Radiation Hardness Assurance (RHA) for Space Systems

Stephen Buchner, NASA/GSFC
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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

What is RHA ?

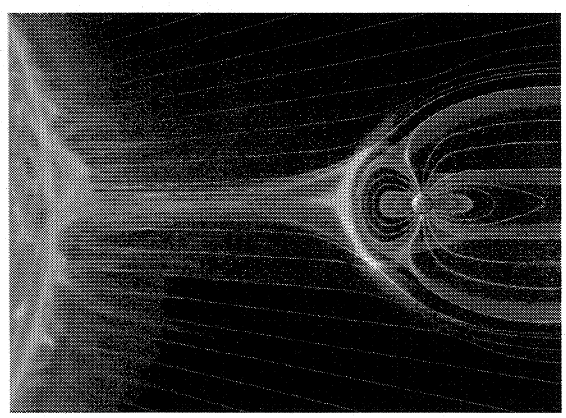
- RHA consists of all activities undertaken to ensure that the electronics and materials of a space system perform to their design specifications after exposure to the space radiation environment

- Deals with environment definition, part selection, part testing, spacecraft layout, radiation tolerant design, and mission/system/subsystems requirements

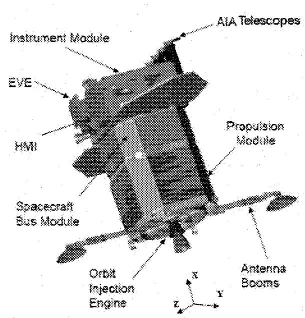
Radiation Hardness Assurance deals not only with the piece part. It includes system, subsystem, box and board levels.

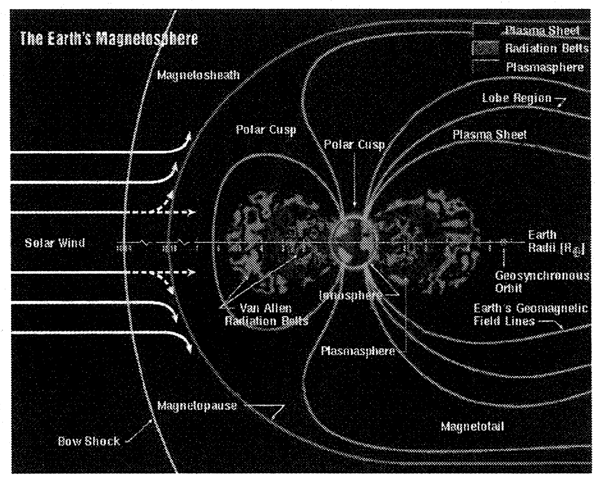
Radiation Environment in Space

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



Solar Dynamic Observatory





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Solar Dynamic Observatory

- **Contains three telescopes to study the sun**
  - Each telescope takes a picture of sun with CCD camera
  - No data processing or storage on board
  - Downlink at 150 Mbps.
  - Data storage on earth will require 250 DVDs a day
- **Geosynchronous Orbit**
  - Exposed to electron belt, solar particles (mostly protons) and galactic cosmic rays
- **Launch date is November 2008 for a 5-year Mission**
  - Spans maximum of solar activity
    - High solar wind
    - Numerous solar particle events (Coronal Mass Ejections and solar flares)
    - Reduced Galactic Cosmic Ray (GCR) flux

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Possible Radiation Effects

- ***Cumulative***
  - **Total Ionizing Dose** (TID = 60 Mrad(Si) – free field)
  - **Displacement Damage** (DD = Particle Fluence)
- ***Transient***
  - **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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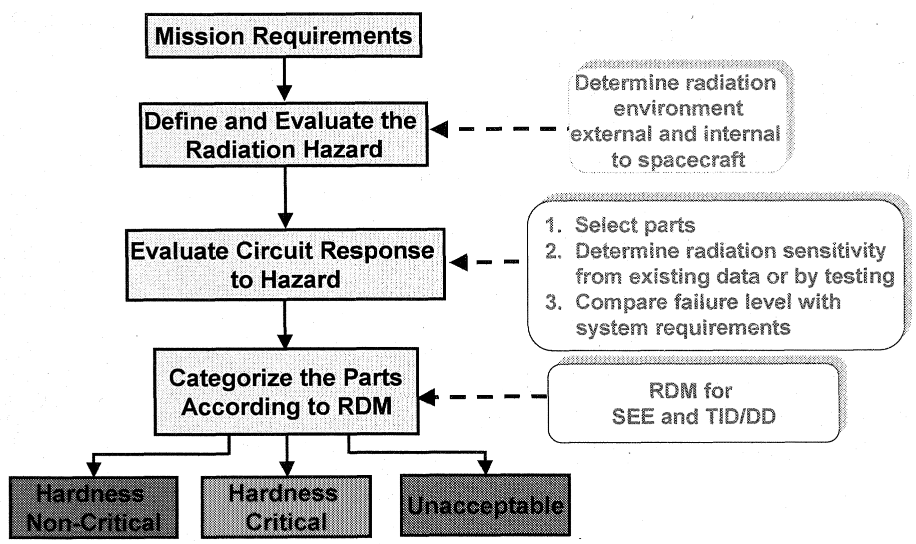
Hardness Assurance (Overview)



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SDO Requirements

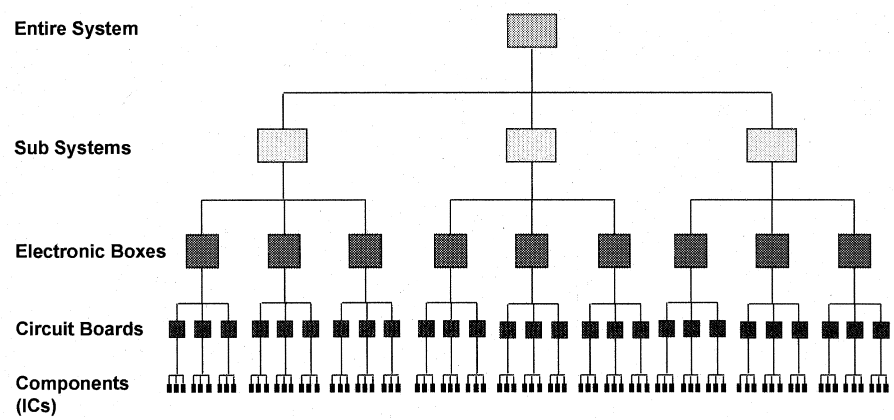
System Level Requirements……

1. 5-year Mission
2. Launch date is 2008
3. Must be operational 95% of the time.
4. Data integrity must be 99.99% valid.
5. Data downlink at a rate of 150 MBPS in Geosynchronous Orbit.
6. Total Mass and Mass Distribution of Spacecraft

SDO Requirements

- ***Flow down to Part Level Requirements***
  - *Survive:*
    - 5 years with total dose of 60 Mrad(Si).
    - Most failures occur near beginning, except for radiation
    - Spacecraft mass distribution determines radiation level of parts
  - *SEE* rates based on budgeted down time that includes:
    - Safe-hold,
    - Eclipses,
    - Instrument calibration,
    - Antenna handover,
    - Momentum shedding,
    - RADIATION

System Hierarchy



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Example – SDRAM Buffer

Temporary buffer to store data from all three telescopes prior to down-linking.

- ***System Requirement:***
  - Data downlink at 150 Mbps
  - 99.99% valid during 95% up time.
- ***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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RHA Challenges

- **Small number of systems, sometimes 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

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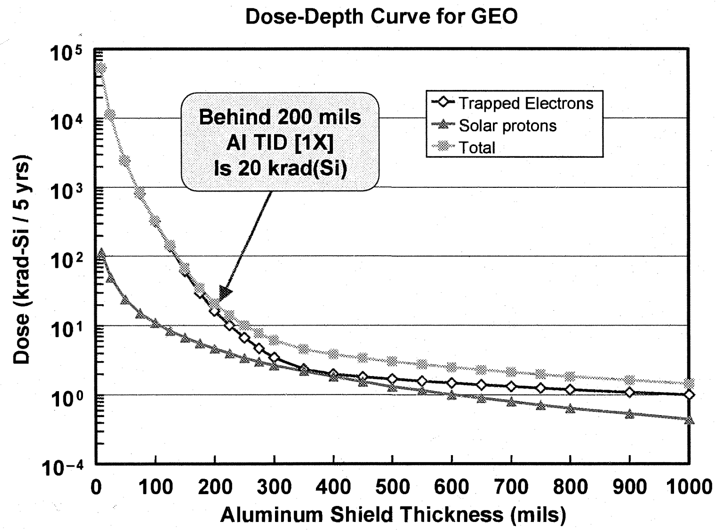
TID Top Level Requirement (SDO)



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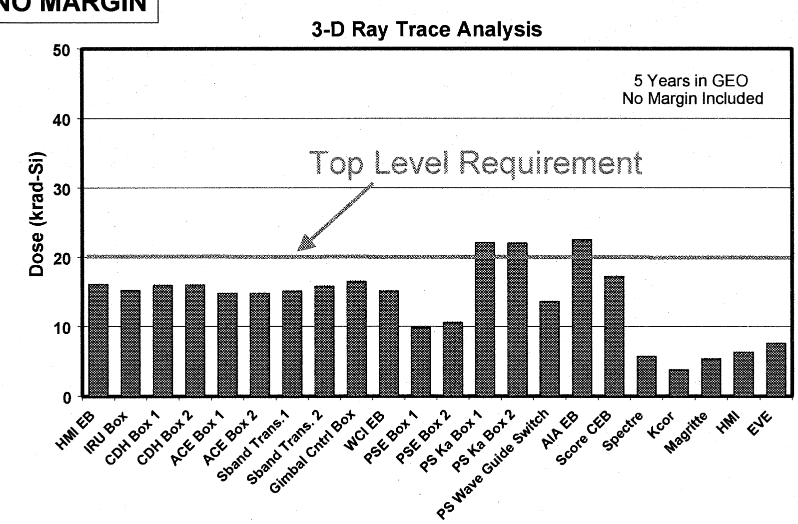
TID Inside Electronic Boxes

NO MARGIN



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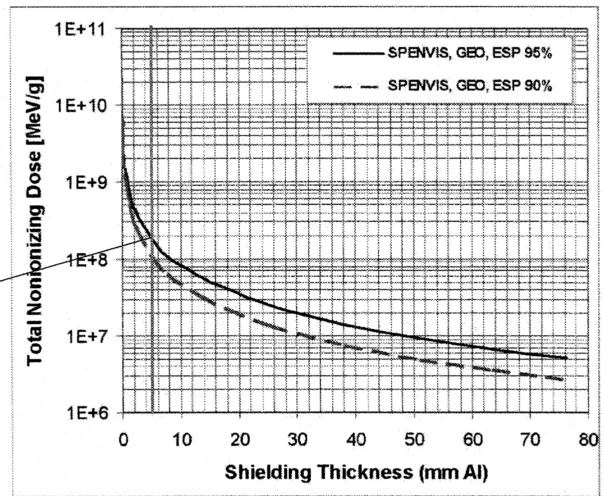
Displacement Damage Dose

200 mils = 5.08 mm

NID =2E+8 MeV/gm



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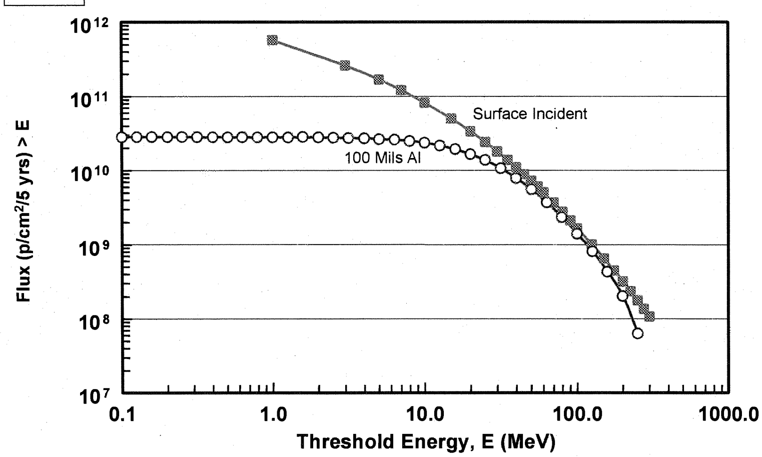
SEE - Proton Flux vs Energy

GEO



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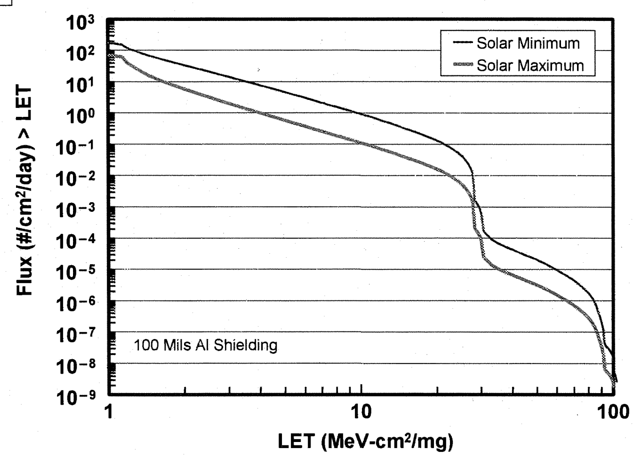
SEE - LET Spectra for GCRs

GEO



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SEE Requirement

- ***Destructive SEEs***
  - No destructive SETs for LETs below 80 MeV.cm^2/mg.
    - Mitigate (e.g., latchup protection circuit)
    - Replace part if cannot mitigate

    (Sometimes have no other choice but to accept part.)
- ***Non-destructive SEEs***
  - No non-destructive SEEs below 40 MeV.cm^2/mg.
    - Mitigate if critical (e.g., majority vote)
    - Replace if cannot mitigate
    - Accept if non-critical (e.g., housekeeping)

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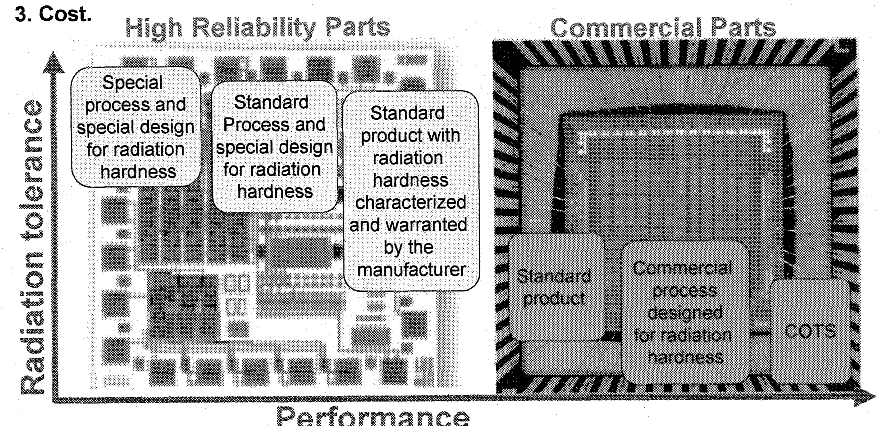
Parts Selection

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

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



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  – **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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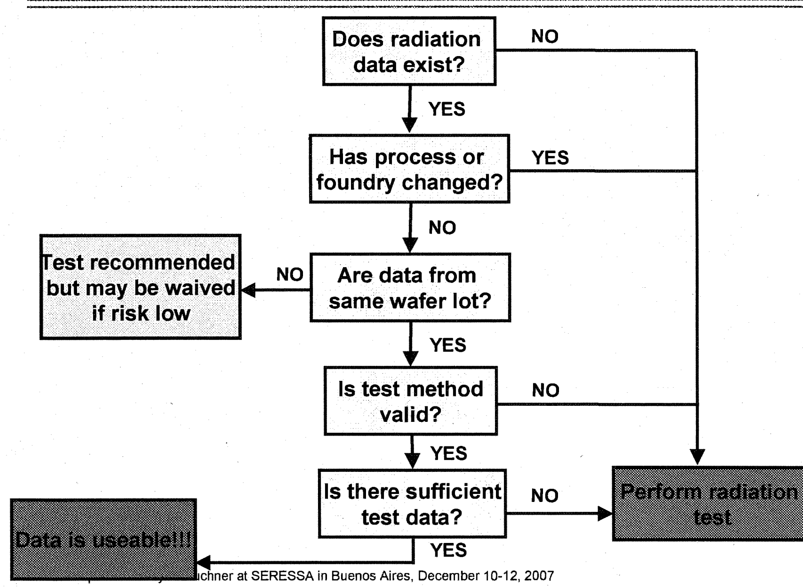
Search for Radiation Data



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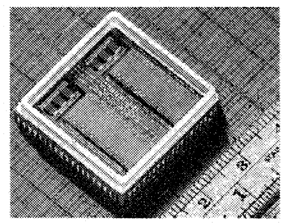
Sources of Radiation Data

- 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 Trans. On Nuc. Sci., 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 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

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

Item #	Part #	Function	Manuf.	TID	Source	Destructive SEEs	Non-destructive SETs	Comments	Approval
278	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

ACCEPTED!

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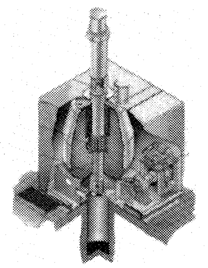
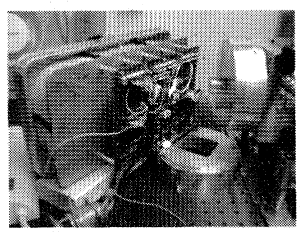
Radiation Test

- **Determine types of tests needed**
  - TID (gamma rays),
  - DD (neutrons or protons),
  - SEE (protons or heavy ions).
- **Define appropriate test levels**
  - Sample size,
  - 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



Total Dose Test (Co^{60})

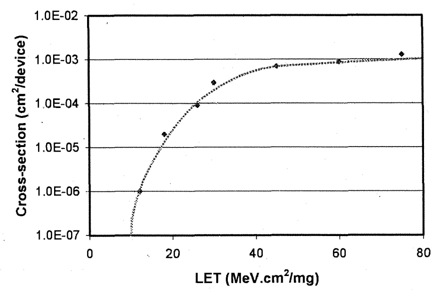
- ***Dose Rate***
  - Linear Bipolars: ELDRS dose rate of 0.01 rad(Si)/s
  - CMOS: High dose rate of 50 to 300 rad(Si)/s
- ***Total Dose***
  - At least 2X of expected mission dose for part
  - 100 krad(Si) better so can use data for other missions
- ***Bias***
  - ELDRS both biased and unbiased
  - 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.

Single Event Test

- ***Protons or Heavy Ions***
  - Determines which accelerator to use
- ***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
- ***Angle***
  - Normal to grazing, depending on application
- ***Temperature***
  - Room temperature for SEU, 100 C for SEL.
- ***Bias***
  - V_{dd} +10% for SEL
- ***Number of parts***
  - Depends on cost of parts, availability of parts, availability of beam time (Minimum of 3)

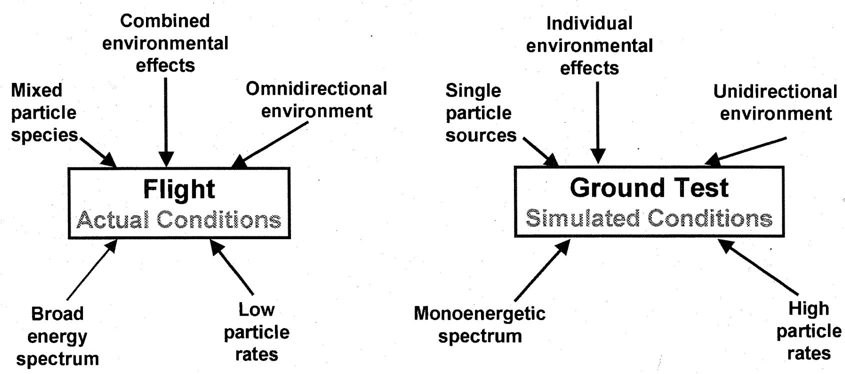
SEE Test Results

- **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**

Radiation Test Issues - Fidelity



How accurate is the ground test in predicting space performance? Example, how does aging affect dose degradation?

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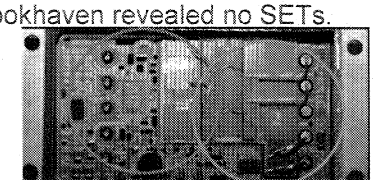
Example of Unexpected Results

- ***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 was range of ions at BNL



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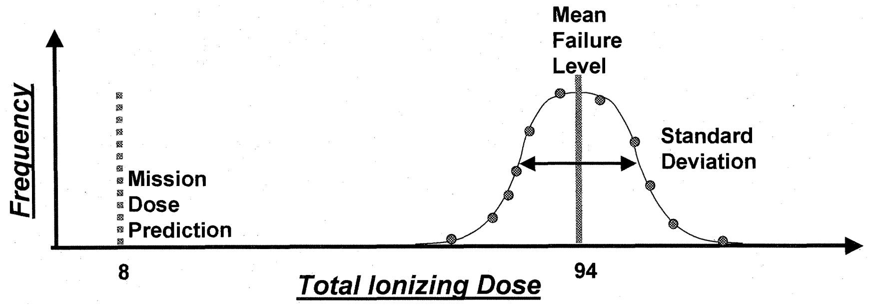
Measurement Statistics

- **Probability of survival**
- **Confidence level**



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Radiation Design Margin

- **Definition of RDM (for TID):**

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

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TID Design Margin Breakpoints

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

RDM < 2	< RDM < 10 <	RDM < 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

Qualitative approach recommended for systems with moderate requirements

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Part Categorization Criteria (PCC)

Log normal distribution law

$$PCC = \exp(K_{TL} s)$$

K_{TL} = One sided tolerance factor based on sample size n, confidence level C and probability of survival Ps

s = standard deviation of sample data

DM < 1-2 < DM < PCC < DM

Unacceptable | Hardness Critical | Hardness Non-Critical

After MIL HDBK-814

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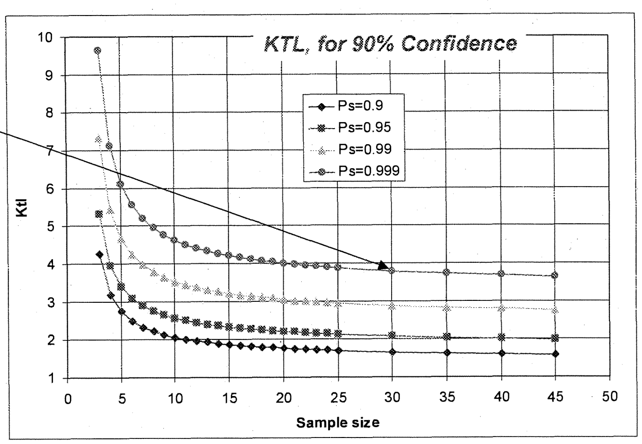
Parts Categorization Criteria

Ps=0.999
C=0.9
N=30 samples
Gives
K=3.79

PCC=exp(3.79*0.365)
=3.99



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TID- Example of Application

PM155

Rspec= 30 krad

One sided tolerance limit 42 krad

Design dose= 60 krad

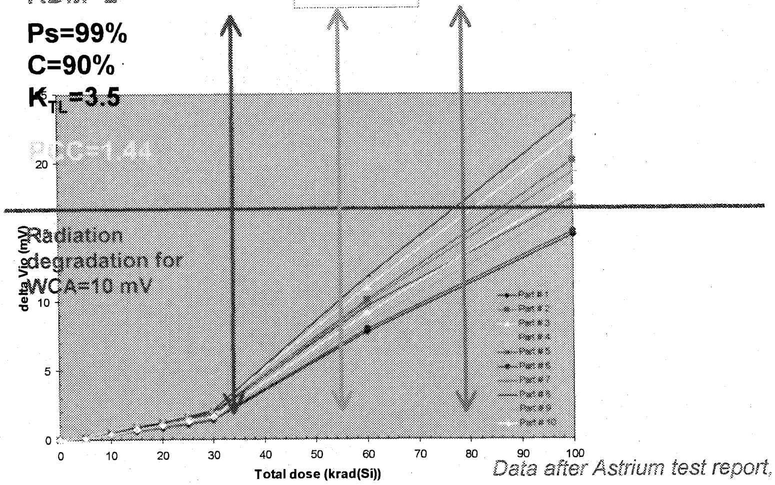
RDM=2

Ps=99%

C=90%

K_{TL}=3.5

RCC=1.44

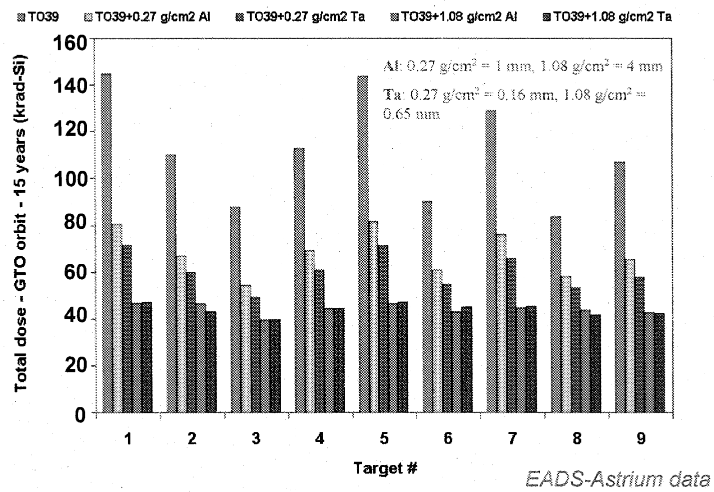


Data after Astrium test report, 1997

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
- ***Increase the failure level***
  - Test in the application conditions
  - Test at low dose rate (CMOS only)
  - Tolerant designs (cold redundancies, etc.)
  - Relax the functional requirements

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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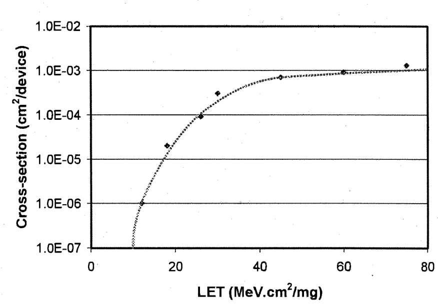
SEE - Analysis Requirements

- ***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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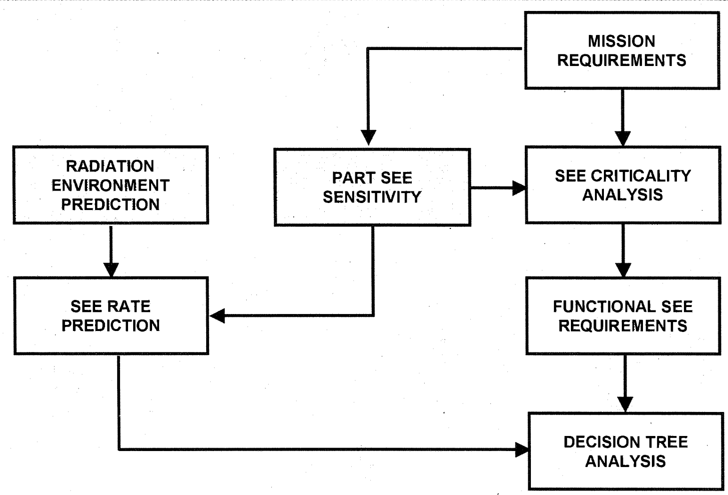
SEE - Analysis Flow



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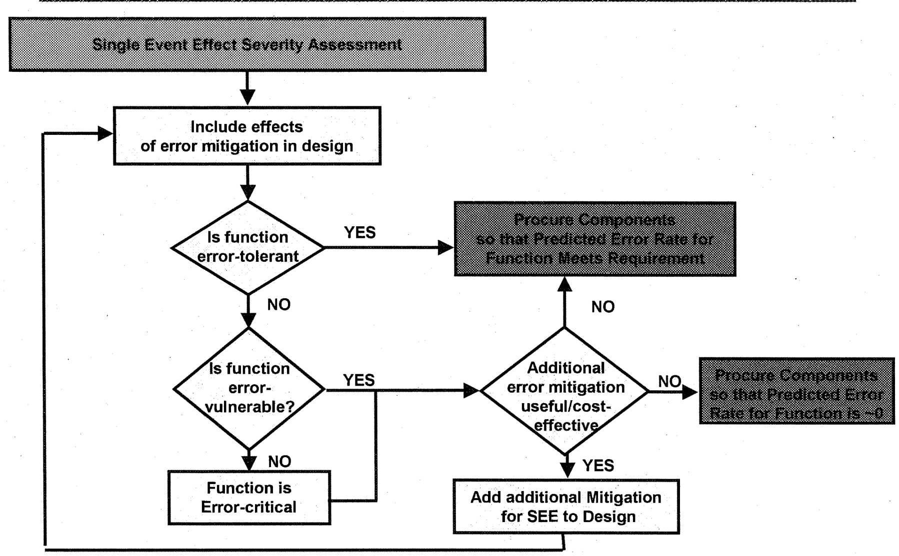
SEE - Decision Tree



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  - Evaluate circuit response to hazard
    - Search for data or perform a test
  - Categorize the parts
    - TID/DD
    - SEE
- **Conclusion**

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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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