Radiation Hardness Assurance (RHA) for Space Systems

Stephen Buchner, NASA/GSFC

Introduction

- A mission is proposed by scientists who have convinced NASA that their objectives are worth the cost.
- A set of requirements is established with various levels.
- Then, hopefully, they assign a radiation effects engineer to the project. Ken assigns me to project.
- What is the first thing I have to do and what follows?
- Based on level requirements, the radiation engineer first establishes the radiation environment
- Rad. environment based on orbit, launch date, launch duration and shielding. Specifies TID, DD and SEE requirements (particle spectrum).

To be presented by Stephen Buchner at 4th International School on the Effects of Radiation on Embedded Systems for Space Applications (SERESSA), West Palm Beach, FL, December 2008 and published on http://nepp.nasa.gov/ and http://radhome.gsfc.nasa.gov.

RHA Outline

- **Introduction**
- Programmatic aspects of RHA
- RHA Procedure
  - Establish Mission requirements
  - Define and evaluate radiation hazard
  - Select parts
  - Evaluate circuit response to hazard
    - Search for data or perform a test
  - Categorize the parts
    - TID/DD
    - SEE
- Conclusion

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What is RHA ?

- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment.
- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, and mission/system/subsystems requirements

Radiation Hardness Assurance does not deal with piece parts alone but includes system, subsystem, box and board levels.

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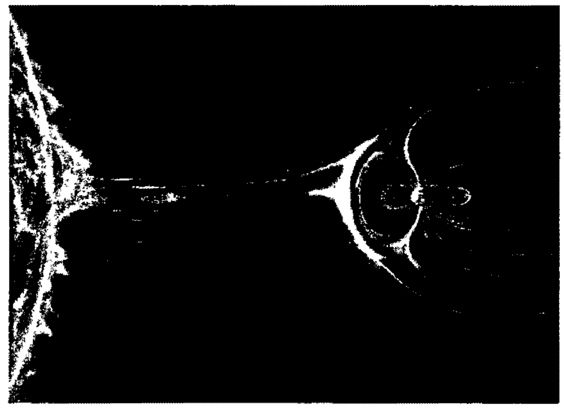
Radiation Environment in Space

Discuss, LEO, Polar, MEO, GEO, interplanetary, Moon, Mars and Jupiter.

1. ***Solar Wind***
   - Solar Cycle
   - Solar Flares
   - Coronal Mass Ejections
2. ***Radiation Belts***
   - Proton Belts
   - Electron Belts
3. ***Cosmic Rays***
   - Galactic Origins



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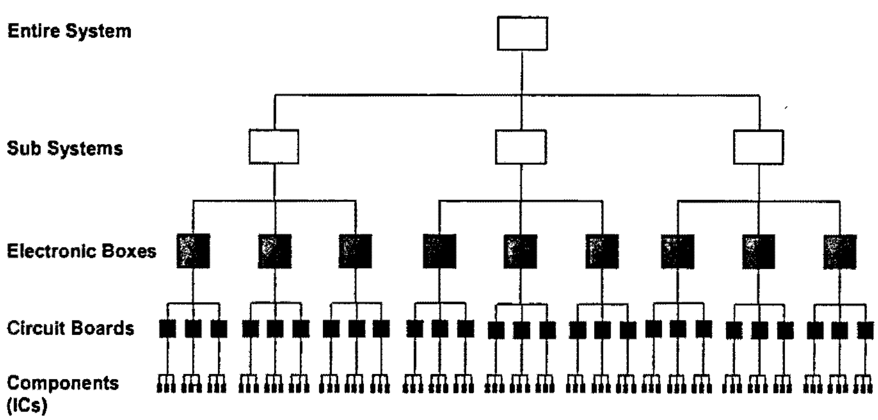
System Hierarchy



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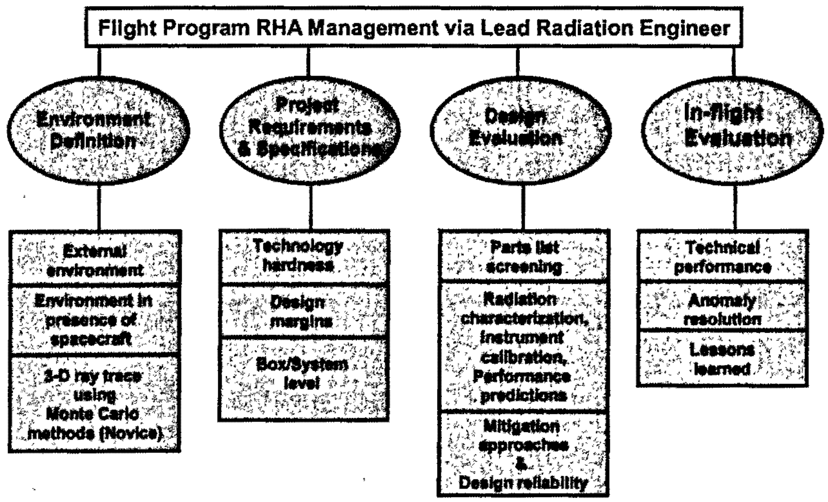
RHA



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Hardness Assurance Method

Mission Requirements

↓

Define and Evaluate the Radiation Hazard ← Determine radiation environment external and internal to spacecraft

↓

Evaluate Circuit Response to Hazard ←
1. Select parts
2. Determine radiation sensitivity from existing data or by testing
3. Compare failure level with system requirements

↓

Categorize the Parts According to RDM ← RDM for SEE and TID/DD

↓

Hardness Non-Critical | Hardness Critical | [redacted]

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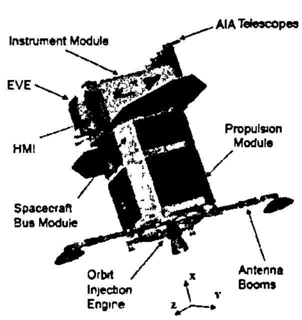
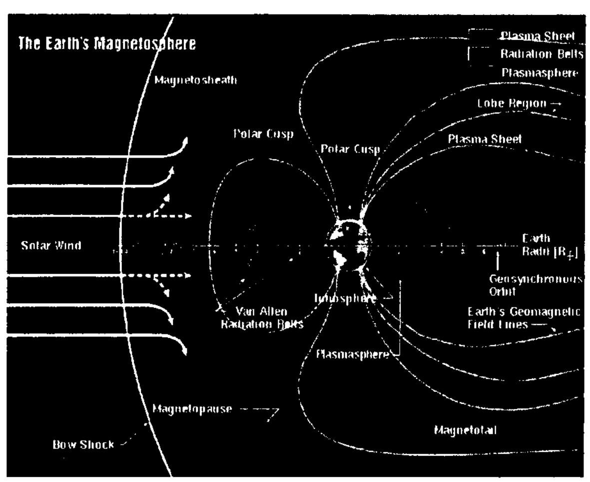
Solar Dynamic Observatory (SDO)





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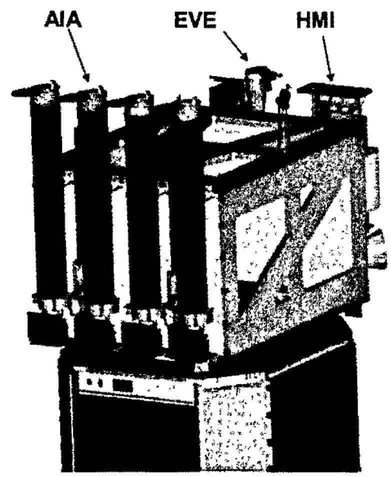
SDO Mission Goals

- **Contains three telescopes to study the sun**
  - The Helioseismic and Magnetic Imager (HMI) will gaze through the Sun at internal processes to help us understand the origins of solar weather.
  - The Extreme Ultraviolet Variability Experiment (EVE) will measure the solar extreme ultraviolet (EUV) irradiance to understand solar magnetic variations.
  - The Atmospheric Imaging Assembly (AIA) will study the solar coronal magnetic field and the plasma it holds to improve our understanding of how the Sun's atmospheric activity drives space weather.



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SDO Mission Requirements

1. **Mission launch date and duration:**
   a) Launch date is November 2008 - increased solar activity.
   b) 5-year mission (10-year option).
   c) Geosynchronous orbit.
2. **Operation Requirement:**
   a) Must be operational 95% of the time.
3. **Data Requirement:**
   a) Data downlink at 150 MBPS (250 DVDs per day).
   b) Data integrity must be 99.99% valid.
4. **Radiation Requirement:**
   a) Continue functioning reliably for five years in radiation environment at geosynchronous orbit.
   b) Single event effects – non-destructive and destructive.
   c) Cumulative radiation effects – TID and DD.

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SDO Part Level Requirements

- ***Cumulative***
  - **Total Ionizing Dose** (TID = 60 Mrad(Si) – free field)
  - **Displacement Damage** (DD = 2×10^{10} MeV/gm – field free)
- ***Single Event***
  - **Non-Destructive** ($LET_{th} > 36$ MeV.cm^2/mg)
    - Single Event Upset (SEU),
    - Single Event Transient (SET),
    - Single Event Functional Interrupt (SEFI).
  - **Destructive** ($LET_{th} > 80$ MeV.cm^2/mg)
    - Single Event Latchup (SEL)
    - Single Event Burnout (SEB)
    - Single Event Gate Rupture (SEGR)

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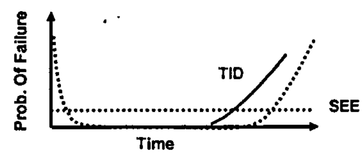
Additional Information

- **Most failures follow "U-shaped" failure probability, except for radiation**
  - TID failure most likely at end of mission
  - SEE failure probability uniform over time



- **Non-destructive SEE rates based on budgeted down time that includes:**
  - Eclipses,
  - Instrument calibration,
  - Antenna handover,
  - Momentum shedding,
  - RADIATION
- **Destructive SEEs should not happen**

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RHA Challenges

- **Small number of systems, sometimes only one, with no redundancy**
  - Requirement for high probability of survival
  - Often no qualification model
- **Electronic parts**
  - Many part types, small buys of each part type
    - No leverage with manufacturers
  - Use of Commercial Off-The-Shelf (COTS) parts
    - No configuration control
    - Obsolescence
    - Little radiation data in databases
    - Frequently only available in plastic
  - Use of hybrids
- **SDO's Approach**
  - Assign sufficient funding to purchase rad-hard parts and, where necessary, do lot specific testing.

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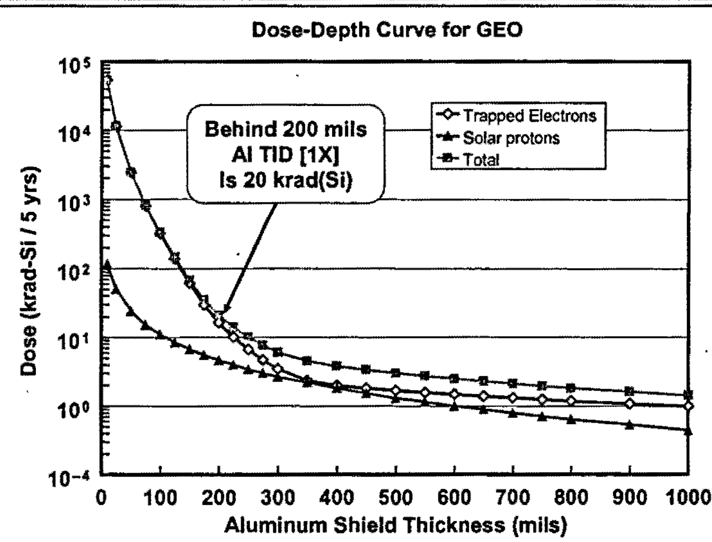
TID Top Level Requirement (SDO)



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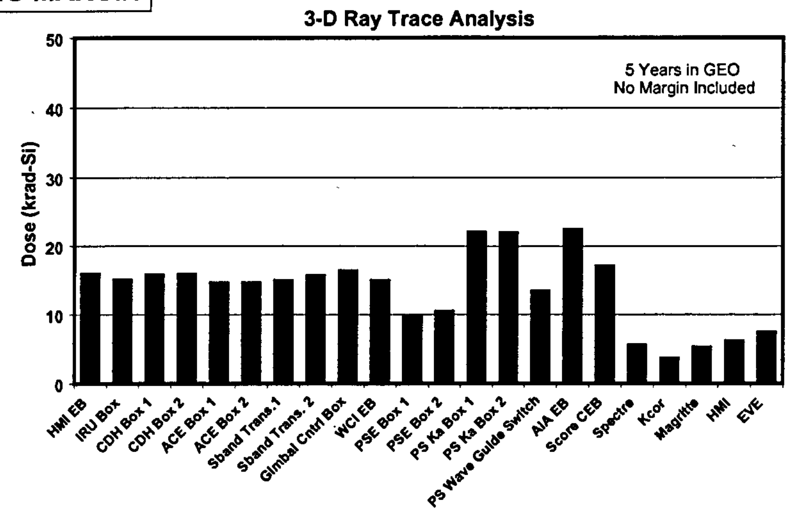
TID Inside Electronic Boxes

NO MARGIN



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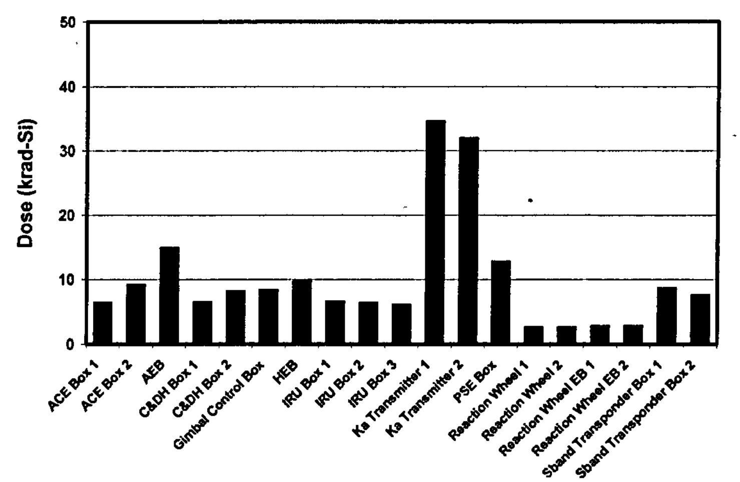
TID Inside Electronic Boxes

MARGIN OF 2 USING ACCURATE SPACECRAFT MODEL



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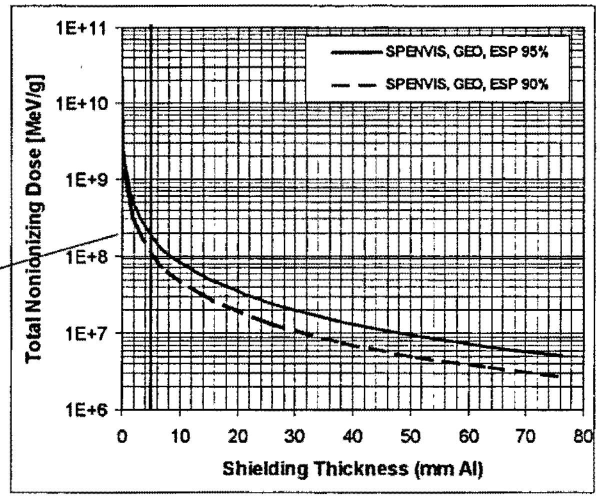
Displacement Damage Dose

Needed for optical components:
- LEDs,
- Optocouplers,
- CCD Imagers.

200 mils = 5.08 mm

NID =2E+8 MeV/gm



J. Srour (Private Communication)

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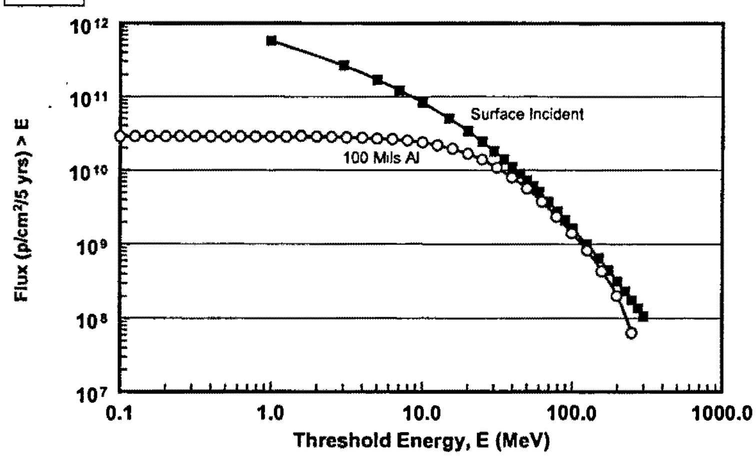
SEE - Proton Flux vs Energy

GEO



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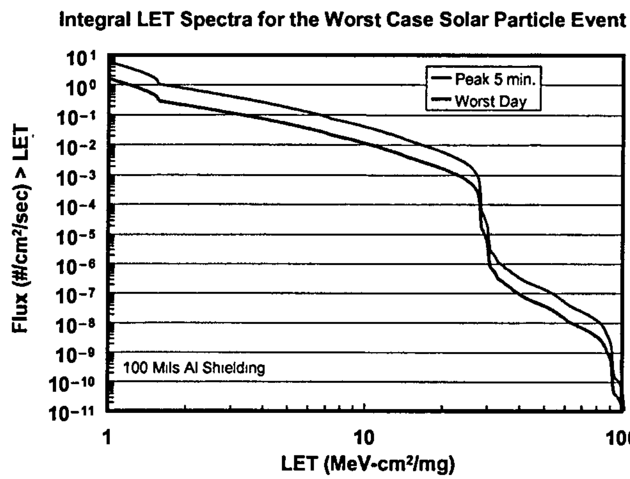
Worst Case Environment



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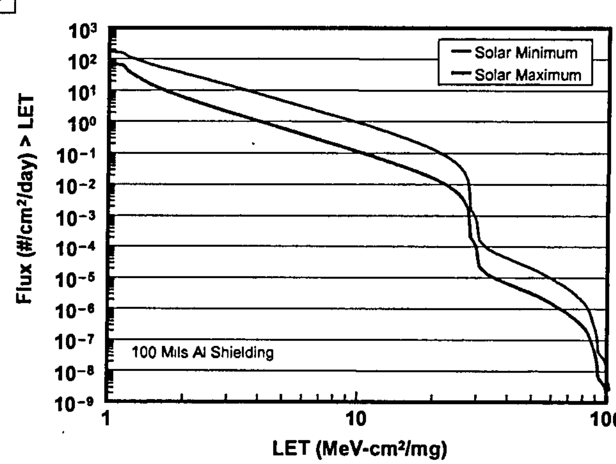
SEE - LET Spectra for GCRs

GEO



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Handling SEEs

- ***Destructive SEEs***
  - No destructive SETs for LETs below 80 MeV.cm^2/mg.
    - Mitigate (e.g., latchup protection circuit)
    - De-rate (Power MOSFETs have V_{sd} de-rated to 35%)
    - Replace part if cannot mitigate

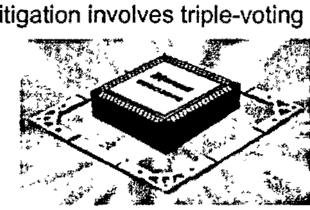
    (Sometimes have no other choice but to accept part.)

- ***Non-destructive SEEs***
  - No non-destructive SEEs below 36 MeV.cm^2/mg.
    - Mitigate if critical (e.g., majority vote)
    - Replace if critical and cannot mitigate
    - Accept if non-critical (e.g., housekeeping)

Example of Mitigation on SDO

SDRAM (Maxwell) used as a temporary buffer to store data from all three telescopes prior to down-linking.

- ***SDRAM Requirement***
  - SDRAM suffers from SEFIs due to ion strikes to control circuitry.
  - Mitigate SEFIs by rewriting registers frequently.
  - At temperatures above 42 C, SDRAM stops working.
  - Determined it was due to a timing issue
  - New mitigation involves triple-voting three SDRAMs



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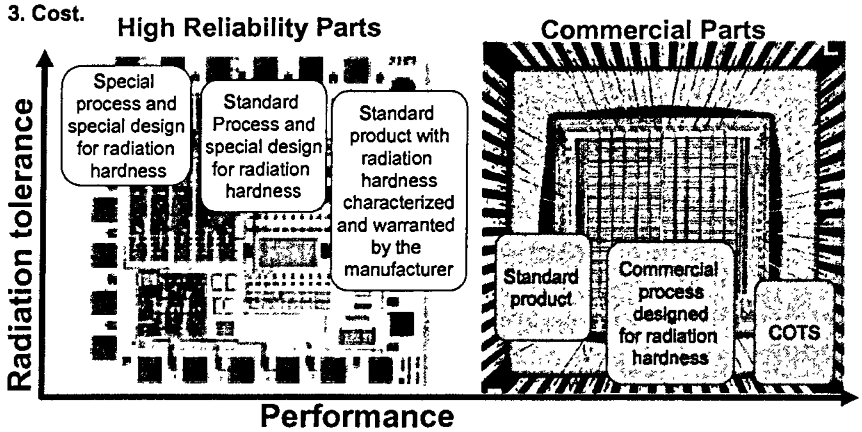
Parts Selection

Initially based on <u>function</u> and <u>performance.</u>
Additional factors are:

1. **Reliability,**
2. **Availability,**
3. **Cost.**



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  - Select parts
  - **Evaluate circuit response to hazard**
    - **Search for data or perform a test**
  - Categorize the parts
- Analysis at the function/subsystem/system level
  - TID/DD
  - SEE
- Conclusion

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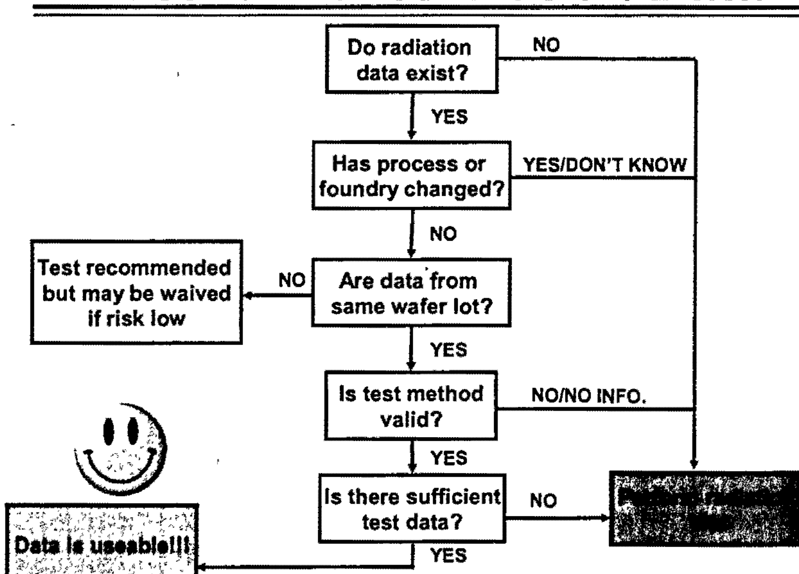
Search for Radiation Data



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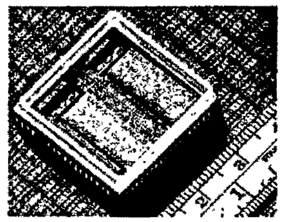
Sources of Radiation Data

- In house data from previous projects (LRO and SDO)
- Available databases:
  - NASA-GSFC: http://radhome.gsfc.nasa.gov
  - ESA: http://escies.org
  - DTRA ERRIC: http://erric.dasiac.com
- Other sources of radiation data:
  - IEEE NSREC Data Workshop,
  - IEEE Transactions On Nuclear Science
  - RADECS proceedings.
  - Vendor data



Stacked devices and hybrids can present a unique challenge for review and test

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Evaluation of Radiation Data

Part #	Generic Part #	Function	Manufac.	TID	Source	Destructive SEEs	Source	Non-destructive SEEs	Source	Comments
5962-06233	UT54ALVC 2525	Rad Hard Clock Driver	Aeroflex	1 Mrad	Manuf	>111 MeV cm^2/mg	Manuf	>52 MeV cm^2/mg for Vdd=2V	Manuf	Use

DSCC Number

Meets SDO requirements for SEL

Meets SDO requirements for SEL

Meets SDO requirements for SETs

A good part

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Evaluation of Radiation Data

Part Number	Generic Part Number	Function	Manuf.	TID/DD	Source	Destructive SEE	Source	Non-destructive SEE	Source	Notes
5962-87615012A	54AC08LMQB	Quad 2-Input AND gate	National	No radiation data		>100 MeV cm^2/mg	Manuf	>40 MeV cm^2/mg	Manuf	Lot specific testing needed.

Dash indicates not TID rad-hard

Could not find lot-specific data

Meets SDO requirements for SEL

Meets SDO requirements for SETs

Recommendation

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Evaluation of Radiation Data

For IBEX they selected an ADC – AD7875TQ.
This is a LC2MOS, 12-bit, 100 kHz sampling ADC.
No radiation data on the part.
Stapor used radiation data from JPL, which is not longer on the web- which was reported in 1996 for the AD7874. Their part has a LDC of 2005. Must confirm from the manufacturer that the architectures are the same (transistor level) and that the process did not change between 1996 and 2005.
The data showed parametric failure at 20 krad at high dose rate. This process contains bipolar parts so it could be ELDRS sensitive, which means that a derating factor has to be used.
The anticipated dose for the device, which is spot shielded is 2 krad. Therefore the RDM falls below 10, which usually means lot specific testing is required to mitigate the increased risk.

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Evaluation of Radiation Data

For IBEX they selected SN5406J HEX inverter (item 282). This is not spot shielded so the TID = 6.2 krad. The part was tested by NASA/GSFC and found that all parametric values were within spec up to 100 krad with testing at 100 mrad/s. This is based on a test report from 1994 and the parts have LDC's of 0605. The part was made by TI. It is unsure if the process has remained the same. Stapor had to contact the manufacturer to ensure that the process had not changed.

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Evaluation of Radiation Data

For IBEX they selected the ADM485AR, which is a driver (item274). This was manufactured in National's 36/40 bipolar process. All other parts manufactured in this process pass 100 krad, except three parts which fail at around 60 krad. Therefore, the part was accepted.

Another part is the UC2843AD8. There is data on the UC1845. Amazingly these are the same parts. They have different numbers because they operate over different temperature ranges as a result of, for instance, packaging material (if plastic). Therefore, generic data is OK if the RDM is >10.

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Evaluation of Radiation Data

Part Number	Generic Part Number	Function	Manuf.	TID/DD	Source	Destructive SEE	Source	Non-destructive SEE	Source	Notes
5962F995470 1VXC	HS-117RH	Adj. Positive Voltage Regulator	Intersl	300 krad	Manuf Test report	>87.4 MeV cm^2/mg	Manuf Test report	< 15 MeV cm^2/mg	Manuf Test report	Evaluate SET threat and mitigate if necessary

"F"
indicates rad-hard
to 300 krad, but
not ELDRS tested,
use de-rating factor

Meets SDO
requirements
for
destructive SEEs

Does not
meet SDO
requirements
for SETs

Recommendation

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Evaluation of Radiation Data

Part Number	Generic Part Number	Function	Manfac.	TID/DD	Source	Destructive SEEs	Source	Non-destructive SEE	Source	Comment
REF 02AJ	5962R855140 1VGA	Voltage Reference	Analog Devices	100 krad	Manuf	None	NASA data	SET sensitive	Technology	1 Derate for ELDRS 2 Analyze SETs and mitigate if necessary

"R"
indicates rad-hard
to 100 krad, but
not ELDRS tested,
use de-rating factor

Meets SDO
requirements
for
destructive SEEs

Glitches on
output. Must know
amplitude and width

Recommendation

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Evaluation of Radiation Data

Part #	Function	Manuf.	TID	Source	Destructive SEEs	Non-destructive SETs	Comments	Approval
RMA-SLH1412D/MP-PX	DC/DC CONV,+/-12VDC	Orbital Sciences Corporation	50 krad	?	N/A	N/A	MOSFET derated to 50% of rated BVDS to minimize risk of SEB	Accepted

Hybrid

Source not listed

No data

No data

Insufficient de-rating

Should be rejected

NOT on SDO

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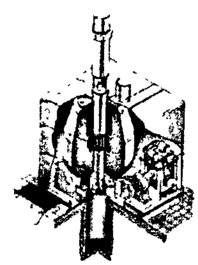
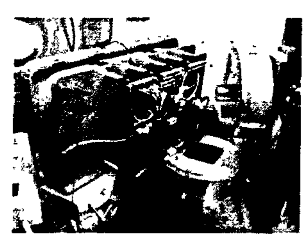
Radiation Test

- **Determine types of tests needed**
  - TID (gamma rays, x-rays, protons),
  - DD (neutrons or protons),
  - SEE (protons, heavy ions, laser).
- **Define appropriate test levels**
  - Sample size (# for TID > # for SEE),
  - Particle type,
  - Fluence and flux,
  - Dose and dose rate.
- **Operate part as in application, i.e., bias, frequency, software, etc.**
  - *Not always possible*

Gamma ray testing with Co60 cell



Proton testing at UC Davis



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Total Dose Test (Co^{60})

- ***Dose Rate***
  - Linear Bipolars: ELDRS dose rate of 0.01 rad(Si)/s
  - CMOS: High dose rate of 50 to 300 rad(Si)/s
- ***Total Dose***
  - At least 2X of expected mission dose for part
  - 100 krad(Si) better so can use data for other missions
- ***Bias***
  - ELDRS both biased and unbiased
  - CMOS - bias to V_{dd} and V_{ss}, inputs grounded, outputs floating
- ***Temperature***
  - Room temperature (or application temperature), annealing step
- ***Minimum Number of Parts***
  - 10 with 2 for controls,
  - Quad parts - must test all four.

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Single Event Test

- ***Protons, Heavy Ions (energy) or Laser***
  - Determined by information needed (BNL vs TAMU)
- ***Air or Vacuum***
  - For high-speed prefer air.
- ***Flux***
  - Low enough to prevent "pile-up" of transients
- ***Fluence***
  - Determined by statistics:
    - For SEUs minimum of 100 upsets or 1×10^7 particles/cm^2
    - For SEL minimum of 1×10^7 particles/cm^2 if no SELs
- ***Angle***
  - Normal to grazing, depending on application
- ***Temperature***
  - Room temperature for SEU, 100 C for SEL.
- ***Bias***
  - V_{dd} +10% for SEL, V_{dd} -10% for SEU.
- ***Number of parts***
  - Depends on cost of parts, availability of parts, availability of beam time (Minimum of 3)

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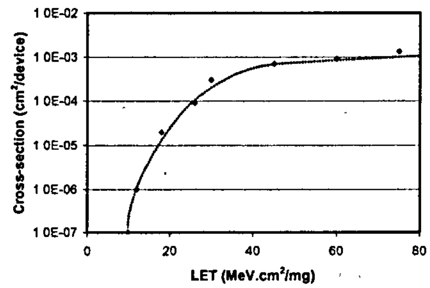
SEE Test Results (Heavy Ions)

- **Fit data with Weibull curve.**
  $\sigma = \sigma(sat)\cdot(1-\exp(-(x-LET(th))/W)^{s})$
- **Extract fitting parameters:**
  - LET(th)
  - Width (W)
  - Shape (S)
  - σ(sat)
- **Use fitting parameters in CREME96 or SPENVIS to calculate SEE rate.**



- **Compare calculated rate with mission requirements**

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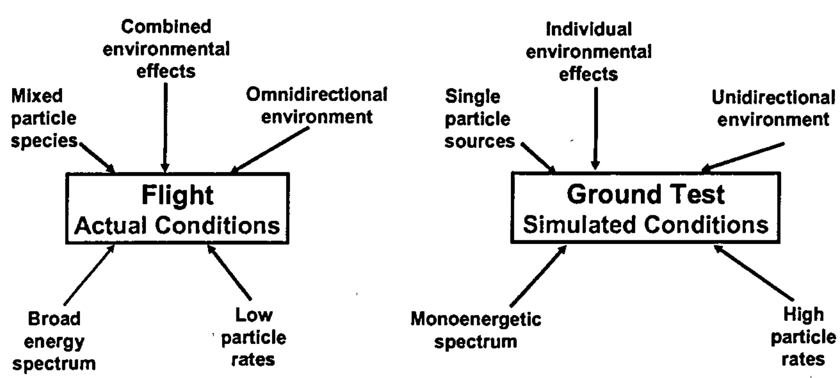
Radiation Test Issues - Fidelity

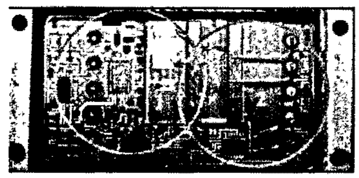


How accurate is the ground test in predicting space performance?
Examples:
1. How does aging affect TID?
2. Does TID affect SEE rate?

Example of Unexpected Results

- ***Solid State Power Controller (SSPC) from DDC (RP-21005DO-601P)***
  - DDC replaced FET from Signetics with non rad-hard FET from IR.
  - Heavy-ion testing at Texas A&M revealed the presence of SETs causing the SSPC to switch off.
  - Pulsed laser testing revealed that the ASIC was sensitive to SETs, and that large SETs caused the SSPC to switch off.
  - Replaced DDC SSPC with Micropac SSPC
  - Previous SEE testing of ASIC at Brookhaven revealed no SETs.

Problem attributed to short range of ions at Brookhaven National Laboratory



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RHA Outline

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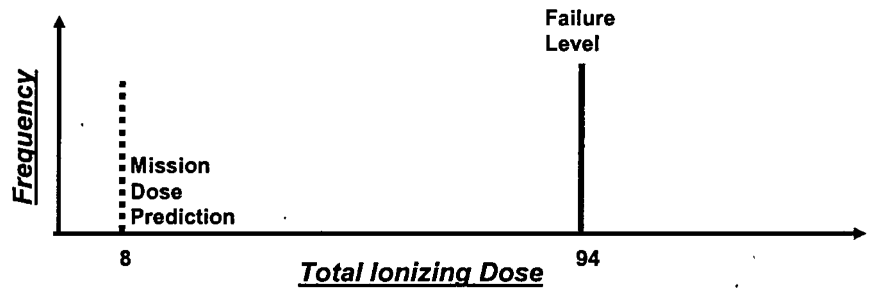
Measurement Statistics

If mission dose and failure levels have no uncertainty, then, as long as failure level > mission dose,

- Probability of survival = 100%
- Confidence level = 1



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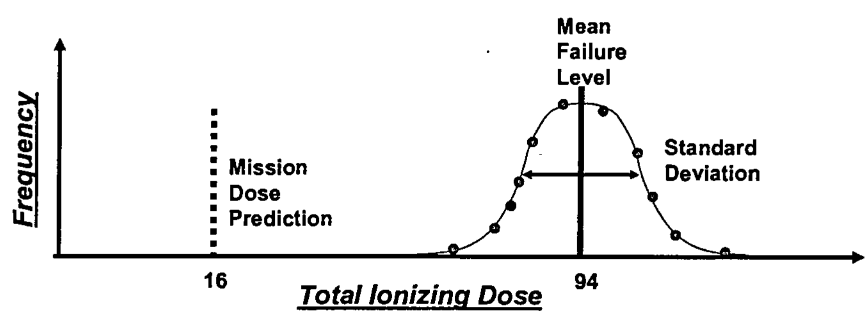
Measurement Statistics

Because of uncertainty in dose and variation in failure levels, statistics must be used to calculate

- Probability of survival (< 100%) and
- Confidence level (< 1)



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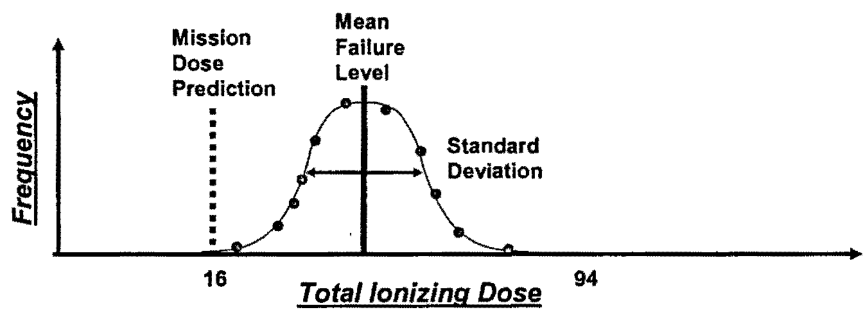

TID Design Margin Breakpoints

$$\text{RDM} = \frac{\text{Mean failure level}}{\text{Maximum TID for mission}}$$

RDM < 2 < RDM < 10 < RDM < 100 < RDM

RDM < 2	2 < RDM < 10	10 < RDM < 100	100 < RDM
Unacceptable	Hardness Critical-HCC1	Hardness Critical-HCC2	Hardness Non-Critical
Do not use	Radiation lot testing recommended	Periodic lot testing recommended	No further action necessary

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TID Mitigation

- ***Reduce the dose levels***
  - Improve the accuracy of the dose level calculation
  - Change the electronic board, electronic box layout
  - Add shielding
    - Different location on spacecraft
    - Box shielding
    - Spot shielding
  - Paramatric failure vs functional failure
  - Not a critical function (AD670)
- ***Increase the failure level***
  - Test in the same conditions as the application
  - Test at low dose rate (CMOS only)
  - Tolerant designs (cold redundancies, etc.)
  - Relax the worst case functional requirements

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TID Mitigation

- ***Accept Failure***
  - Paramatric failure vs functional failure
    - Parametric failure occurs before functional failure and may be tolerated, e.g., increase in I_{cc} may have no effect
  - Device does not perform a critical function (AD670)
    - Used as part of circuit for measuring temperature.
    - Fails at less than 5 krad(Si)
    - Decided to use the part because after failure other methods to measure temperature

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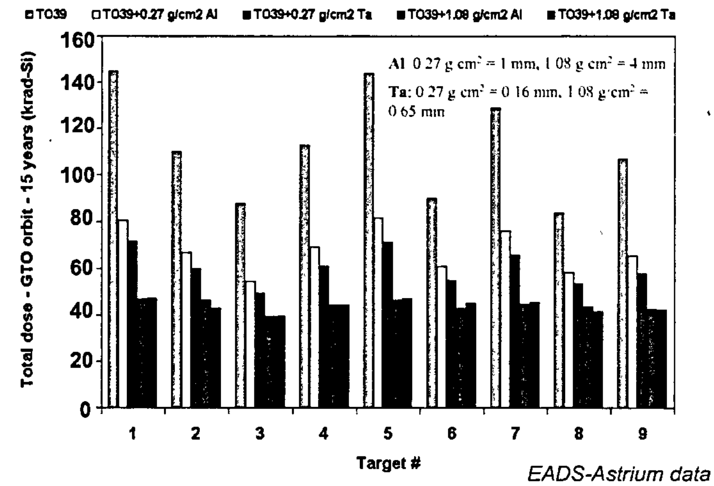
TID Mitigation – Spot Shielding



EADS-Astrium data

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TID Mitigation - Examples

- ***TMS320C25 (DSP) Texas Instruments – LEO polar***
  - TID soft: 3 krad(Si) (functional failure)
  - Duty cycle in the application: 10% on
  - TID tolerance with application duty cycle: 10 krad

  The device has operated flawlessly during the mission

- ***FPGA 1280 ACTEL - GEO***
  - TID soft: 3 krad functional at high dose rate.
  - TID at 1 rad/h: ~ 14 krad functional, 50 mA power consumption increase (max design value) after 8 krad.
  - Spot shielding with Ta: received dose = 4 krad

EADS-Astrium data

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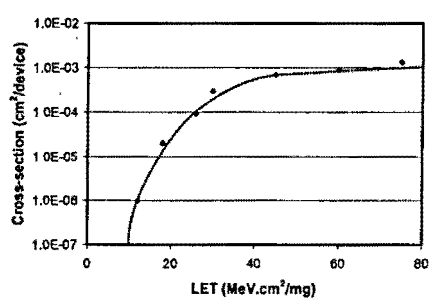
SEE - Analysis Requirements

- ***LET_{th} > 80***
  - SEE risk negligible, no further analysis needed
- ***80 > LET_{th} > 15***
  - SEE risk moderate, heavy-ion induced SEE rates must be analyzed. In many cases SEEs can be tolerated. Requires analysis.
- ***15 > LET_{th}***
  - SEE risk high, heavy ion and proton induced SEE rates to be analyzed. In many cases can tolerate the SEEs



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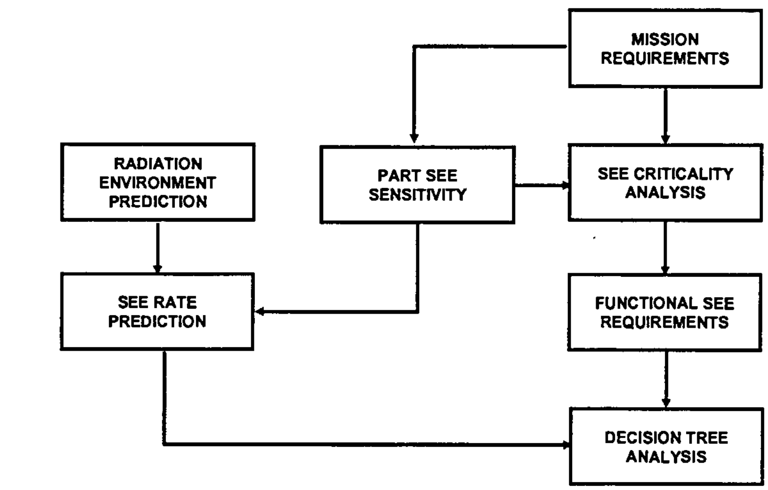
SEE - Analysis Flow



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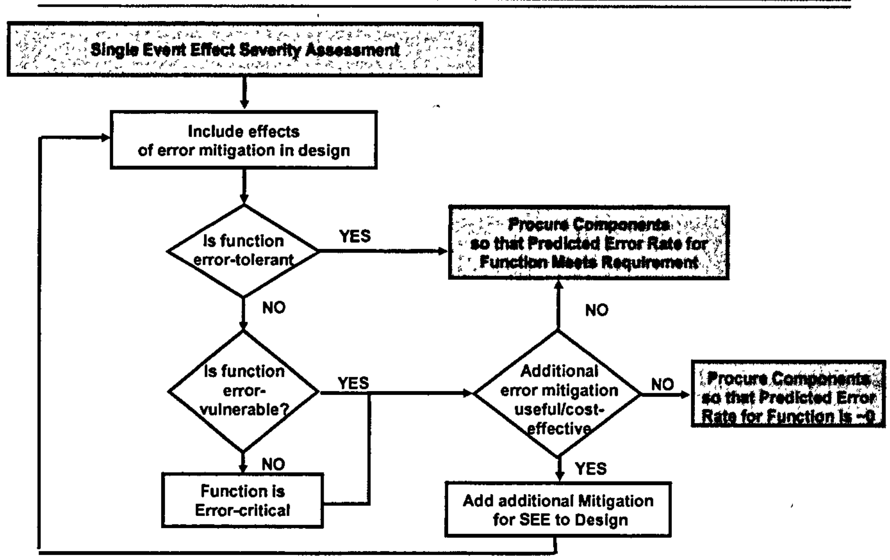
SEE - Decision Tree



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Conclusion

- The RHA approach is based on risk management and not on risk avoidance
- The RHA process is not confined to the part level, but includes
  - Spacecraft layout
  - System/subsystem/circuit design
  - System requirements and system operations
- RHA should be taken into account in the early phases of a program, including the proposal and feasibility analysis phases.

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What You Should Remember

- Definition of RHA: a series of steps to ensure that parts/boxes/subsystems will meet mission requirements when operating in a radiation environment with a probability of survival (P) and a confidence level (C).
- Step 1: determine mission requirements.
- Step 2: define the radiation environment.
- Step 3: select the parts.
- Step 4: obtain radiation data – search or test.
- Step 5: categorize the parts using RDM and PCC.

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