# NESC Avionics RHA Guidelines: Motivation, Philosophy and Overview

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# Abbreviations

BNL--Brookhaven National Laboratory

CMOS—Complementary Metal-Oxide-Semiconductor

COTS—Commercial Off The Shelf

DSEE—Destructive SEE

DSNE—"Cross-Program **D**esign **S**pecification for **N**atural **E**nvironment

GSN—Goal Structure Notation

HUPTI—Hampton University Proton Therapy Institute

LBNL—Lawrence Berkeley Laboratory

LEO—Low Earth Orbit

LET—Linear Energy Transfer

MBMA—Model-Based Mission Assurance

MBSE—Model-Based System Engineering

MEAL—Mission, Environment, Application, and Lifetime

MGH—Massachusetts General Hospital

MOSFET—Metal-Oxide-Semiconductor Field Effect Transistor

NDSEE—Nondestructive SEE

RHA—Radiation Hardness Assurance

RMC—Reverse Monte Carlo

SEB—Single-Event Burnout

SEE—Single-Event Effects

SEECA—SEE Criticality Analysis

SEGR—Single-Event Gate Rupture

SEL—Single-Event Latchup

SME—Subject Matter Expert

SOTA—State-Of-The-Art

TAMU—Texas A&M University

TID—Total Ionizing Dose

TNID—Total Non-Ionizing Dose (aka Displacement Damage Dose, or DDD)

# A Guide to the Guidelines: Outline

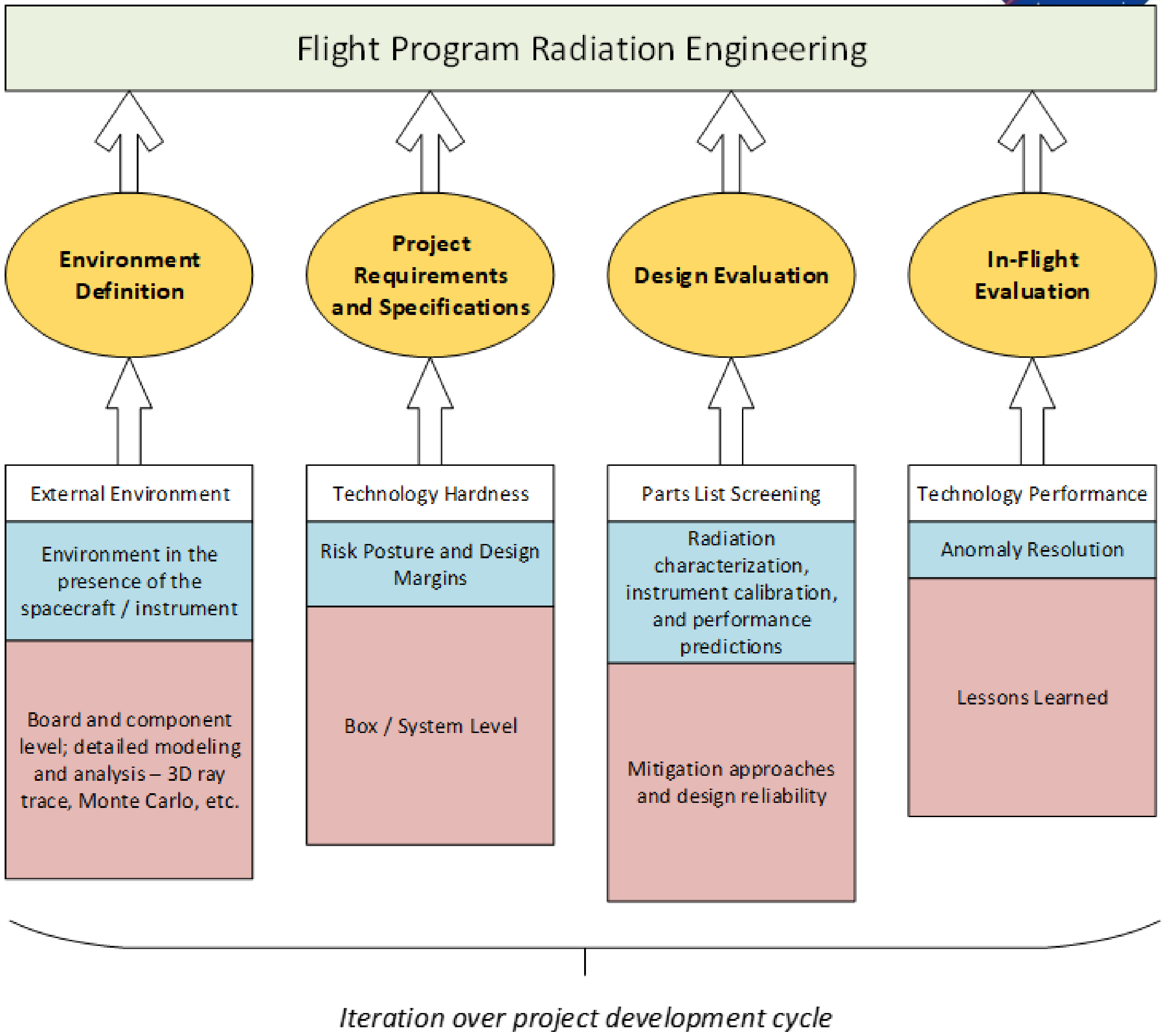
- Introduction: Motivation
  - Why guidelines are needed and why they are needed now
  - Why guidelines and not a requirements document
- Guiding philosophy for the guidelines
  - Radiation Hardness Assurance (RHA) guidelines for each threat tailored to mechanism of effect, dominant sources of uncertainty and emphasize multidisciplinary information needed for RHA
  - Guidelines emphasize not just best practices, but why these practices are best
  - Main target audience is Human Exploration hardware providers
    - Environments defined in “Cross-Program Design Specification for Natural Environment” (DSNE)
- A brief look at what is in the guidelines
  - This presentation (being for SEE Symposium) Focuses on Single-Event Effects (SEE)

# Why A Guideline and Why Now?


- Why a guideline and not a requirements document?
  - Document must be done in time to influence upcoming missions
    - Requirements documents require laborious deliberation
    - Guidelines/best practices require only consensus of subject matter experts (SME)—not buy in from diverse disciplines/parties
  - Document must apply to a broad range of missions/technologies
  - Hard to cover all projects with one requirements document
  - Many vendors use alternate standards in any case
    - Guidelines include rationale for best practice
    - May be easier to determine whether alternate standard meets intent based on rationale
- RHA is a very dynamic field
  - New generations of technology every 2-5 years
  - Breakdown of classical (Dennard) scaling of CMOS means rapid introduction of new materials, technologies, device architectures
- Guideline can capitalize on new editions of several standards
  - MIL-STD 1750 for testing Power MOSFETs and similar devices
  - JESD57A for general SEE testing

# Philosophy: RHA As Risk Assessment and Mitigation

- RHA assesses the risk the radiation environment poses to mission success
  - Evaluate and analyze of the environment
    - Threat severity—and which threat pose the greatest risks to mission success—varies with environment
  - Establish of appropriate requirements
    - Depends on mission goals, technologies, limitations…
  - Evaluate whether design meets requirements
    - Iterative—may involve redesign, implementation of mitigation techniques
  - Evaluate performance in flight
    - Determines not just whether RHA efforts were successful, but whether changes may be needed for future missions
- RHA is a complicated, highly interdisciplinary activity
  - Information flows between radiation analyst, systems engineers, designers, other subject matter experts, etc.
  - Analyses carried out at all levels—transistor to system
    - Most testing done at part level
    - Qualification is by analysis  constrained by test results



# RHA Is a Highly Integrated Activity

**Destructive Nature of Radiation Testing Means Validation Done by Analysis Informed by Testing**

Analysis Needs Drive Test Methods and Requirements

- Tests must supply information required by analysis to achieve its goals
- Test methods driven (examples at right)
  - Analysis goals
  - Dominant errors to be controlled
  - Nature and mechanism of radiation effect
  - Technology, materials and structures in the test parts
  - Need for test sample to be representative of flight parts
- RHA requires broad range of input:
  - Design and system engineers
  - Other Subject Matter Experts (SME)
  - Part manufacturers/vendors
  - Project managers

## Analysis Goal

1) Risk Avoidance
2) Application qualification
3) General characterization (any application)

## Errors to Control

1) Poisson fluctuations
2) Part-to-part variation

## Design Mitigation

1) Error correction/voting
2) SEL protection circuit

## Testing Goals

1) Safe-Operating Conditions
2) Bounding rate and consequences
3) Bounding rate and consequences (all applications, temperatures…)

## Control for Errors

1) Increase event counts for σ points
2) Increase test sample size

## Effect on Testing

1) Emphasize MBU, SEFI… over SEU
2) Validate protection circuit (test for destructive, latent damage)

# What's In The Document? What's Relevant for SEE?



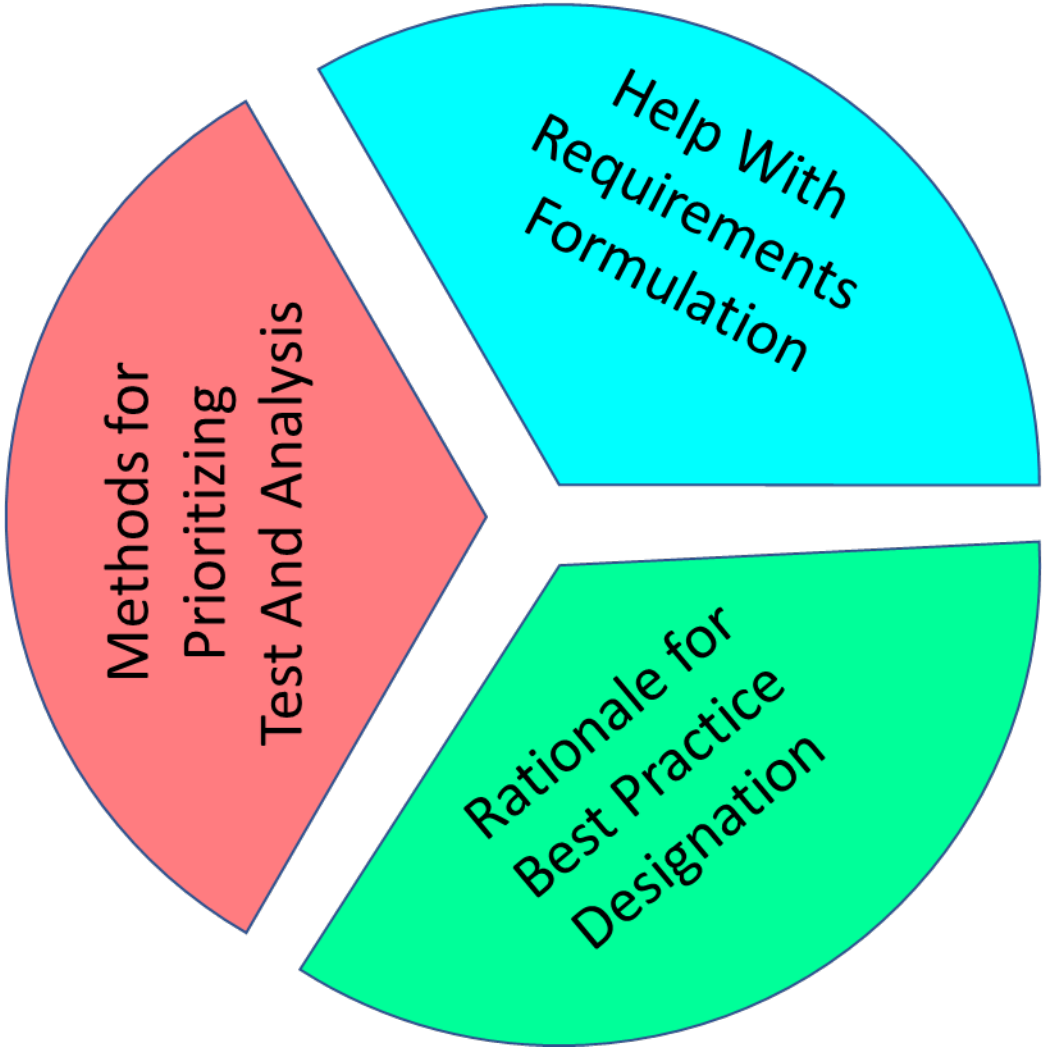
Relevant

Directly Related

**Emphasis: providing practical guidance to analysts working RHA for any project, especially Human Exploration**

# Guidelines Provide Context for Increasing RHA Efficacy

- Valuable Content
  - Discussion on development of requirements
    - What makes a good requirement
    - What criteria to take into account
    - Traceability of requirements
- Rationales for why practices are designated “best”
  - Ensuring SEE susceptibilities are revealed
    - Ensures consequences can be assessed by designers and other interested parties
  - Compatibility with risk assessment and rate estimation tools and procedures
- Prioritizing resources and schedule of RHA efforts
  - High cost and time-consuming nature of RHA pose challenges for ensuring scarce resources used wisely
  - Placing SEE risks in context based on application demands and other criteria ensures efficient use
  - Ensuring most significant risks are addressed early provides time for resolving complex design issues
- Also 12 pages of RHA references



# SEE Section Provides Best Practices + Rationale for Them

- Guideline provides an opportunity to include explanatory material as well as recommended (best) practices.
  - Rationales/reasons for best practice designations allow informed assessment of risks arising from deviations.

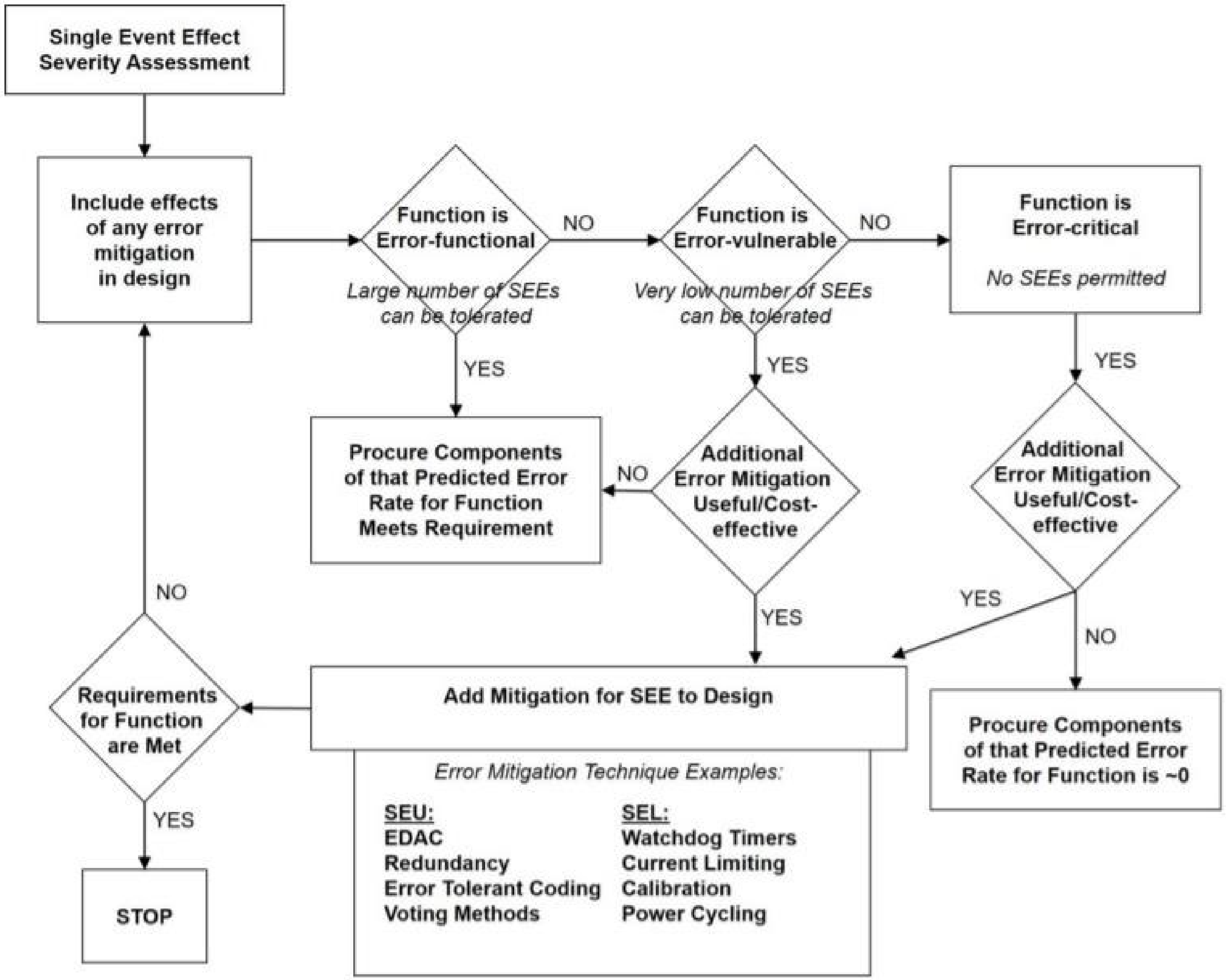
| Sample Best Practice | Reason(s) |
|---|---|
| SEE testing best done with heavy ions | 1) Required for reliable rate estimation/bounding<br>2) Required for adequate coverage/generate all SEE modes |
| Nondestructive SEE (NDSEE), SEL require heavy ion fluences~$10^7$ ions/$cm^2$; SEB/SEGR~$10^5$-$10^7$ ions/$cm^2$ | 1) Required to achieve adequate coverage of SEE modes<br>2) SEB/SEGR angular dependence may allow lower fluence |
| For NDSEE, SEL highest Test LET used should exceed 60-75 $MeVcm^2/mg$; for SEB/SEGR, >37 $MeVcm^2/mg$ | 1) Ensures most credible SEE modes will be observed, or that if not observed, probability during mission is small<br>2) SEB/SEGR angular dependence allows lower max. LET |
| Proton test fluences need to be $10^{10}$ – $10^{12}$ /$cm^2$ | 1) Coverage (only ~1 in 290000 protons generates a recoil ion w/ LET>1 $MeVcm^2/mg$) |
| Testing should bound worst case conditions: e.g. CMOS at maximum voltage and temperature for application | 1) These are conditions most likely to reveal SEL susceptibility |
| Test facilities should provide high enough beam energy | 1) Ensures ions penetrate through device sensitive volume<br>2) May provide greater fidelity to space environment |

# Criteria for Developing Good SEE Requirements

- Criteria for SEE requirements
  - Must be traceable, may derive from reliability (lifetime), availability, accuracy (e.g. bit-error rate, resolution…)
  - May be from “bottom-up,” by piece part (onset LET, rate…) or “top down, allocation from higher level
  - Must be verifiable—usually by analysis informed by testing of representative samples
- Considerations for development of requirements
  - Radiation effect mechanism characteristics
    - Single-particle effect that can happen any time with equal probability (given a constant the environment)
    - NDSEE and SEL follow cosine law. Because flux vs. effective LET decreases less rapidly than flux vs. LET, minimum onset LET requirements for NDSEE and SEL tend to be higher than for SEB/SEGR, which do not follow cosine law.
  - Technology or device type
    - SEL affects CMOS
    - SEB/SEGR affect power transistors
    - Device with a high field across dielectric may experience SEGR-like dielectric rupture…
    - Devices with complex control logic likely to be susceptible to Single-Event Functional Interrupt (SEFI)
  - Definition of “representative sample” for testing depends on manufacturing, mechanisms and device type
    - Usually for SEE, representative means “same fabrication line, same process and same mask set”; little lot-to-lot variation
    - Lot-to-lot and part-to part variation may be greater for some commercial parts
    - Variability may also be greater for destructive SEE
- Establishing good and non-contradictory requirements is essential and often neglected

# Perspectives and Prioritization I: SEECA

- Not all SEE have equal consequences
- SEE Criticality Analysis (SEECA)
  - Examines a SEE mode's reliability and availability consequences
  - Mode defined as
    - Error functional—tolerable even if common
    - Error vulnerable—low rate may be OK
    - Error critical—not tolerated/mitigation needed
- Process involves iterative analysis, testing and mitigation—and if needed parts substitution
- Analysis is in terms of part/system criticality
  - Initial analysis can take place prior to testing
  - Results can be used to prioritize testing and mitigation efforts for maximum system improvement
  - Similarity to process of Failure Modes, Effects and Criticality Analysis makes process familiar to most hardware designers



# Perspectives and Prioritization II: MEAL

- MEAL informs all aspects of mission
  - Requirements definition
  - Parts Qualification
  - Design and Mitigation
  - Especially useful for evaluating heritage
- **Mission** sets the goals, type of mission and factors such as risk tolerance and resources for mitigation
  - Risk budget of same application differs with mission
- **Environment** determines severity of stresses to which mission systems exposed
- **Application** determines technologies needed and therefore vulnerabilities to environmental stresses
- Lifetime can increase risk nonlinearly
  - Sublinearly if goals reached before end of mission
  - Superlinearly as probability or rare events increases
- Changes in any aspect of MEAL can
  - Change mission probability of success
  - Invalidate Qualification
  - Increase stresses on critical systems

***Environment*:** Conditions Present

- Radiation, thermal, EEE, etc.

***Mission*:** defines goals, criticality

- Orbit/risk tolerance, resources
- Technologies needed
- Progression/phases


***Application*:** Functions required

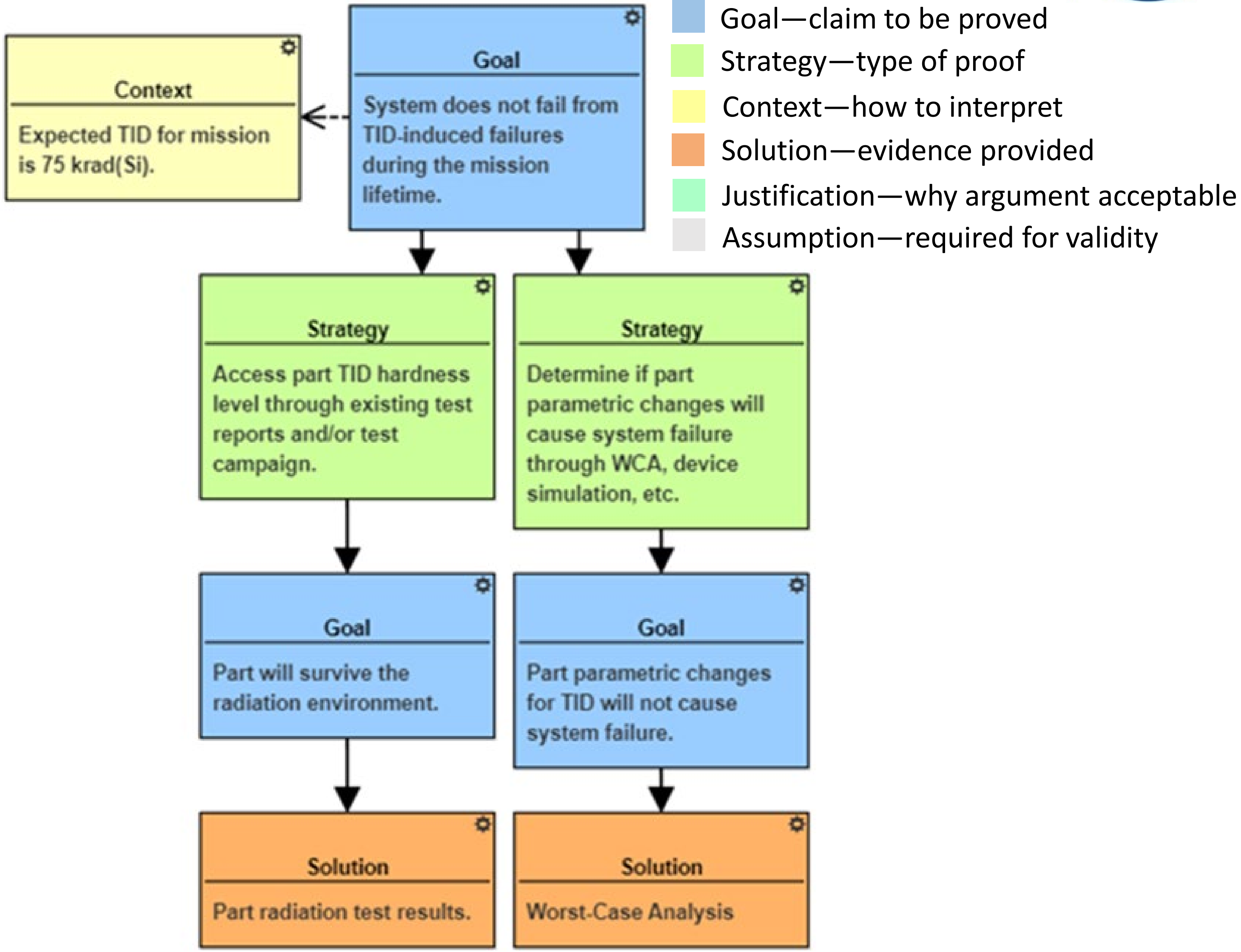
- Includes design, parts, conditions and interactions from part to system level

***Lifetime*:** Total period system must perform its function(s); may include many phases

- From design to decommissioning

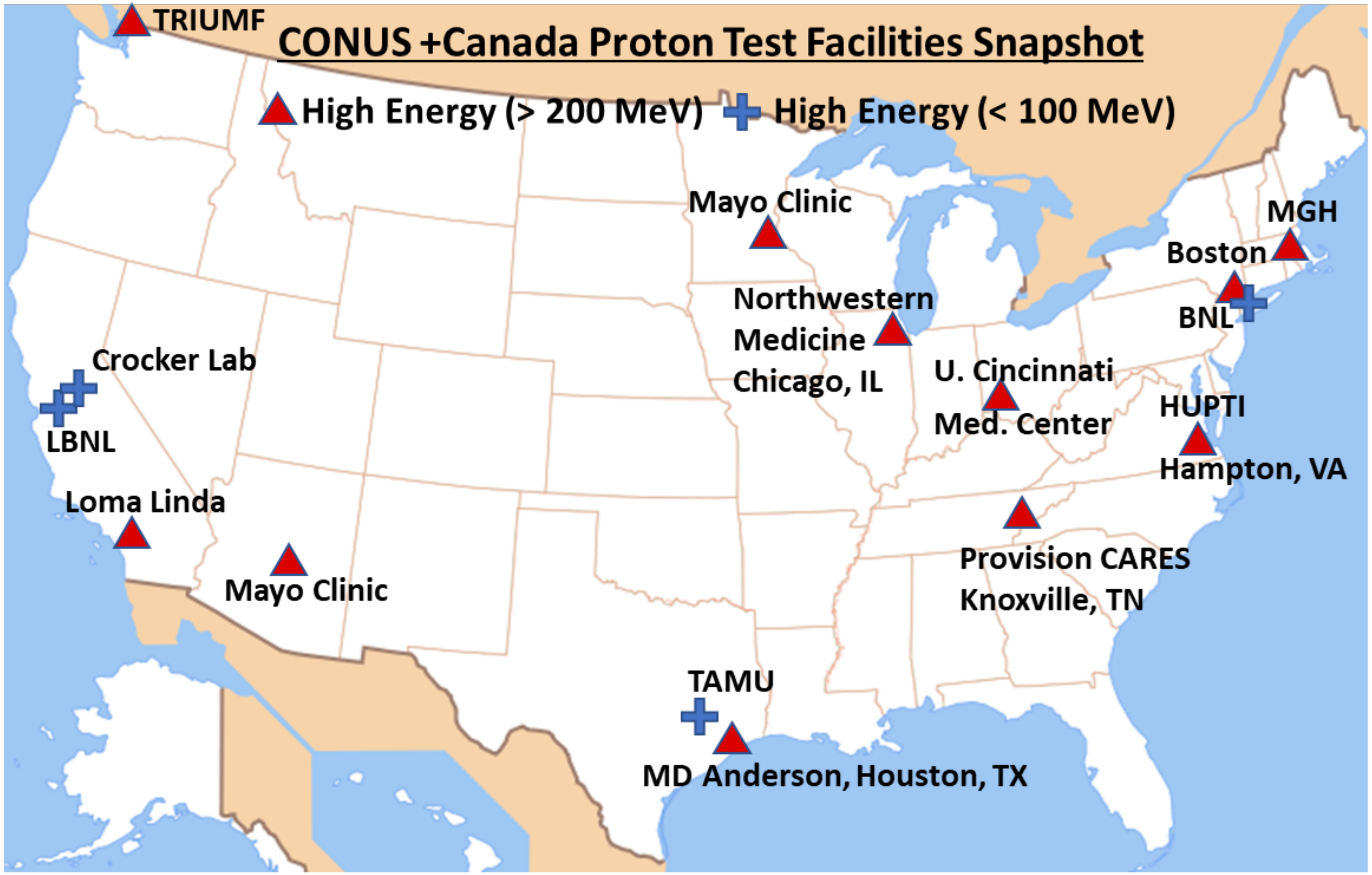
# Perspectives and Prioritization III: MBMA and GSN

- Model-Based Mission Assurance (MBMA)
  - Framework in which mission assurance activities are carried out on system models and then validated on real systems
  - Analogous and often used in concert with Model-Based System Engineering (MBSE)
- Goal Structure Notation (GSN)
  - GSN—a graphical notation tool that makes explicit the logic of RHA arguments
  - Structured notation emphasizes logical connections and supporting arguments
  - Explicit structures may make shortcomings in arguments more evident
  - Applies to particular MEAL
- SEECA, MEAL and GSN are complementary
  - Ensure RHA validation is supported by evidence
  - RHA efforts directed toward maximizing risk reduction



# Summary of Proton Test Facilities and Guidelines

- Medical proton accelerators continue to fill the need for electronics testing
- Guideline and technical memo present current situation
  - Some facilities have allowed electronics testing in their facility on limited basis
  - Some have long been proton testing workhorses
  - Testing situation is highly fluid, with new facilities expressing interest and old facilities dropping out
  - Consult the most recent guidance
- Guidelines also provide advice and important information for testers
  - How beam structure and dosimetry differ for different accelerators
  - How to work with medical facilities
  - Beam dynamics
  - Helpful hints!

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# Conclusion

- NESC RHA guidelines have been completed (Available to NASA and government personnel)
  - Technical memo covers same content and is available for wider distribution
  - Emphasis is on not just detailing best practices, but also documenting rationale for selection of best practices
- Guideline Format poses several advantages
  - Can be developed based on consensus of subject matter experts on what constitute best practices
  - Allows inclusion of explanatory material and rationales
  - Many commercial space companies propose alternate standards—inclusion of explanatory materials makes it easier to assess whether alternate standard meets the intent of best practices.
- In addition to SEE best practices, guidelines consider several useful topics
  - Developing good requirements
  - Useful tools for radiation analyses—SEECA, MEAL and Goal Structure Notation as used for MBMA
  - Snapshot and useful information for SEE testing at Medical Proton Accelerator Facilities
  - General radiation topics
    - On-orbit/Operational monitoring, role of sample size and coordination of testing and analysis also discussed.
- Although intended audience if NASA Human Exploration, guidelines should benefit any program.
- Link: https://ntrs.nasa.gov/api/citations/20210018053/downloads/20210018053.pdf?attachment=true

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