A Methodology for Cost Effective Radiation Characterization of COTS Hardware for Space Use

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Figure 2: *Earthrise* Credit: NASA

A. Meeting the Moment

When humanity returns to the lunar surface, the opportunity to capture inspiring imagery like the *Earthrise* photo will depend on the technical performance of the Handheld Universal Lunar Camera (HULC). Proper testing and development of the COTS imagery system for the Artemis Lunar Surface mission will help ensure HULC is ready for its moment to shine. Radiation environments are challenging for modern electronics. Without a cost-effective means of performing radiation tests, the HULC would not be ready when its *Earthshine* opportunity arises. While COTS products provide a cheap and easy solution for many space applications, most are susceptible to ionizing radiation. Such COTS systems often require modification, yet programs do not want to incur large cost and schedule impacts. This poster will guide other developers regarding single-event effect (SEE) testing decisions when using COTS.

B. Environmental Considerations

The Earth's magnetosphere creates belt of trapped ionizing radiation that should be considered. It additionally shields from most radiation from other sources. Outside the magnetosphere, Solar Particle Events (SPE) and Galactic Cosmic Rays (GCR) are the abundant sources of ionizing radiation.

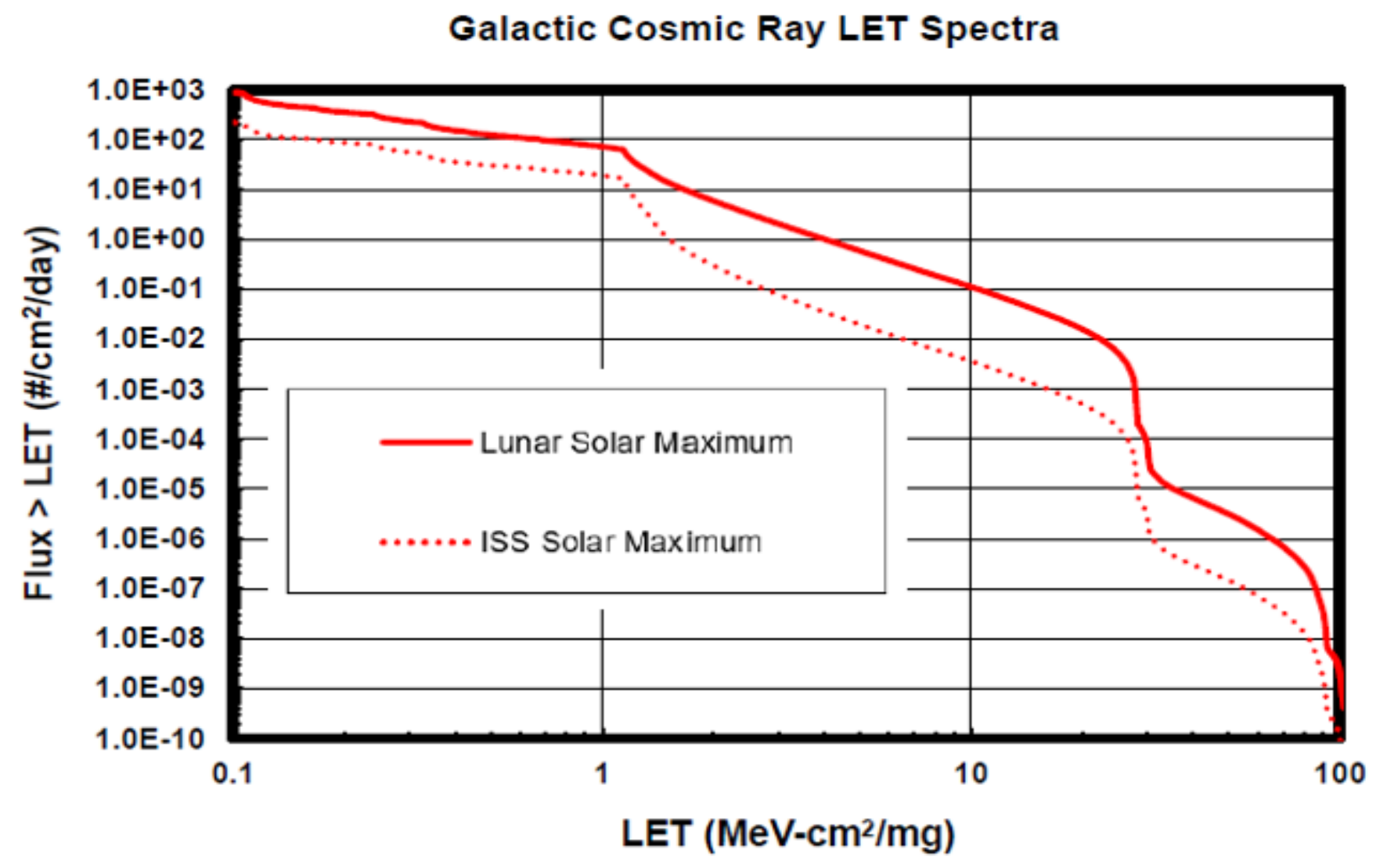


Figure 3: Comparisons of particle flux during worst case scenarios for GCR between lunar surface and ISS. Note flux approximately 10-15x higher on lunar surface than LEO estimates.

Credit: CREME96, NASA Goddard

C. Proton Radiation

The basics of Proton Testing

- Low cost \$1-\$2k/hr, more readily available (scheduled within months)
- Most common source of ionizing radiation in space
- High energy (>200 MeV) protons energetic enough to pass through systems with little concern for packaging are easily produced, can produce LETs ~ 0.02MeV-cm^2/mg
- Secondary ions produced by proton strikes can have LET typically up to 8, in rare instances between 15-25

Benefits of Proton testing

- Pros: COTS screening, high energy to penetrate packaging, more available than heavy ion, cheaper than heavy ion, typically larger beam window
- Cons: requires higher dose (longer times) for equivalent coverage, uncertain LET from secondary ionization,
- Consider: good entry point for data, validate mitigation, easy to test at most facilities

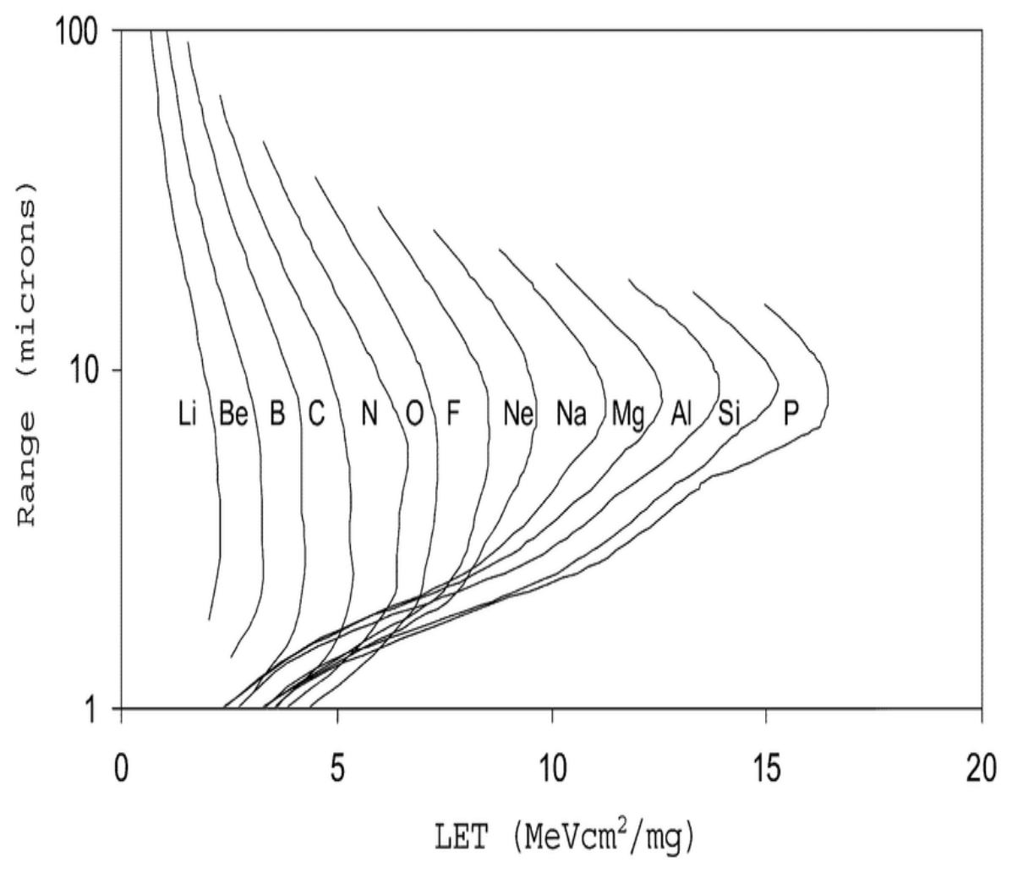


Figure 4: Range in silicon of secondary ions produced by proton strikes Credit: NASA Goddard

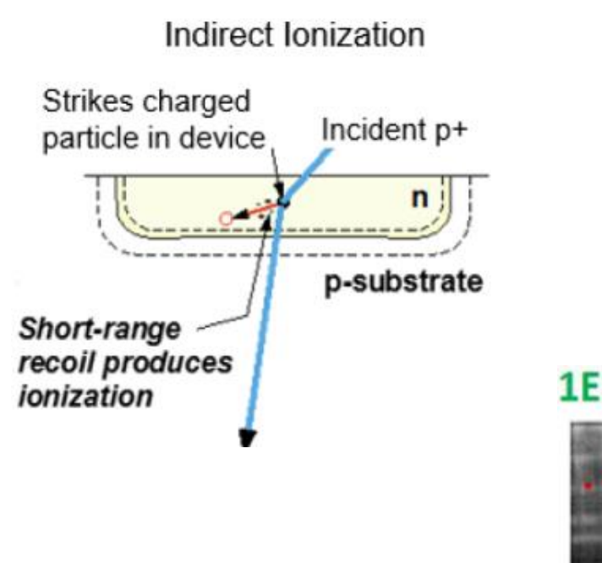


Figure 5: Indirect ionization by proton radiation Credit: NASA Goddard

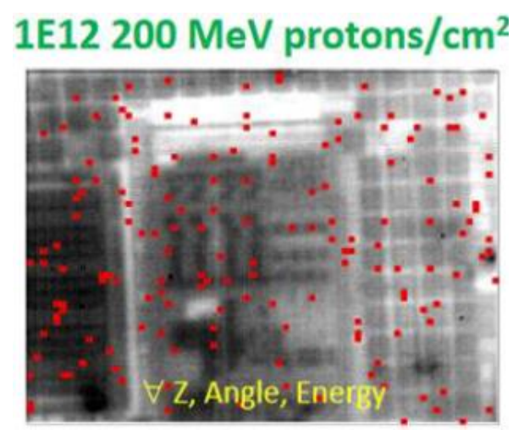


Figure 6: Secondary heavy ions produced after coverage of 200MEV protons at fluence 1e12 Credit: NASA Goddard

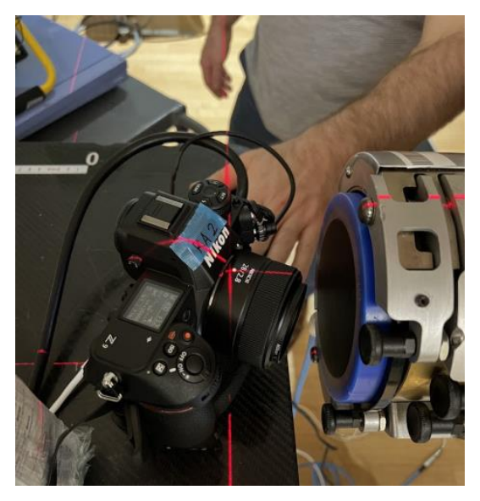
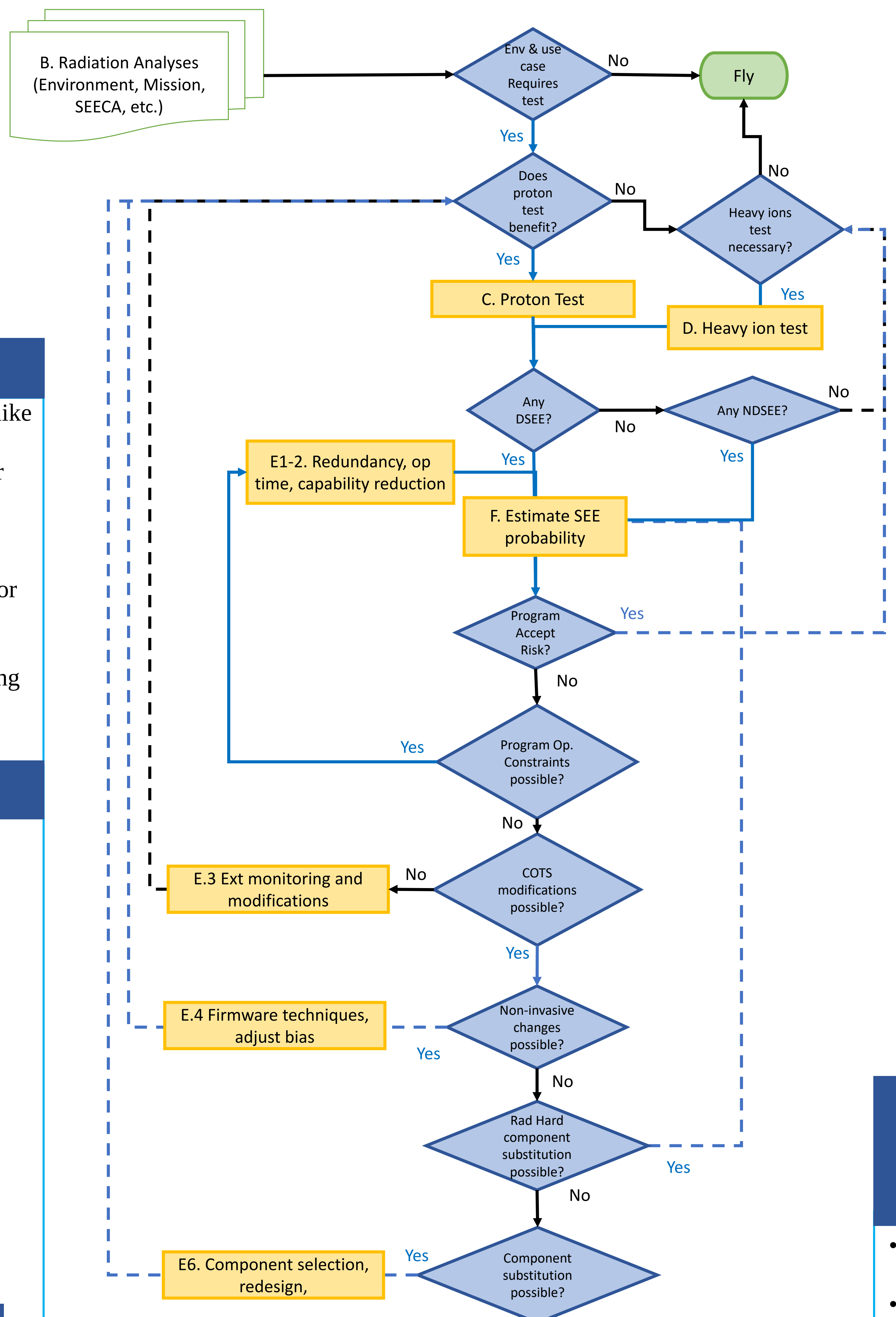


Figure 7: Z9 in proton beam

Figure 1: Decision tree for SEE testing



D. Heavy Ion Radiation

Basics of Heavy Ion Radiation

- Test expensive (\$5k-\$7k/hr) and low availability (scheduled within years), test objectives and facility capabilities must be considered
- Are highly energetic particles that cannot be shielded due to energy
- Requires synchrotrons to develop high enough energy to penetrate most parts
- Lower energy emitters (cyclotrons) available, requires modifications of part and system packaging for test

Heavy Ion Testing

Benefits of Piece part testing

- Pros: DSEE and NDSEE cross-section for part selection, more flexible testing than system level, validate some mitigation techniques before system implementation
- Cons: no benefit for some COTS systems, unknown system effects
- Consider: beam energy to penetrate packaging, cost to prep, facility time, cost

Benefits of System testing

- Pros: Broad analysis of system response and mitigations, simulates worst case environment
- Cons: Expensive, difficult to procure, complex data capture, beam energy required
- Consider: Range of beam, cost, test complexity, test objective

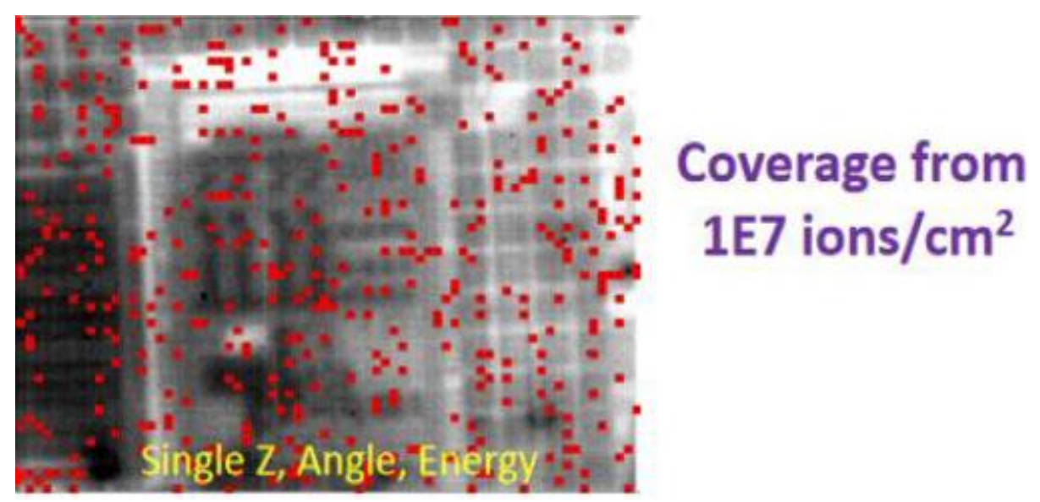


Figure 8: Ionization coverage of heavy ions at fluence 1e7 Credit: NASA Goddard

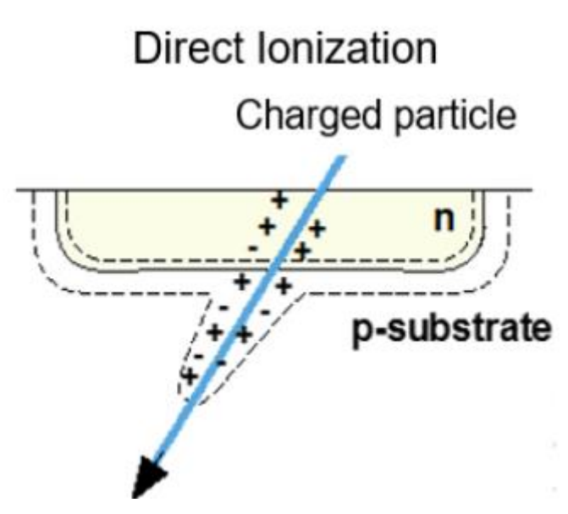


Figure 9: Direct ionization by heavy ion radiation Credit: NASA Goddard

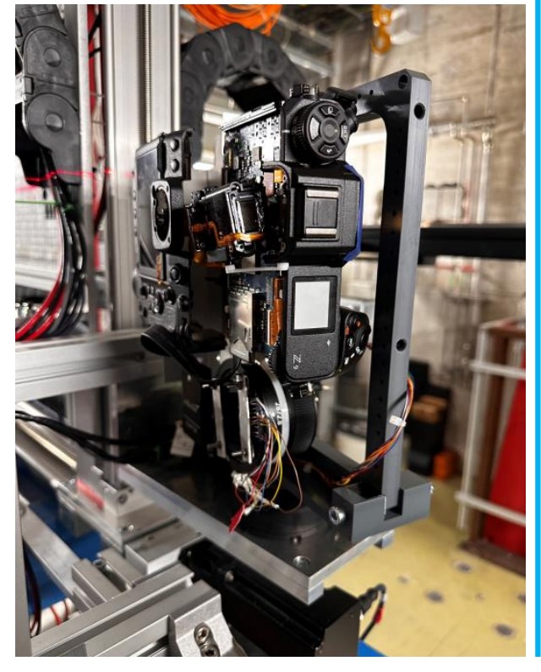


Figure 10: Z9 unpackaged in heavy ion beam at GSI

E. Mitigation Methods

Risk of SEEs can never be 0%. The following methods can reduce the probability of destructive and non-destructive SEE; a system level analysis considering these methods should be considered. Multiple methods can be used to increase radiation tolerance.

1. Operational
   a) Reduced operating time
   b) Full power resets
2. Redundancy/spares
3. Ext watchdog timer (WDT)
4. Redesign (no hardware changes)
   a) Reduce operating bias
   b) Firmware and memory
      i. Triple Modular Redundancy (TMR)
      ii. Configuration Memory Scrubbing
      iii. Error Detection and Correction (EDAC)
      iv. Internal WDT
5. Rad hard components
   a) Large, expensive, and custom footprints
   b) No need to test
6. Rad tolerant components

a) Requires testing of each component to determine LET cross-section and limits
b) Reducing voltage bias further reduces susceptibility

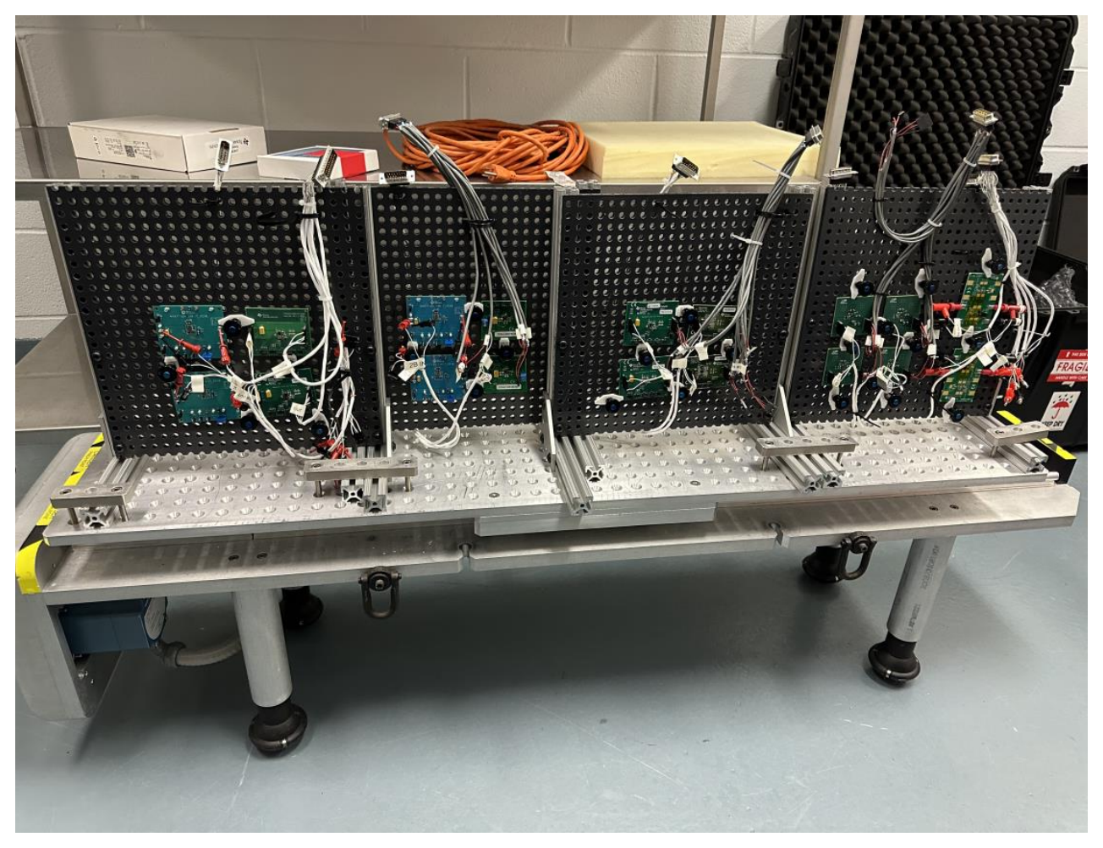


Figure 11: Component piece part heavy ion testing at NSRL

F. Estimating likelihood of SEE in a system

- There exist several ways to calculate the expectation or rate of events for a given environment with respect to single event effects [1-3] on individual components
  - The basic principle brings together environment contributors and device cross-section [2, 3]
  - Test costs and feasibility can limit data gathering for full cross-section information [4, 5]
- In order to determine a bounding case given a dataset with limited number of LET data – use Petersen's single-event figure of merit (FOM) [6, 7]

$$FOM = C_{env} \times \frac{\sigma_{sat}}{(LET_{0.25})^2}$$

  - Empirical power law relationship seen in past technologies simplifies the number of variables
  - FOM and CREME96 [1] rate agree well for σ_{sat} > 100μm^2 and LET$_0$ < 50 MeV-cm^2/mg; even when they disagree FOM a good indicator of high rates [8]
- For all identified failure rates, the risk is additive:
  - Assuming constant failure rate will give the reliability function $R(t) = e^{-\lambda t}$
  - Number of parts
  - Duration in susceptible state

G. A Real-Lunar Example: HULC A COTS Product requiring Radiation Characterization and Redesign

- NASA Human Space Flight Program chose the next handheld camera for use both in LEO and Lunar locations. The choice was based on technical performance.
- Lunar Environment flux ~ 15x more heavy ions than ISS, determined proton testing performed to test for radiation susceptibility and analysis of environment revealed SEE test and analysis required
- Proton chosen for system test, results est. 60% chance of failure in 24 hours from COTS power IC
- Vendor agreed to redesign and investigated replacement ICs to improve tolerance
- Proton screening on several candidates quickly reduced candidates to narrow field
- Results of heavy ion testing allowed est. of SEEs w/ FOM for each IC candidate
- Concurrent proton testing w/ temporary protection/mitigation allowed for further board level screening
- Initial results from heavy ion were not promising, additional mitigation added by reducing voltage and adding one rad hard component
- Heavy ion test results from NSRL with new mitigation showed promise using FOM analysis
- Additional proton performed on subsystems including the lens, view finder, memory card, and Wi-Fi showed SEEs, though risk was acceptable
- Components added to manufacturer's board design and prototypes created
- Proton testing of new board resulted in no DSEE. NDSEEs still present as expected
- View finder failure occurred, previously undetected because of beam line/time exposure low
- Heavy ion testing for complete system was planned to test for DSEE
- Testing was to be performed in June at GSI, however, facility failures delayed the test

Results

- Conservative estimates of the test have indicated that the product has improved from a 60% chance of failure in a day to a 0.36% chance of failure in a day, a 166x improvement

H. Conclusion

Following the processes described in this poster, the HULC project produced a camera that is up to the radiation challenges presented by the Artemis missions. This generation's *Earthrise* photos will be captured during these missions. Implementing appropriate radiation mitigations in the design ensures HULC is ready to capture awe-inspiring moments like the Artemis lunar landings and share those experiences with all of humanity.

Figure 12: Z9 in use during promotional image Credit: NASA

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References

1. A. E. Wilson, M. Wirthlin and N. G. Baker, "Neutron Radiation Testing of RISC-V TMR Soft Processors on SRAM-Based FPGAs," in *IEEE Transactions on Nuclear Science*, vol. 70, no. 4, pp. 603-610, April 2023, doi: 10.1109/TNS.2023.3235582
2. J. Tylka, and others, "CREME96: A Revision of the Cosmic Ray Effects on Micro-Electronics Code", IEEE Trans. Nucl. Sci., 44(6), 1997, pp. 2150-2160.
3. R. A. Weller et al., "General Framework for Single Event Effects Rate Prediction in Microelectronics," in IEEE Transactions on Nuclear Science, vol. 56, no. 6, pp. 3098-3108, Dec. 2009, doi: 10.1109/TNS.2009.2033916.
4. Heavy Ion Orbital Environment Single-Event Effects Estimations (Rev. A)
5. CubeSat Radiation Hardness Assurance Beyond Total Dose: Evaluating Single Event Effects (usu.edu)
6. A. V. Sogoyan, A. A. Smolin and A. I. Chumakov, "Single event rate estimation based on limited experimental data," 2020 20th European Conference on Radiation and Its Effects on Components and Systems (RADECS), Toulouse, France, 2020, pp. 1-5, doi: 10.1109/RADECS50773.2020.9857733.
7. E. L. Petersen, J. B. Langworthy and S. E. Diehl, "Suggested Single Event Upset Figure of Merit," in IEEE Transactions on Nuclear Science, vol. 30, no. 6, pp. 4533-4539, Dec. 1983, doi: 10.1109/TNS.1983.4333166.
8. E. L. Petersen, J. C. Pickel, J. H. Adams and E. C. Smith, "Rate prediction for single event effects-a critique," in IEEE Transactions on Nuclear Science, vol. 39, no. 6, pp. 1577-1599, Dec. 1992, doi: 10.1109/23.211340.
9. Data, What Is It Good For? (nasa.gov)
10. D. Sinclair and J. Dyer, "Radiation Effects and COTS Parts in SmallSats," 27th Annual AIAA/USU Conference on Small Satellites 2013, Logan, Utah