NASA Radiation Hardness Assurance (RHA) Standard: Status for 2022 NEPP ETW

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Introduction

- A NASA Agency-level RHA standard is required that can be readily adopted by flight programs and projects
  - NASA-STD-8739.10 contains a radiation section (high level information)
- NASA requirements documents often levy additional external RHA D&C Standards
  - SMC-S-010 Air Force Space Command EEE Parts Standard (Appendix A refers to RHA)
- In 2019, NESC commissioned an RHA study under task TI-19-01489
  - Supported by NASA radiation/avionics SMEs from GSFC, LaRC, MSFC, JPL, and JSC
  - In 2021, the product was published “Avionics RHA Guidelines” https://ntrs.nasa.gov/citations/20210018053
  - Recommends that an Agency-level RHA Standard be developed by OSMA
- The initial RHA Standard formulation effort was kicked off in 2022
  - Limited task supported by a core group of radiation personnel over ~7 1-hour telecons
- This presentation shows the progress to date, forward work recommendations and solicits NEPP concurrence / direction on the proposed approach.

High Level Dos and Don'ts

- Dos:
  - Establish an RHA taxonomy
  - Focus the “shall” statements on RHA process requirements and MEAL tailoring
    - RHA timeline, documentation, risk acceptance process
    - As opposed to imposing specific part requirements (e.g., 100 krad, 75 MeV-cm^2/mg)
  - Include technical rationale “the why”
    - Focus: data requirements to assess radiation threats for different types of effects
    - Focus: implications of different RHA approaches
    - Technology maturation leads to new threats
    - Not intended as a comprehensive RHA textbook
  - Empower radiation engineers, not replace them
    - Inject RHA into the early project formulation and design
  - Work the document from the top down for consistency
- Don’ts:
  - Override existing Center, Program, or IP RHA standards
  - Use the terminology “COTS”

Table of Contents

- RHA process requirements introduced first (BLUF)
  - The supporting sections follow
- The order in this presentation will deviate from the section order in the document

Contents

Definition of Terms

- Standard sections
- Define lax radiation terms
  - Radiation hard
  - Radiation tolerant
  - Etc.

Contents

RHA Taxonomy

- Critical section of the standard
- The SEE RHA Taxonomy is the most mature section of the document

Contents

SEE Taxonomy: Novel Initiative

- No systematic method is currently defined to categorize EEE parts from the RHA perspective
  - Neither is a standard terminology
- An initial attempt was made to mirror the EEE Parts "grade" taxonomy
  - But converged on categorizing RHA approaches instead
    - There is much more to RHA than selecting a part type
- There are currently defined five SEE RHA categories denoted S0-S4
  - S0 is "do nothing", S4 is the equivalent of "old school rad-hard"
  - Several considerations are included under the description of each category
    - Including predominant use of SEE RHA parts, part radiation selection criteria, anticipated scope of SEE design, test, and analysis, typical SEE RHA activities, etc.
- Each mission class (SMD) & criticality (HEO) is associated with a default RHA category
  - The association is not subject to a "shall" statement
- Details on next slides (this is a draft – more discussions needed)

SEE Taxonomy (continued)

RHA Type	S0 (do nothing)	S1	S2	S3	S4
Human Space Flight Criticality Default	N/A	Crit 3		Crit 2R	Crit 1,2
Mission Class Default	N/A	D-, E	D	C	A, B
Risk tolerance posture	Highest	High	Medium-High	Medium-Low	Low
RHA integral to the design process	No	No	Yes	Yes	Yes
Predominant EEE Parts Radiation Usage	Non-RHA parts and CCAs	Non-RHA parts and CCAs	Non-RHA parts with pre-design screening or flight heritage[1].	RHA parts with risk avoidance or characterization data to medium LET (30-40 MeV-cm^2/mg)	MILSPEC RHA parts with risk avoidance or characterization data to high LET (60-75 MeV-cm^2/mg)[2]
Anticipated scope of systems engineering	None	Focused on do-no-harm to other system components	Is typical class D different from S1? Conversely, do statements for S3/S4 apply here too?	SEE threats to reliability and availability drive the system architecture. Use of rad-tolerant parts vs. rad-hard may have significant implications to system availability in the radiation environment and can lead to dramatic increase in the radiation systems engineering effort.	
Anticipated scope of SEE design	None	None to interface-limited[3]	Current monitoring, current limiting, watch-dog timers, autonomous power cycling, etc.	SEE threats to reliability and availability drive the circuit & SW/VHDL design. Part selection for risk avoidance (i.e., SEE rad-hard vs. rad-tolerant) lowers SEE design scope vs. analysis-driven design mitigation implementation	
Anticipated scope of SEE testing	None	CCA-level high energy proton testing	Combination of CCA- and part-level, high-energy proton and heavy ion testing[4]	Piece-part heavy ion characterization test data should be available. Additional testing as needed for NDSEE characterization, low-LET-threshold parts proton susceptibility, and CCA-level for complex system interactions (e.g., SW and HW) validation.	

[1]Relevant and statistically significant
[2]60-75 MeV-cm2/mg may be tailored for benign environments
[3]E.g., implementation of current monitoring and power cycling capability external to the CCA
[4]High energy protons (~200 MeV) often used as the main test solution. Heavy ion testing performed for specific part types e.g., with thick sensitive regions [RHA guidelines]

SEE Taxonomy (continued)

RHA Type	S0 (do nothing)	S1	S2	S3	S4
Human Space Flight Criticality Default	N/A	Crit 3		Crit 2R	Crit 1,2
Mission Class Default	N/A	D-, E	D	C	A, B
DSEE part selection (survivability) criteria	**Not enforced**	**Enforced**			
SEGR/SEB/SEDR acceptance criteria	None	High energy protons for DSEE[5]	Test-constrained (e.g., 20 MeV-cm^2/mg)	Risk avoidance (37 MeV-cm^2/mg)	
SEL acceptance criteria	None			Risk avoidance (37-75[6] MeV-cm^2/mg) or quantification	
DSEE data source	None	CCA-level test	CCA- and/or piece-part	Piece-part characterization	
Risk assurance result	None	Limited risk analysis[7]	Limited risk analysis	Risk quantification	
A priori confidence reliability will be met	None		Limited	Risk quantification: Up to high[8] Risk avoidance: Superior	
NDSEE part selection (availability) criteria	**Not enforced**			**Enforced**	
NDSEE acceptance criteria	None			Risk avoidance: threshold or max piece-part rate requirement Risk quantification: full characterization requirement	
Typical NDSEE data source	None	CCA-level test	CCA- or piece-part test	Piece-part characterization	
Risk assurance product	None	Limited risk analysis[9]		Full analysis characterizes and quantifies probability of all unmitigated SEE at the interface	
A priori confidence availability will be met	None			Risk avoidance: Superior[10] Risk quantification: Up to high[8]	

[5]DSEE risk remaining for specific part types e.g., with thick sensitive regions [RHA guidelines]

[6]60-75 MeV-cm2/mg may be tailored for benign environments

[7]Proton-data-derived heavy ion DSEE susceptibility quantification is unreliable

[8]With successful implementation of SEECA-, and Systems Engineering tasks

[9]See RHA Guidelines Document for CCA-level test limitations

[10]Does not eliminate the need for SEE analysis (need to clarify this statement)

SEE Taxonomy (continued)

RHA Type	S0 (do nothing)	S1	S2	S3	S4
Human Space Flight Criticality Default	N/A	Crit 3		Crit 2R	Crit 1,2
Mission Class Default	N/A	D-, E	D	C	A, B
SEE RHA activities					
SEE circuit and criticality analysis (SEECA)	N/A	Component SEE analyses limited by design insight and statistics. CCA-level test observables must enable do-no-harm validation at system level as applicable.	Design and test strategy informed by SEECA. SEE mitigation analysis may be limited by test observables and statistics. Test observables must enable do-no-harm validation at system level as applicable.	SEECA informs part selection, design and test strategy. High resolution SEE circuit analysis is enabled by detailed part-level characterization data, including downstream non-recoverable effects of SET[11]. Full tracing of SEE impacts at circuit, assembly, and system level informs threat mitigation and risk acceptance.	
Complex parts test and analysis		Characterization of high level observables (e.g., SEFI) in the flight application	Use SEECA to determine if characterization at element & function level is needed to meet objectives	Characterization at element & function level by default. Complexity of modern electronics (and proprietary design) may limit the ability to obtain full characterization; holistic approaches to SEECA and testing may be required to inform risk quantification.	
High-current SEE		Confirmation of mitigation/recovery by radiation test[14]		Confirmation of mitigation/recovery by radiation test[14] and confirmation of no latent damage[12]	
Other non-recoverable SEE		Risk assessment for less-common non-recoverable SEE[13] recommended as feasible		Systematic risk assessment for less-common non-recoverable SEE[13]	
Similarity[15]		Recommended as feasible		Required. Specific situations including new technologies require SEE LAT.	

[11]Generic SET waveform use requires holistic assessment of margin in the context of application criticality. Application-specific SET tests required for insufficient margin and/or critical applications

[12]Reference GSFC note, summarize Ray's input of what is acceptable

[13]Including but not limited to I_{GS} degradation (micro-SEGR), NVROM bit flips, stuck bits, etc.

[14]With sufficient statistical significance

[15]Analysis required to validate applicability of previous test data to the flight design

Taxonomy

- Intend to explore a similar approach for TID/TNID

RHA Process Requirements

- The shall statements are here

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RHA Process Requirements (high level)

- At formulation stage, Programs and Projects shall:
  - Assign an RHA lead
  - Select RHA approaches for SEE, TID, TNID per the categories defined in the Taxonomy section
    - Requires projects to perform an early and meaningful radiation assessment per the MEAL factors
      - This assessment inform the radiation test scope, schedule and budget
    - Large programs/projects may identify multiple categories based on criticality
  - If the RHA approach doesn't match the default for mission class / criticality / risk tolerance posture, projects shall accept a radiation risk & formulate a mitigation plan
- At design milestones, Programs and Projects shall complete specific radiation activities and provide specific document deliverables, or accept a radiation risk & formulate a mitigation plan
  - An IRCP and EDD are required for SRR
  - Test reports, Radiation NSPARs, supporting data (parts lists… circuit designs…), Analysis reports, Radiation system integration
  - Define an exception / simplified approach for Class D / Crit 3 designs (?)

NASA Agency RHA Standard

2022-06 NEPP ETW

Radiation Threats Tree

Threat Index					Mitigation	Notes
1	Total Dose					
1.1		Total Ionizing Dose				
1.1.1			ELDRS			
1.1.2			Variability			
1.1.2.1				Lot-to-lot	RLAT	
1.1.2.2				Sample-to-sample	KTL, RDM	
		Total Non-ionizing Dose				
	Single-Event Effects					
		Destructive SEE				
			SEL			
			SEB			
			SEGR/SEDR			
			Stuck Bits			
			?			
		Non-destructive SEE				
			SET			
			SEU			
		SEE impact propagation			SEECA	
		Incorrect testing				
			Particle range			
			Irradiation angle			
			Test circuit conditions			
				Bias		
				Loads		
			Temperature dependence			
			Variability			
				Manufacturing processes		
				Sample-to-sample		
			Uncertainty			
				Test fluence		
				Derating		
			Endpoints			
				Coverage limited by device complexity		
				Duty cycle		
		Test facility availability				

- Itemizes items required for inclusion in an IRCP
  - Can be considered an IRCP creation checklist
  - Still in draft form (will grow)

RHA Process Requirements

- Define minimum requirements for radiation deliverables
  - What is a box radiation analysis report required to contain?
    - Radiation survivability and availability in the mission
      - SEE rates, TID/TNID information, etc.
    - Information required for system integration of radiation effects
      - Radiation effects manifestation at the interfaces
      - External input required for recovery
- In the IRCP, programs and projects shall establish a process and responsibilities for dispositioning equivalent-risk- , and elevating risk-increasing radiation non-compliances
  - NSPARs and waivers
- Define additional criteria triggering radiation risk
- …?

Radiation Threats

- This section contains the technical rationale
- The "radiation threats tree" (i.e., the IRCP development checklist) will be included here

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Radiation Threats

- The focus is on technical information describing how to correctly perform threat assessment for SEE, TID, and TNID
  - Not intended as a comprehensive RHA textbook

5.2.1.1 Single-Event Latchup (SEL)

SEL refers to a parasitic thyristor structure becoming conductive due to a single particle interaction. SEL are associated with high current and may cause overheating and catastrophic failure. Non-destructive SEL can cause latent degradation leading to shortened lifetime. Outside cryogenic levels, SEL susceptibility increases with temperature. The effective LET is accepted as unifying parameter. Risk avoidance is achieved by part selection with high SEL LET threshold, typically past 2x the LET at the Fe knee. Risk quantification requires 1. Cross-section characterization vs. LET with sufficient resolution to determine threshold, knee region, and saturation cross-section (6+ data points), 2. Effect manifestation characterization (e.g., destructive vs. non-destructive, current, absence of latent damage) and SEECA analysis, and 3. Rate (probability) calculation using an industry-standard model such as RPP/CREME96.

5.2.1.2 Single-Event Gate / Dielectric Rupture (SEGR/SEDR)

SEGR / SEDR refers to destructive oxide breakdown due to a single particle interaction. Susceptibility increases with the potential difference across the oxide. SEGR refers to gate rupture in MOSFETs. SEDR refers to MOS Caps rupture in ICs. For planar components, normal incidence constitutes worst case. Testing at slanted angles is incorrect and does not apply. Other component geometries such as FinFETs require determination of worst-case incidence angle. Complex dependence on particle atomic number Z renders risk quantification unfeasible. Risk avoidance is accomplished by establishing safe operating limits (SOAs). SEGR may manifest as catastrophic failure or gate current degradation (micro-SEGRs). Post-irradiation gate stress (PIGS) testing confirms gate integrity. No effective SEGR/SEDR circuit mitigation/circumvention techniques are known.

5.2.1.3 Single-Event Burnout

SEB refers to a high-current state in a device due to a single particle interaction (JESD57A). Susceptible device types include power MOSFET, BJT, Schottky diodes, etc. SEB causes catastrophic failure of the device or permanent degradation. As for SEGR, risk quantification is unfeasible; risk avoidance is accomplished by establishing SOAs.

TID Threats and Risks

In principle, any component for which dielectric properties are important could be susceptible to TID degradation as charge becomes trapped in those dielectrics their and alters properties. In optical devices, trapped charges may result in color centers that darken the material and absorb optical signals. In semiconductor devices, charge can become trapped in transistor dielectrics, resulting in increased leakage current, changes in threshold voltage, reduced gain and a range of other effects. The fact that ionizing dose accumulates gradually suggests that TID degradation would also worsen gradually over time. In individual transistors—and even in many integrated circuits, degradation does manifest as deterioration of device performance and parameters, culminating in eventual functional failure. However, in many devices, the initial degradation may be masked—visible neither in input nor output parameters. In such devices, severe degradation or catastrophic failure can manifest with little warning.

Because the purpose of dielectrics in semiconductor parts is to control the flow of charge, normal part functionality is usually not affected by changes in dielectric quality. As such, the quality of dielectric materials that underlie TID susceptibility can vary from part to part within a wafer diffusion lot and especially from one wafer diffusion lot to the next. Because of this variability and the fact that TID testing is destructive, the goal of TID RHA is to use data for a test sample representative of (or bounding on) the flight parts in their application(s). Often, device-to-device variation in TID susceptibility is the dominant uncertainty in whether flight parts will meet requirements. As such, the goal of TID testing is to infer the TID response distribution from the variability in the test sample.

If the distribution of TID response is wide, thick-tailed or multimodal , large test samples will be required to infer the variability distribution. To avoid the expense of testing such large numbers of parts and to improve the odds that the test sample is representative of flight parts, TID test samples are drawn from the same wafer diffusion lot as the flight parts. As long as flight-lot distributions are well behaved (unimodal, thin-tailed, not too broad) test sample sizes of 5-10 parts yield sufficient understanding of TID response variability that flight part response can be bounded with good confidence. Guidelines for how to assess the likelihood that a part's variability will be well behaved have been published previously.[RHA Guidelines]

Example IRCPs

- TBD
- Perceived as a major effort as no appropriate existing documents have been identified
- May be added to future updates of the Standard

Contents

Proposed Forward Work

- Increase meeting cadence (weekly?) subject to SME availability
  - Identify additional SME availability for specific areas (TNID, TID)
    - Limited TNID expertise; Solar cells vs. bipolars and other opto-electronics
- Draft TID & TNID Taxonomy sections (lead SMEs TBD)
  - Followed by SEE, TID & TNID deep dives
- Continue maturation of the radiation threats tree
- Draft SEE, TID & TNID Threats sections to draft (started)
  - Followed by deep dives
- Continue maturation of the RHA Process Requirements “shall statements”
- Definition of terms
- Review by the larger NASA / Radiation community and incorporate feedback
  - Continue advertising RHA Standard status at radiation meetings (e.g., NSREC, RADECS)
- Review process by NEPP / OSMA / Office of Chief Engineer stakeholders
  - Formal approval process TBD
- Targeting document deliverable by the end of FY23
  - Subject to expediency of review process and comment dispositioning

List of Acronyms

BLUF: Bottom Line Up Front

CCA: Circuit-Card Assembly

COTS: Commercial-off-the-Shelf

D&C: Design and Construction (Standards)

DDD: Displacement Damage Dose

DSEE: Destructive SEE

EDD: Environments Definition Document

HEO: Human Exploration and Operations Mission Directorate

HW: Hardware

IRCP: Ionizing Radiation Control Plan

LET: Linear Energy Transfer

MEAL: Mission, Environment, Application, and Lifetime

MIL-SPEC: Military Specification

NDSEE: Non-destructive SEE

NEPP: NASA Electronic Parts and Packaging Program

NESC: NASA Engineering & Safety Center

NSPAR: Non-Standard Part Approval Request

NVROM: Non-Volatile Read-Only Memory

OSMA: (NASA) Office of Safety and Mission Assurance

RHA: Radiation Hardness Assurance

RHA Part: Radiation Hardness Assured Part

SEB: Single-Event Burnout

SEGR/SEDR: Single-Event Gate/Dielectric Rupture

SEE: Single-Event Effect(s)

SEECA: SEE Criticality Analysis

SEFI: Single-Event Functional Interrupt

SEL: Single-Event Latchup

SET: Single-Event Transient

SEU: Single-Event Upset

SME: Subject Matter Experts

SMD: Science Mission Directorate

SRR: System Requirements Review

SW: Software

TID: Total Ionizing Dose

TNID: Total Non-Ionizing Dose

VHDL: VHSIC (Very High Speed Integrated Circuits) Hardware Description Language