PACE 2012

Radiation

14 – 18 May, 2012

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Mission Parameters and Radiation Analysis Assumptions

- **Launch date**
  - Assumed October 1, 2019
- **Orbit**
  - Earth orbit 700 km altitude
    - Sun-synchronous 98.19^{o} inclination
    - Local noon
  - Trapped particles predominate radiation environment
- **Duration**
  - Considered 3 years, 5 years
- **Radiation sources considered**
  - Trapped electrons and protons
  - Solar protons (ESP model at 95% confidence level)

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Environment Forecast Tools

- **Trapped proton and electron fluences**
  - PSB97 and AE-8 NASA standards
- **Solar proton fluences**
  - Emission of Solar Protons (ESP) Total Fluence
  - Based on data from 21 solar maximum years (cycles 20-22)
  - Uses maximum entropy – upper bound at 95% confidence level
  - Calculates cumulative/worst case solar proton fluences
- **Total ionizing dose**
  - SHIELDOSE-2, v2.10
  - Target material: silicon
  - Shielding configuration: solid aluminum spheres
  - Generates proton results without nuclear attenuation
- **Models are implemented on SPENVIS website**
  - http://www.spenvis.oma.be/, an ESA system

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Solar Cycle Effects

- **<u>Solar maximum</u>**
  - Galactic cosmic ray fluxes lower
  - Solar particle events are more frequent and of greater intensity
- **Solar minimum**
  - Galactic cosmic ray fluxes higher
  - Solar particle events are less frequent and of lower intensity
- **Mission duration is during solar maximum and solar minimum**

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Mission Total Dose Comparison

- **Dose is dominated by trapped protons and electrons**
- **If feasible, reduce dose (no margin) to 15 krad (Si)**
  - Not possible for all subsystems, but a good guideline
- **For 2.5 mm ≈ 100 mil aluminum equivalent, > 12 krads (Si) Total Ionizing Dose**
- **Standard safety factor x2 requires design for 23 krads (Si) at 2.5 mm Al equivalent**

3 year mission

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
0.050	1.968	0.014	1.718E+06	1.672E+06	3.184E+03	3.986E+03	3.820E+04	1.676E+06	1.680E+06
0.100	3.937	0.027	9.452E+05	9.170E+05	1.914E+03	4.001E+03	2.223E+04	9.189E+05	9.229E+05
0.200	7.874	0.054	4.255E+05	4.081E+05	1.008E+03	4.017E+03	1.241E+04	4.091E+05	4.131E+05
0.300	11.811	0.081	2.325E+05	2.192E+05	6.316E+02	4.034E+03	8.579E+03	2.198E+05	2.239E+05
0.400	15.748	0.108	1.445E+05	1.335E+05	4.395E+02	4.054E+03	6.455E+03	1.340E+05	1.380E+05
0.500	19.685	0.135	9.848E+04	8.891E+04	3.313E+02	4.075E+03	5.168E+03	8.924E+04	9.331E+04
0.600	23.622	0.162	7.267E+04	6.397E+04	2.648E+02	4.097E+03	4.336E+03	6.424E+04	6.833E+04
0.800	31.496	0.216	4.743E+04	3.989E+04	1.895E+02	4.144E+03	3.209E+03	4.008E+04	4.422E+04
1.000	39.370	0.270	3.523E+04	2.836E+04	1.488E+02	4.203E+03	2.521E+03	2.850E+04	3.271E+04
1.500	59.055	0.405	2.116E+04	1.509E+04	9.778E+01	4.350E+03	1.628E+03	1.519E+04	1.954E+04
2.000	78.740	0.540	1.518E+04	9.141E+03	7.243E+01	4.801E+03	1.166E+03	9.213E+03	1.401E+04
2.500	98.425	0.675	1.157E+04	5.772E+03	5.708E+01	4.836E+03	8.999E+02	5.829E+03	1.067E+04
3.000	118.110	0.810	9.005E+03	3.691E+03	4.710E+01	4.543E+03	7.236E+02	3.738E+03	8.281E+03
4.000	157.480	1.080	6.267E+03	1.555E+03	3.504E+01	4.172E+03	5.052E+02	1.590E+03	5.762E+03
5.000	196.850	1.350	4.937E+03	6.377E+02	2.800E+01	3.895E+03	3.765E+02	6.657E+02	4.561E+03
6.000	236.220	1.620	4.285E+03	2.467E+02	2.348E+01	3.714E+03	3.010E+02	2.702E+02	3.984E+03
7.000	275.590	1.890	3.928E+03	9.178E+01	2.036E+01	3.571E+03	2.449E+02	1.121E+02	3.683E+03
8.000	314.960	2.160	3.716E+03	3.240E+01	1.807E+01	3.462E+03	2.041E+02	5.046E+01	3.512E+03
9.000	354.330	2.430	3.588E+03	1.084E+01	1.636E+01	3.386E+03	1.748E+02	2.720E+01	3.413E+03
10.000	393.700	2.700	3.482E+03	3.427E+00	1.503E+01	3.314E+03	1.498E+02	1.846E+01	3.332E+03
12.000	472.440	3.240	3.352E+03	2.652E-01	1.307E+01	3.223E+03	1.165E+02	1.333E+01	3.236E+03
14.000	551.180	3.780	3.264E+03	6.734E-03	1.169E+01	3.160E+03	9.258E+01	1.170E+01	3.172E+03
16.000	629.920	4.320	3.212E+03	5.171E-05	1.065E+01	3.126E+03	7.599E+01	1.065E+01	3.136E+03
18.000	708.660	4.860	3.183E+03	5.578E-07	9.779E+00	3.110E+03	6.410E+01	9.779E+00	3.119E+03
20.000	787.400	5.400	3.151E+03	0.000E+00	9.044E+00	3.088E+03	5.411E+01	9.044E+00	3.097E+03

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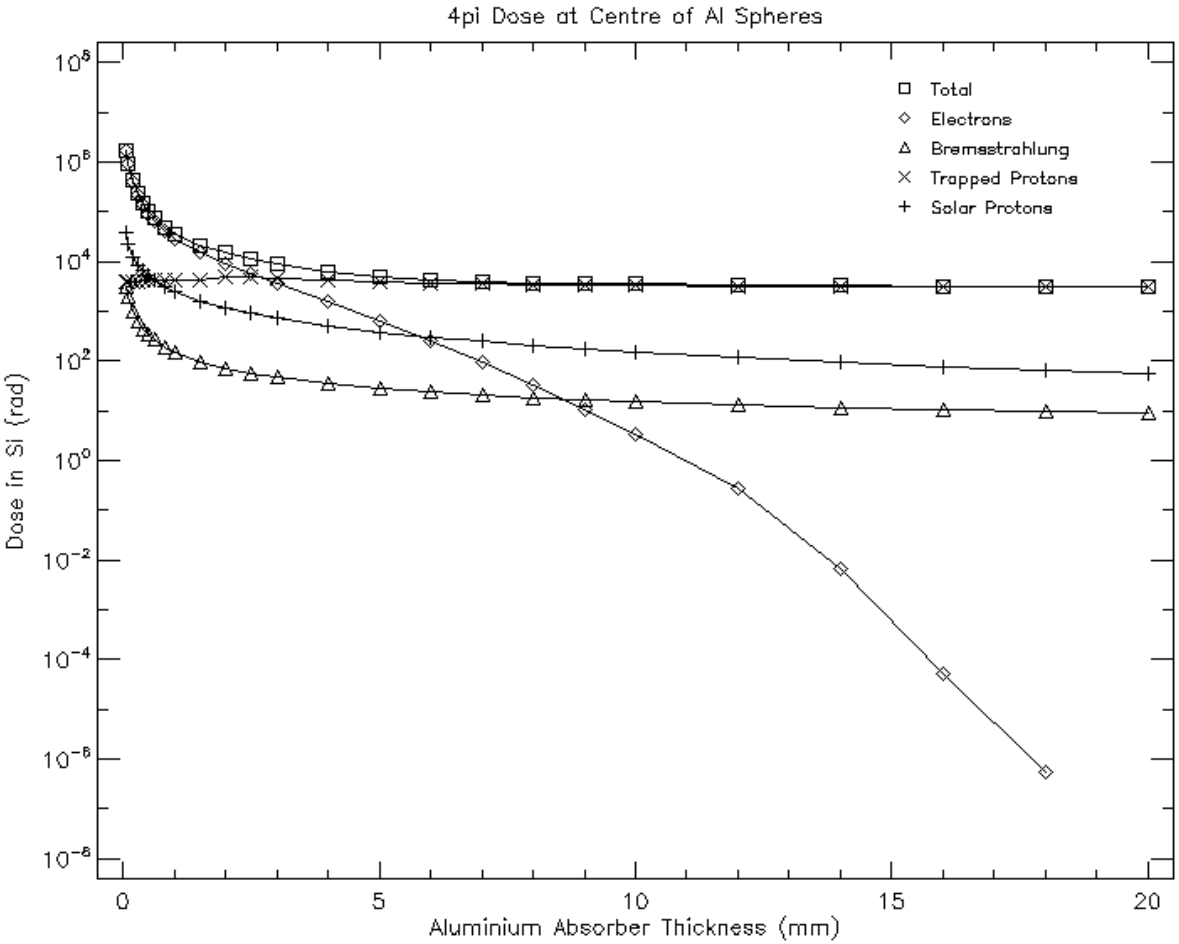
Mission Total Dose Comparison

- **Dose is dominated by trapped protons and electrons**
- **If feasible, reduce dose (no margin) to 15 krad (Si)**
  - Not possible for all subsystems, but a good guideline
- **For 2.5 mm ≈ 100 mil aluminum equivalent, 12 krads (Si) Total Ionizing Dose**
- **Standard safety factor x2 requires design for 23 krads (Si) at 2.5 mm Al equivalent**

3 year mission



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- **Dose is dominated by trapped protons and electrons**
- **If feasible, reduce dose (no margin) to 15 krad (Si)**
  - Not possible for all subsystems, but a good guideline
- **For 2.5 mm ≈ 100 mil aluminum equivalent, > 21 krads (Si) Total Ionizing Dose**
- **Standard safety factor x2 requires design for 41 krads (Si) at 2.5 mm Al equivalent**

5 year mission

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
0.050	1.968	0.014	2.890E+06	2.787E+06	5.306E+03	6.644E+03	9.032E+04	2.793E+06	2.799E+06
0.100	3.937	0.027	1.593E+06	1.528E+06	3.191E+03	6.668E+03	5.443E+04	1.532E+06	1.538E+06
0.200	7.874	0.054	7.206E+05	6.801E+05	1.679E+03	6.695E+03	3.206E+04	6.818E+05	6.885E+05
0.300	11.811	0.081	3.962E+05	3.654E+05	1.053E+03	6.723E+03	2.302E+04	3.664E+05	3.731E+05
0.400	15.748	0.108	2.478E+05	2.226E+05	7.325E+02	6.756E+03	1.780E+04	2.233E+05	2.300E+05
0.500	19.685	0.135	1.701E+05	1.482E+05	5.521E+02	6.791E+03	1.454E+04	1.487E+05	1.555E+05
0.600	23.622	0.162	1.263E+05	1.066E+05	4.414E+02	6.828E+03	1.242E+04	1.071E+05	1.139E+05
0.800	31.496	0.216	8.313E+04	6.648E+04	3.158E+02	6.906E+03	9.422E+03	6.680E+04	7.371E+04
1.000	39.370	0.270	6.205E+04	4.726E+04	2.480E+02	7.005E+03	7.535E+03	4.751E+04	5.451E+04
1.500	59.055	0.405	3.759E+04	2.515E+04	1.630E+02	7.250E+03	5.034E+03	2.531E+04	3.256E+04
2.000	78.740	0.540	2.705E+04	1.523E+04	1.207E+02	8.002E+03	3.689E+03	1.536E+04	2.336E+04
2.500	98.425	0.675	2.067E+04	9.620E+03	9.514E+01	8.060E+03	2.894E+03	9.715E+03	1.778E+04
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8.000	314.960	2.160	6.557E+03	5.399E+01	3.011E+01	5.769E+03	7.040E+02	8.410E+01	5.853E+03
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12.000	472.440	3.240	5.803E+03	4.421E-01	2.178E+01	5.371E+03	4.096E+02	2.222E+01	5.393E+03
14.000	551.180	3.780	5.614E+03	1.122E-02	1.949E+01	5.267E+03	3.275E+02	1.950E+01	5.286E+03
16.000	629.920	4.320	5.498E+03	8.618E-05	1.775E+01	5.210E+03	2.703E+02	1.775E+01	5.227E+03
18.000	708.660	4.860	5.428E+03	9.296E-07	1.630E+01	5.183E+03	2.290E+02	1.630E+01	5.199E+03
20.000	787.400	5.400	5.356E+03	0.000E+00	1.507E+01	5.146E+03	1.941E+02	1.507E+01	5.162E+03

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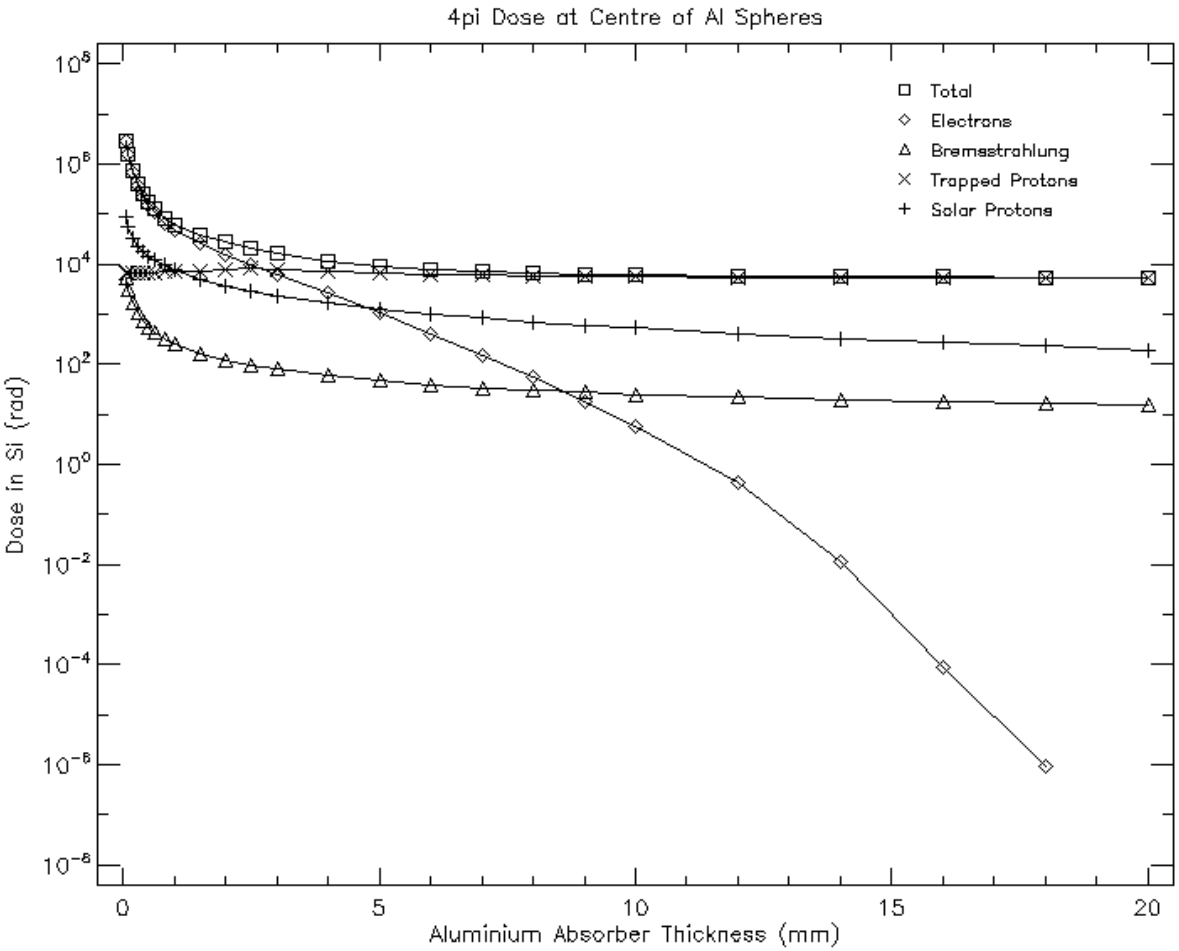
5 year mission



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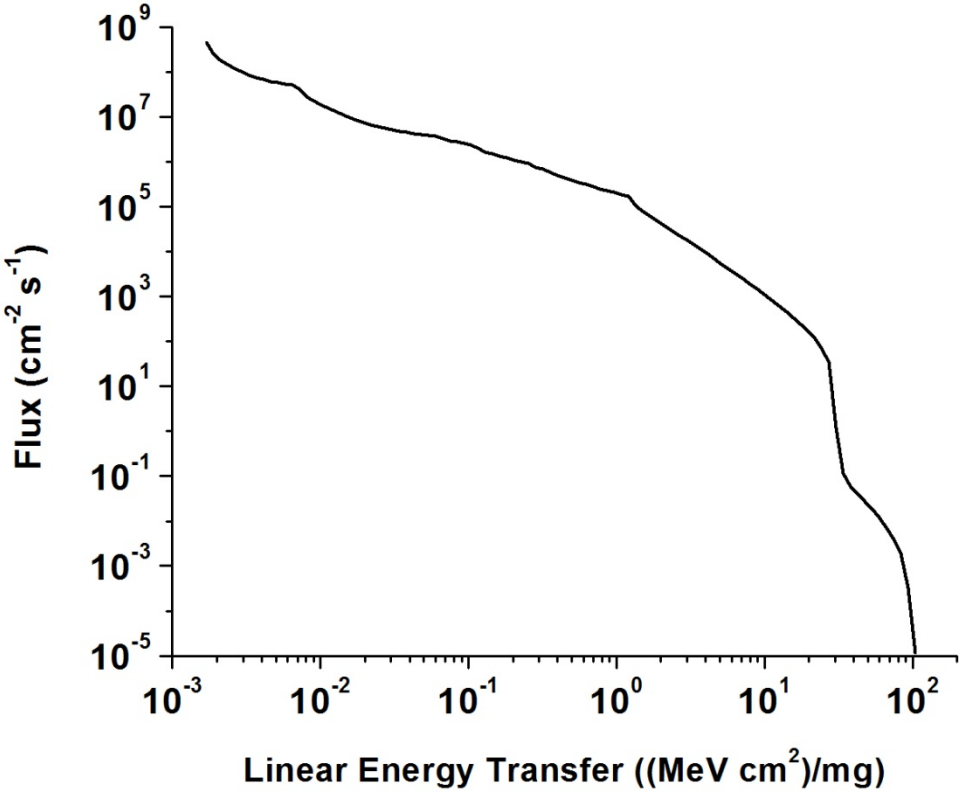
Heavy Ion Flux for Single-Event Effects

- **Flux for mission timeframe**
- **Values just include galactic cosmic rays**
  - Solar heavy ions could be significant depending on solar activity
- **Spectrum is used to evaluate single-event effects**
  - Soft errors
  - Destructive errors
    - SEL, SEGR, etc.
- **Cannot shield these particles**

LET Flux for PACE Mission



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Summary of Environmental Risks for EEE Parts

	Plasma Charging	Trapped Protons	Trapped Electrons	Solar Protons	Cosmic Rays
LEO (low inclination)	No	Yes	Moderate	Yes	Yes
LEO (polar)	No	Yes	Moderate	Yes	Yes
MEO/HEO	Moderate	Yes	Yes	Yes	Yes
GEO	Yes	No	Severe	Yes	Yes
Interplanetary	During phasing orbit	During phasing orbit	During phasing orbit	Yes	Yes

- **Yellow indicates significant hazard**
- **PACE is in LEO**

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PACE Recommendations

- **Predominant total ionizing dose (TID) is due to trapped particle flux**
  - Dose for 3 years with 2x margin is 23 krad(Si) with ≈ 2.5 mm aluminum shielding
  - Dose for 5 years with 2x margin is 41 krad(Si) with ≈ 2.5 mm aluminum shielding
  - Need to consider dose effects on cold spares and nominally-off devices – *i.e.*, powered and un-powered behave differently
  - TID affects end-of-life performance, which could threaten final operations
- **Single-event effects (SEEs) are caused by solar protons, solar particle events, and galactic cosmic rays**
  - EEE parts will be exposed to the full space environment
  - Mitigation techniques for soft errors and transients are required for vulnerable components – will be application specific
    - Memories, FPGAs, linear bipolar components, mixed-signal devices, etc.
  - Cannot shield to mitigate single-event effects
  - Major destructive concerns are single-event latchup (bulk CMOS), single-event gate rupture (power BJT/MOSFET), and single-event burnout (power BJT/MOSFET)

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Backup Slides

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Single-Event Effect Types

- **Can be induced by both heavy ions and protons**
  - Potentially destructive
    - Single-event latchup (SEL)
      - EEE components with bulk CMOS/BiCMOS
    - Single-event burnout (SEB)
      - Power bipolar transistors and power MOSFETs
    - Single-event gate rupture (SEGR)
      - Power MOSFETs, DC/DC converters, point-of-loads
    - Single-event hard error (SHE)
  - Non-destructive
    - Single-event upset (SEU)
      - Single- and multiple-bit upset
    - Single-event transient (SET)
      - Can be digital or analog
    - Single-event functional interrupt (SEFI)
      - Primarily affects components with control logic/registers
      - SDRAM, Flash, A/D converter, D/A converter, processors

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Single-Event Effects Definitions

- **Potentially destructive**
  - SEL: loss of device functionality due to a single-event-induced high current state
  - SEB: possible device destruction caused by positive current feedback in the drain or collector region, initiated by a single-event
  - SEGR: possible device destruction due to a high-current state in the gate oxide that can lead to thermal breakdown, initiated by a single ion passing through the gate oxide
  - SHE: a single-event that causes a permanent change to the operation of the device – *i.e.*, a stuck bit
- **Non-destructive**
  - SEU: a change of state induced by an energetic particle that may occur in digital, analog, and optical components, i.e. a bit flip
  - MBU: an event induced by a single energetic particle such as a cosmic ray or proton that causes multiple upsets or transients during its path through a device or system
  - SET: a “soft” error in that a reset or rewriting of the devices causes normal behavior thereafter
  - SEFI: a condition where a devices stops operating in its normal mode and requires a power reset

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New Solar Particle Models

- **Solar Particle Event Fluence Model (SPE Fluence Model)**
  - R. Nymmik et al., sponsored by Moscow State University
  - Based on power function distributions of event fluences
- **PSYCHIC**
  - M. Xapsos et al., sponsored by NASA
  - Extends energy range of protons > 300 MeV
  - Includes model for solar minimum
  - Includes models for solar heavy ions
- **Update to galactic cosmic ray model**
  - R. Nymmik et al., sponsored by Moscow State University

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Sample SEE Specification (1 of 3)

1. **Define single-event effects**
2. **Component SEE specification**
   1. No SEE may cause permanent damage to a system or subsystem
   2. Electronic components shall be designed to be immune to SEE-induced performance anomalies or outages that require ground-intervention to correct
   3. If a device is not immune to SEEs, analysis for SEE rates and effects must take place based on the linear energy transfer threshold (LET_{th}) of the candidate devices as follows:

Device Threshold	Environment to be Assessed
$LET_{th} < 20$ (MeV·cm^2)/mg	GCR, trapped protons, SPE
$LET_{th} = 20\text{-}75$ (MeV·cm^2)/mg	GCR, SPE
$LET_{th} > 75$ (MeV·cm^2)/mg	No analysis required

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Sample SEE Specification (2 of 3)

2. Component SEE (continued)

4. For any device not immune to SEL, or any other potentially destructive condition, protective circuitry shall be added to eliminate the possibility of damage – must be verified by analysis or test
5. For SEE, the *criticality* of a device in it's specific application shall be defined into one of three categories: error-critical, error-functional, or error-vulnerable
6. Improper operation caused by an SEE shall be reduced to acceptable levels as defined by the project – this can include EDAC, part selection, redundancy, or acceptance of errors

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Sample SEE Specification (3 of 3)

2. Component SEE (continued)

7. A design's resistance to SEE for a specified radiation environment shall be demonstrated

3. SEE guidelines

1. Wherever practical, procure SEE-immune devices
2. If device test data does not exist, ground testing shall be required. For commercial components, testing should be conducted on the flight procurement lot

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