Radiation Hardness Assurance (RHA) for Space Systems

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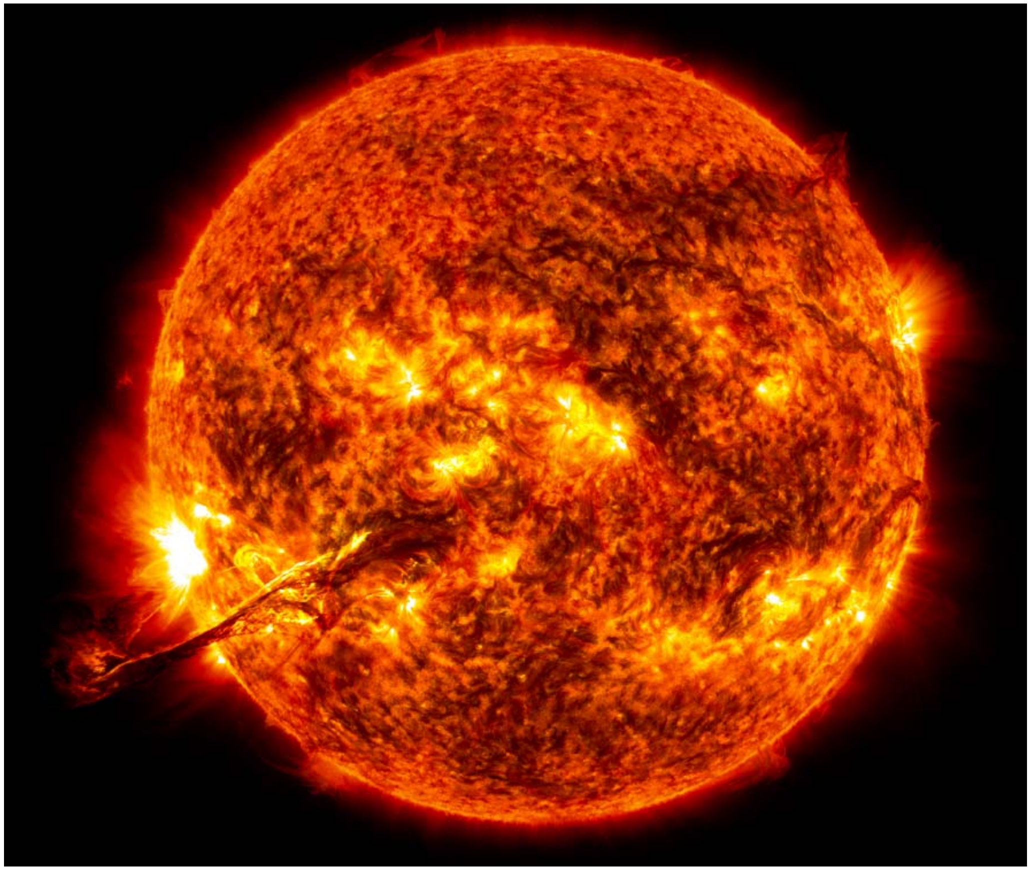
Presented by S. Buchner at SERESSA at Puebla, Mexico, December, 2015

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

Radiation Hardness Assurance deals with TID, SEE and DDD of systems, subsystems, box, board and piece parts.

Why is RHA Important ?

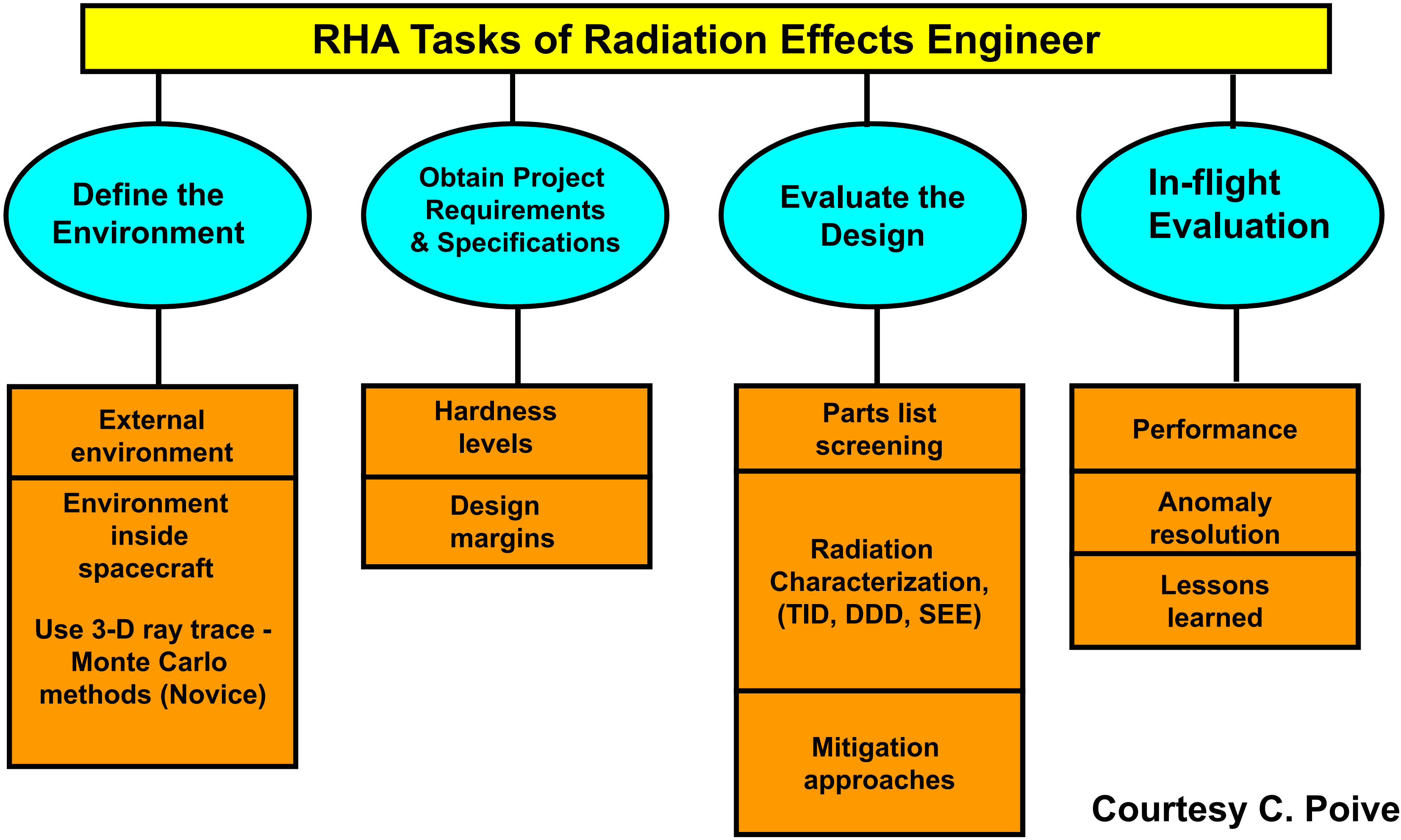


Solar Dynamics Observatory (SDO). Launched 2/11/2010, $850 Million.

Steps Involving RHA

- A mission is proposed by scientists.
- A set of requirements at various levels is established.
- A radiation effects engineer is assigned to the project.
- The task of the engineer is to assure that the spacecraft will operate properly in a radiation environment (RHA).
- The radiation engineer establishes the radiation environment, which is determined by orbit, launch date, launch duration and shielding.
- Based on level requirements and environment the TID/DD and SEE tolerances to radiation are established.
- Parts are selected based on TID/DD and SEE levels and operational requirements for use or testing.
- Final approval is given when all parts have been qualified.

RHA Tasks



RHA Tasks of Radiation Effects Engineer

Define the Environment
- External environment
- Environment inside spacecraft

  Use 3-D ray trace - Monte Carlo methods (Novice)

Obtain Project Requirements & Specifications
- Hardness levels
- Design margins

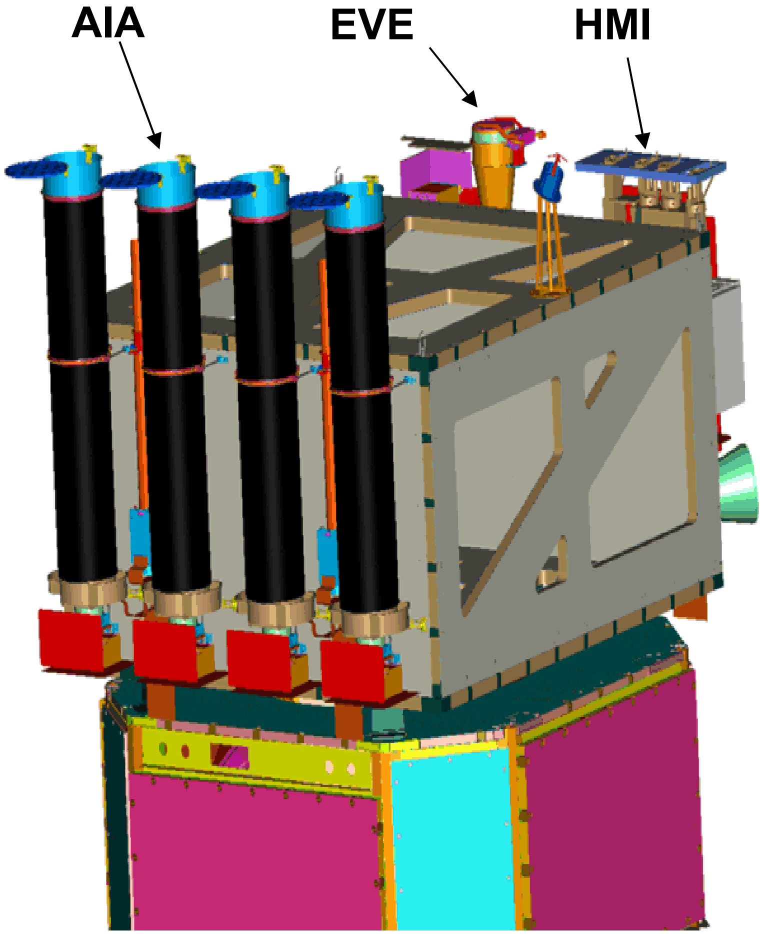
Evaluate the Design
- Parts list screening
- Radiation Characterization, (TID, DDD, SEE)
- Mitigation approaches

In-flight Evaluation
- Performance
- Anomaly resolution
- Lessons learned

Courtesy C. Poivey, ESA

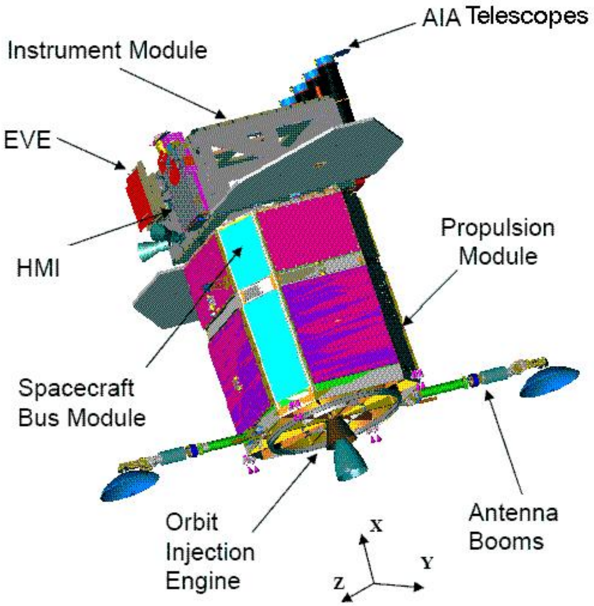
Example of Radiation Hardness Assurance for Solar Dynamics Observatory (SDO)

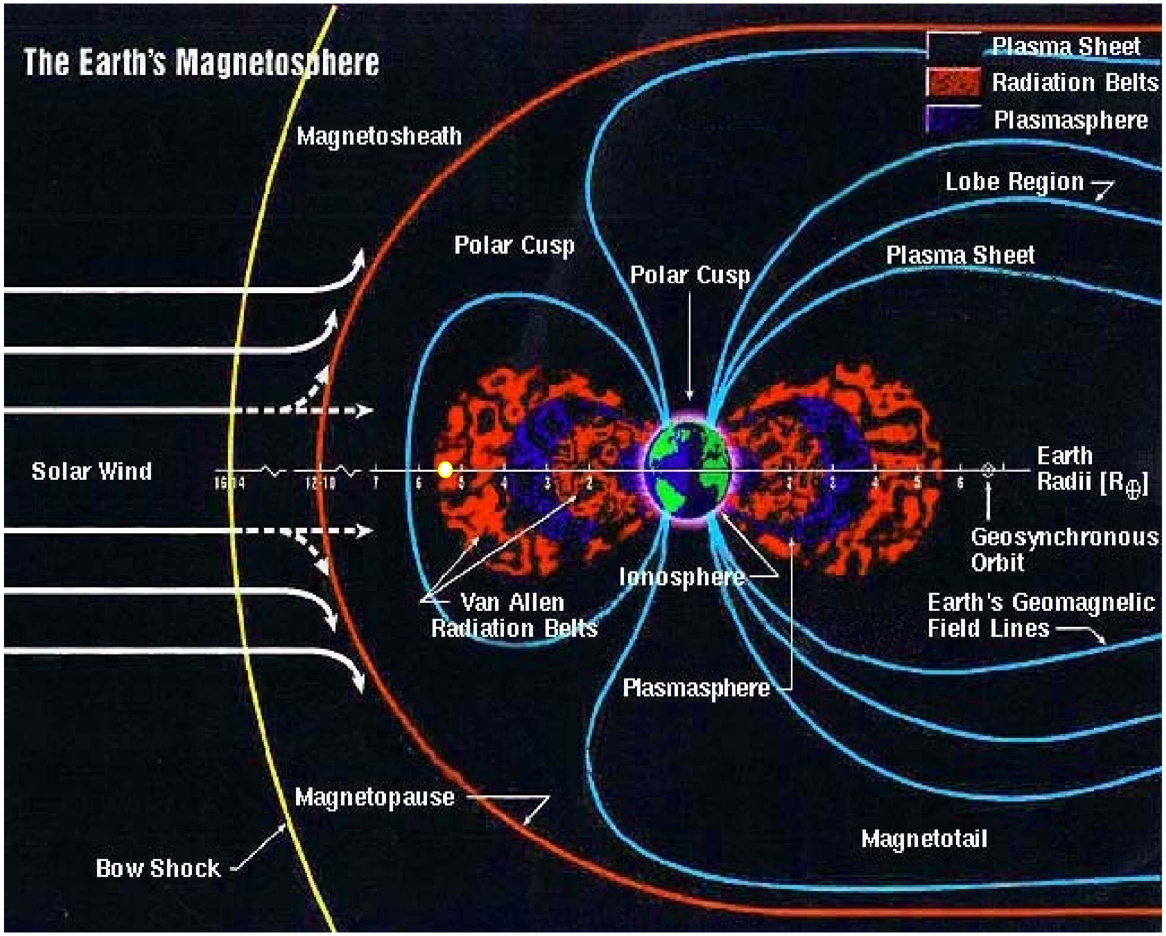
Proposed Mission (SDO)



- **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.

Environment for SDO





Geo is 5.45xR$_{earth}$

1. Trapped electrons
2. Solar protons
3. Galactic cosmic rays

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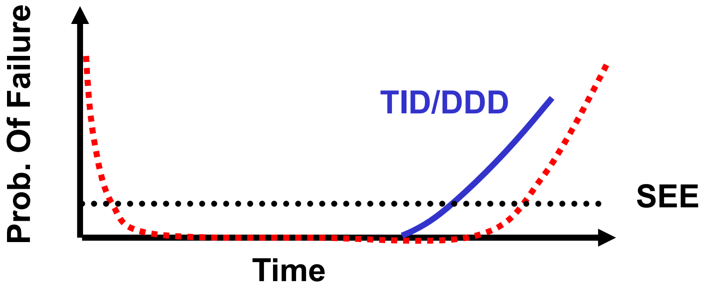
SDO Mission Requirements

1. **Mission launch date and duration:**
   a) Launch date was February 2010 - increased solar activity.
   b) 5-year mission (10-year option).
   c) Geosynchronous orbit – over White Sands, New Mexico.
2. **Operation Requirement:**
   a) Must be operational 95% of the time (Down time = 2190 hours in 5 years).
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 – must not fail due to TID, SEE, DDD.

Radiation-Induced Failure on SDO

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



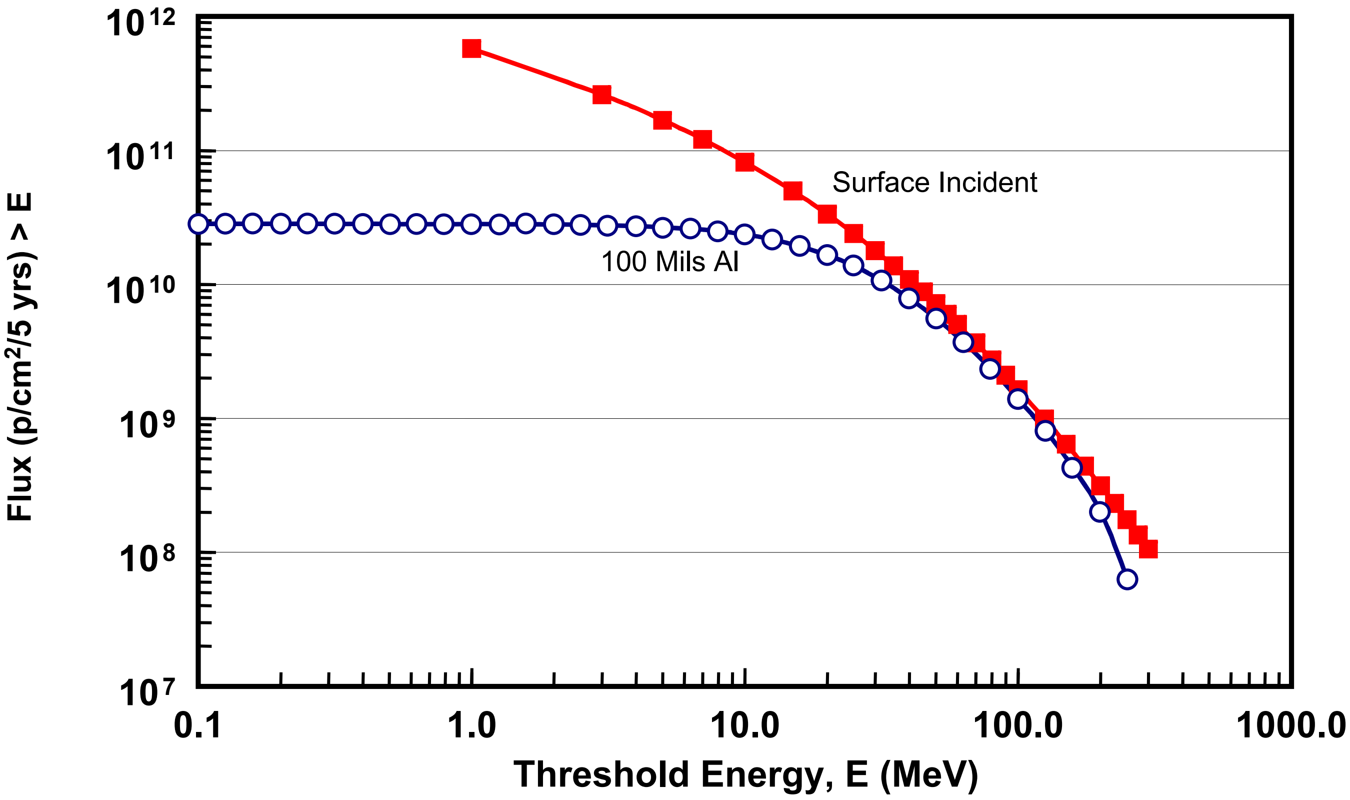
- **Non-destructive non-critical SEE rates based on budgeted down time that includes:**
  - Eclipses,
  - Instrument calibration,
  - Antenna handover,
  - Momentum shedding,
  - RADIATION
- **Destructive SEEs should not be permitted to happen**
- **Must survive TID and DDD received during mission**

Define and Evaluate Radiation Hazard - TID

(SPENVIS, CREME96, Space Radiation, CRÈME-MC)

SEE - Proton Flux vs Energy

Input:
1. Orbit (GEO, LEO)
2. Launch date (Solar Cycle)
3. Mission duration
4. Shielding



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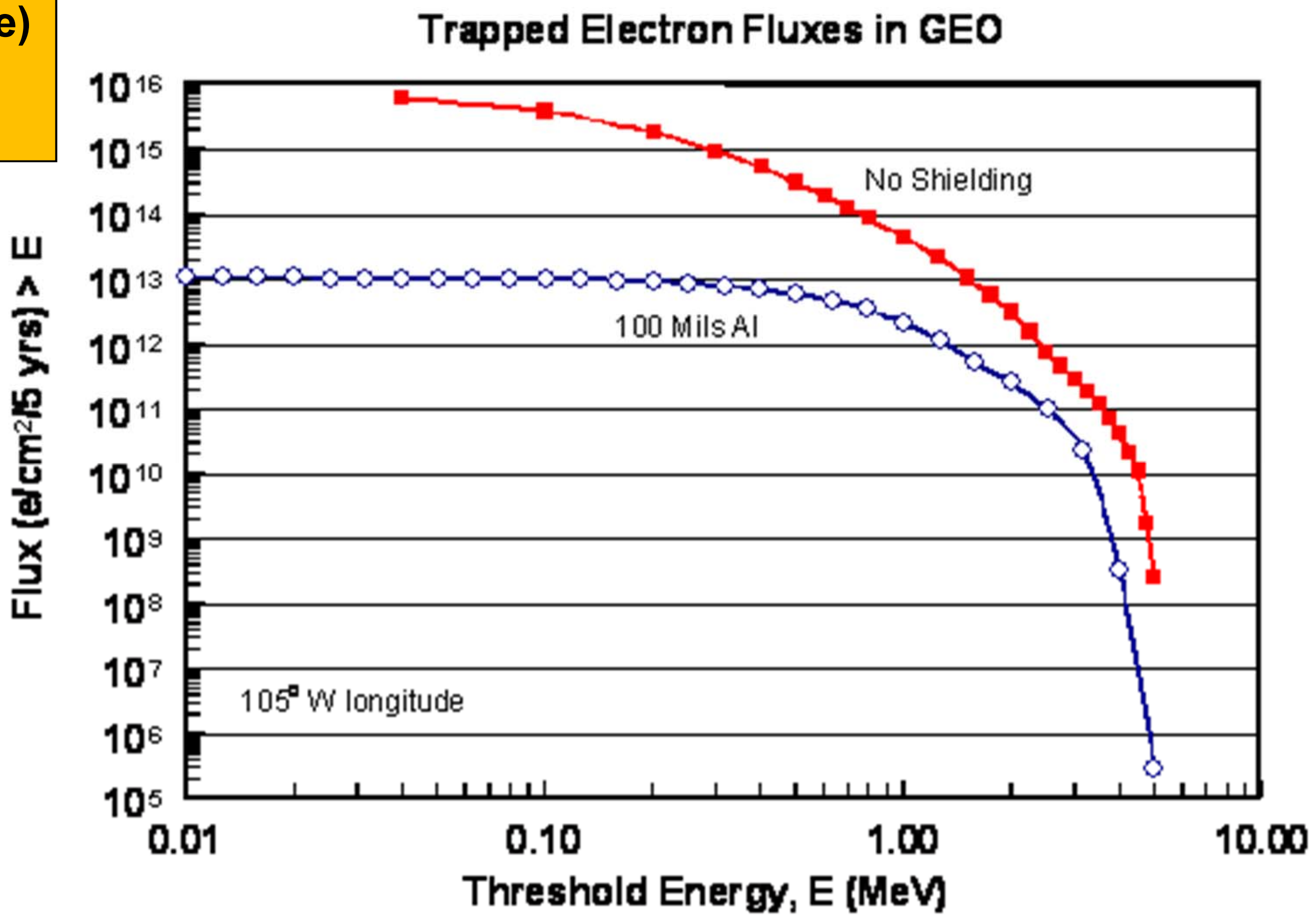
SEE - Electron Flux vs Energy

Input:
1. **Orbit (GEO, LEO)**
2. **Launch date (Solar Cycle)**
3. **Mission duration**
4. **Shielding**



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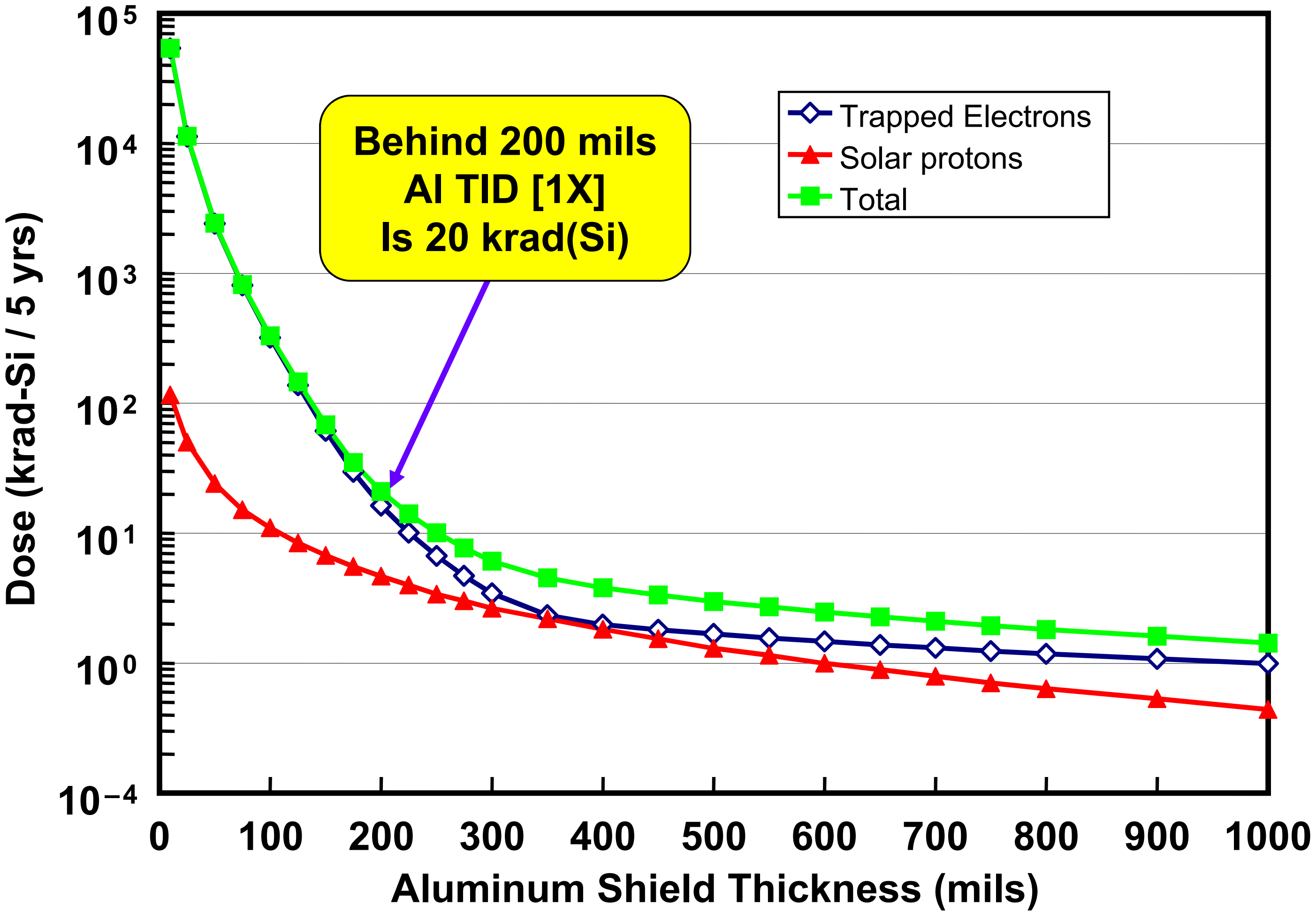
TID Top Level Requirement (SDO)



Dose-Depth Curve for GEO

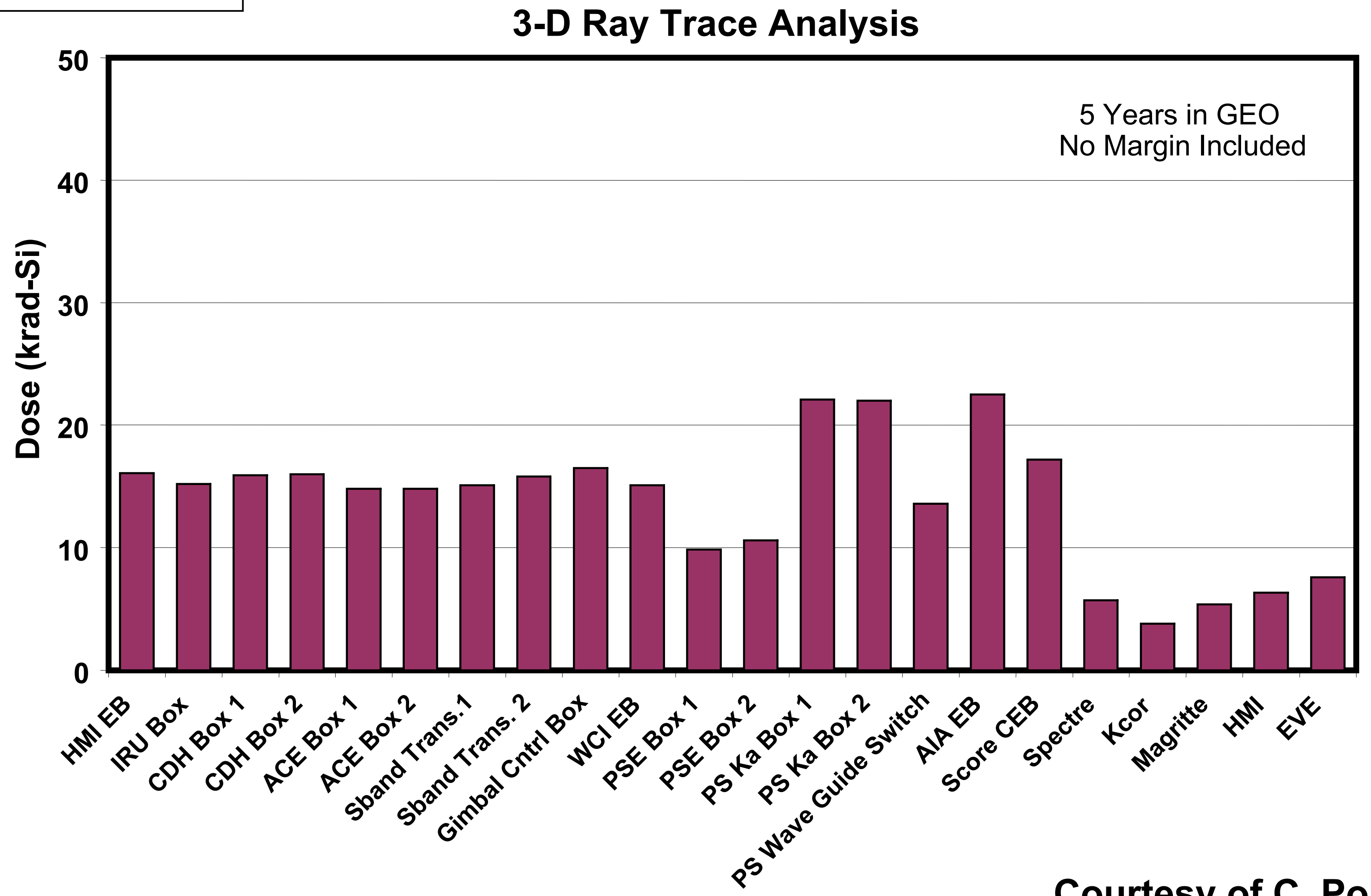
Behind 200 mils
Al TID [1X]
Is 20 krad(Si)

SDO Part Level Requirements

- ***Cumulative***
  - **Total Ionizing Dose** (TID = 60 Mrad(Si) – free field)
  - **Displacement Damage** (DD = 2×10^{10} MeV/gm – field free)

TID Inside Electronic Boxes

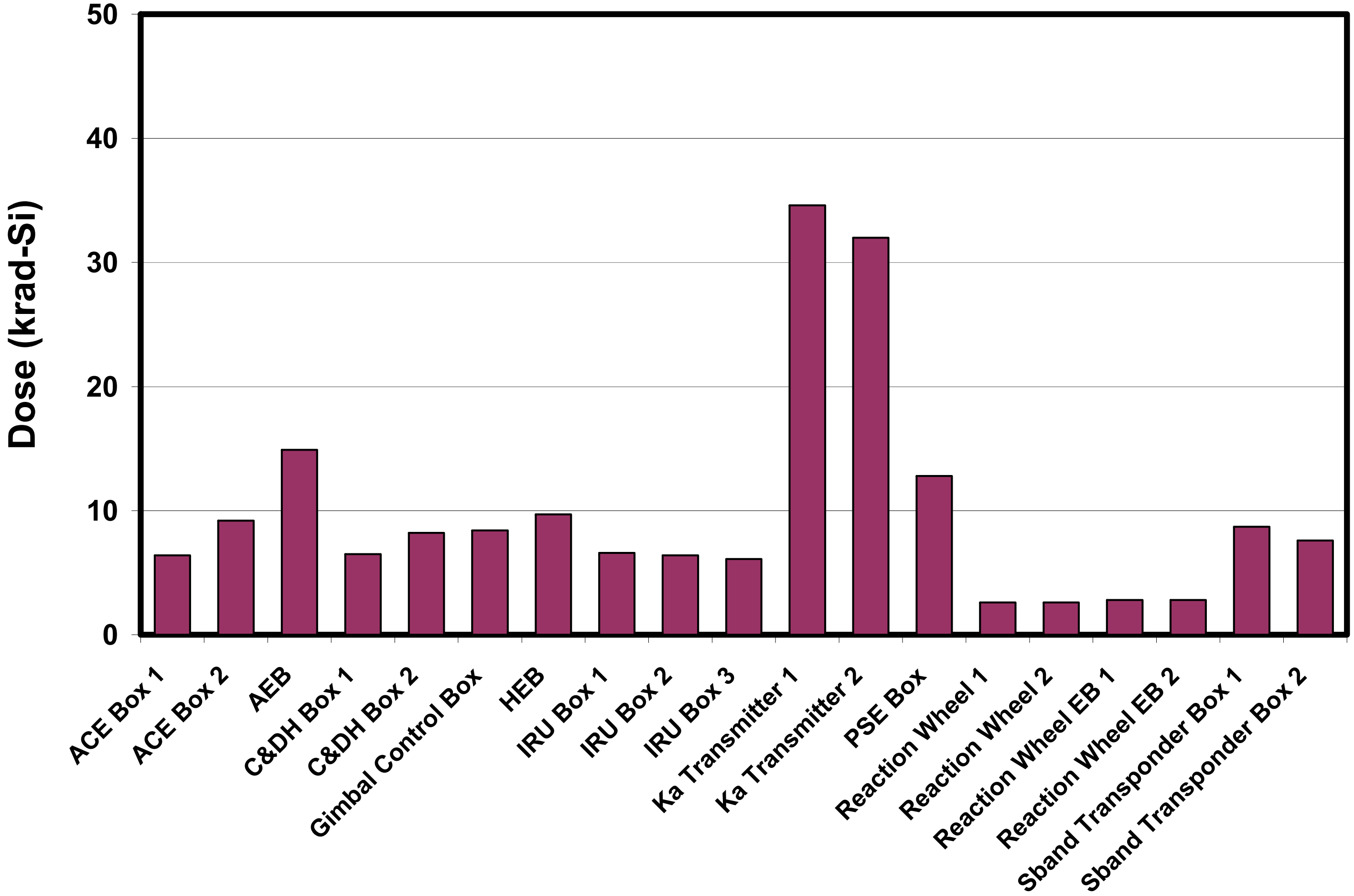
NO MARGIN



Courtesy of C. Poivey

TID Inside Electronic Boxes

MARGIN OF 2 USING ACCURATE SPACECRAFT MODEL and NOVICE



Courtesy of C. Poivey

Define and Evaluate SEE Radiation Hazard from Protons and Heavy Ions

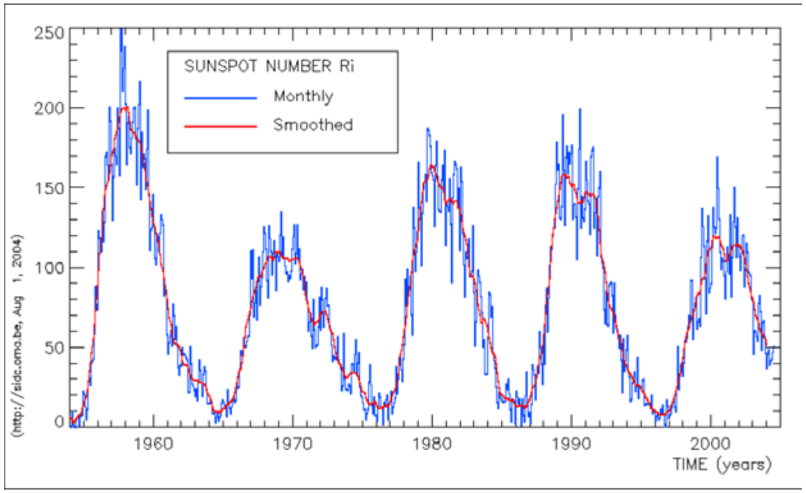
(SPENVIS, CREME96, Space Radiation, CRÈME-MC, OMERA)

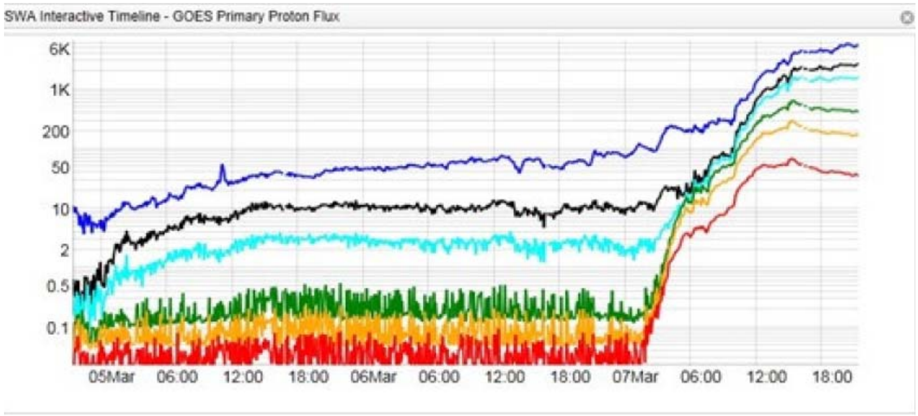
Electrons and Photons do not produce SEEs

Proton Environment at GEO

- No trapped protons (only trapped electrons).
- Most protons from sun – flux varies with sun's activity
  - 95% protons
  - 4% alpha particles
  - 1% all others
- Solar particle events occur randomly and so are described by probability and confidence levels.
- Ionizing vs non-ionizing processes

Proton Environment – Long vs Short term Variations





Solar Cycle

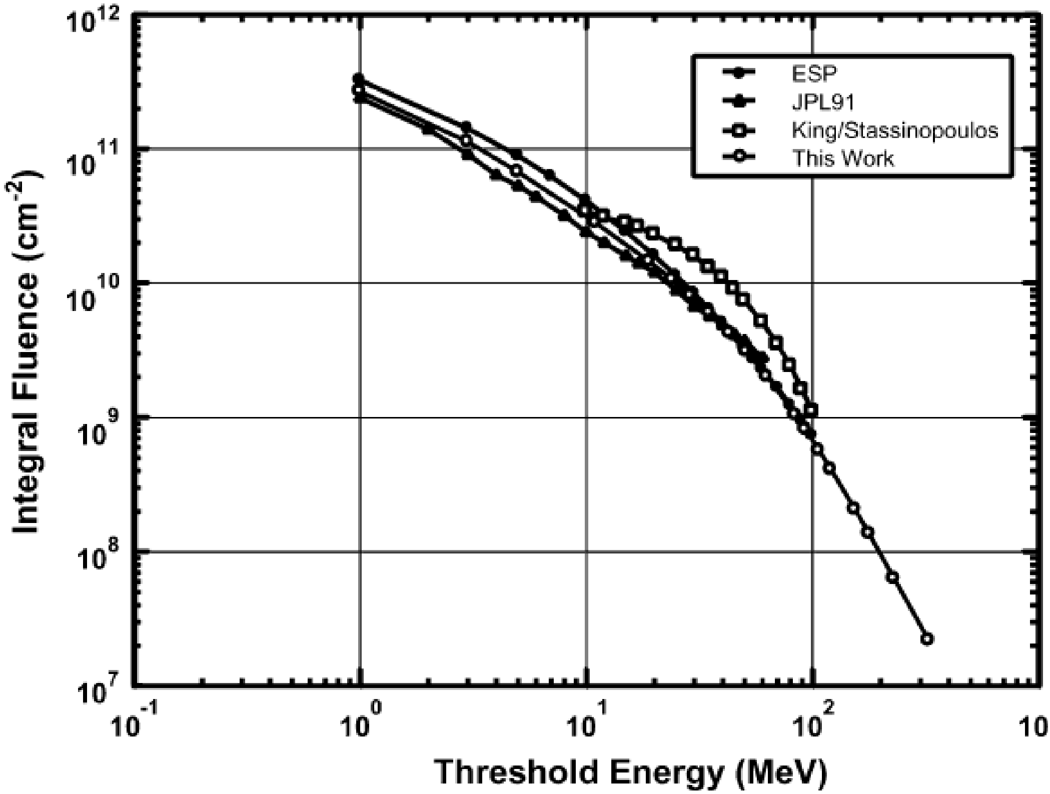
as measured by sunspot number - 11 years

Solar Particle Event

as measured by GOES at GEO – proton spectra

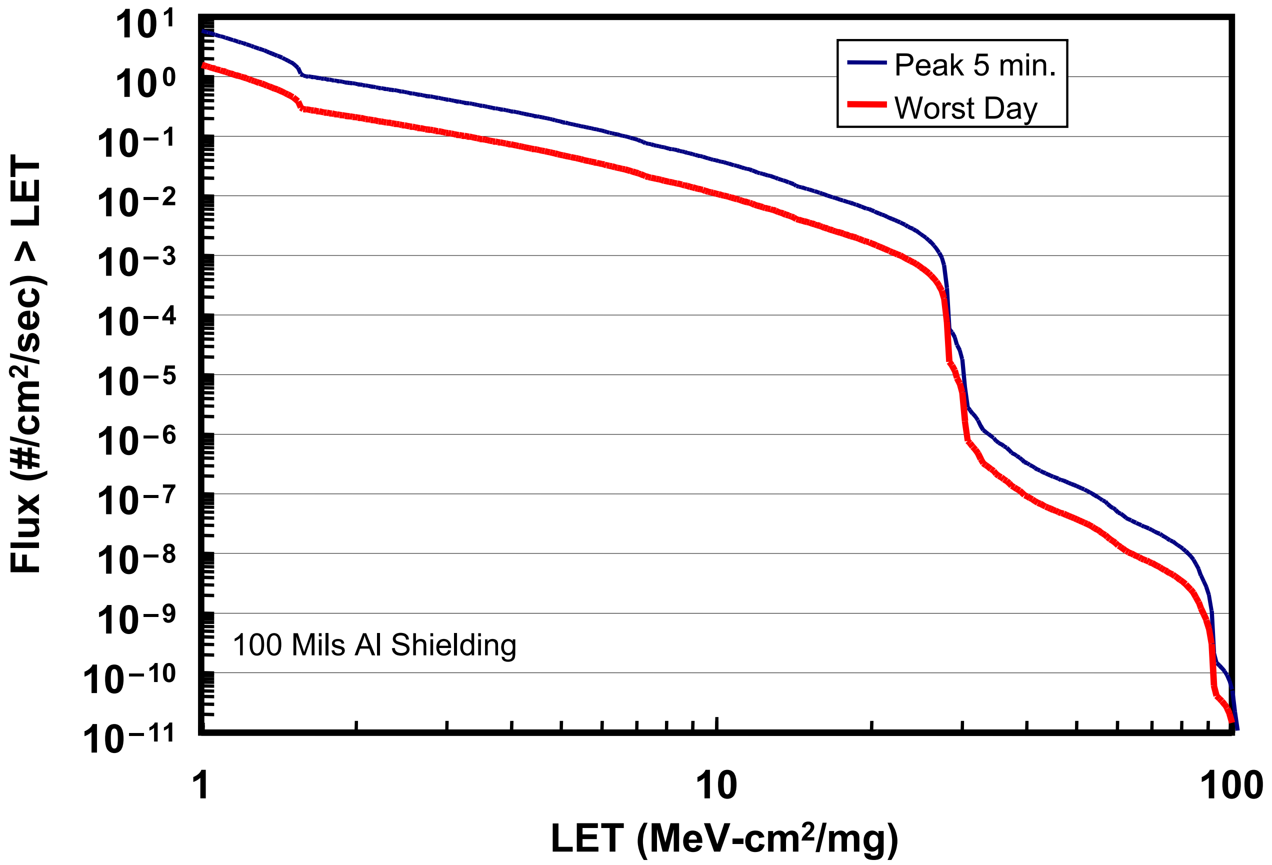
Worst Case Proton Environment

- Cumulative solar proton flux for two years at the 90% confidence level



Worst Case Particle Environment

Integral LET Spectra for the Worst Case Solar Particle Event



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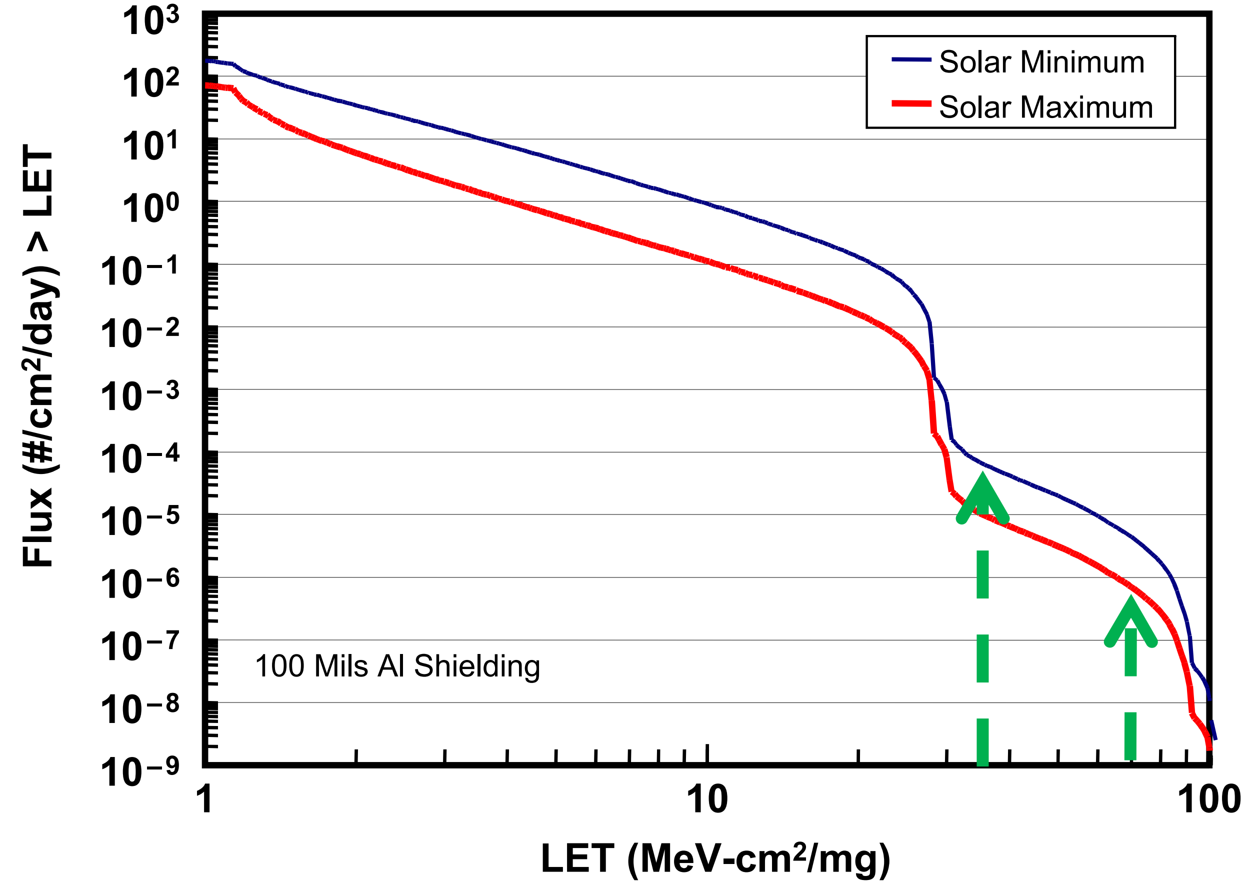
Galactic Cosmic Rays – Heavy Ions

GEO



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SDO Part Level Requirements

- ***Single Event***
  - **Non-Destructive** (Suggested $\mathrm{LET}_{th} > 36$ MeV.cm^2/mg)
    - Single Event Upset (SEU),
    - Single Event Transient (SET),
    - Single Event Functional Interrupt (SEFI).
  - **Destructive** ($\mathrm{LET}_{th} > 80$ MeV.cm^2/mg)
    - Single Event Latchup (SEL)
    - Single Event Burnout (SEB)
    - Single Event Gate Rupture (SEGR)

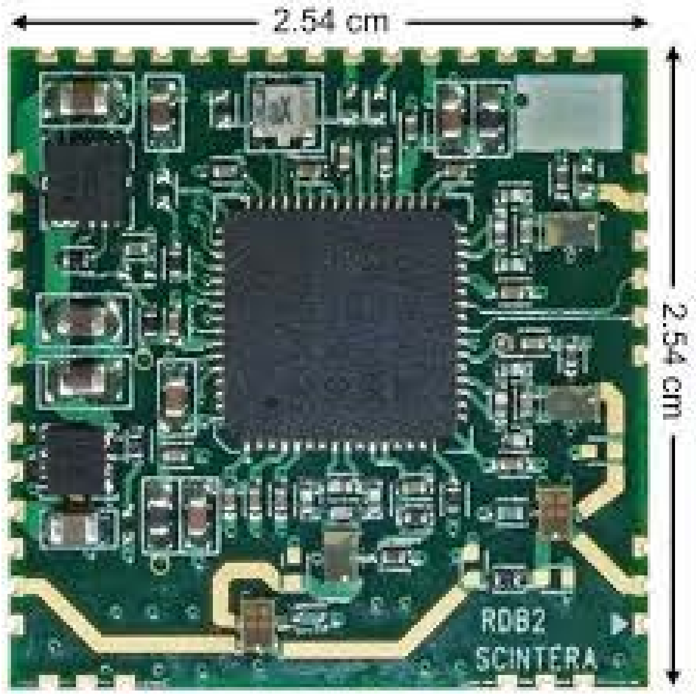
Decisions based on SEE Rate

- ***Destructive SEEs***
  - No destructive SETs for LETs below **80 MeV.cm^2/mg**.
    - Mitigate (e.g., latchup protection circuit)
    - De-rate (COTS Power MOSFETs have V_{sd} de-rated to 35%, rad-hard Power MOSFETs to 60%)
    - Replace part if cannot mitigate

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

CONSULT WITH DESIGNER

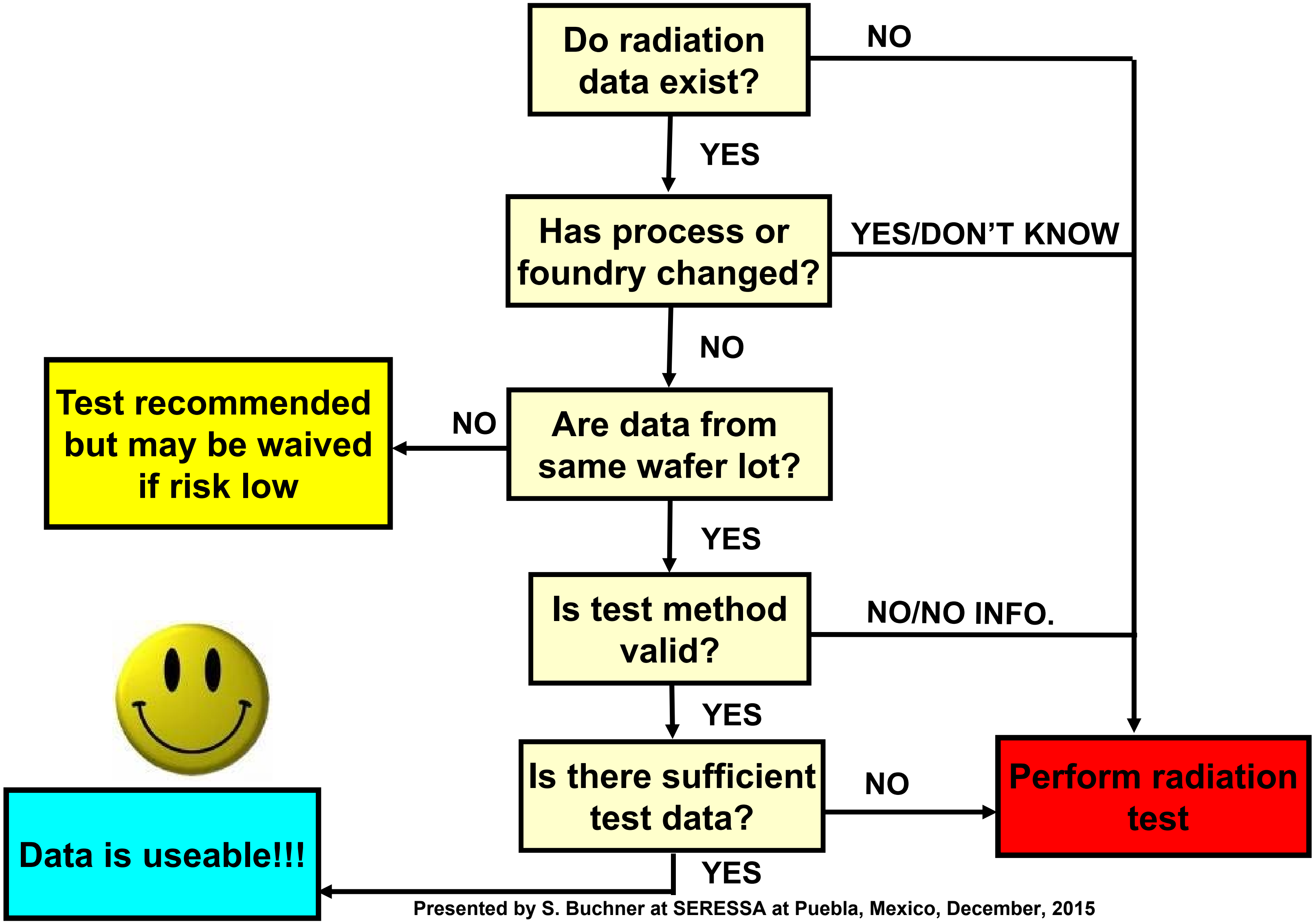
Obtain Parts Lists from Designers



Steps to Qualify

1. If a radiation-hardened part has been certified by DSCC (Defense Supply Center Columbus), no further analysis is required. ACCEPT
2. If a radiation-hardened part that has been certified by a manufacturer is selected, no further analysis is required, provided one trusts the manufacturer. Visit manufacturing facility. ACCEPT PROVISIONALLY
3. If part has been tested by another organization CHECK VALIDITY OF TEST
4. If the part is not certified to be radiation hard, SEARCH FOR DATA.
    - Same date/lot code on package is not sufficient
    - COTS parts should be from same wafer lot
5. If no data, TEST FLIGHT LOT

Search for Radiation Data



Do radiation data exist?

NO

YES

Has process or foundry changed?

YES/DON'T KNOW

NO

Are data from same wafer lot?

NO

Test recommended but may be waived if risk low

YES

Is test method valid?

NO/NO INFO.

YES

Is there sufficient test data?

NO

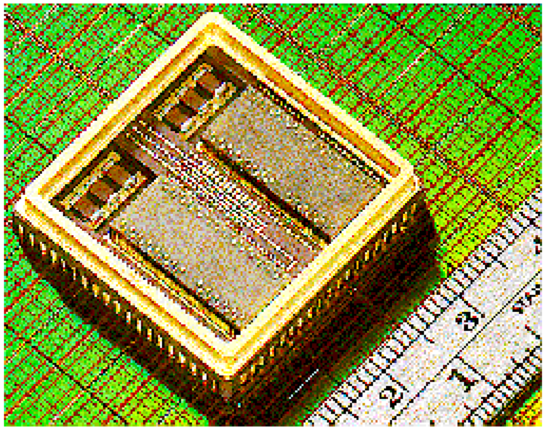
Perform radiation test

YES

Data is useable!!!

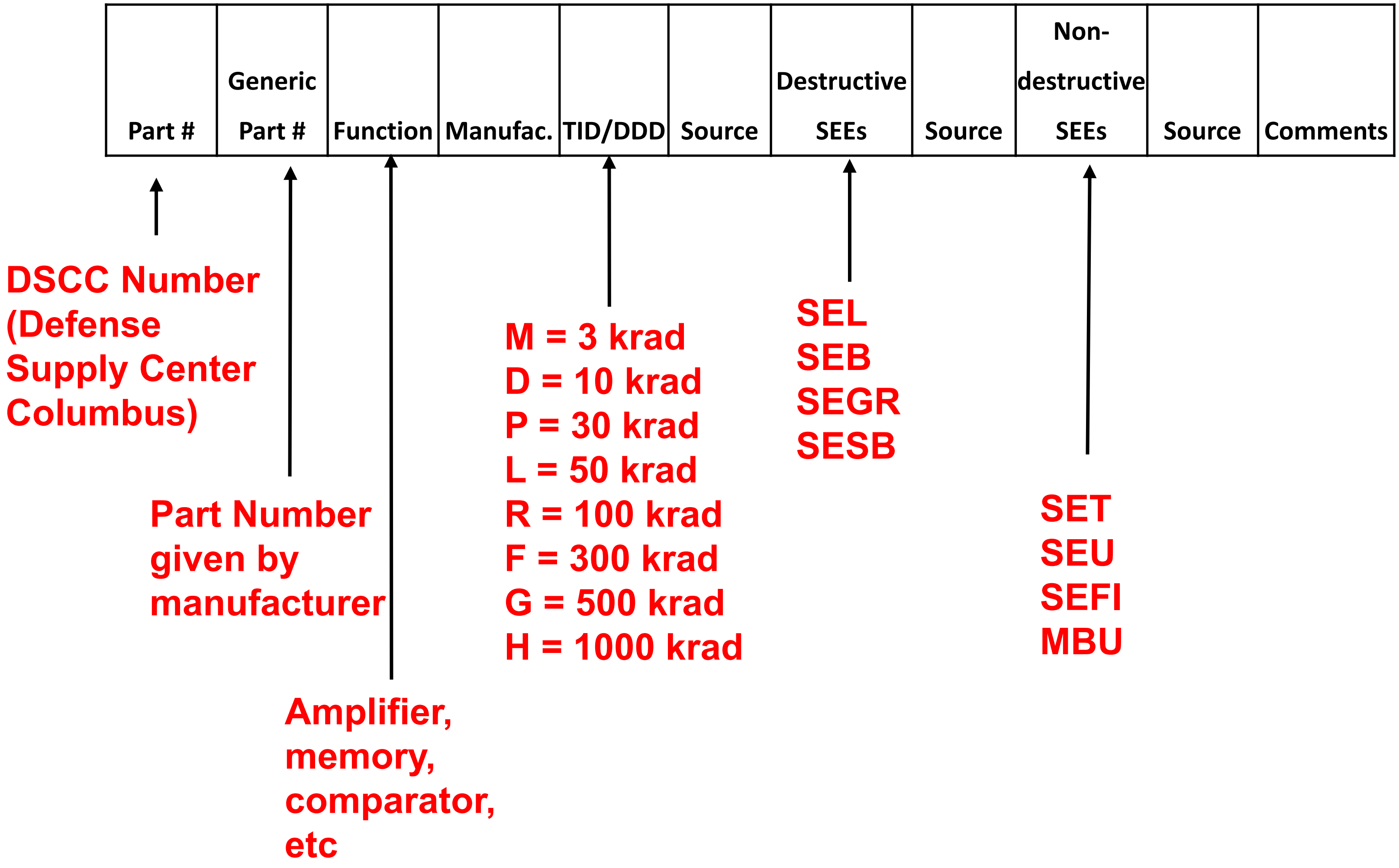
Sources of Radiation Data

- In house data from previous projects – use leftover parts
- Available databases:
  - NASA-GSFC: http://radhome.gsfc.nasa.gov
  - NASA-JPL
  - ESA: http://escies.org
- 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

Evaluation of Radiation Data



Part #	Generic Part #	Function	Manufac.	TID/DDD	Source	Destructive SEEs	Source	Non-destructive SEEs	Source	Comments

DSCC Number (Defense Supply Center Columbus)

Part Number given by manufacturer

Amplifier, memory, comparator, etc

M = 3 krad
D = 10 krad
P = 30 krad
L = 50 krad
R = 100 krad
F = 300 krad
G = 500 krad
H = 1000 krad

SEL
SEB
SEGR
SESB

SET
SEU
SEFI
MBU

Evaluation of Radiation Data

Part #	Generic Part #	Function	Manufac.	TID	Source	Destructive SEEs	Source	Non-destructive SEEs	Source	Comments
5962-06233	UT54ALVC2525	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
(Defense Supply Center Columbus)

Meets SDO requirements for SEL

Meets SDO requirements for SEL

Meets SDO requirements for SETs

A good part

Evaluation of Radiation Data

Part Number	Generic Part Number	Function	Manuf.	TID/DD	Source	Destructive SEE	Source	Non-destructive SEE	Source	Notes
5962-87615012A	54AC08LM QB	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

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

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.

Meets SDO requirements for destructive SEEs

Glitches on output. Must know amplitude and width

Recommendation

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

IBEX not SDO

Evaluation of Radiation Data

- An ADC (AD7875TQ) was selected for IBEX.
  - ➢ This is a 12-bit, 100 kHz sampling ADC in a CMOS process.
  - ➢ No radiation data for this part (LDC of 2005), but data on JPL site for the AD7874 in 1996. Rad. Effects engineer claims that AD7874 more complicated device, therefore should be more sensitive to TID.
  - ➢ Data for AD7874 showed parametric failure at 20 krad.
  - ➢ The anticipated dose for the AD7875, which is spot shielded, is 2 krad (RDM is about 10).
  - ➢ Is the data relevant?
  - ➢ Process Change in 2001. REJECT.

Evaluation of Radiation Data

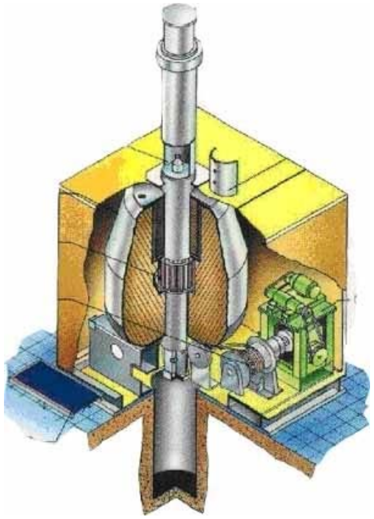
- **IMU manufactured by Kearfott**
  - Contains non-radiation hardened parts
  - Suggested doing TID testing on the parts
  - Test equipment not available and not sufficient spares
  - Kearfott informed us that an identical IMU was in another satellite in orbit
  - Member of SDO team contacted a friend at satellite manufacturer who gave us all the information we needed for a case of beer
  - Determined that satellite was
    - In GEO orbit
    - Had similar shielding
    - Had been in space for two years
  - Decision was to accept and monitor satellite for failure, which never happened.

If No Radiation Data Exists

Perform Testing

Total Dose Testing

- **Determine radiation sources**
  - TID (gamma rays, x-rays, protons),
- **Define appropriate test levels**
  - Sample size,
  - Dose and dose rate.
- **Generic vs application- specific testing**
  - **Generic: worst case for bias, frequency, etc**
  - **Application specific: not always possible**



Gamma ray testing with Co^{60} cell

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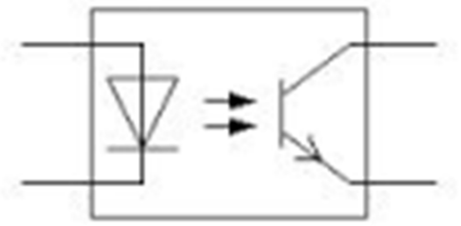
Total Dose (Co^{60})

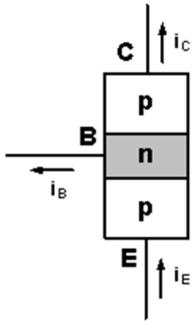
- ***Dose Rate***
  - Linear Bipolars: ELDRS dose rate of 0.01 rad(Si)/s
  - CMOS: High dose rate of 50 to 300 rad(Si)/s
- ***Total Dose***
  - At least 2X of expected mission dose for part
  - 100 krad(Si) better so can use data for other missions
- ***Bias***
  - ELDRS both biased and unbiased
  - CMOS – biased generally but specific biases in some cases such as ASICS.
- ***Temperature***
  - Room temperature (or application temperature), annealing step
- ***Minimum Number of Parts***
  - Cost is sometimes an issue (>$10,000/part)
  - NASA: 10 with 2 for controls,

Displacement Damage (p or n)

- ***Protons or neutrons***
  - DD tests for optical parts (optocouplers, LEDs, CCDs, solar cells, etc) and for bipolar parts (operational amplifiers, voltage references)
  - Protons preferred over neutrons because they cause both DD and TID.
  - Low-energy protons (2 MeV) cause much more DD than high-energy protons.
  - Neutron testing can be done at a fast-burst reactor or an accelerator with a proton beam directed at a target that emits neutrons.



Optocoupler

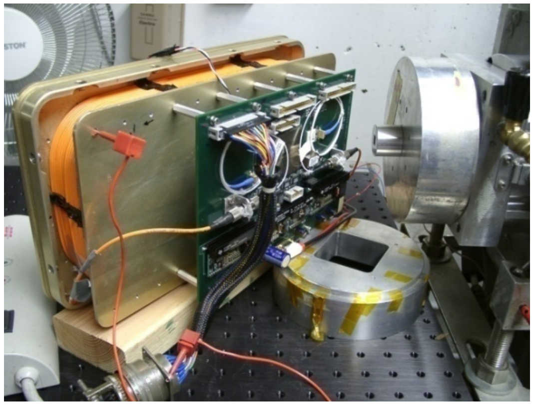


Bipolar Transistor

Solar Cell

Single Event Effects

Proton testing at UC Davis

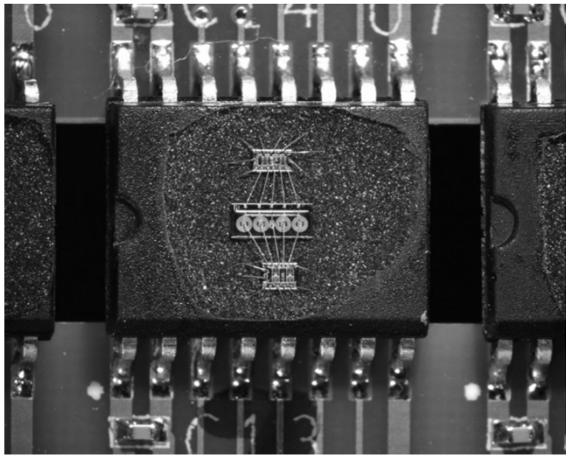


- ***Protons, Heavy Ions (energy) or Laser***
  - Determined by information needed (BNL vs TAMU)
- ***Air or Vacuum***
  - For high-speed prefer air.
- ***Flux***
  - Low enough to prevent “pile-up” of transients
- ***Fluence***
  - Determined by statistics:
    - For SEUs minimum of 100 upsets **per mode** or 1x10^7 particles/cm^2
    - For SEL minimum of 1x10^7 particles/cm^2
- ***Angle***
  - A variety of angles, depending on application – essential for RHBD
- ***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), criticality of part.

Innovative Approaches to Testing

Screening Parts Using SEL

- ***Replace opto-isolators to save power***
  - MIS Mission uses 75 isolators
  - Power consumption if opto-isolators are used is 10 W
  - Replace with galvano-isolators to reduce power to 2 W
  - Parts selected were:
    - **Analog Devices: ADuM1410/12**
    - **Texas Instruments: ISO7240**
    - **NVE: IL515 and IL715**
  - These are COTS parts that need radiation testing
  - ***Used pulsed laser to check for SEL***



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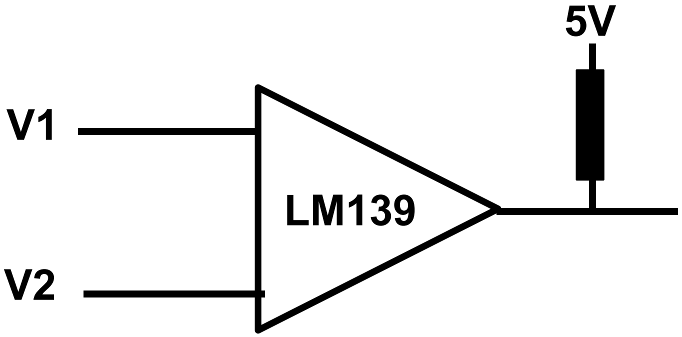
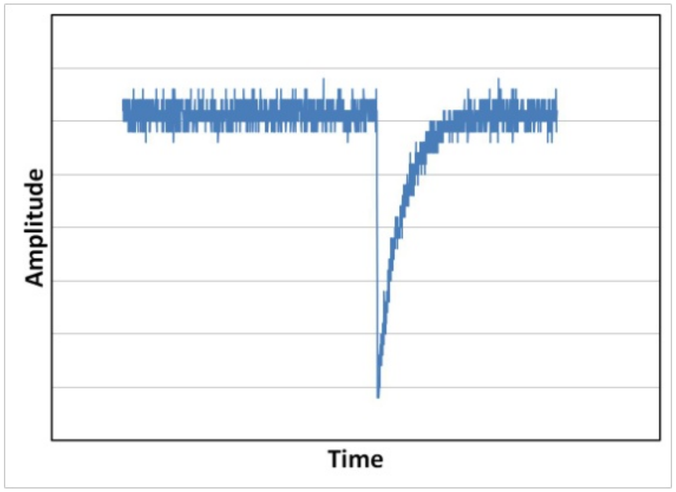
Single Event Test – Worst Case

- ***Use a laser to measure worst-case SETs***
  - Linear devices, such as op-amps, voltage regulators, and comparators give rise to analog SETs that depend on specific configuration.
  - Cannot retest a part for each application because of time and expense.
  - Pulsed laser can provide worst-case transients, i.e., in orbit, the SETs won't be worse.

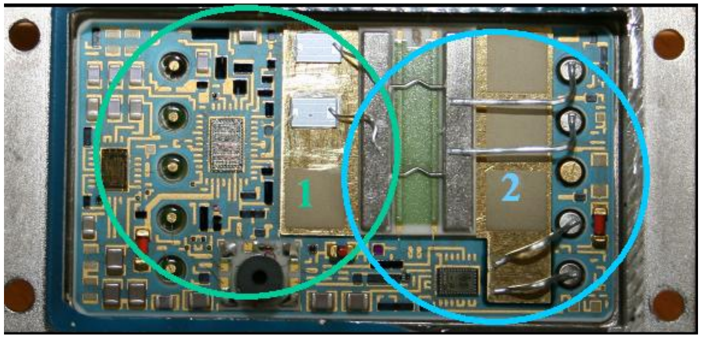




Example of Unexpected Results

- ***Solid State Power Controller (SSPC) from DDC (RP-21005DO-601P)***
  - DDC replaced FET from Signetics with non rad-hard FET from IR.
  - Parts engineer suspicious and asked for testing.
  - 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.
  - Previous SEE testing by GSFC of ASIC at Brookhaven revealed no SETs.
  - Replaced DDC SSPC with Micropac SSPC
  - SEE testing successful at TAMU

Problem attributed to short range of ions at Brookhaven National Laboratory

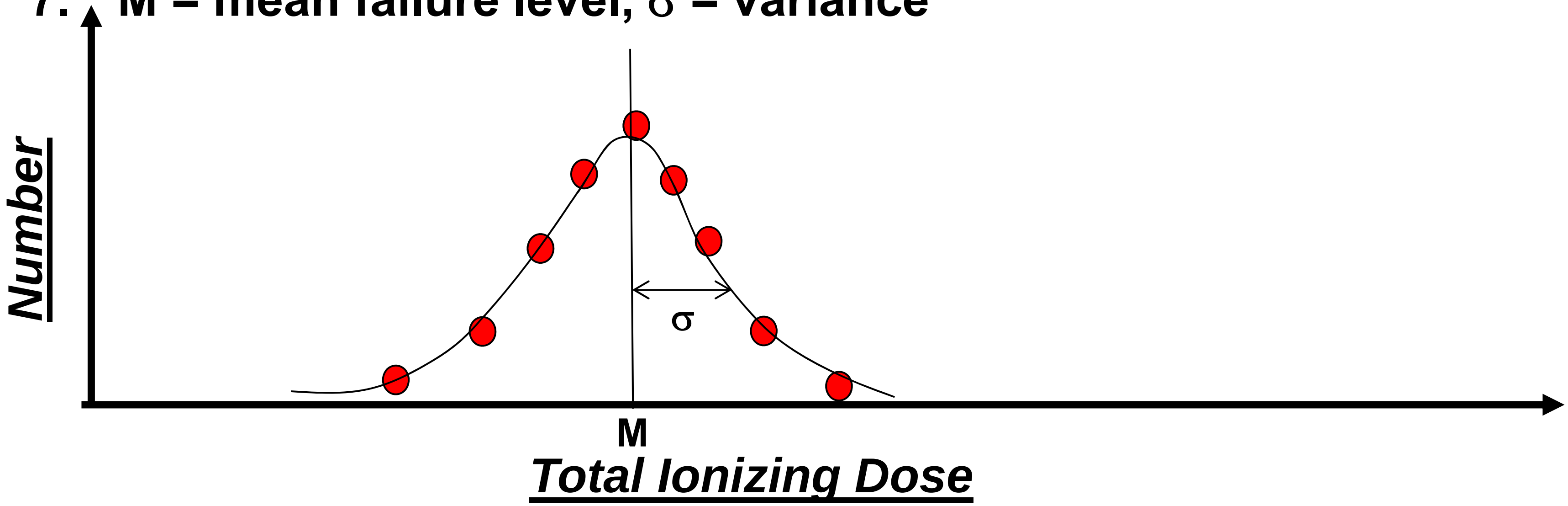


Categorize the Parts

TID and SEE

TID - Measurement Statistics

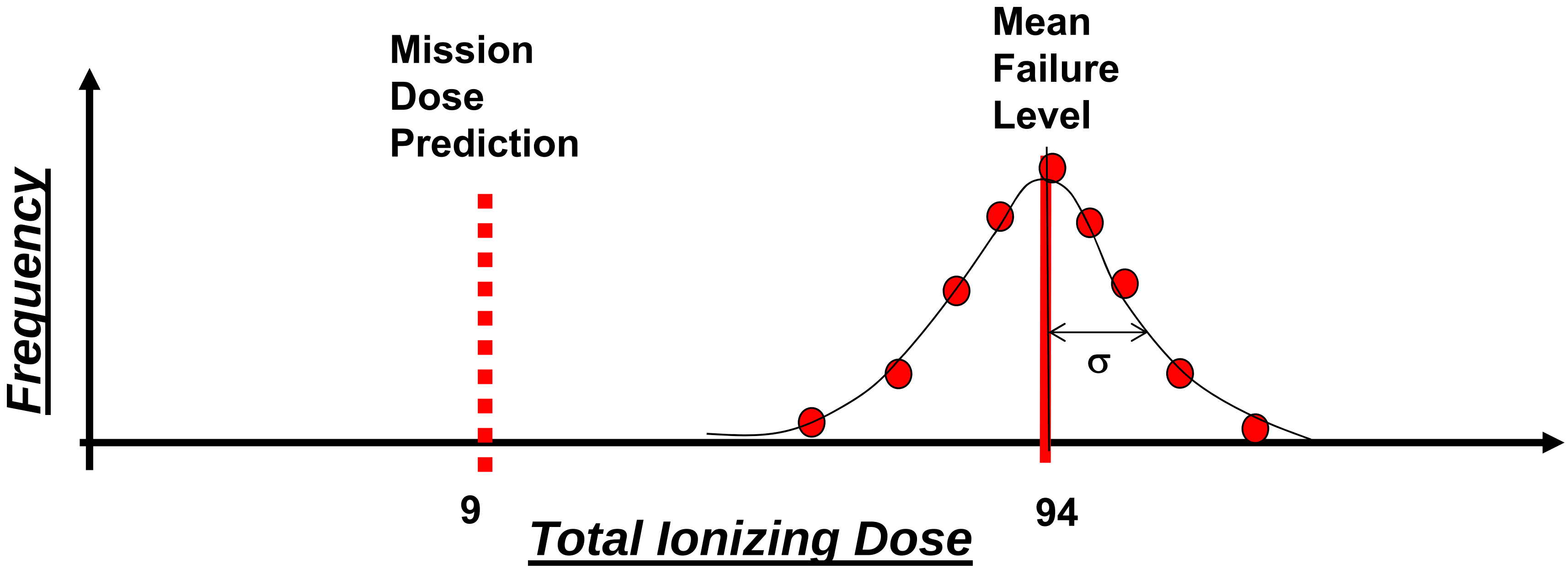
1. Purchase lot for total dose testing – flight, engineering, radiation testing.
2. Decide on number of parts for radiation testing
3. Decide on parametric or functional failure
4. Decide on dose step size
5. Measure the dose at which failure occurs
6. Plot number of failures vs dose
7. M = mean failure level, σ = variance



Presented by S. Buchner at SERESSA at Puebla, Mexico, December, 2015

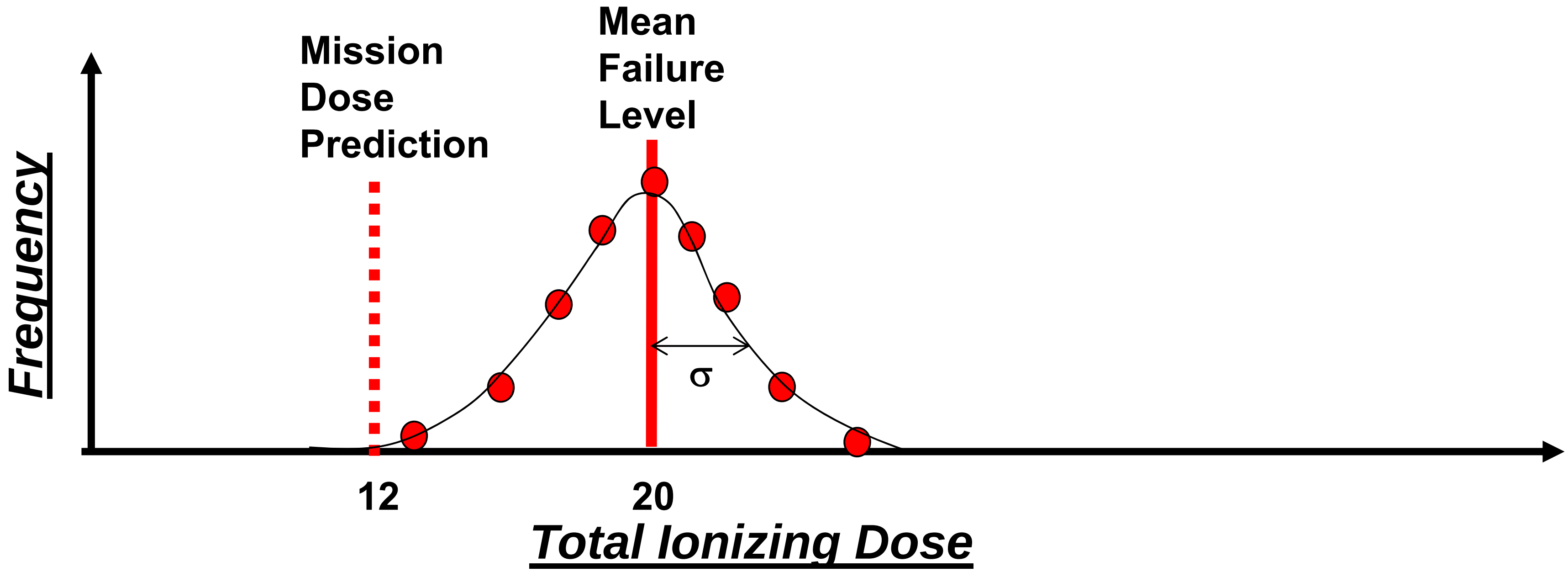
TID - Measurement Statistics

- Statistical analysis must be done to obtain the PCC (part categorization criteria) used to distinguish between hardness critical and hardness non-critical, i.e., pass/fail
- PCC depends on one-sided tolerance factor K(M,σ,N), which depends on M, σ and N. Obtain values from published tables.
- If RDM > 10, can accept the lot



TID - Measurement Statistics

- If RDM < 10, need to do the PCC calculation.
- Result gives the probability of the lot passing with a certain confidence level, i.e., 90% probability of passing with a confidence level of 95%



TID - Design Margin Breakpoints

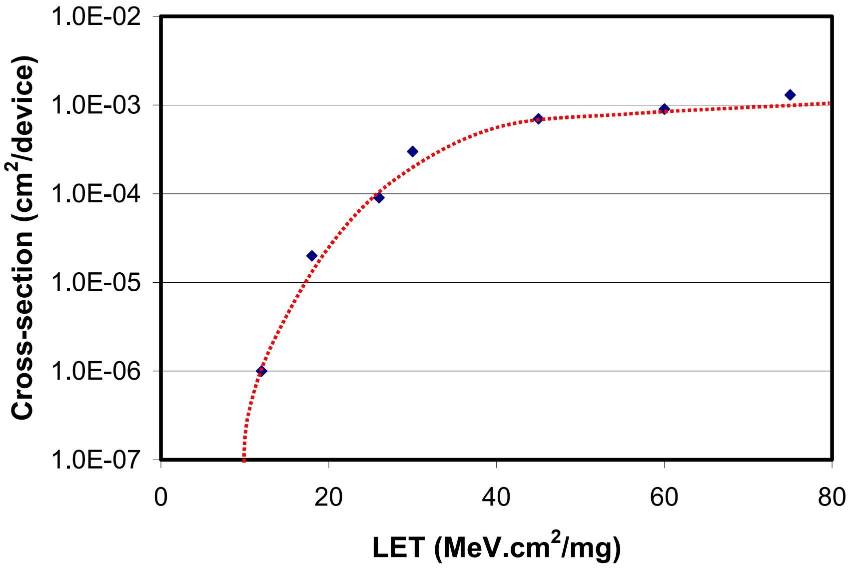
$$\text{RDM} = \frac{\text{Mean failure level}}{\text{Maximum TID for mission}}$$

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

SEE Test Results (Heavy Ions)

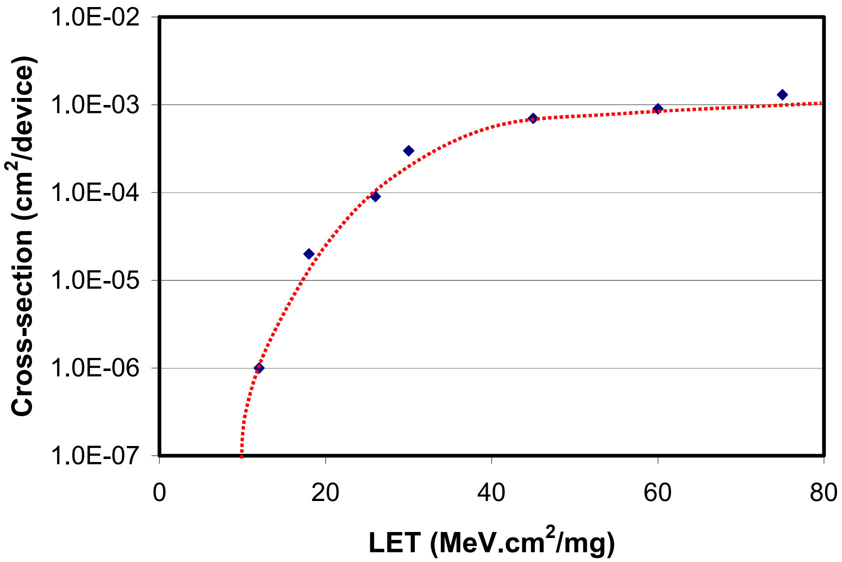
- ***LET_{th} > 80***
  - SEE risk **negligible**, no further analysis needed
- ***80 > LET_{th} > 15***
  - SEE risk **moderate**, heavy-ion induced SEE rates must be calculated.
- ***15 > LET_{th}***
  - SEE risk **high**, heavy ion and proton induced SEE rates must be calculated.



SEE Test Results (Heavy Ions)

- **Fit data with Weibull curve or Error Function.**

  $\sigma = \sigma(sat)\cdot(1-\exp(-(x-LET(th))/W)^{s})$
- **Error bars are essential**
- **Extract fitting parameters:**
  - LET(th)
  - Width (W)
  - Shape (S)
  - σ(sat)
- **Use fitting parameters in CRÈME-MC or SPENVIS to calculate SEE rate.**



- **Compare calculated rate with mission requirements.**

Mitigation Approaches

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 (effective for e^-)
- ***Increase the failure level***
  - Don’t test using worst case conditions
  - Test at low dose rate (CMOS only) if N_{it} negligible.
  - Tolerant designs (cold redundancies, etc.)
  - Relax the worst case functional requirements (e.g., speed)

TID Mitigation

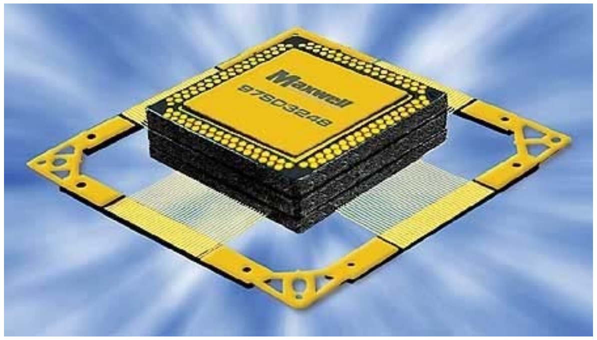
Accept Failure

- 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 available to measure temperature

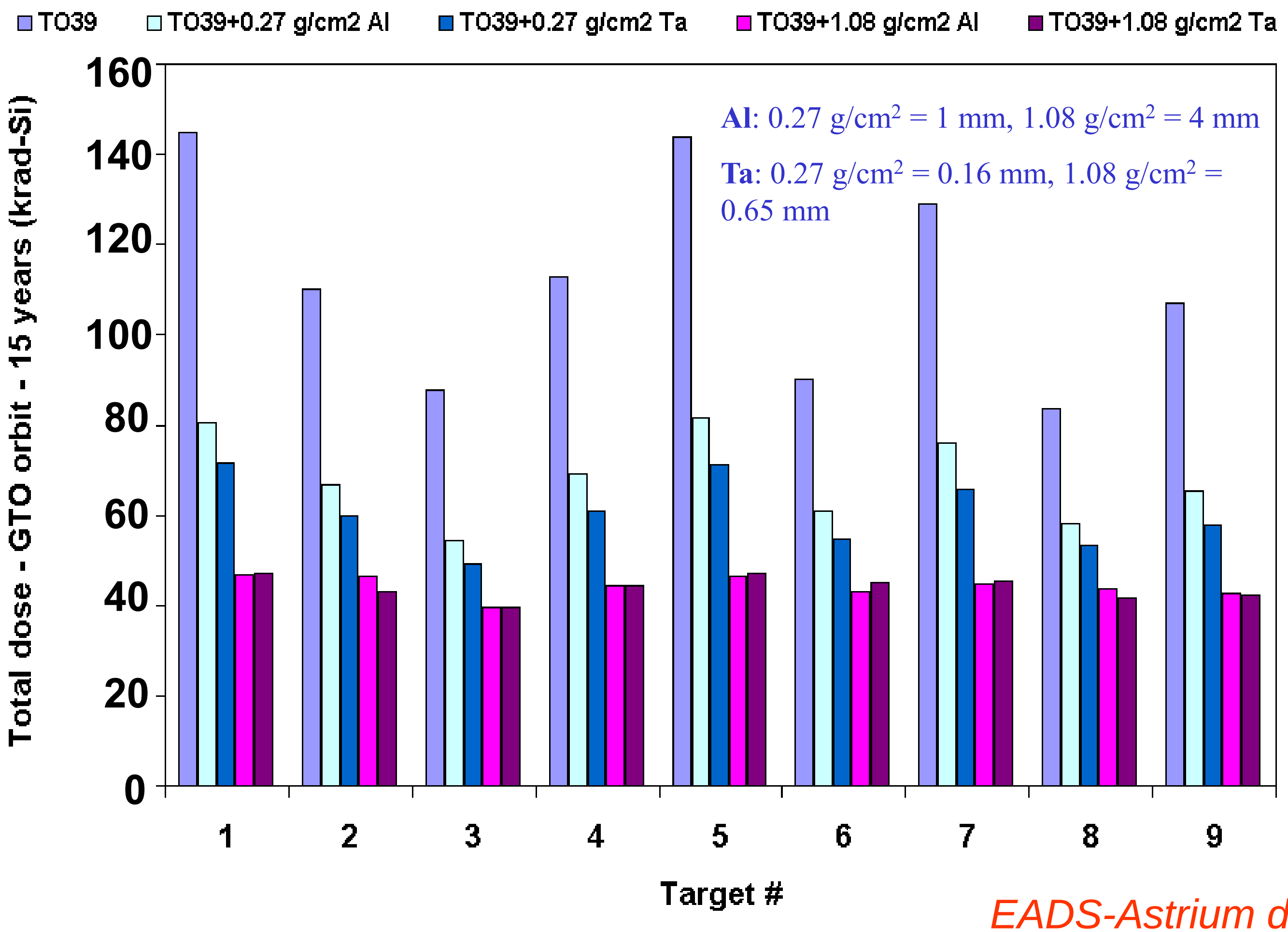
Example of Mitigation on SDO

SDRAM (Maxwell/Elpida) 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, cannot write to SDRAM.
  - Determined it was due to a timing issue in rewriting registers.
  - New mitigation involves triple-voting three SDRAMs.



TID Mitigation – Spot Shielding



Al: 0.27 g/cm^2 = 1 mm, 1.08 g/cm^2 = 4 mm

Ta: 0.27 g/cm^2 = 0.16 mm, 1.08 g/cm^2 = 0.65 mm

EADS-Astrium data
Courtesy of C. Poivey

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

SEE Mitigation

- ***Non-Destructive***
  - Add filters to outputs of linear parts
  - Use triple modular redundancy (TMR) – spatial redundancy
  - Perform multiple readings before making a decision – temporal redundancy
  - Use error detection and correction (EDAC) where possible.
  - [there are numerous other approaches available to the part designer that are not available to the circuit designer].

- ***Destructive***
  - Add current limiting resistors in the case of single event latchup
  - Reduce voltage on power MOSFETs to prevent single event burnout and single event gate rupture.

Final Step is to Sign off on Approval for Parts List

Some Thoughts

- There can be hundreds of different active parts on a spacecraft that have to meet requirements for radiation tolerance.
- Radiation effects engineers spends 95% of their time on 5% of the parts, such as FPGAs, Processors, ADCs, etc
- Generally, are not concerned with TID and SEE in resistors, capacitors and diodes, but there are exceptions.
- Many manufacturers claim a part is radiation-hard if the part has TID immunity. They completely ignore SEE.

Some Thoughts

- Linear bipolars must be tested for both TID and DD. They should be checked for ELDRS using low dose rates with gamma rays.
- CMOS parts should be checked for Single Event Latchup.
- Long lead times for parts procurement.
- Some parts are expensive to test - $100K per part. May have to modify test protocol.
- Obsolescence – by the time the design is ready and radiation testing has been done, the parts are obsolete.

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 (lot/date code not reliable)**
    - **Obsolescence**
    - **Little radiation data in databases**
  - Use of hybrids
- **SDO's Approach**
  - Assign sufficient funding to purchase rad-hard parts and, where necessary, do testing. (About 50 part types tested for TID).

Final Points

- 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.