test equipment for state-of-the-art can run $Ms!*

## Radiation Effects Test and Analysis

- Goal: Provide dedicated infrastructure to support new and existing device evaluation for radiation specific issues
  - Provide a quick-turn capability for gathering radiation knowledge on technologies of interest to Exploration
  - Keep evaluation capabilities on par with commercial technology advances
    - Allows cost-effective evaluation of space-specific issues
    - Keeps labs "state-of-the-art"
  - Provide a heavy ion test capability on par with that developed for protons at IU for ISS for device evaluation
- Recommendation
  - Utilize existing strengths at GSFC, JPL, and JSC
    - GSFC and JPL are recognized strengths for radiation effects for the agency (and the aerospace industry)
    - JSC has historical base for human presence coupled with electronics
  - Support high energy heavy ion test facility at MSU for commercial device/assembly evaluation
    - Includes purchase of time for Exploration technologies evaluations



## Evaluation of Technologies Specific to Exploration

- Goal: Provide evaluation of technologies of specific interest to Exploration
  - High and cold temperature
  - Long-life
  - Nuclear exposure, etc.
- Recommendation
  - Utilize strengths at GSFC, JPL, GRC, MSFC, LaRC, ARC, and JSC
    - GSFC and JPL have traditional "One NASA" experience for electronic parts reliability leadership

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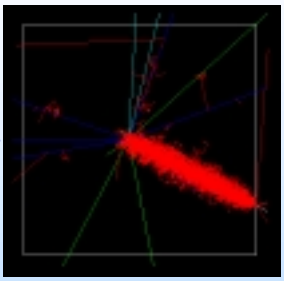

Sample 100 MeV proton reaction in a 5 um Si block. Reactions have a range of types of secondaries and LETs.
*(after Weller, 2004)*

## Electronics and Radiation Environment Investment Areas

- Understanding extreme value statistics as it applies to radiation particle impacts
  - Small probability risk analysis (if 1 in 1e9 particles can cause an effect, how do we test, model, and interpret for system risk?)
- System Radiation Risk Tools
  - Interpreting device effects at the system level
- High-Energy SEU Microbeam Two-Photon Absorption Laser
  - Ability to determine fault cause in modern devices
- Portable High-Speed Device Testers
  - Required to provide a cost-effective meaningful answer
- Physics Based Modeling Tool
  - Provide an answer to shortfalls in tools such as CREME96
- Radiation hardening of devices
  - Development of substrate engineering processing methods to decrease charge generation and enhance recombination in CMOS
  - Improved radiation hardening of sensors/detectors
- Improved solar heavy ion model
  - System risk analysis requires this
- Update to AE-8 and AP-8
  - Important to CEV and phasing orbits
- Standard radiation environment "engineering-grade" sensor for all missions for long-term technology performance tracking and anomaly resolution. Commensurate technology database.



## Summary

- 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.
- To cope with the uniqueness of the Exploration missions' hazard, a program infrastructure and commensurate targeted research are suggested.