Radiation Hardness Assurance (RHA)

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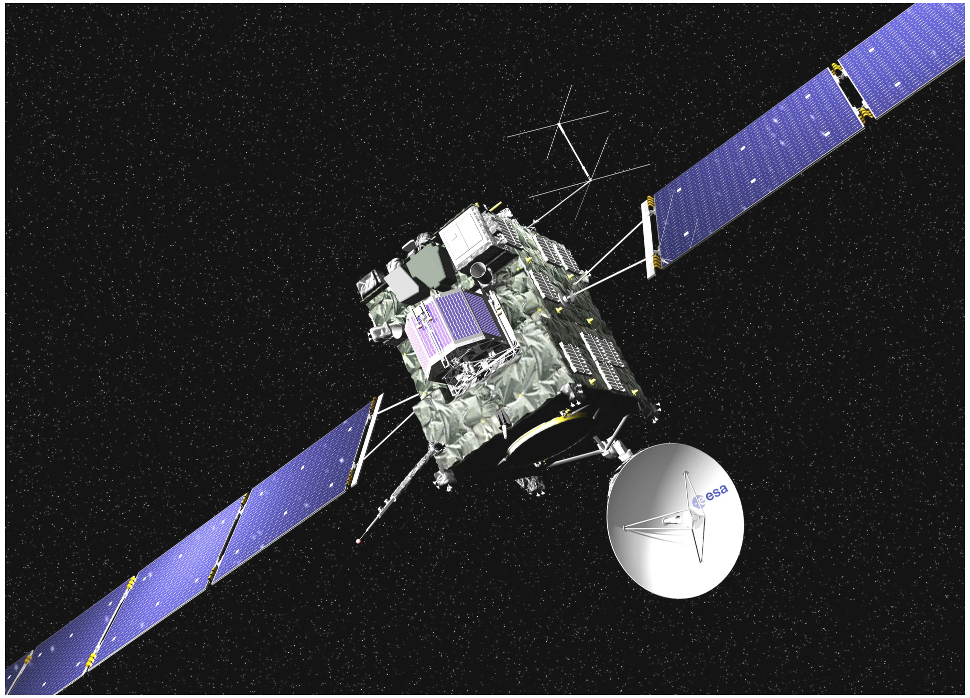
Consultant

Motivation

- Several spacecraft have been affected failed due to TID and SEE, that have led to mission failure.

- The cost of a failed mission can be quite substantial – hundreds of millions of dollars.

- Adopt an approach to minimize the chance of failure.



Radiation-Hardness Assurance

- RHA is a method that ensures that the electronics and materials of a space system perform according to their design specifications during and after exposure to the space radiation environment.

- Mission requirements determine levels of radiation survivability:
  - *Total Ionizing Dose (TID)*
  - *Single-Event Effects (SEEs)*
  - *Displacement Damage Dose (DDD)*

- RHA deals with *mission requirements, environment definition, radiation effects, part selection, part testing, spacecraft layout, radiation-tolerant design, worst-case analysis, and mitigation*.

- RHA is aimed at reducing radiation-induced failures. It is not possible to eliminate risk, but it is possible to manage risk to make it acceptable.

RHA is a Vital Activity

- RHA is just one of several activities that include modeling and testing thermal, mechanical, vacuum and electrical systems, to ensure that the mission will be successful.

- The following spacecraft requirements are impacted by radiation:
  - **Reliability** – *degree of confidence that the data are accurate*
  - **Availability** – *probability that a system is operational when needed*
  - **Survivability** – *probability that the spacecraft will continue operating properly during and after radiation exposure.*
  - **Maintainability** – can the spacecraft equipment be rapidly restored *after suffering a radiation-induced outage*

Steps Involving RHA

1. A mission is proposed by scientists to an agency like NASA or ESA.
   – Study the sun, earth-observation, mission to other planets, etc

2. A set of requirements at various levels is established based on the mission goals, :
   – Downlink and uplink speeds
   – Data reliability
   – Data storage
   – Down time: eclipse, resetting inertial guidance, mission length, etc
   – Size, Weight and Power (SW&P) requirements

3. A radiation effects engineer (REE) is assigned to the project at the outset.
   – This should always be the case but is frequently not done due to budgetary constraints or lack of appreciation of the role of the REE.

Steps Involving RHA

4. The radiation environment is established based on orbit, launch date, mission duration and shielding. The result are particle spectra to which the active parts will be exposed
5. Handle failure modes in parts due to radiation (TID, SEE and DDD) and calculate the part’s survivability
6. Parts are selected by designers for each subsystem that meet the operational requirements
7. Selected parts are evaluated by REE regarding whether their TID, DD and SEE levels meet mission requirements. This is done by first scouring data bases

Steps Involving RHA

8. Radiation testing is performed on parts for which there is no radiation data. REE must write test plan, do the testing, and perform analysis of results

9. Mitigation is suggested for parts that don’t meet requirements

10. Replacement parts are suggested in consultation with design engineer for those that do not qualify

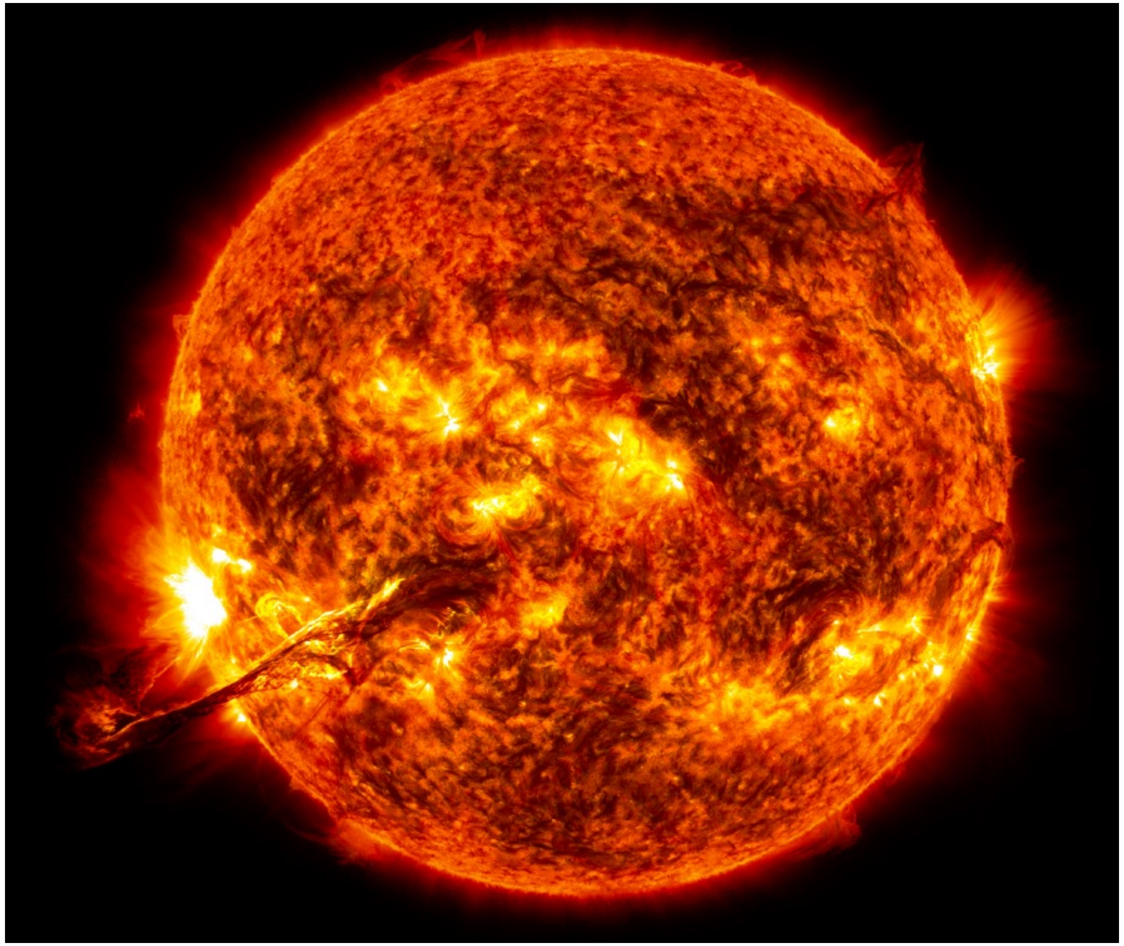
11. Final approval is given when all parts have been qualified

12. Anomalies in space are tracked and analyzed for future reference

Example of Radiation Hardness Assurance
Solar Dynamics Observatory (SDO)

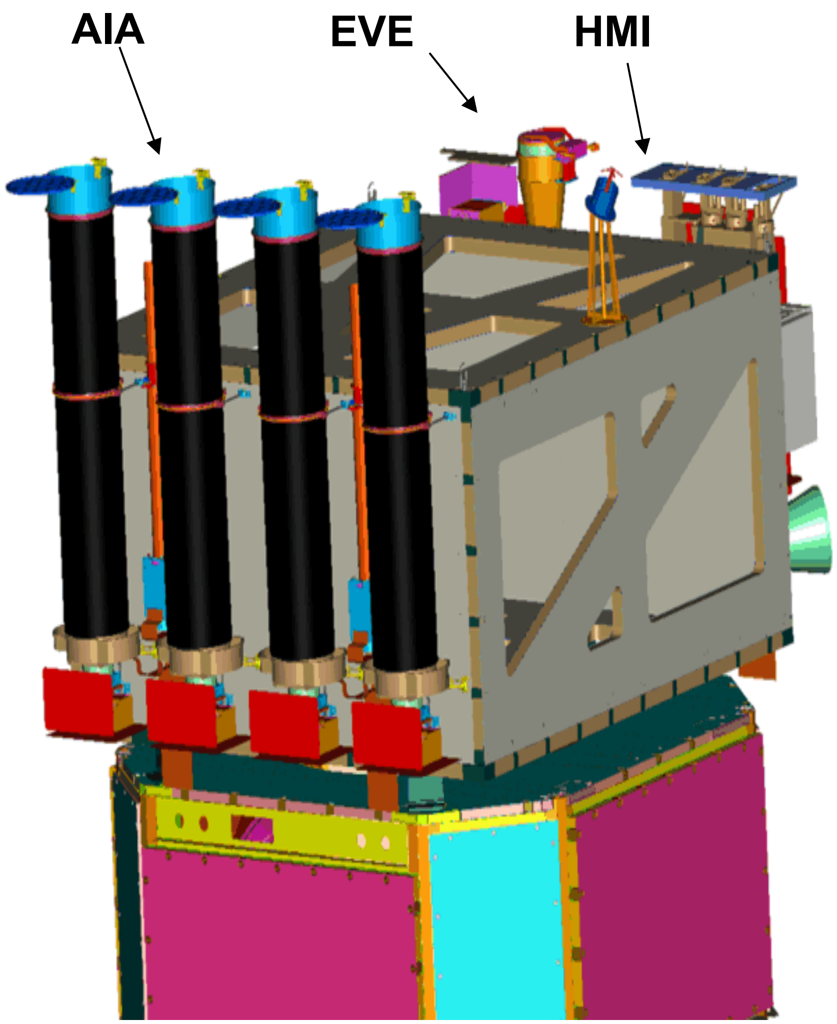
Solar Dynamics Observatory

Launched 2/11/2010.



Purpose of SDO Mission

- To study the energy sources in the sun during maximum in solar cycle:
  - 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.
- Needed congressional approval because of large cost $850 million.
- Has been extremely successful and is still operational



Mission Requirements – Radiation

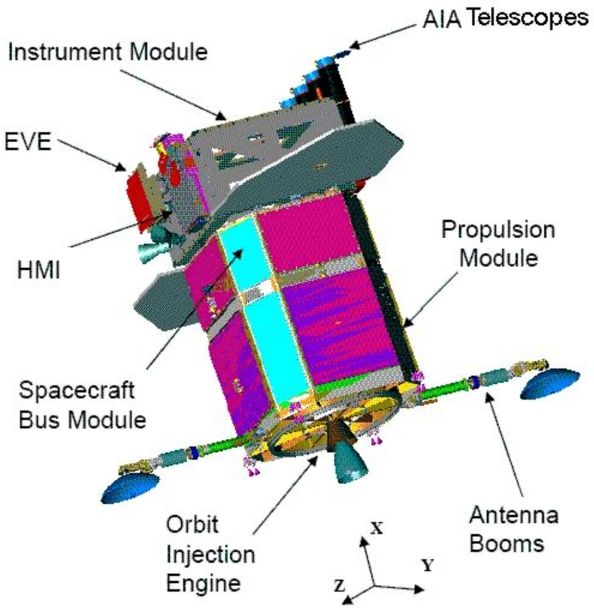
1. **Mission launch date and duration (TID, SEE DDD):**
   a) Launch date was February 2010 - increased solar activity.
   b) 5-year mission (10-year option).
   c) Minimum on-board processing and maximum exposure time requires geosynchronous orbit – over White Sands, New Mexico.

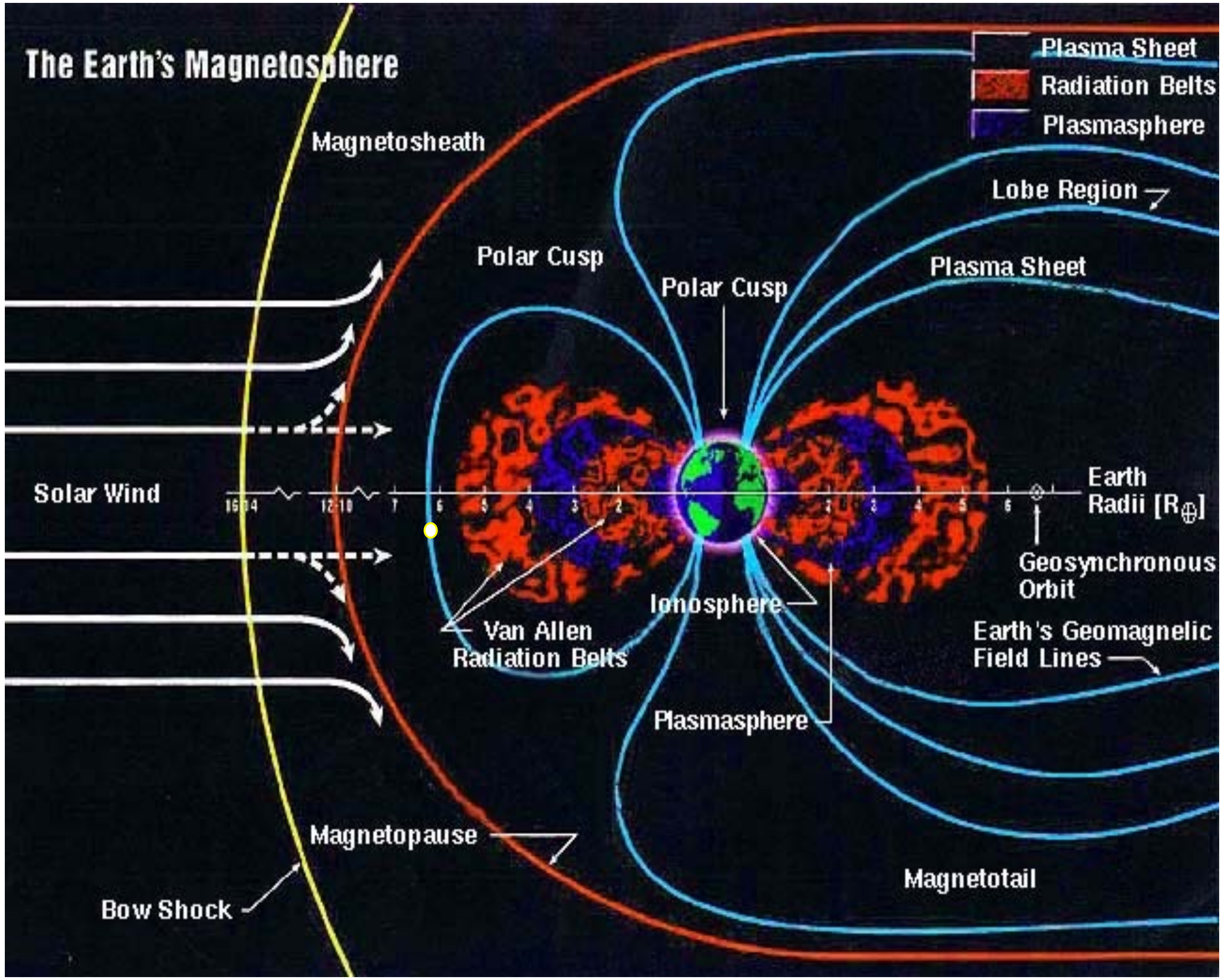
2. **Operation Requirement (SEE):**
   a) Must be operational 95% of the time (Down time = 2190 hours in 5 years).

3. **Data Requirement (SEE):**
   a) Data downlink at 150 MBPS (250 DVDs per day).
   b) Data integrity must be 99.99% valid.

1. Establish the Environment

Establish Radiation Environment





Geo is 5.45xR_{earth}
1. **Trapped electrons**
2. **Solar protons**
3. **Galactic cosmic rays**

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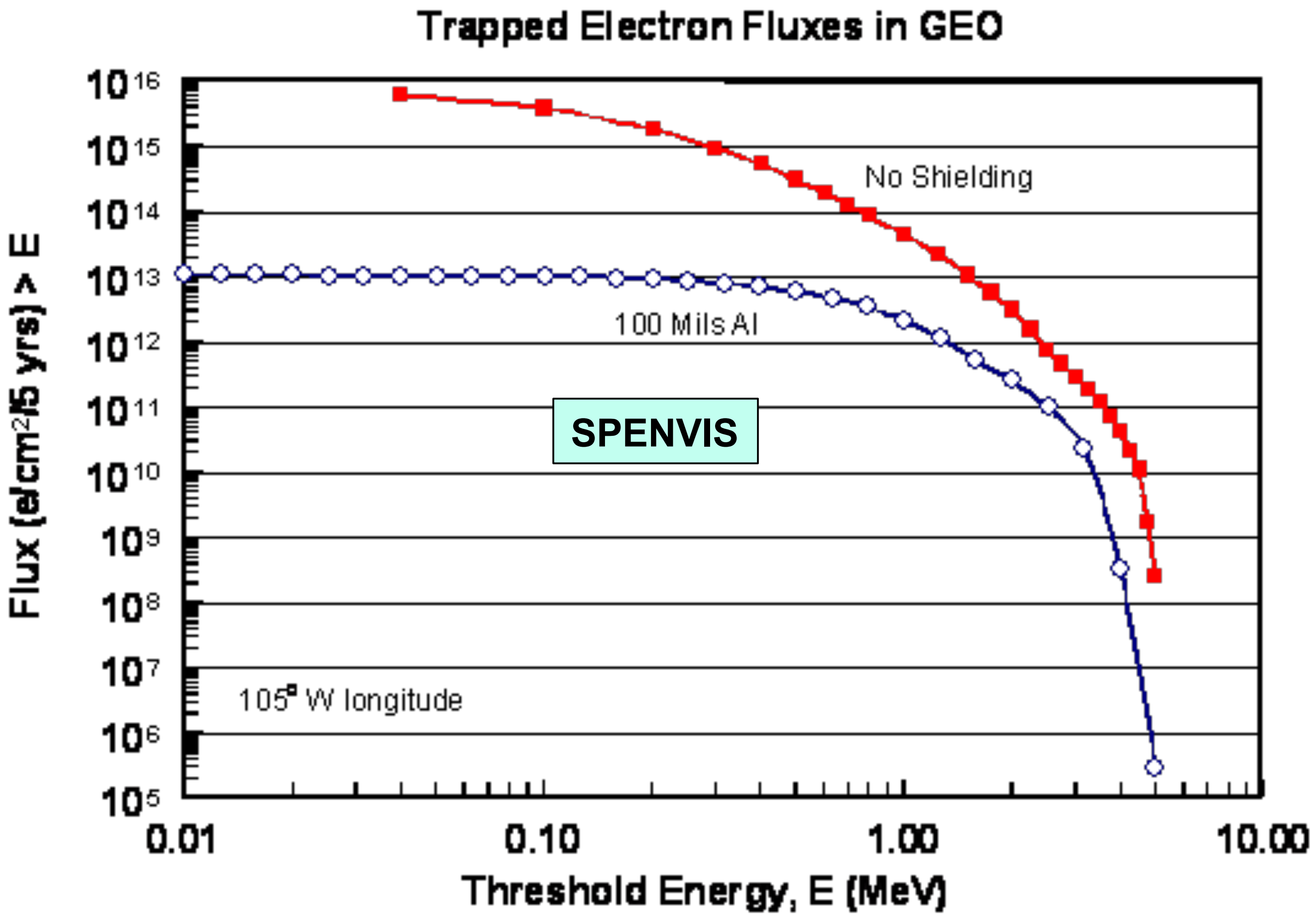
Trapped Electron Flux at GEO

Initial conditions:

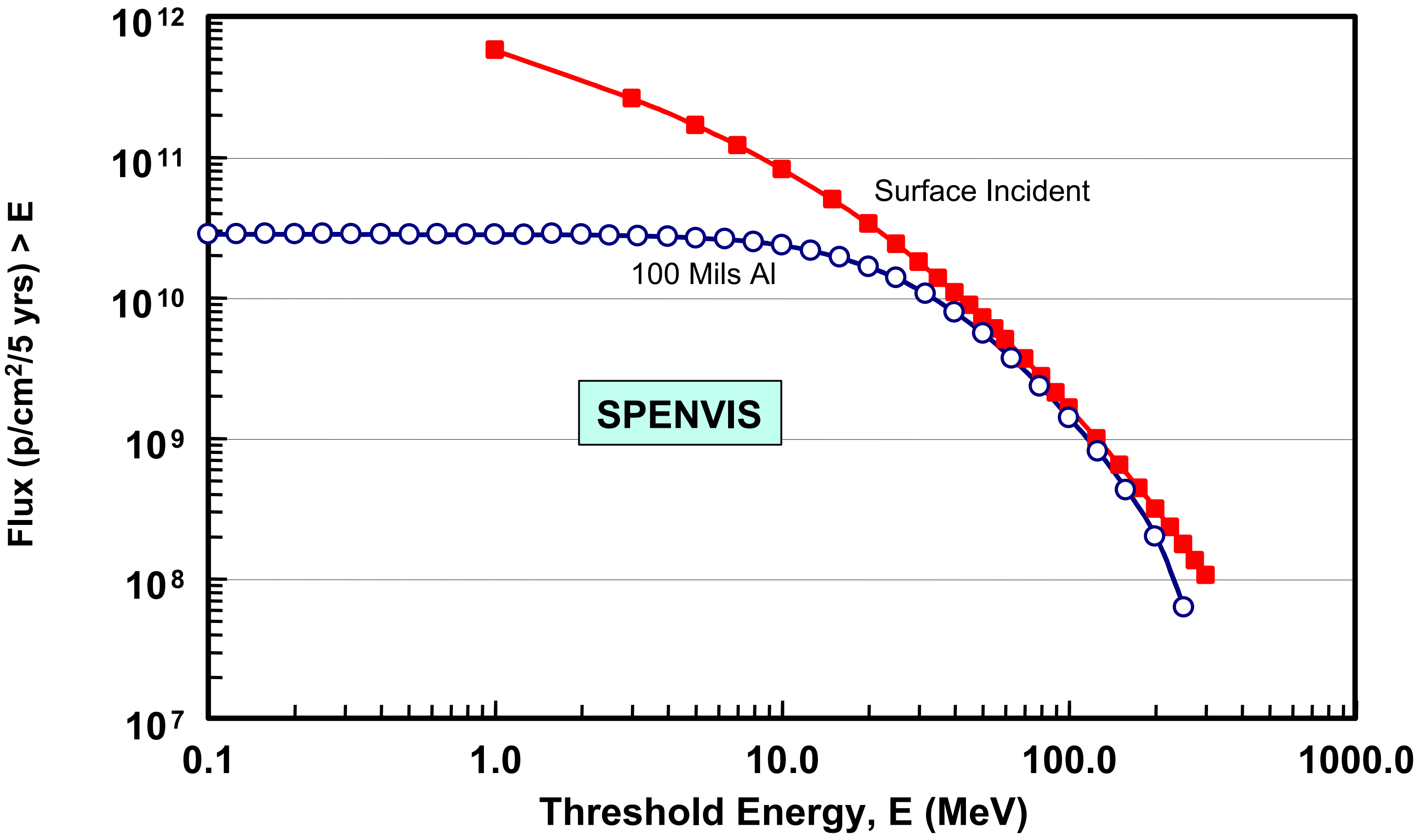
1. **Orbit - GEO**
2. **Launch date – 2010 (solar cycle)**
3. **Mission duration 5-yr requirement /10-yr option**
4. **Shielding – 200 mils**



- **Electrons are the main contributor to TID. No trapped protons.**

Solar Proton Flux at GEO

- Solar protons are the main contributor to DDD, especially in optical imagers such as those on SDO.
- Also contribute to TID for thick shielding.
- Also contribute to SEEs via nuclear interactions in sensitive parts.



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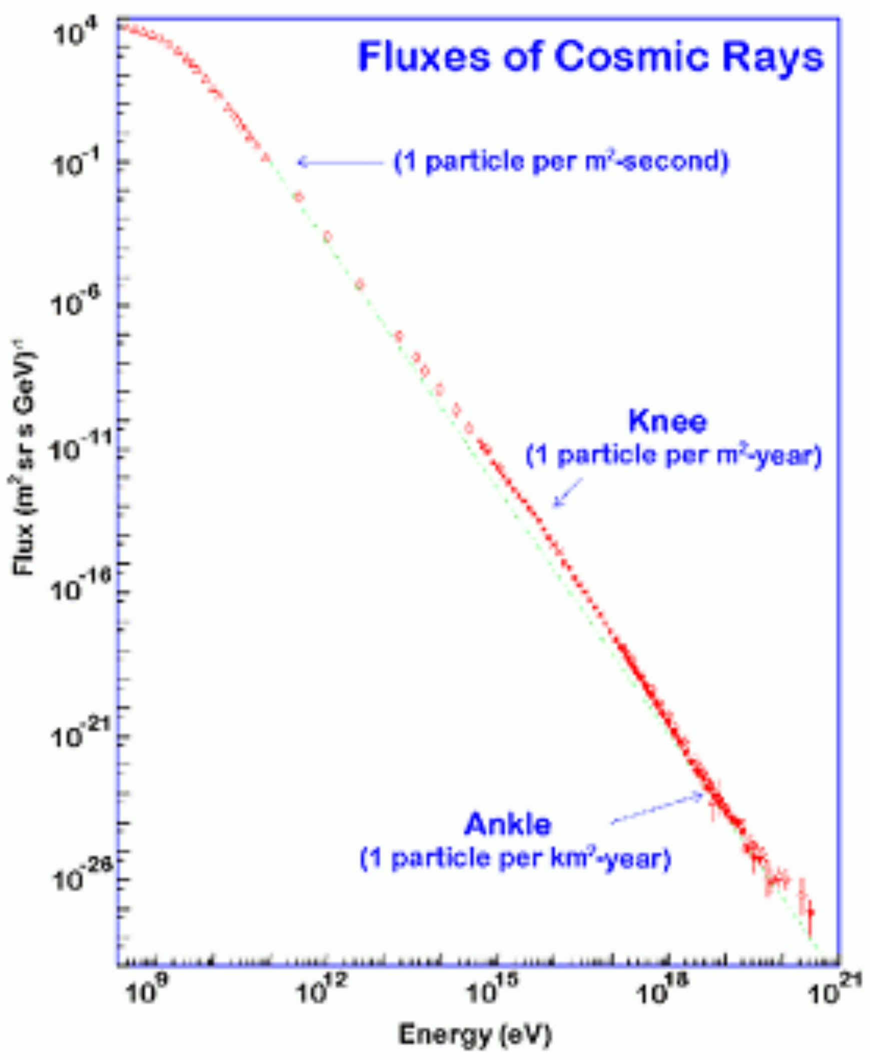
Cosmic Ray Flux - SEE

- **Cosmic rays are the main contributor to SEEs.**
- **Negligible contributions to TID and DDD**



Varies with Solar Cycle

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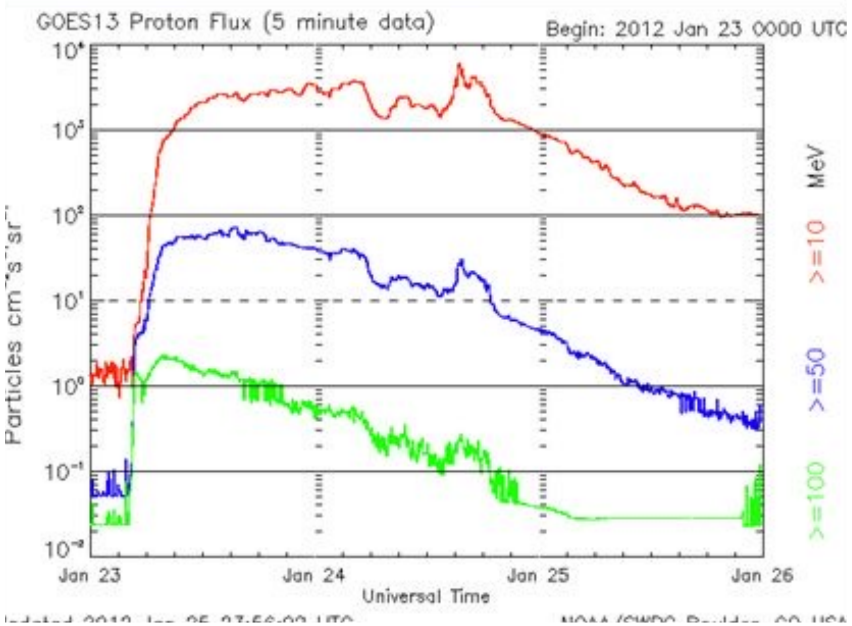
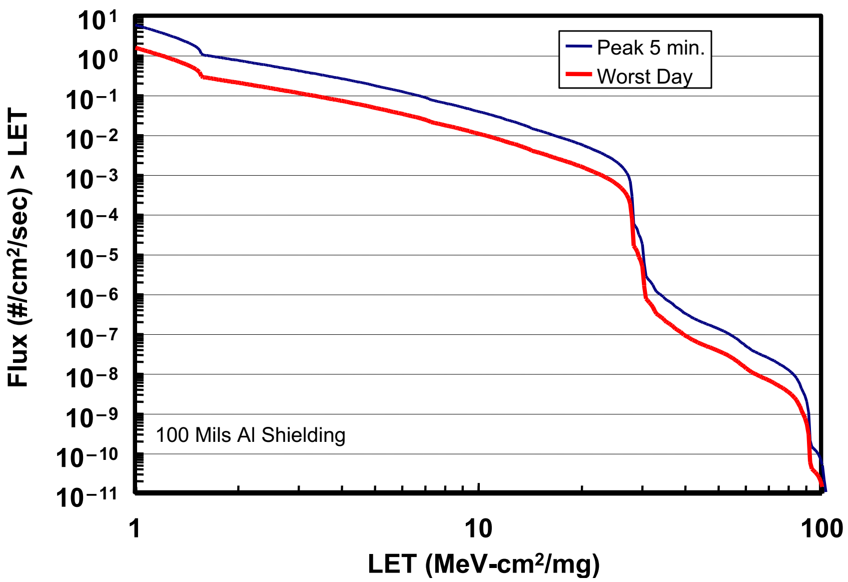
Operate Through…..

Would like to continue taking images of the sun during a solar storm



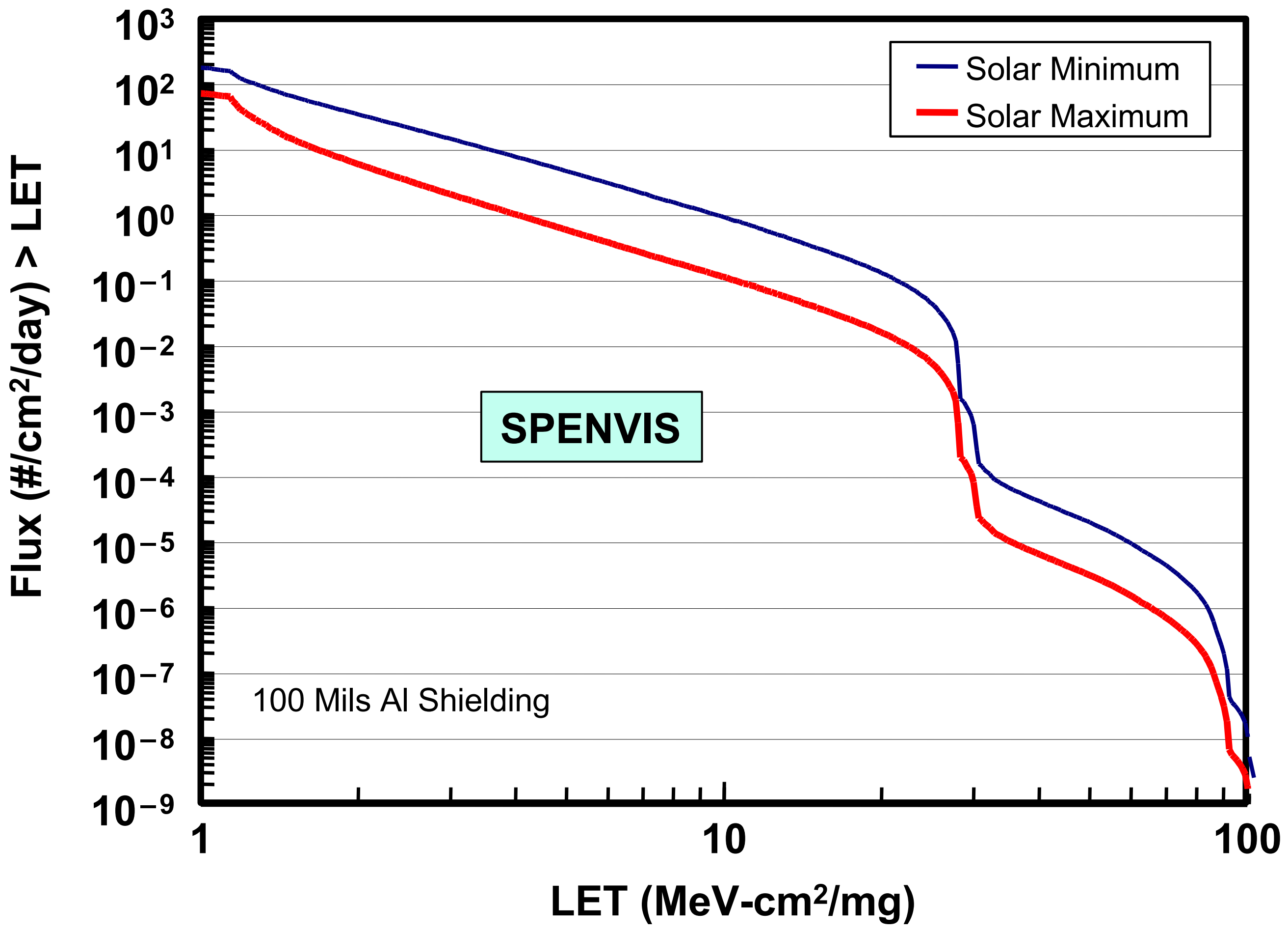
Integral LET Spectra for the Worst Case Solar Particle Event



- Solar wind consists primarily of ionized hydrogen (electrons and protons) – 92% and helium – 8%, and trace amounts of heavier ions
- The wind varies continuously by a small amount.
- During a solar storm, flux observed to increase by 5 orders of magnitude

- Calculate spectra during peak 5 minutes, worst day, and worst week

Solar Wind Affects GCR Flux – at GEO



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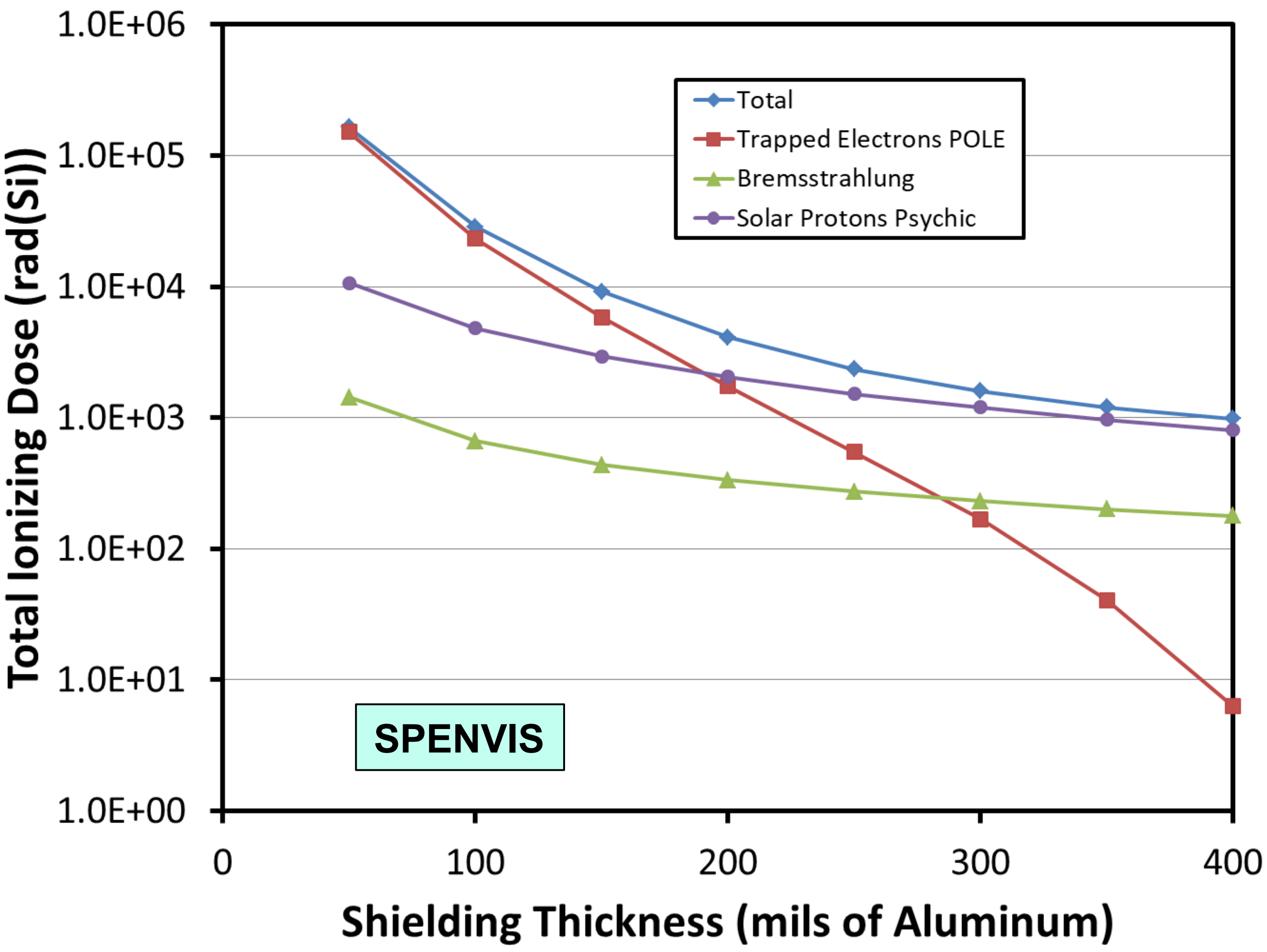
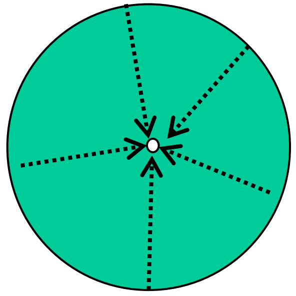
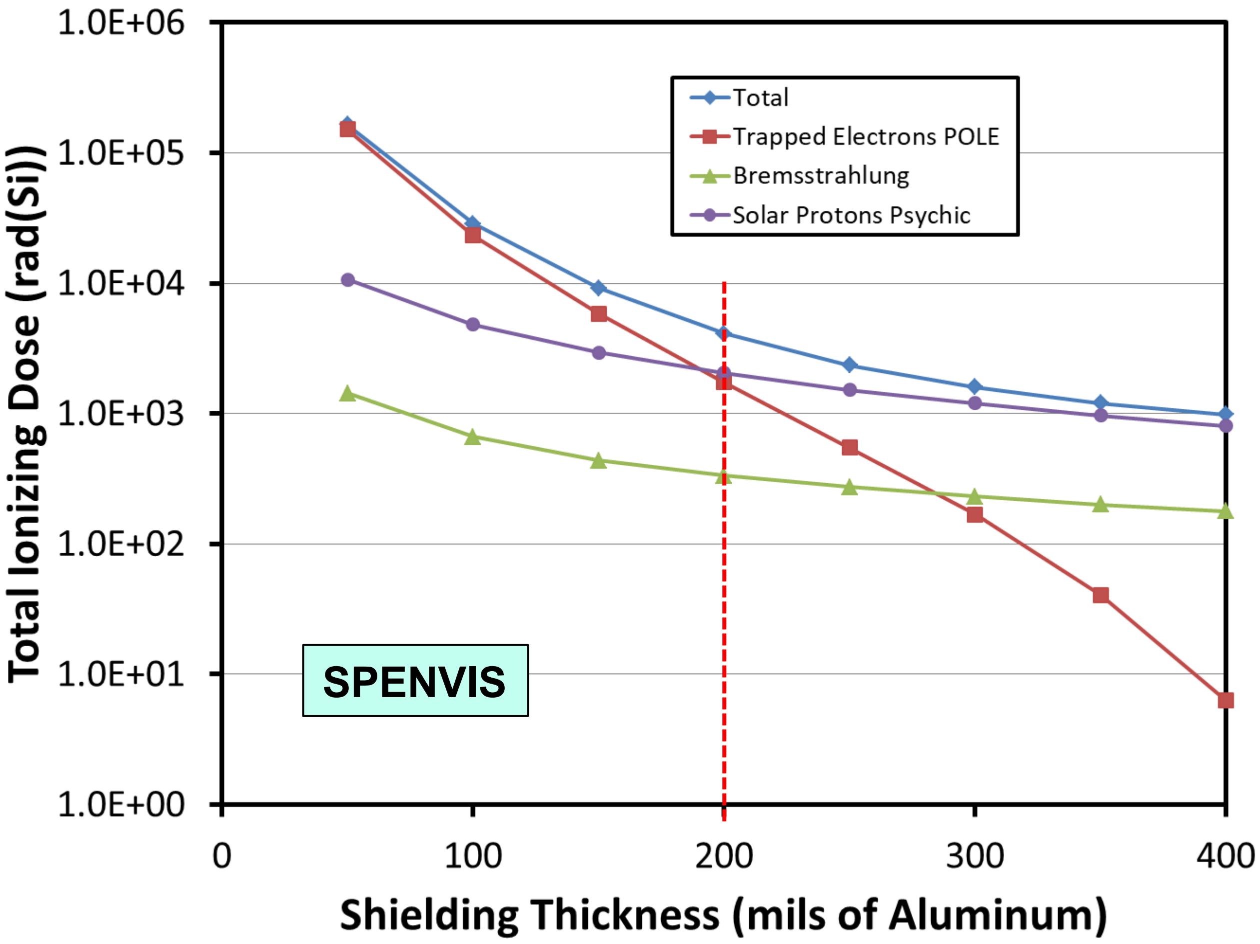
Dose-Depth Curves – 1 Year at GEO





- Dose at the center of an **aluminum** sphere.
- Calculation done before structure of spacecraft finalized.
- For more accurate estimation of dose, use a program like ***NOVICE***
- At low shielding thickness, dose dominated by trapped electrons, and at large shielding thickness, dose dominated by solar protons

Initial TID Level



TID = 40 krad(Si) over 5 years including margin of 2x

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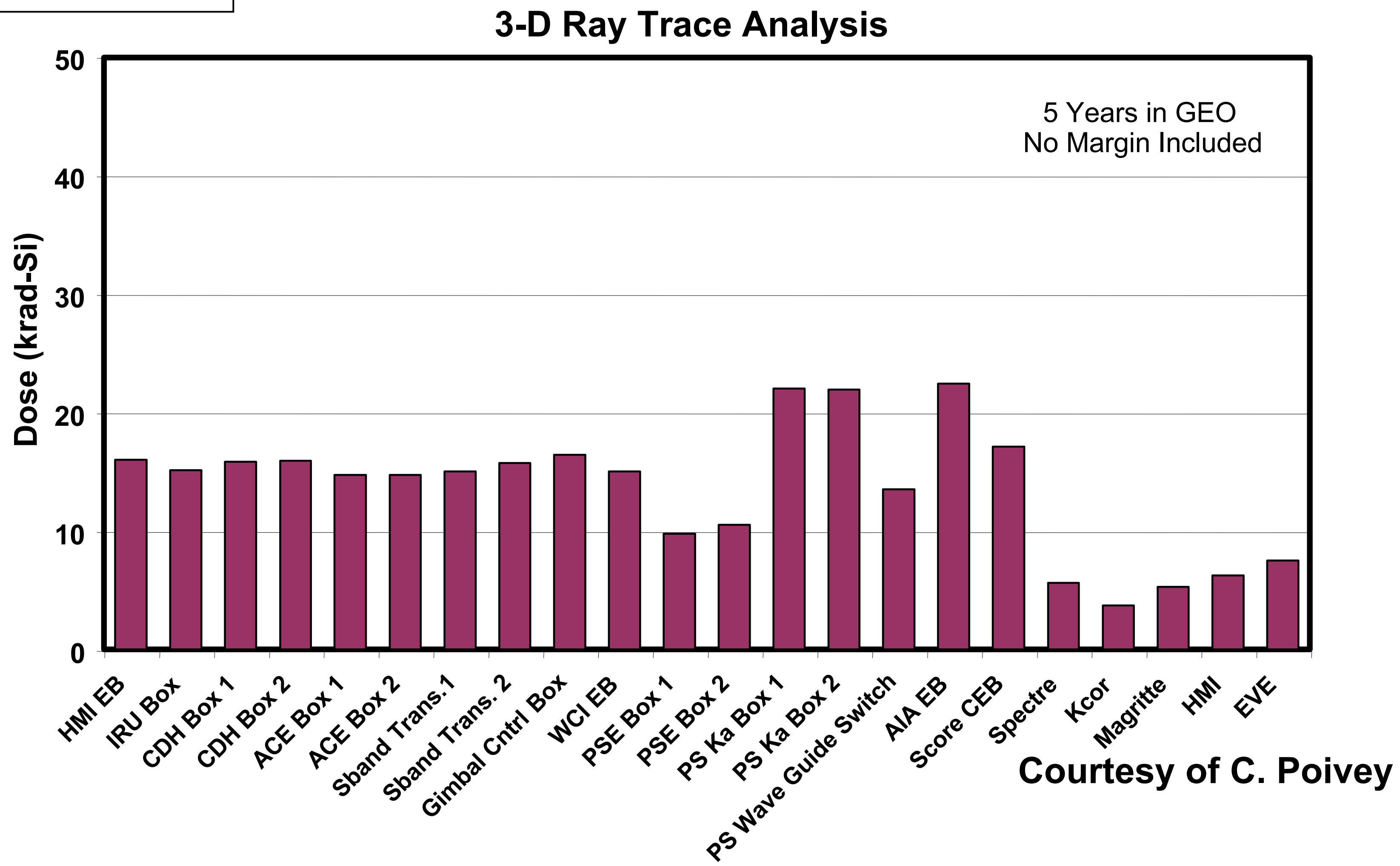
Final TID Levels

NO MARGIN



Courtesy of C. Poivey

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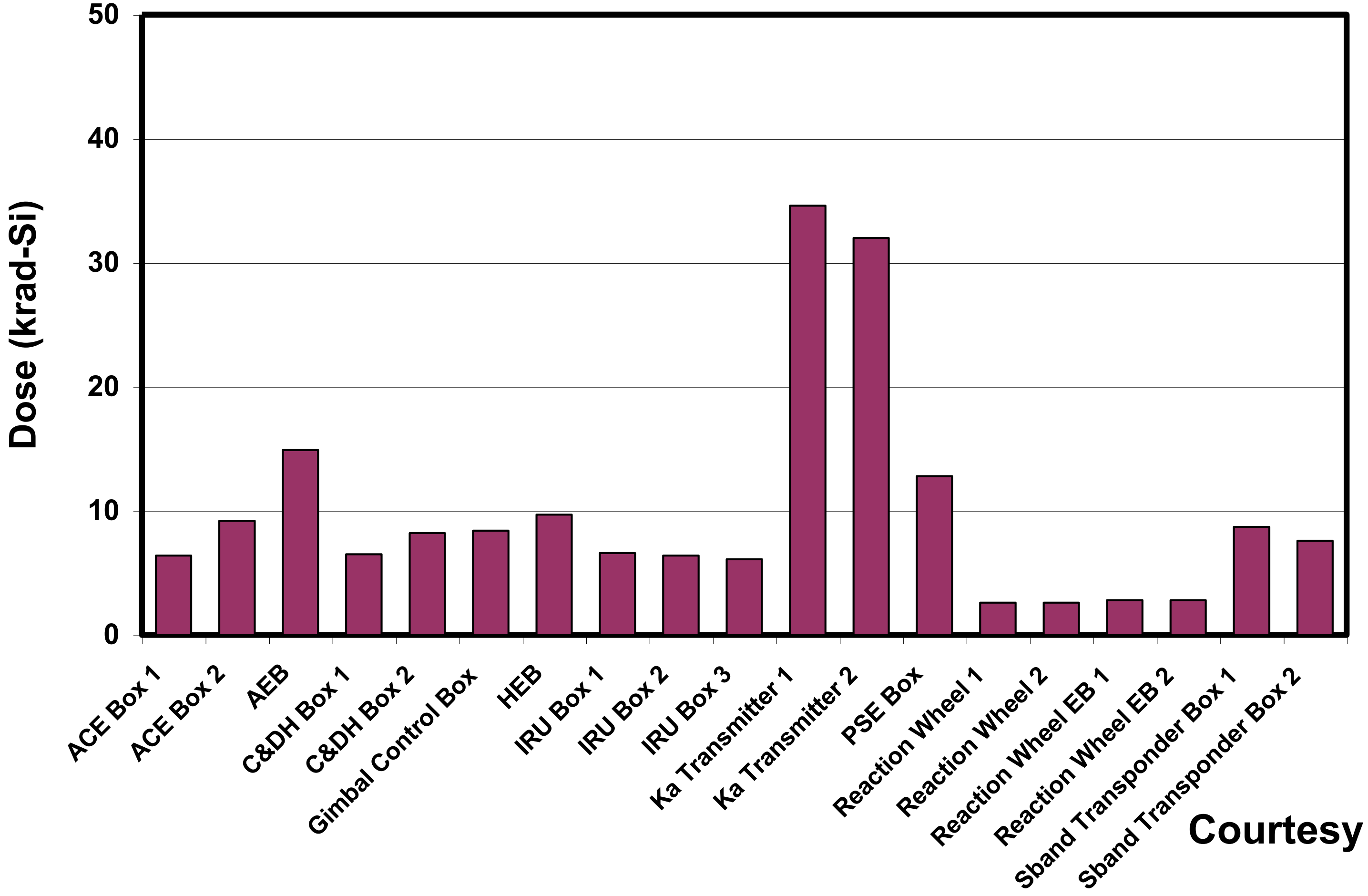
Final TID Levels

MARGIN OF 2 USING ACCURATE SPACECRAFT MODEL and NOVICE



Courtesy of C. Poivey

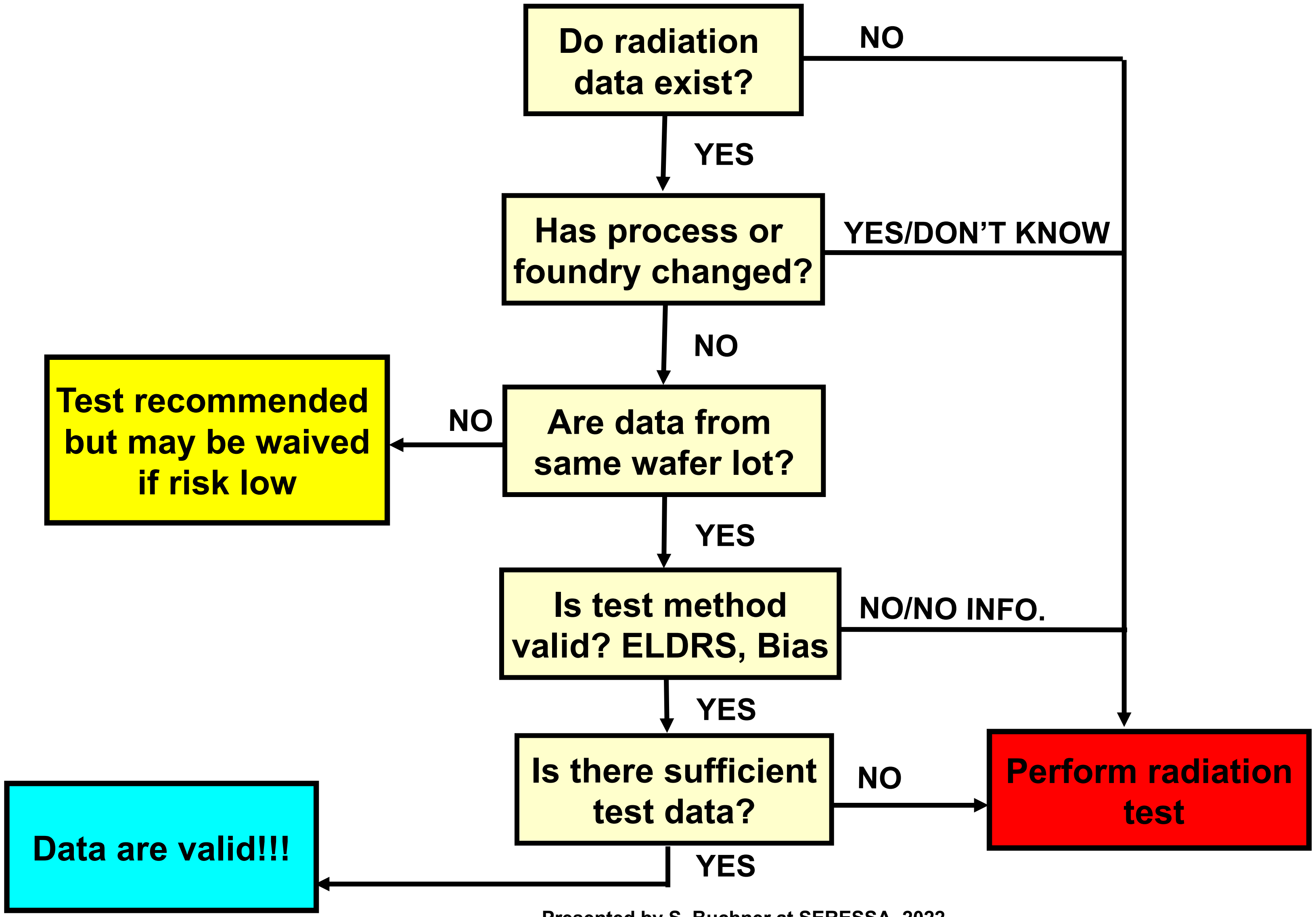
2. Design Engineer Proposes Parts and Radiation Effects Engineer Evaluates them

Parts are Selected

- **The Design Engineer**
  a) Provides a list of *proposed parts, hopefully with radiation effects in mind.*
  b) Must be done in a *timely fashion* due to long lead times when ordering some parts

- **The Radiation Effects Engineer**
  a) Evaluates proposed parts to determine whether they comply with the mission by consulting data bases
  b) Checks to see whether there are *radiation-hardened versions* of the parts available
  c) If not, orders *sufficient parts from same wafer or lot/date code* for radiation testing.
  d) Suggests a different part

Evaluating Parts for TID



Parts are Evaluated

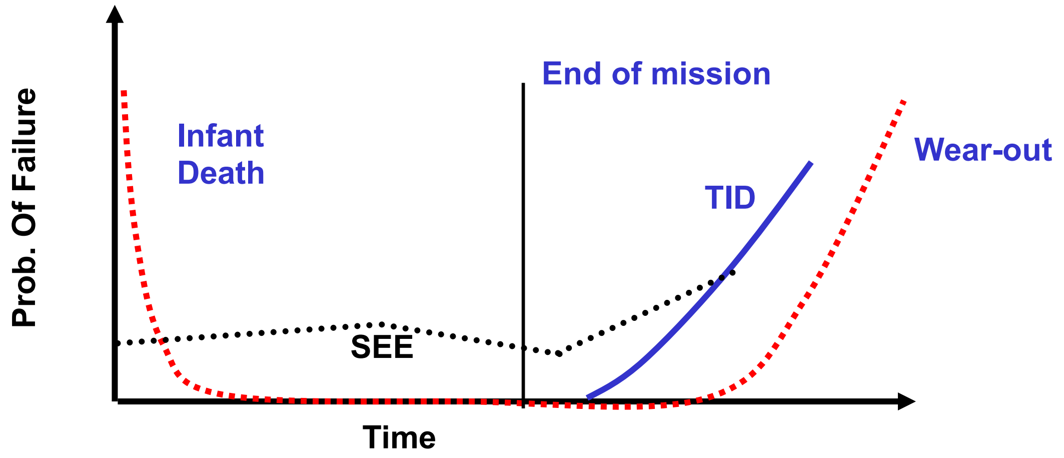
1. **Guaranteed radiation hard:**
   a) If a part is purchased from a vendor on the QML (Qualified Manufacturer's List), and the guaranteed radiation specifications meet those of the mission, then accept.
2. **If there are data available on the part:**
   a) Was the data taken according to specifications?
   b) Is it from same wafer or lot/date code?
   c) Was the data taken less than 5 years prior?
   d) Do you trust the organization taking the data?
   e) Does the part meet specifications with appropriate design margins?
3. **If there are no data available:**
   a) Test for TID, DDD and SEE.
   b) Consult with the design engineer about a replacement part.

Testing is Performed

1. **Sufficient parts are purchased:**
   a) Need sufficient parts for radiation testing, destructive physical analysis and usage requirements – cost could be an issue
   b) At least 12 for TID, 3 for SEE
2. **TID Testing is carried out:**
   a) Gamma-ray testing at a ^{60}Co source
   b) High dose rate vs low dose rate
   c) Biased vs unbiased
3. **Displacement damage in optoelectronic devices:**
   a) Proton or electron accelerator or neutron reactor – flux and energy
   b) Radioactive after exposure
4. **Single-event effects:**
   a) Proton beam
   b) Heavy ion beam
   c) Pulsed laser light

Observations

1. **Most non-radiation failures follow "U-shaped" failure probability.**
2. **Radiation failure:**
   - TID should occur after end of mission
   - Destructive SEEs should not occur
3. **Probability of SEE varies with environment. An SEE can occur at any time, even if the probability is low.**



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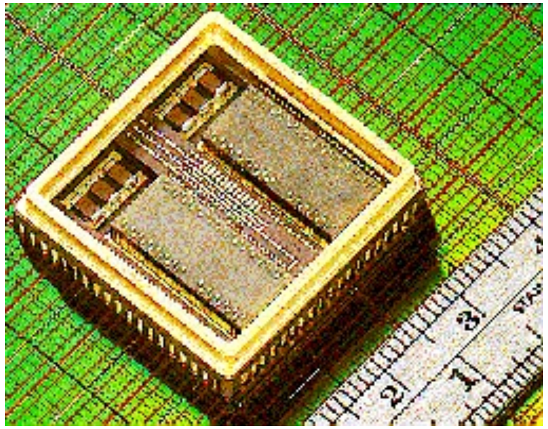
Observations

- **There are two types of ionizing dose failure**
  - Parametric failure (increases in leakage current, slower operation) – in some cases the part can still be used
  - Functional failure – dead
- **Non-destructive, non-critical SEE rates based on budgeted down time that includes:**
  - Eclipses,
  - Instrument calibration,
  - Antenna handover,
  - Momentum shedding,
  - RADIATION
- **Destructive SEEs (SEL, SEB, SEGR) should have a vanishingly low probability**
- **Use of LOT/DATE code does not guarantee all parts are the same, especially for COTS**

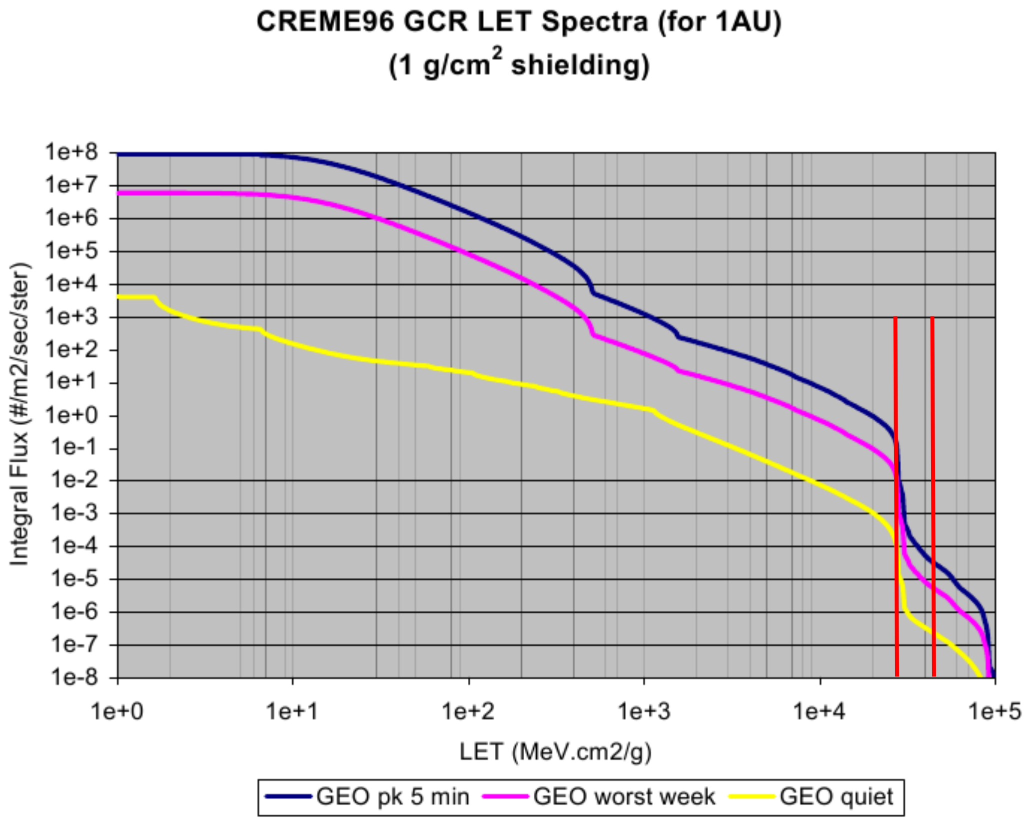


Stacked devices and hybrids can present a unique challenge for review and test

3. Determine SEE Requirements
Error Rates

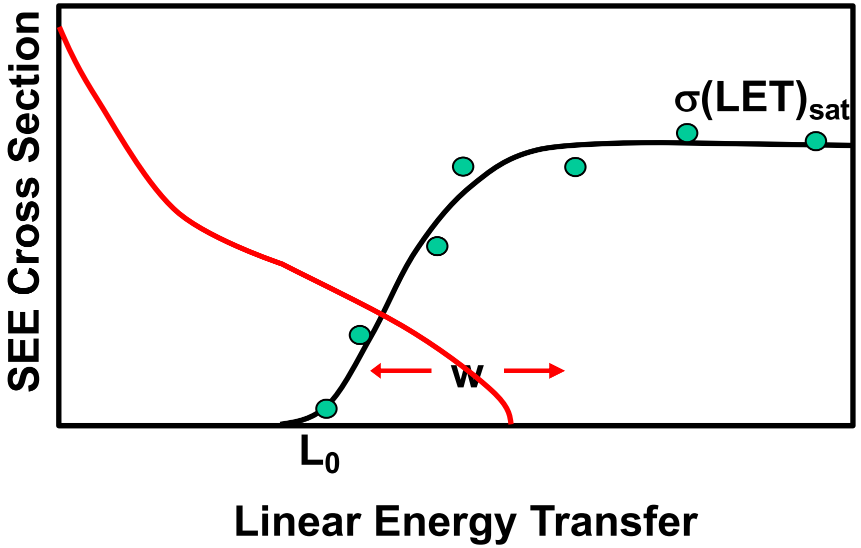
SEE Requirements for SDO

- ***Single-Event Minimum LET***
  - **Non-Destructive** (Suggested LET_0 > 36 MeV.cm^2/mg)
    - Single Event Upset (SEU),
    - Single Event Transient (SET),
    - Single Event Functional Interrupt (SEFI).
  - **Destructive** (Suggested LET_0 > 80 MeV.cm^2/mg)
    - Single Event Latchup (SEL)
    - Single Event Burnout (SEB)
    - Single Event Gate Rupture (SEGR)



For Error-Rate Calculation σ(LET)

- ***If the error rate is required:***
  - Obtain cross-section vs LET from **literature**
  - If no data are available perform accelerator testing to obtain σ(LET)
  - Fit the data with a Weibull curve to extract out four parameters (L_0, w, s, $\sigma(LET)_{sat}$)

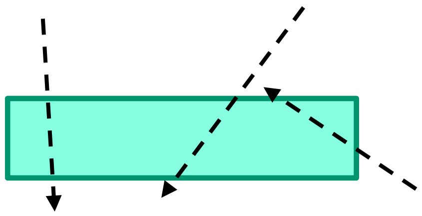


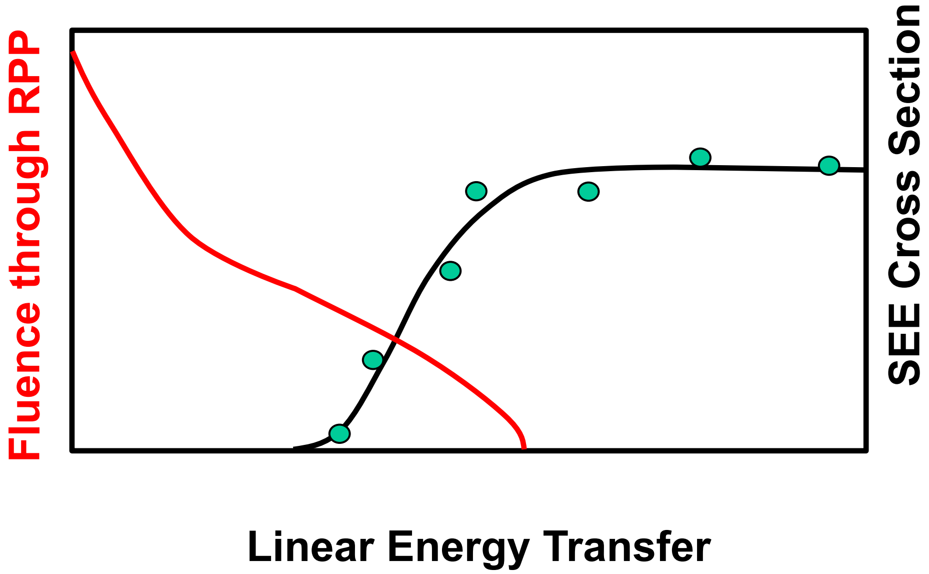
Integral Weibull Curve

$$\sigma(LET) = \sigma(\mathrm{LET})_{sat}\left(1 - \exp\left(-\left(\left(\frac{(L - L_0)}{W}\right)^{s}\right)\right)\right)$$

Obtain σ(LET) for Error Rate

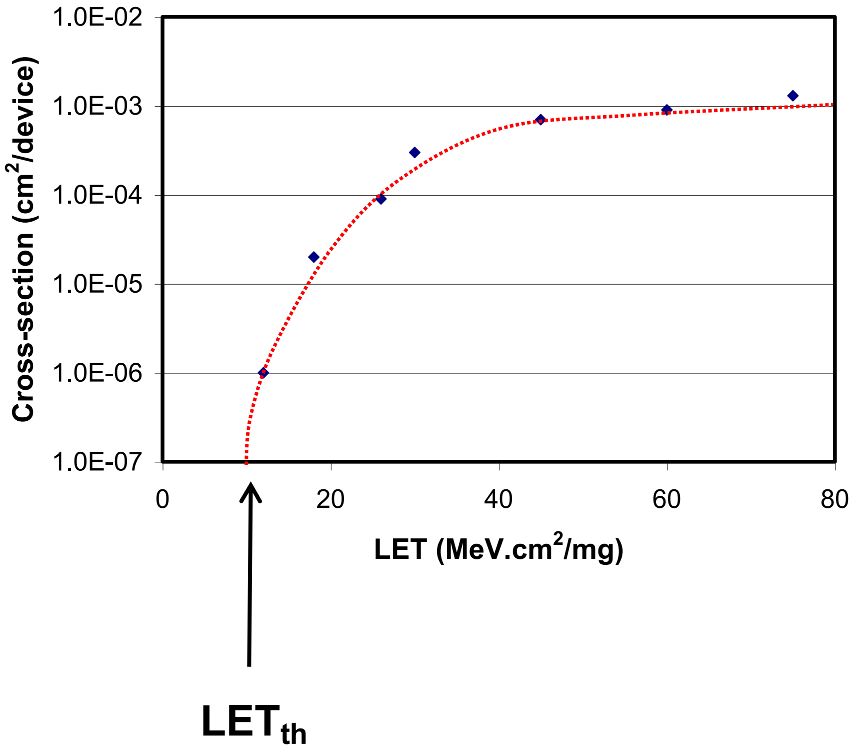
- ***<u>If the error rate is required:</u>***
  - ❑ Use a program, such as SPENVIS, to calculate error rate using integral particle fluence *f*(L,ϕ,cos(ϴ)) and dimensions of sensitive volume (x,y,z).
  - ❑ Determine whether error rate meets requirements





Conditions on LET_{th}

- ***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 effects and rates must be calculated.



4. Examples of Parts Scrubbing

Total number of active parts can run into the hundreds

Sources of Radiation Data

1. IEEE Transactions on Nuclear Science
   - https://ieeexplore.ieee.org/Xplore/home.jsp
2. NSREC Data Workshop Proceedings also published by IEEE
   - https://ieeexplore.ieee.org/Xplore/home.jsp
3. RADECS Data Workshop Conference Proceedings
4. NASA JPL Radiation Effects Database
   - https://parts.jpl.nasa.gov/radiation-effects/
5. NASA GSFC Radiation Effects & Analysis
   - https://radhome.gsfc.nasa.gov/radhome/RadDataBase/RadDataBase.html
6. Defense Logistics Agency Land and Maritime (DLA)
   - https://landandmaritimeapps.dla.mil/offices/doc_control/Resources.aspx
7. European Space Agency (ESA) European Space Components Information Exchange System (ESCIES).
   - https://escies.org/webdocument/showArticle?id=227&groupid=6
8. PMPedia
   - https://pmpedia.space/
9. Manufacturer's data sheets on the WWW

Evaluation of Radiation Data

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

SMD (Standard Microcircuit Drawing Number - Defense Logistics Agency Land and Maritime)

5962RXXXXXXXXX

Part Number given by manufacturer

Amplifier, memory, comparator, CMOS Si

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
σ(LET),
Error-rate,
etc

SET
SEU
SEFI
MBU
(LETth), etc

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

SMD missing radiation level

Meets SDO requirements for TID

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 any 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

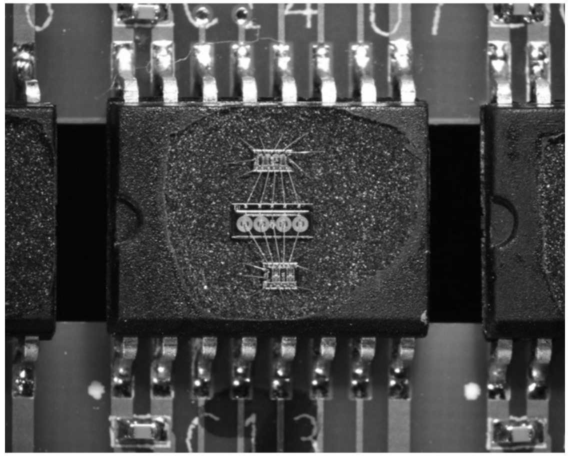
Final Approval is Given

- **If the parts meet radiation specifications, the radiation effects engineer approves.**

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 TID testing
  - ***Used pulsed laser to check for SEL as an initial screen***



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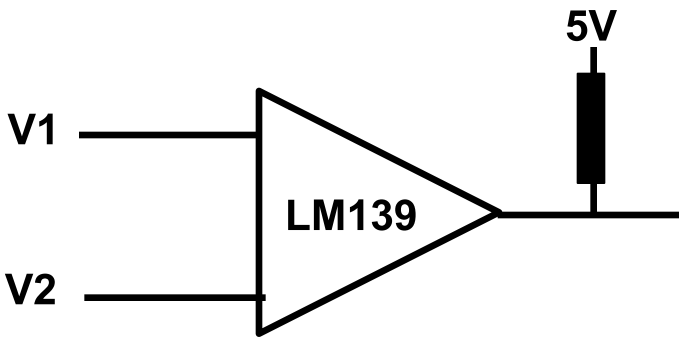
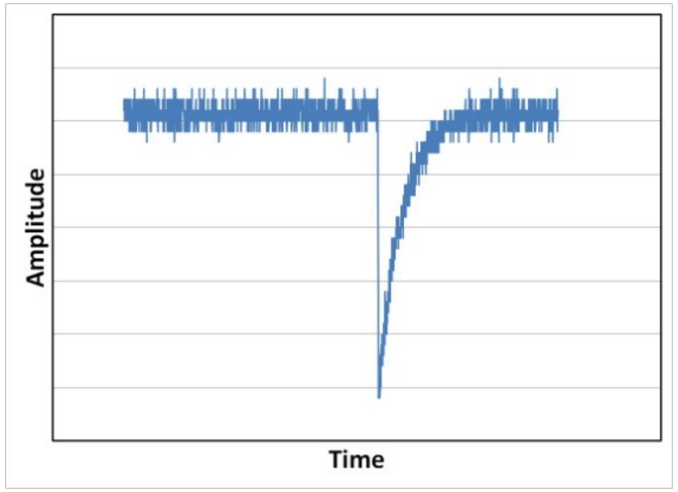
Single Event Test – Worst Case

- ***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.

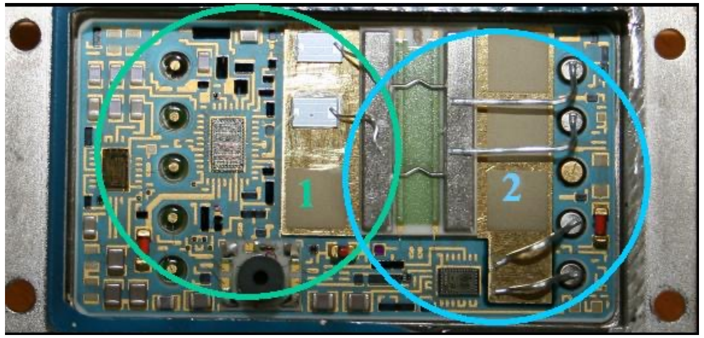




Example of Unexpected Results

- ***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

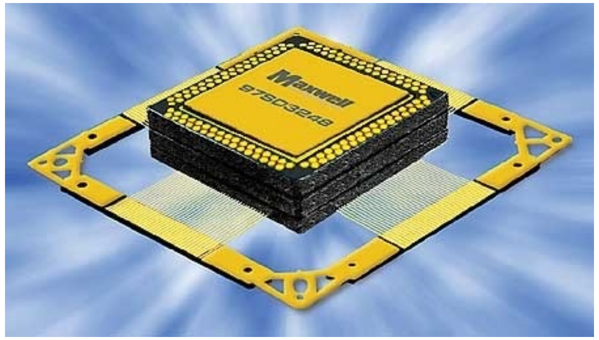
Problem attributed to short range of ions at Brookhaven National Laboratory



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.



Mitigation based on SEE Rate

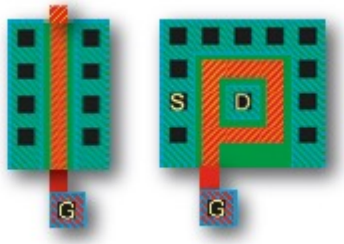
- ***Non-destructive SEEs***
  - If LET_{th} for non-destructive SEEs is below 36 $MeV.cm^2/mg$.
    - Mitigate if critical (e.g., majority vote, EDAC, filters)
    - Add watchdog timer
    - Replace if critical and cannot mitigate
    - Accept if non-critical (e.g., housekeeping)

- ***Destructive SEEs***
  - If LET_{th} for destructive SEEs is 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

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

TID Mitigation

- ***Shielding***
  - Use positioning judiciously to provide shielding to most sensitive devices. – ray trace analysis
  - Localized shielding has little weight penalty
- ***Derating***
  - Operate the device at a lower voltage or a lower frequency
- ***Conservative Circuit Design***
  - Accept a part that will fail parametric requirements but not operational
- ***Extra cold spares***
  - Unpowered devices will not suffer TID degradation (except ELDRS)
- ***Radiation hardening by design***
  - Use rad-hard by design parts to avoid rad-hard by process



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, inductors and capacitors.
- Many manufacturers claim a part is radiation-hard if the part has TID immunity. They completely ignore SEE.
- Lag time between deciding to test part and receiving part from manufacturer can be up to a year. Obsolescence is an issue.

More Thoughts

- Linear bipolars must be tested for ELDRS using low dose rates with gamma rays. Testing takes a lot of time.

- CMOS parts should always be checked for Single Event Latchup.

- Some parts are expensive to test - $100K per part. May have to modify test protocol.

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.