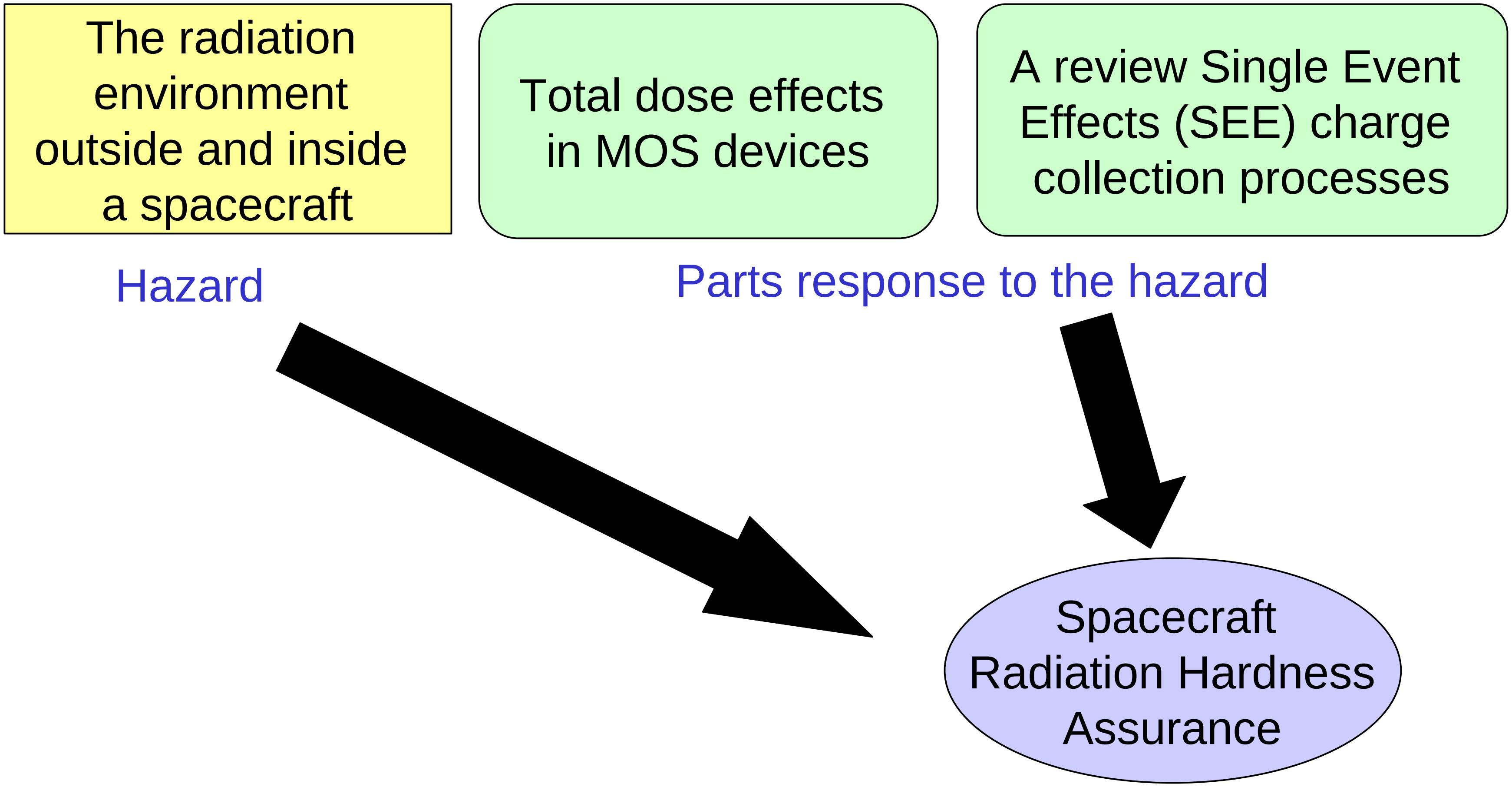
Radiation Hardness Assurance (RHA) for Space Systems

Christian Poivey

SGT/NASA-GSFC

Preamble



This talk will present a NASA approach of Radiation Hardness Assurance for space systems

RHA Outline

- Introduction
- Define the mission radiation environment
- Bound the part response
- Define the function/subsystem/system response
- Management of RHA
- Conclusion

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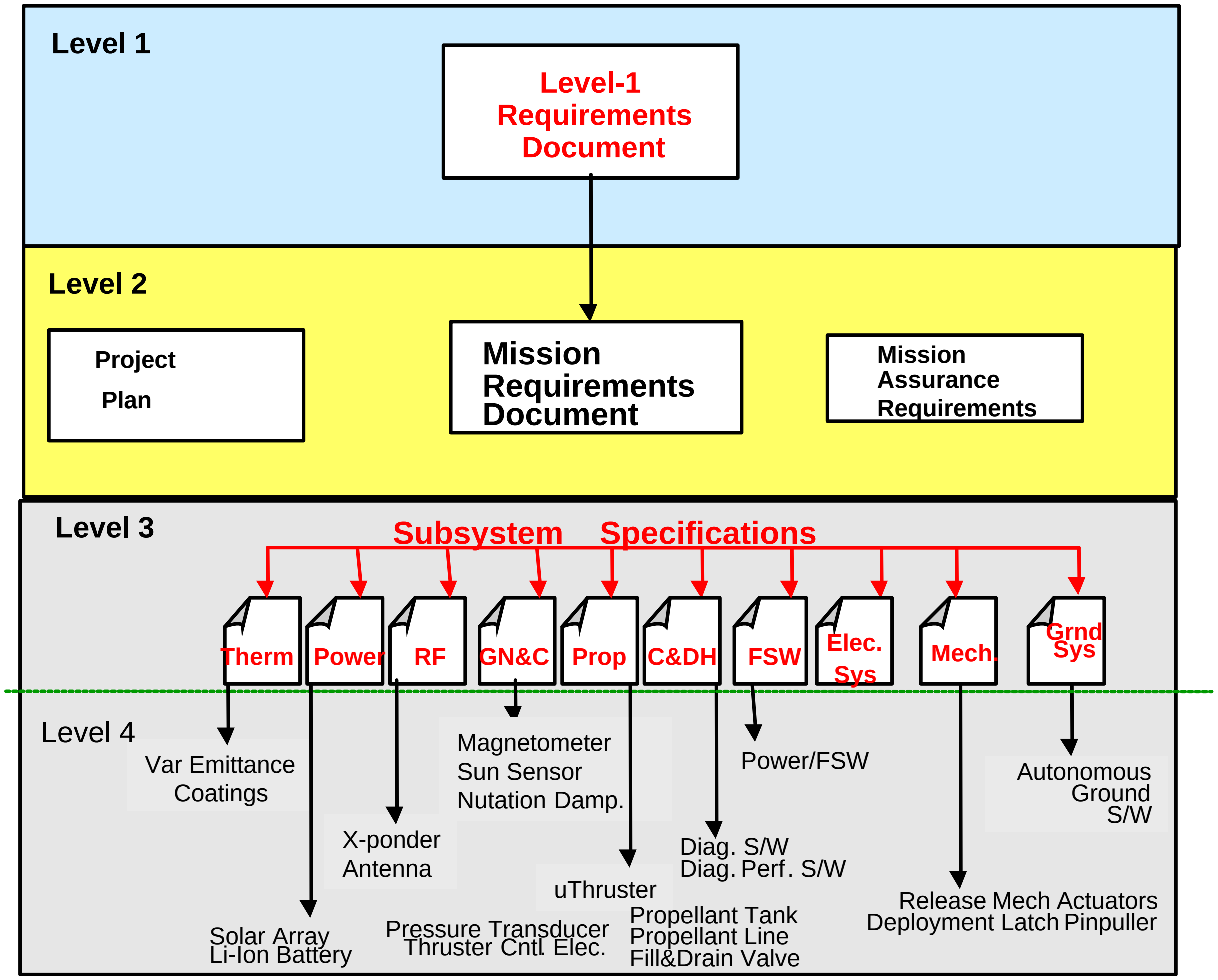
RHA Definition

- 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 environment.

- Deals with mission/system/subsystems requirements, environmental definitions, part selection, part testing, shielding, and radiation tolerant design

Radiation Hardness Assurance goes beyond the piece part level

Project Requirements Flow-Down

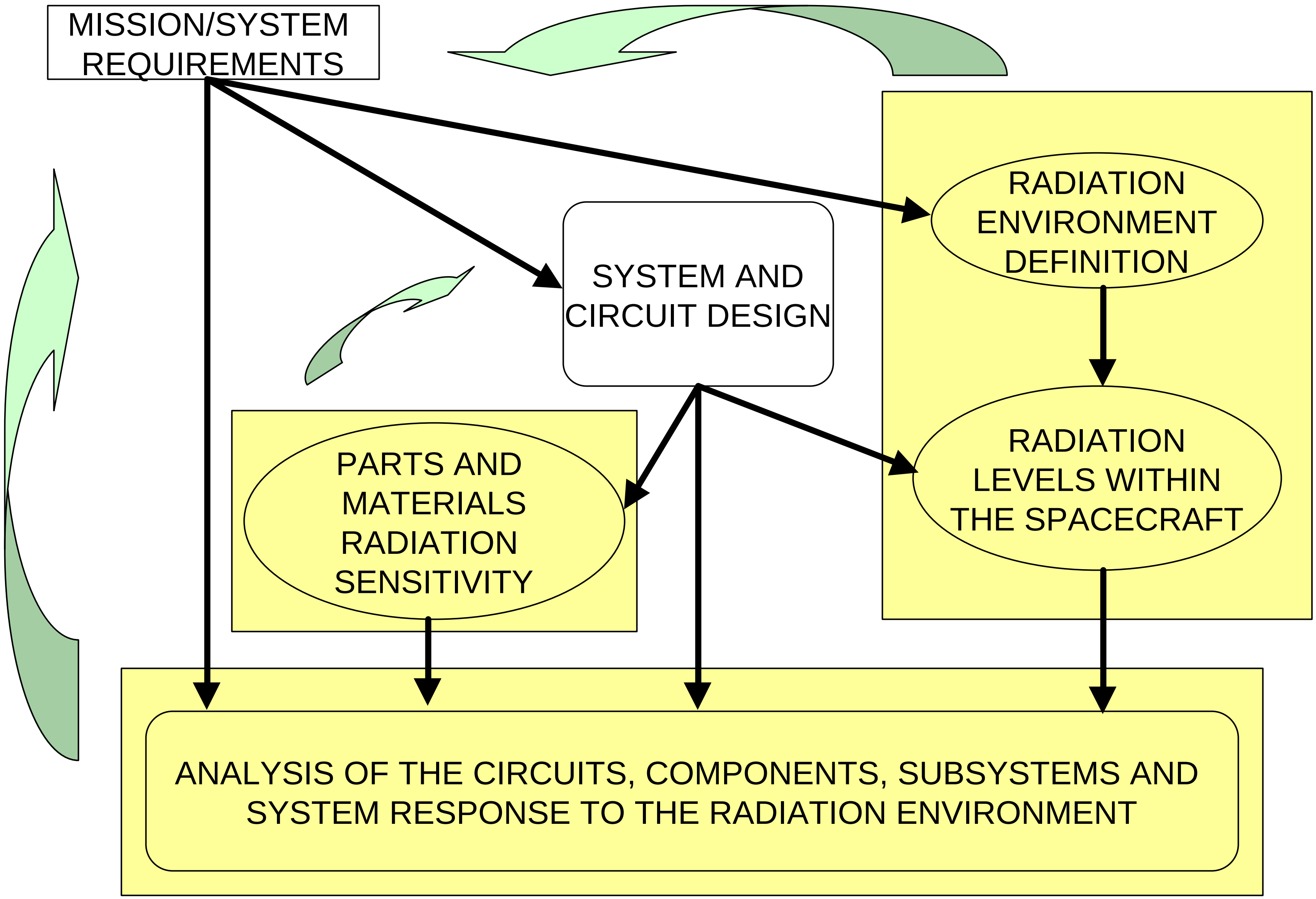


-mission objectives
-orbit
-mission duration
-schedule and cost

-identifies susbsystem impacted
-define verification level
-defines verification method

- performance requirement
- electrical and mechanical interface requirement

RHA Overview



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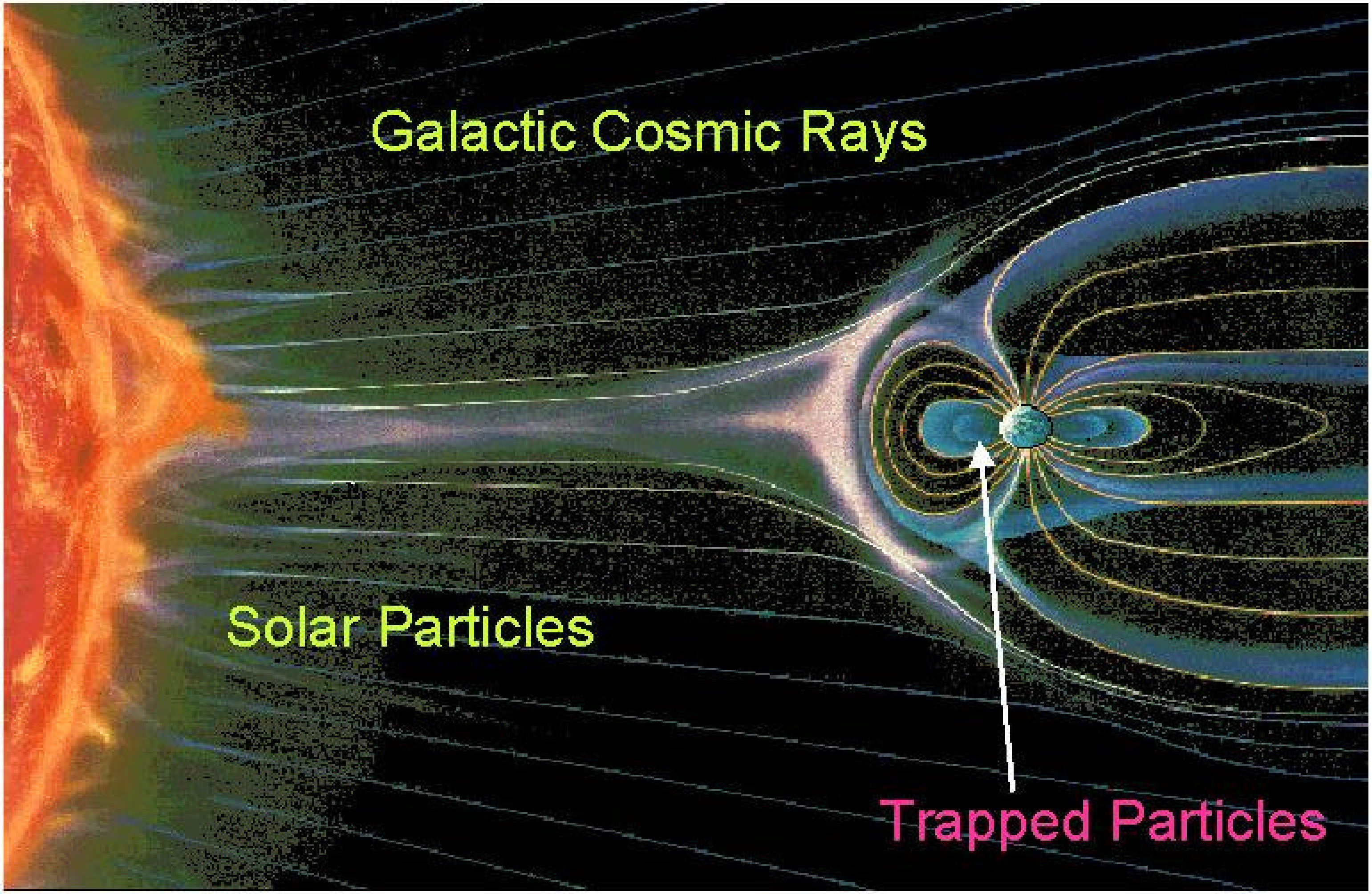
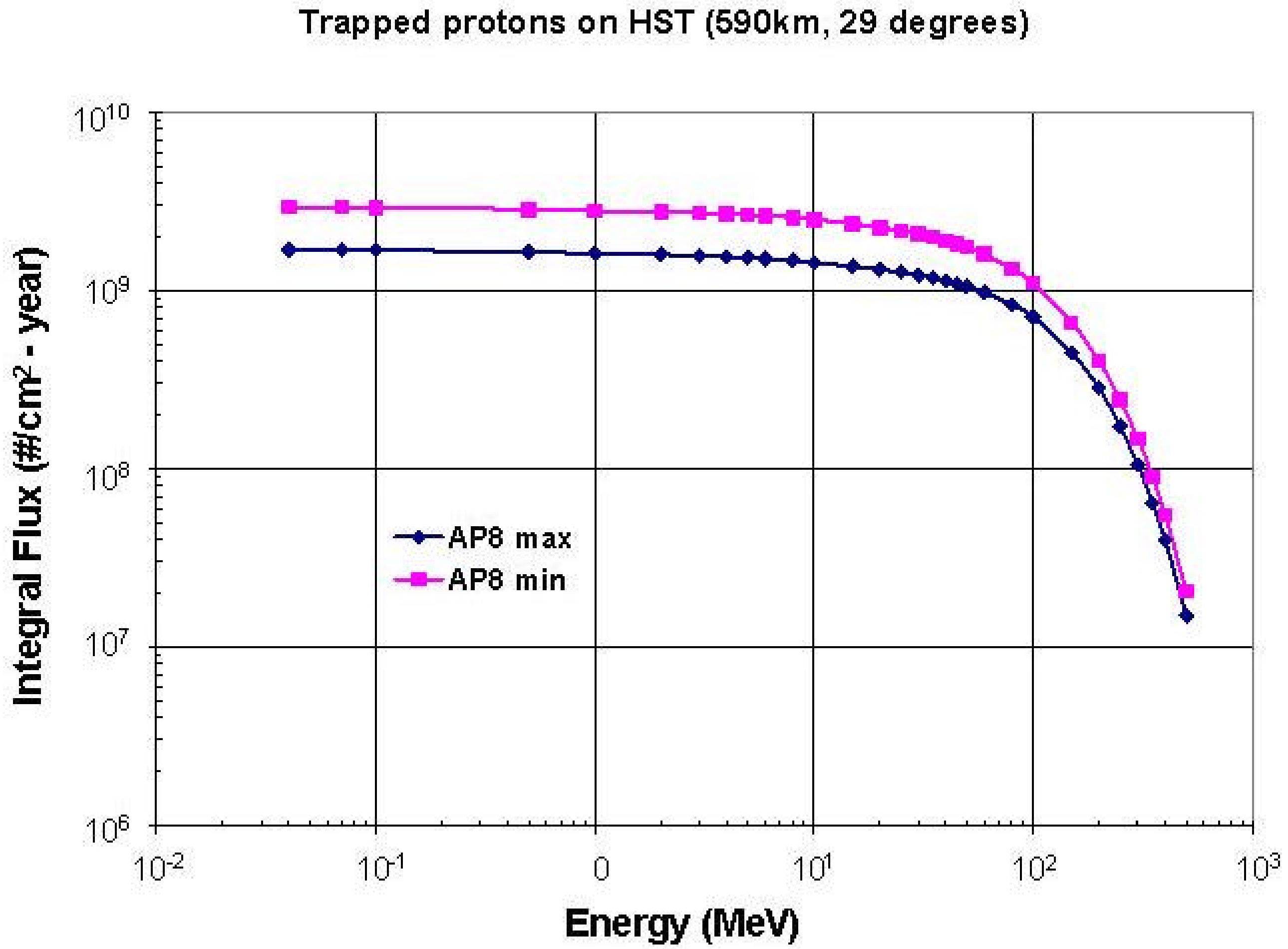
Sources of Radiation to Consider



After Nikkei Science, Inc. of Japan, by K. Endo

Trapped Radiation Belt Models: NASA AP8, AE8

- Conversion of spatial coordinates to geomagnetic B/L coordinates
- Use of AP8/AE8 tabulated spectra



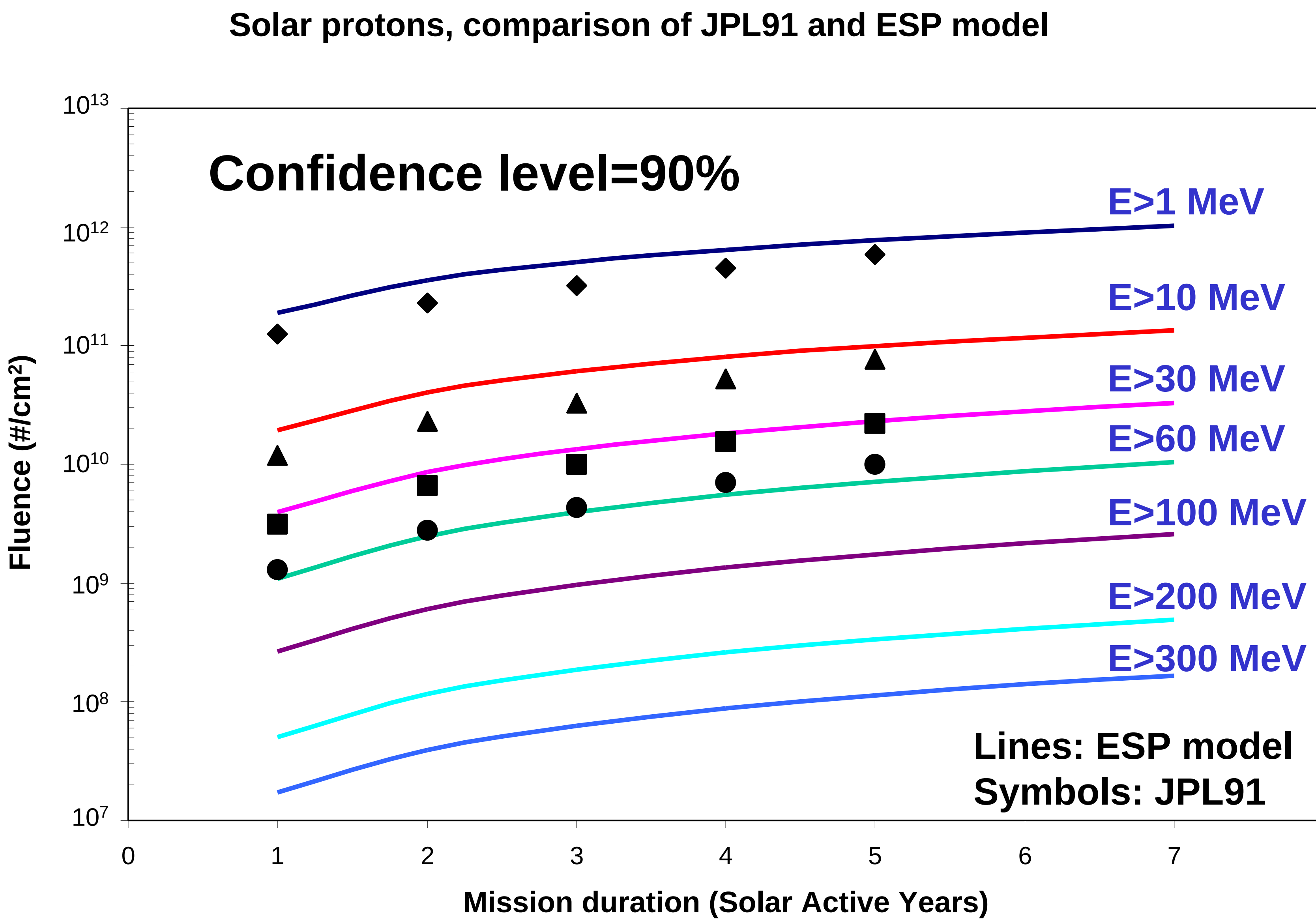
Trapped Radiation Belt Models: NASA AP8, AE8

- 2 extreme cases of solar modulation
- static models that represent omnidirectional average fluxes over 6 months period of time
- B/L coordinates shall be calculated with the geomagnetic models used at the epoch of the generation of AP8/AE8 models
- At low altitude (<1000km), AP8 underestimates the actual fluxes
  - TIROS

Despite their inaccuracies AE8 and AP8 are still the standard models for engineering analysis

Available at: http://www.spenvis.oma.be/spenvis/

Solar Particle Event, Mission Integrated Proton Fluence Models: NASA Emission of Solar Protons (ESP) & JPL1991



After Xapsos IEEE TNS, vol 47-3, 2001

Solar Particle Event and Galactic Cosmic Ray (GCR), Individual Event Model: CREME 96

- Provides GCR fluxes for elements from Z=1 to 92 for solar minimum and solar maximum conditions in an energy range from 0.1 to 1E5 MeV/u.
- Provides SPE fluxes for element from Z=1 to 92 for the worst week, worst day and peak 5 minutes.

Available at: http://crsp3.nrl.navy.mil/creme96/

Effects Induced by the Space Radiation Environment

- Cumulative Effects
  - Induced by electrons and protons
    - Total dose effects
    - Displacement Damage
- Single Event Effects (SEE)
  - Induced by heavy ions and protons
    - Potentially destructive
      - Single Event Latchup (SEL)
      - Single Event Burnout (SEB)
      - Single Event Gate Rupture (SEGR)
    - Non destructive
      - Single Event Upset (SEU)
      - Single Event Transient (SET)
      - Single Event Functional Interrupt (SEFI)
      - Multiple Event Upset (MEU)
      - Multiple Bit Upset (MBU)
      - …
- Other: spacecraft charging*

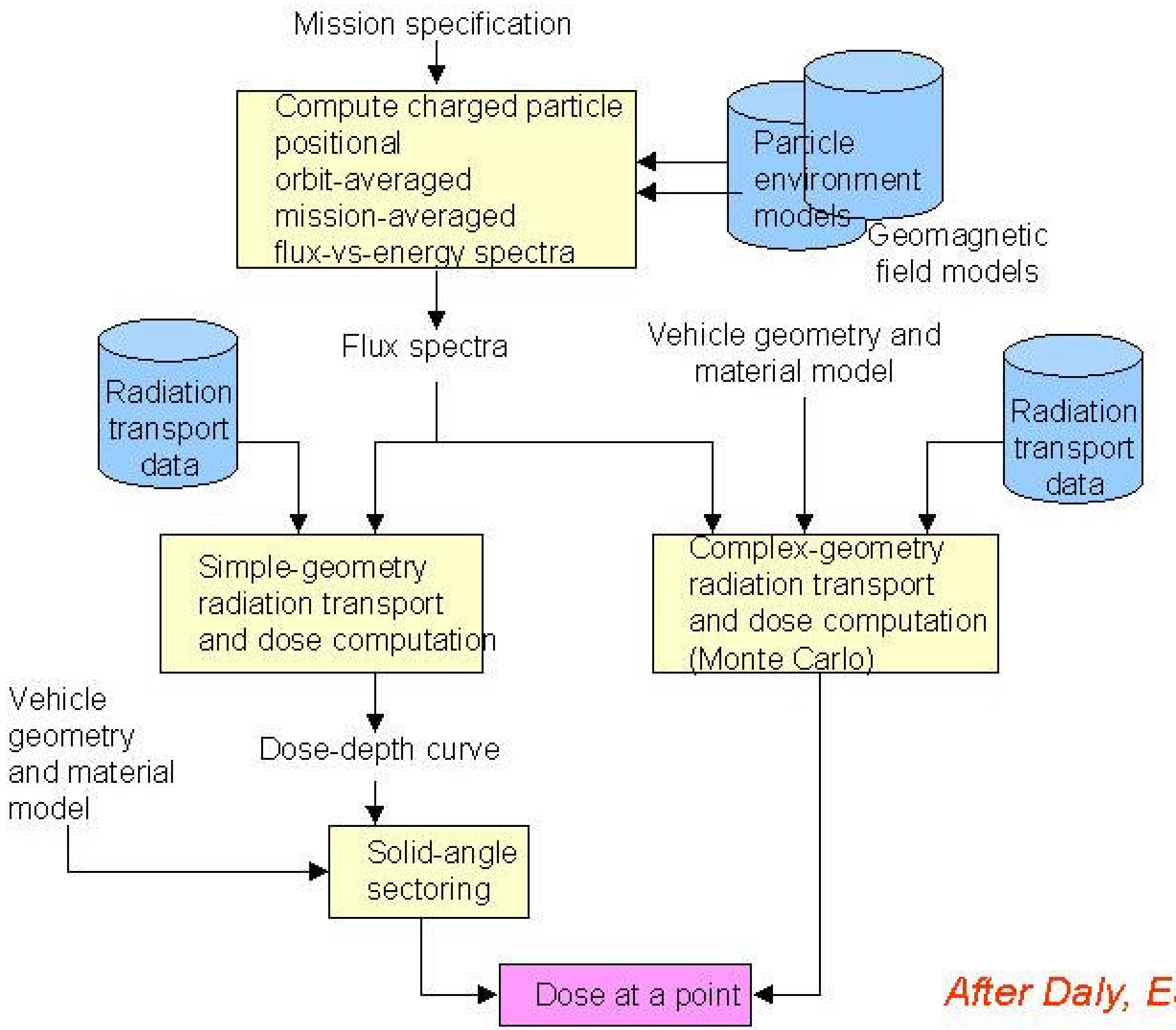
* outside the scope of this short course

Radiation Environment Within the Spacecraft
Quantification of the Different Effects

Observed Effect	**Parameter used for quantification**
Total Dose Effects	Total Ionizing Dose (TID)
Displacement Damage	Displacement Damage Dose (DDD) based on Non Ionizing Energy Loss (NIEL)* or NIEL equivalent fluence for a selected proton energy* or Damage equivalent fluence for a selected electron or proton energy
Single Event Effects (SEE)	Heavy ion Linear Energy Transfer (LET) spectra and proton energy spectra

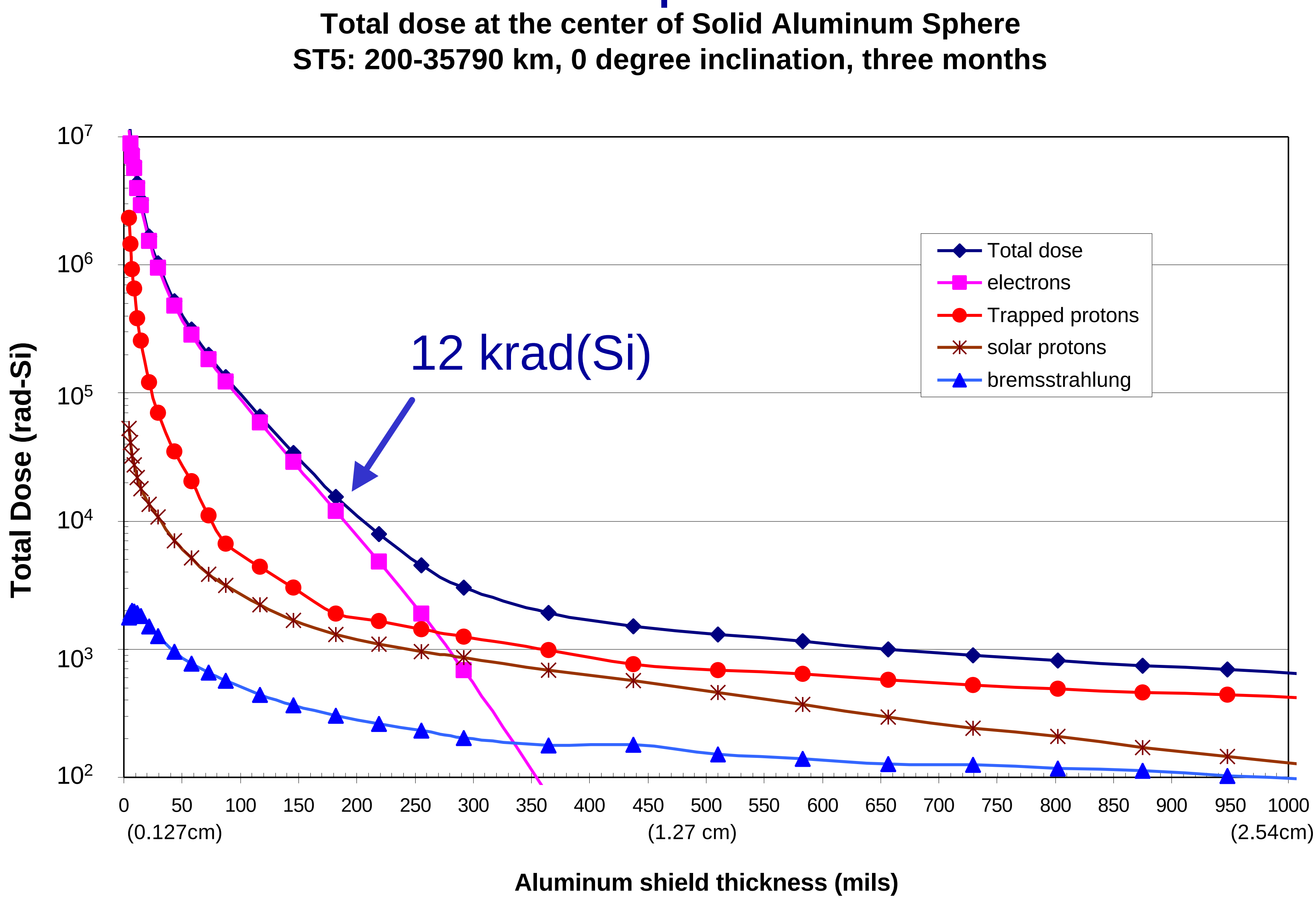
* May not be valid for III-V materials

TID, Computer Methods for Particle Transport

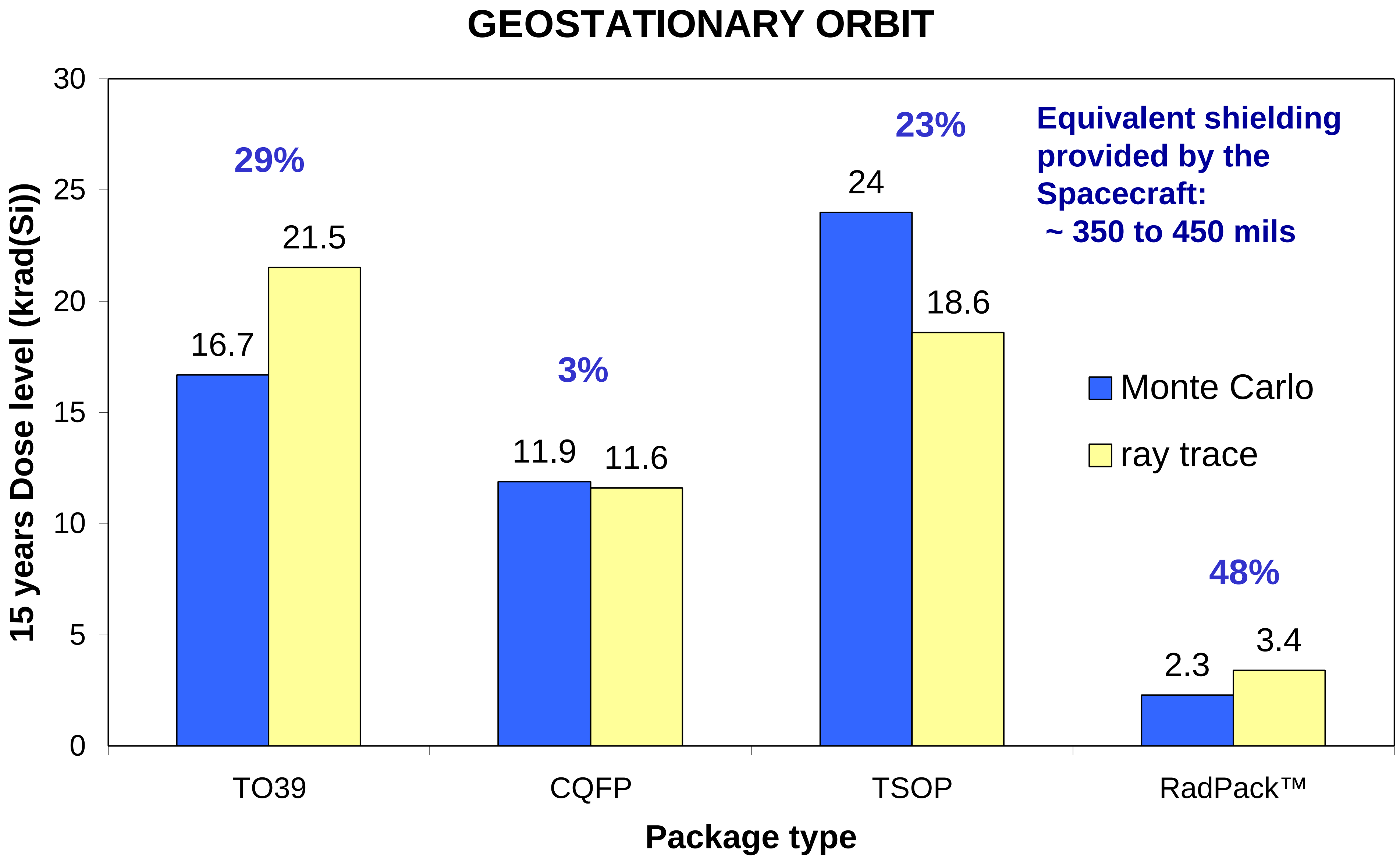


After Daly, ESA report 1989

TID Top Level Requirement : Dose-Depth Curve

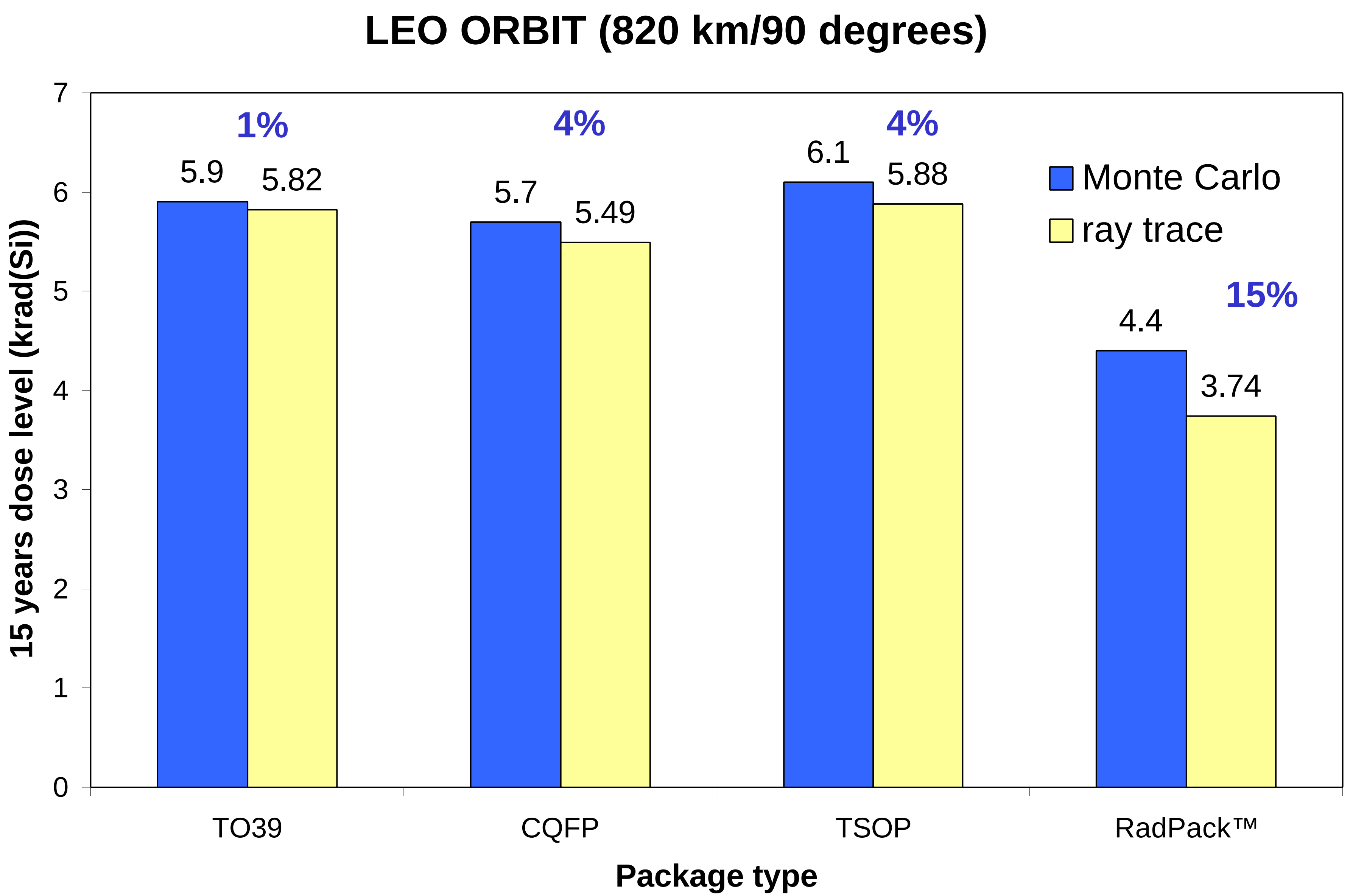


For Electron Dominated Orbits, Sector Analysis/Ray Trace Can Significantly Underestimate or Overestimate the Dose Levels

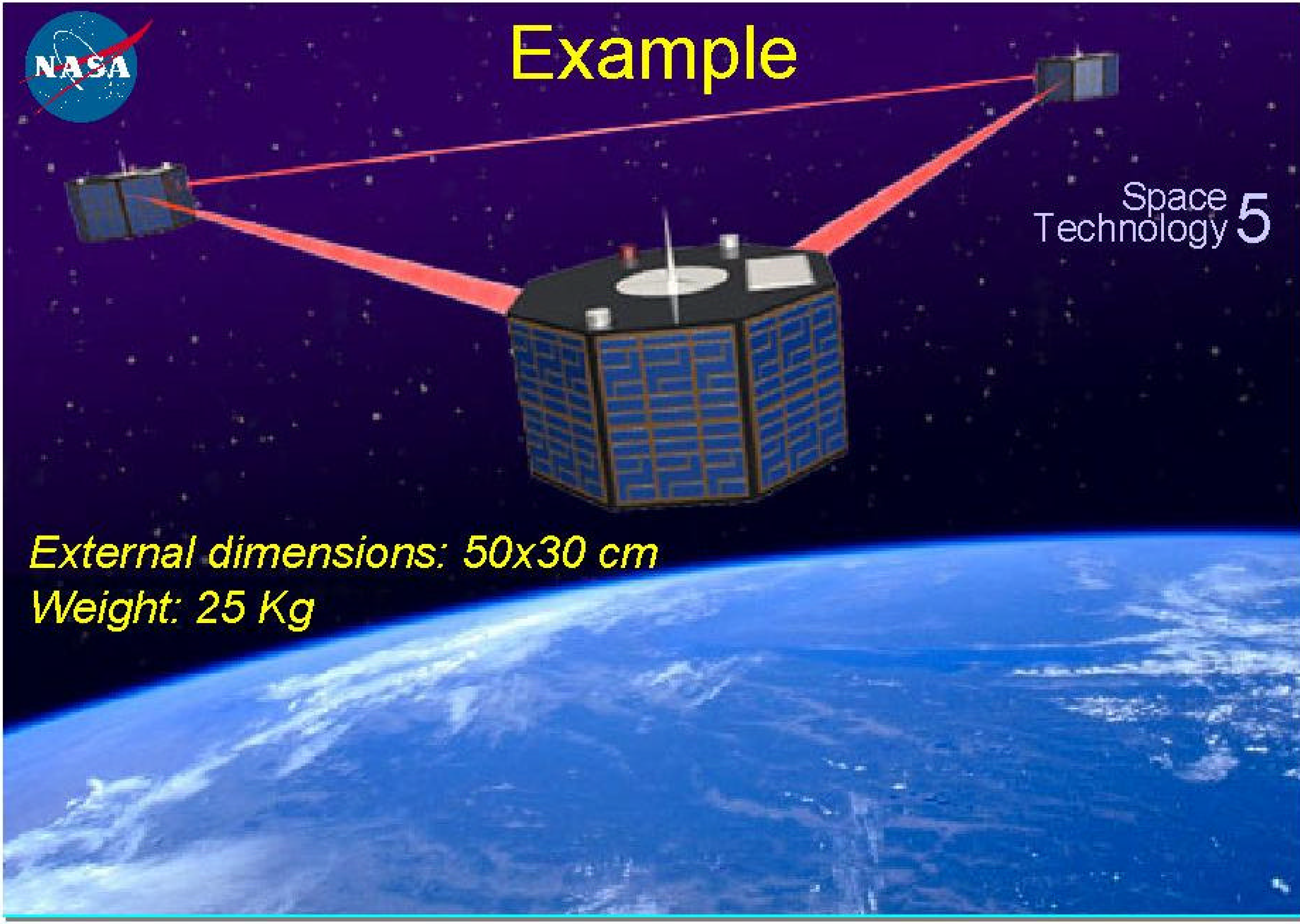


After R. Mangeret, ASTRIUM report, 2001

For Proton Dominated Orbits, Sector Analysis Gives a Good Estimation of the Dose Levels



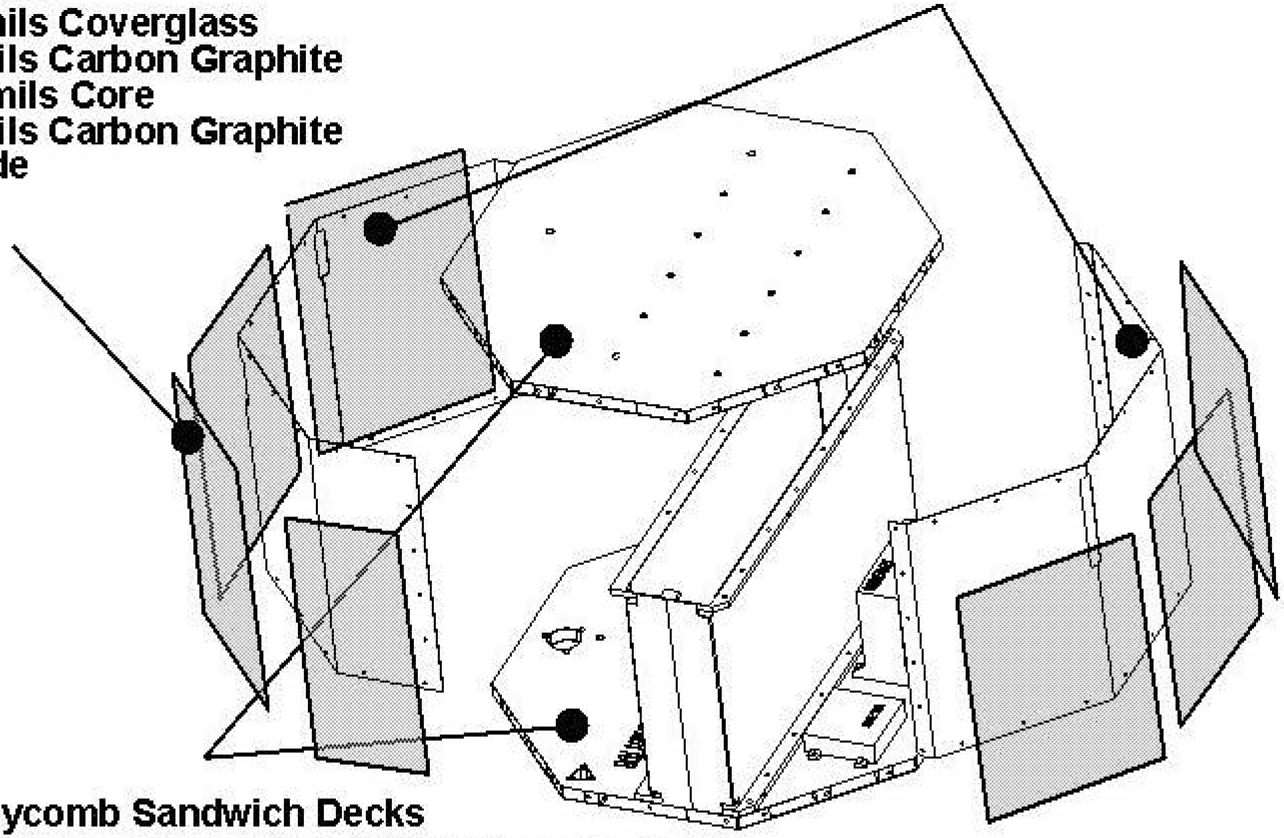
After R. Mangeret, ASTRIUM report, 2001



Courtesy of NASA New Millenium Program (NMP)

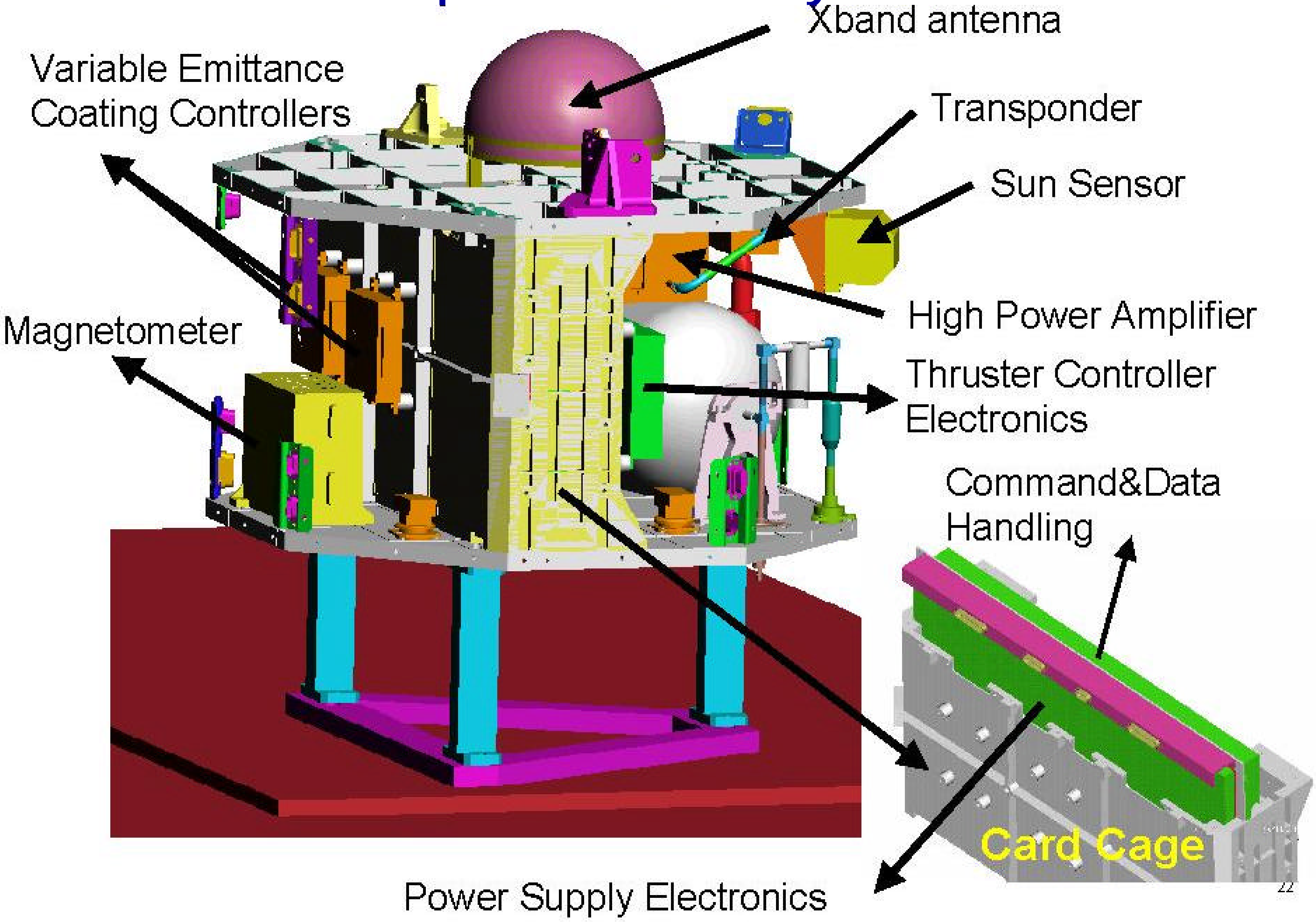
Spacecraft Structure

- Honeycomb Solar Array Panels
  - 8 Panels
  - ~0.175mils
  - Outside
    30 mils Coverglass
    10mils Carbon Graphite
    125mils Core
    10mils Carbon Graphite
    Inside
- Sheet Metal Side Wall serves as closeout
  - 32mils Sheet Al 6061



- Honeycomb Sandwich Decks
  - ½" core (Composite), 0.015" Facesheets (Al)
  - Equivalent ~30mils Al

Spacecraft Layout



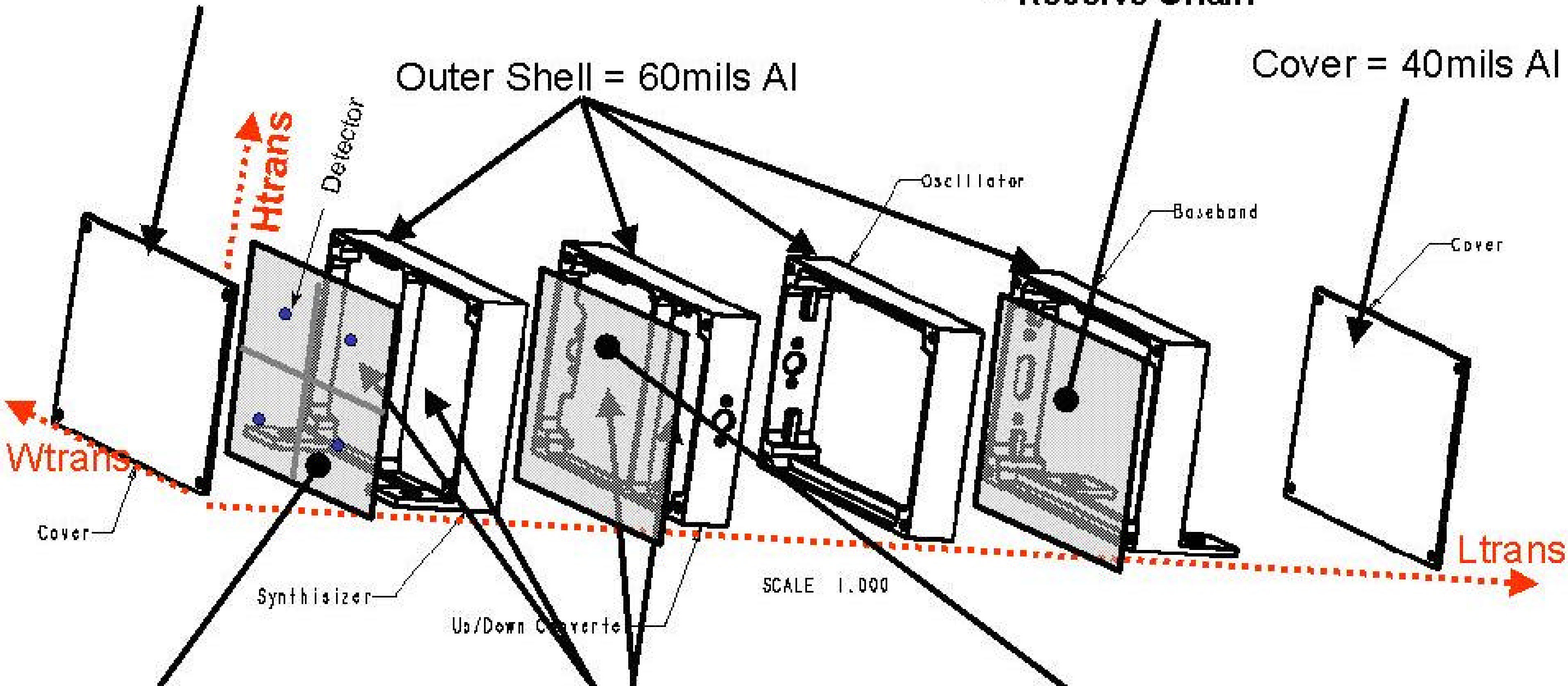
Detail -Transponder

- Component Cavity #3
  - Baseband Processor
  - Oscillator Board
  - Transmit Chain
  - Receive Chain

Cover = 40mils Al

Outer Shell = 60mils Al

Cover = 40mils Al

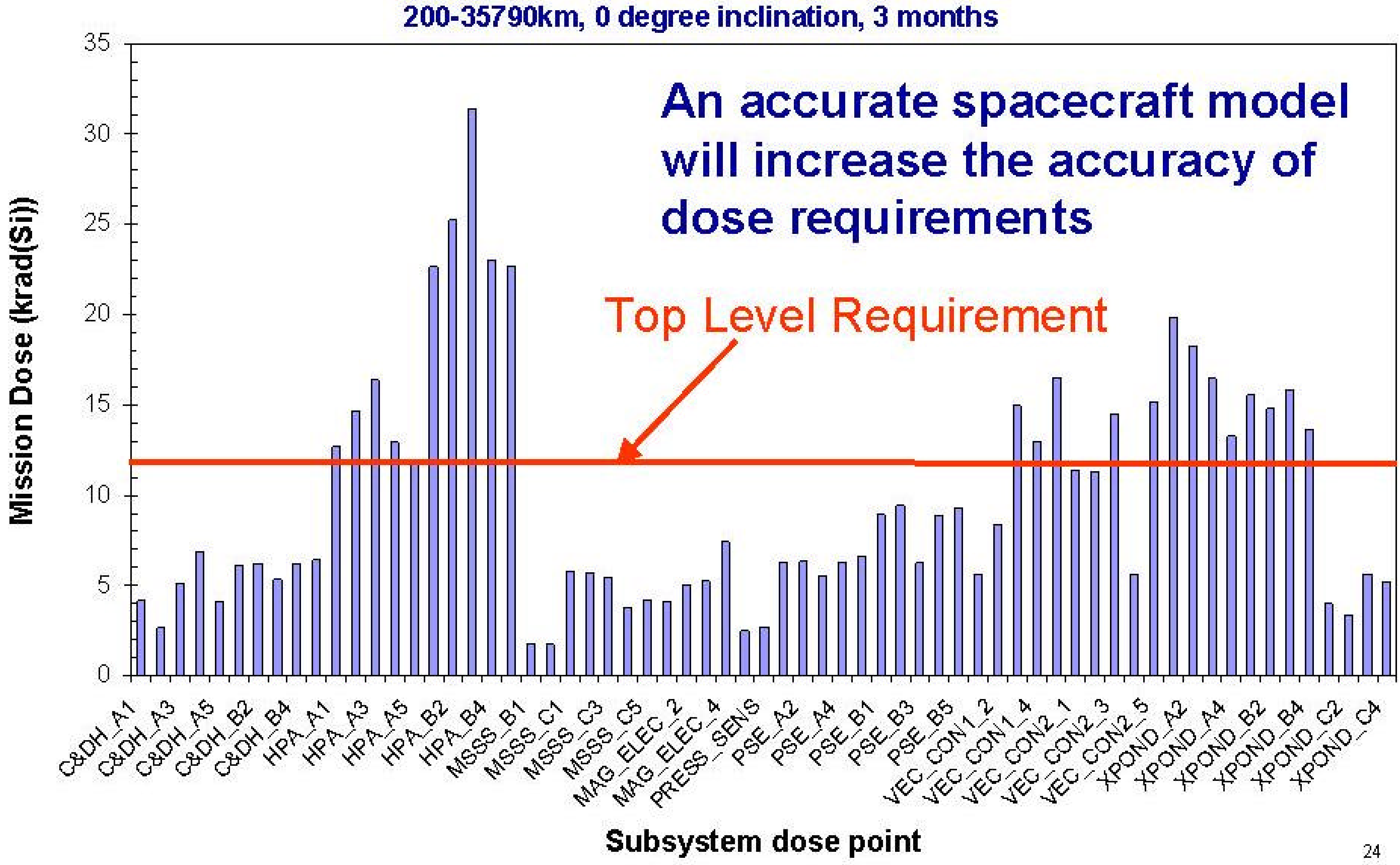


- Component Cavity #1
  - C-Band Synthesizer

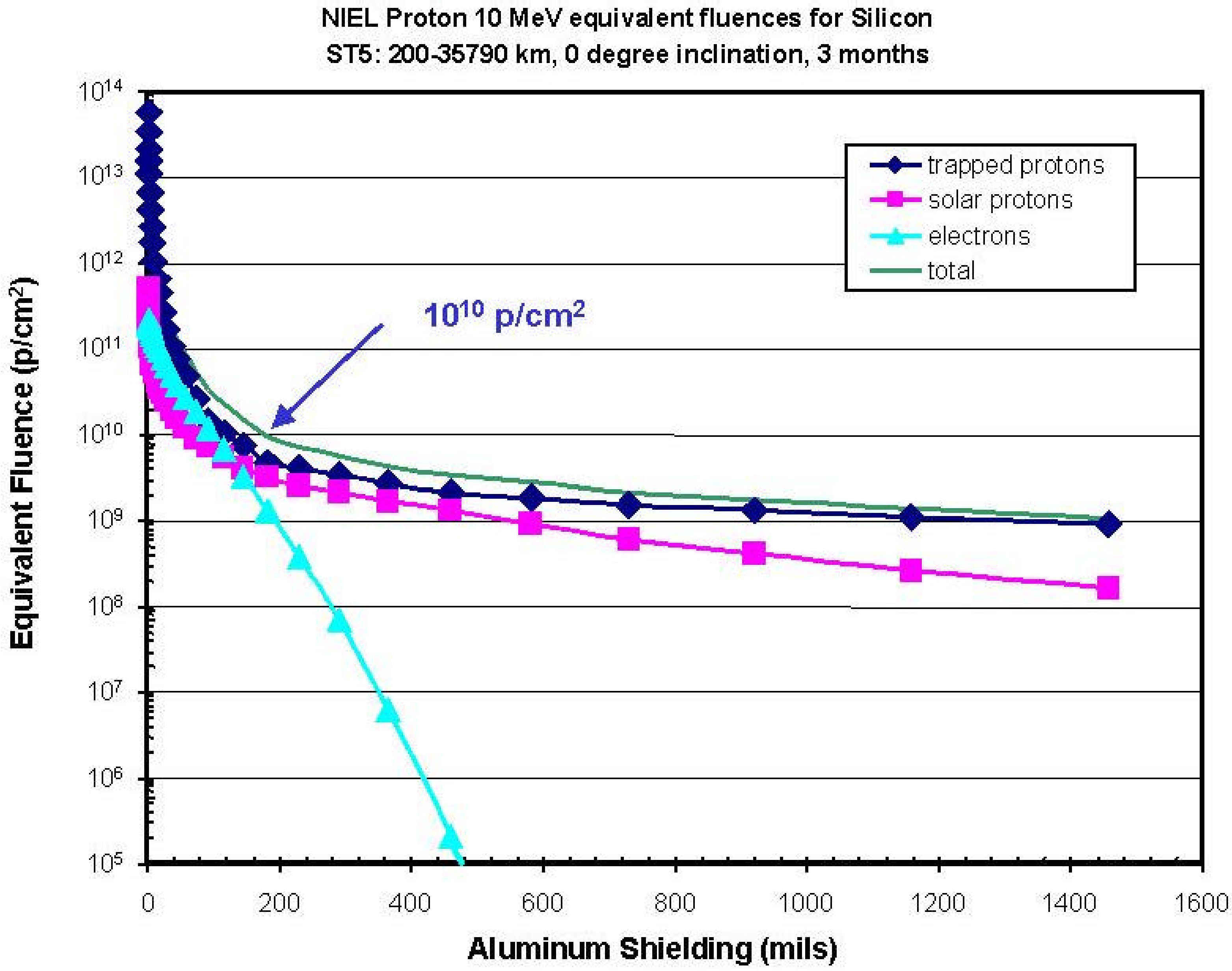
Internal Webs = 40mils Al

- Component Cavity #2
  - L-Band & S-Band Synthesizer
  - Analog Daughter Card

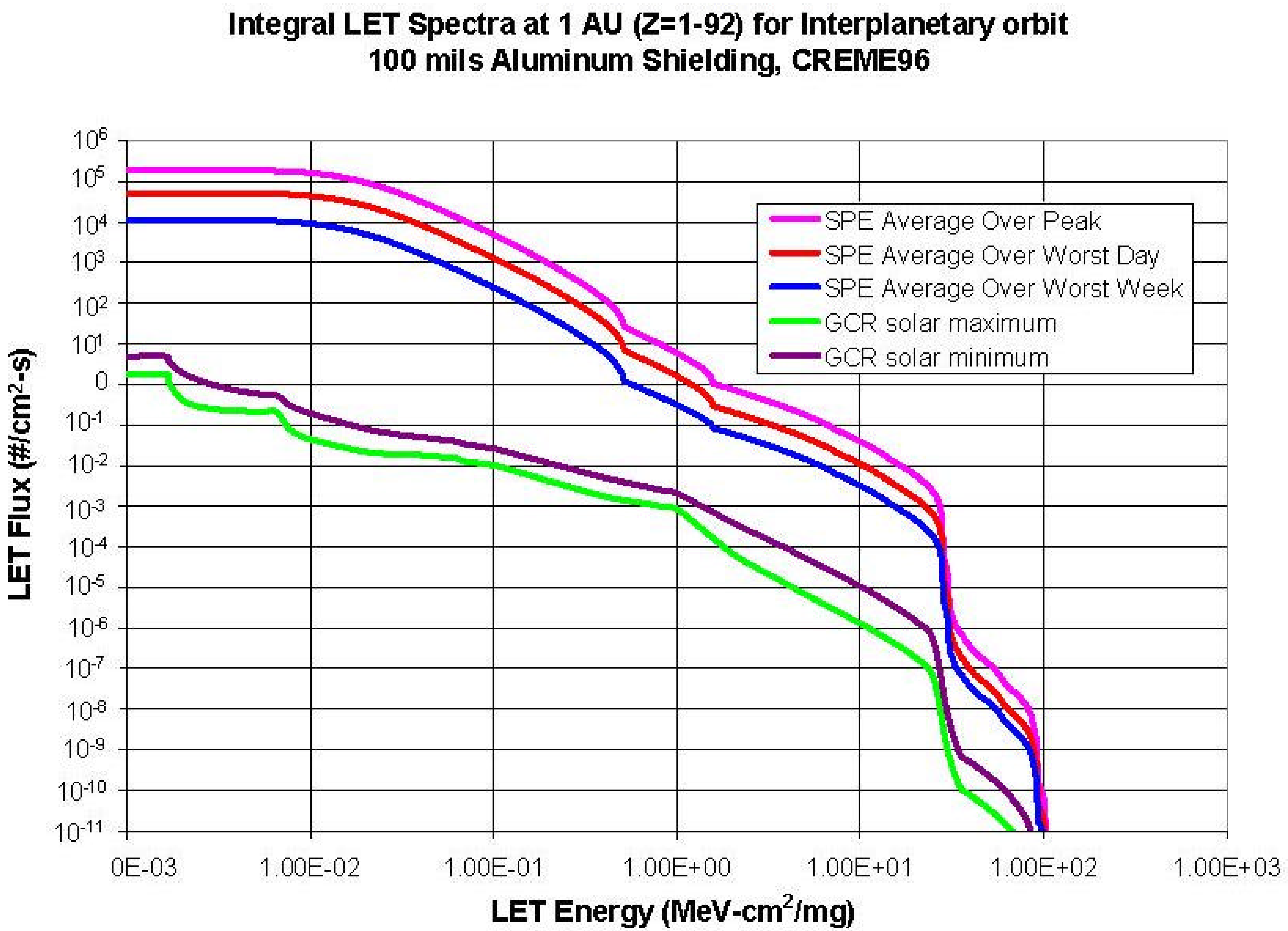
ST5 - Total Mission Dose on Electronic Parts



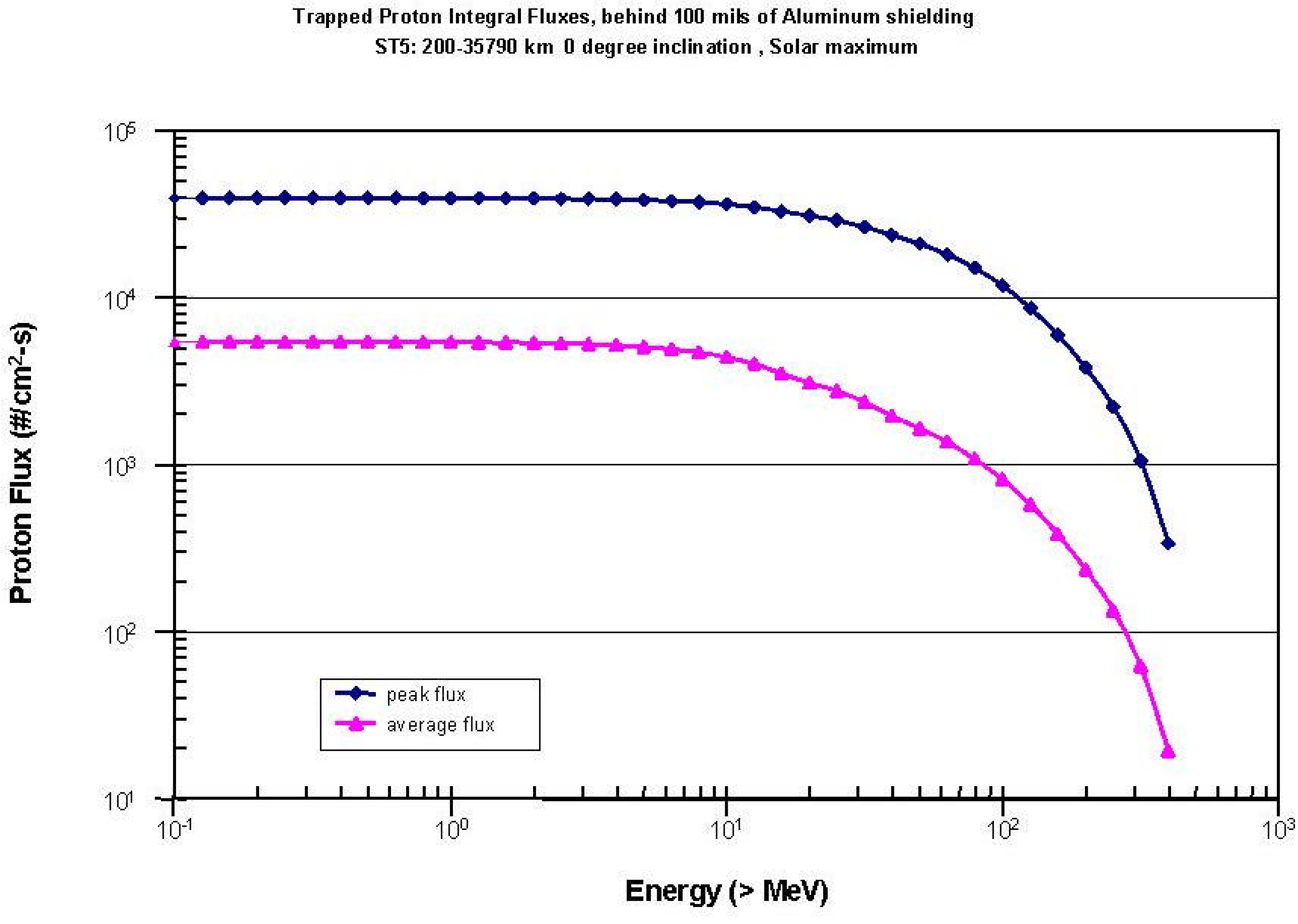
For Displacement Damage, an Equivalent Fluence or a Displacement Damage Dose (DDD) is Defined Based on NIEL



Heavy Ion Environment is Defined for a Conservative Value of Shielding



The Proton SEE Environment is Defined for a Conservative Value of Shielding. Orbit Average and Maximum Fluxes are Defined



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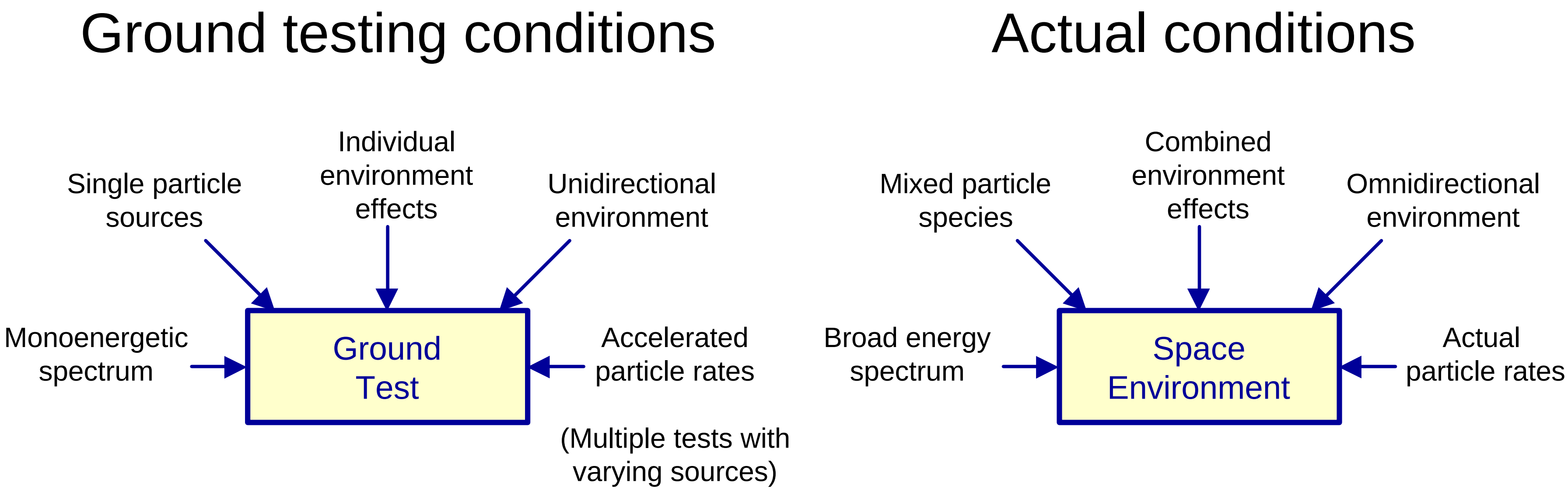
Parts and Material Potential Sensitivities

- Materials
  - Total Dose Effects
  - Displacement Damage
- CMOS electronic parts
  - Total Dose Effects
  - SEE
- Bipolar electronic parts
  - Total Dose Effects
  - Displacement Damage
  - SEE
- Optoelectronic parts
  - Displacement Damage
  - Total Dose Effects
  - SEE
- Solar cells
  - Displacement Damage
  - Total Dose Effects (cover glass)

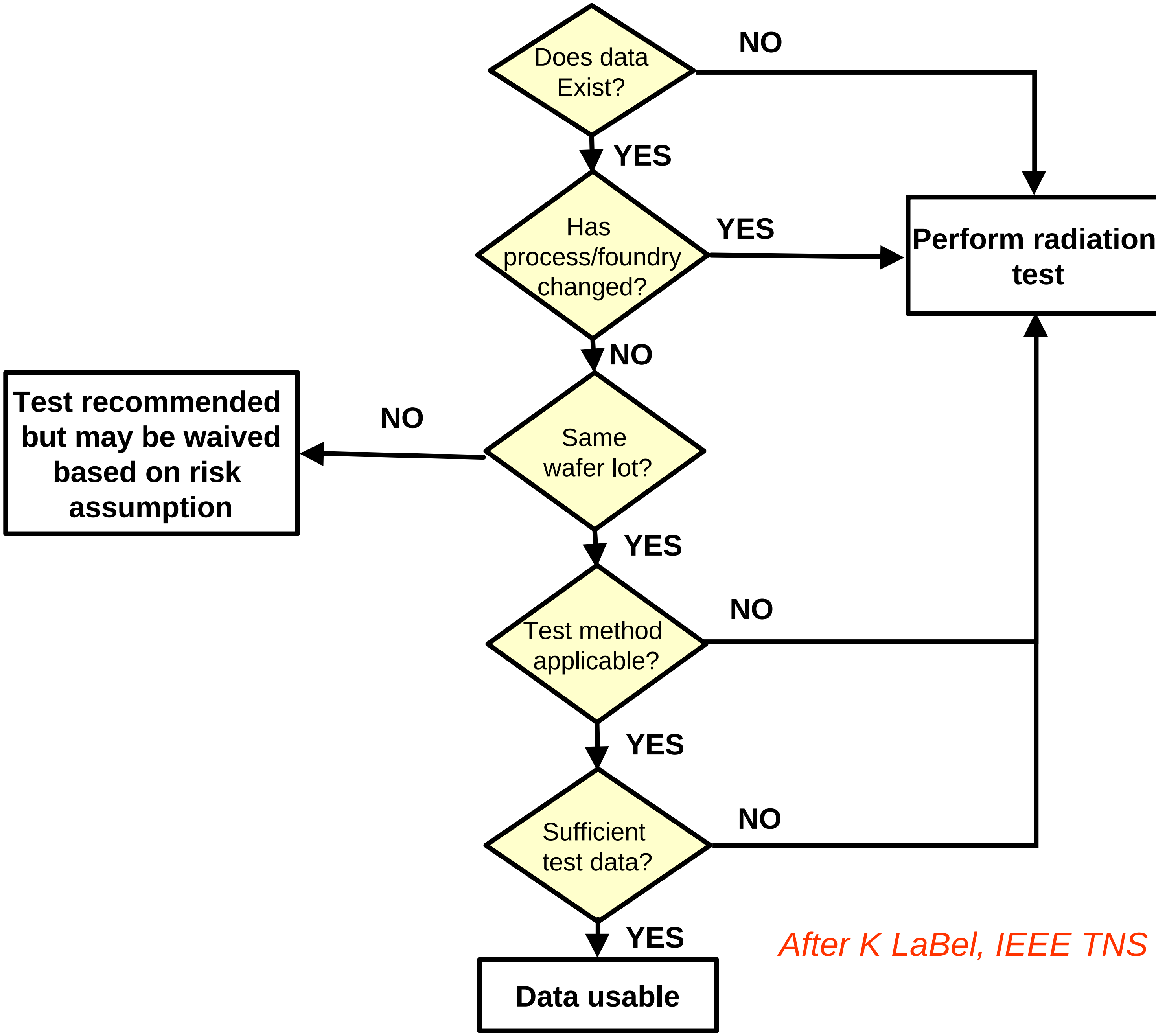
Laboratory Radiation Testing Conditions are Significantly Different from the Actual in Flight Exposure to the Radiation Environment



temperature and bias conditions are also different

After LaBel & Stassinopoulos

Data Search and Definition of Data Usability Flow



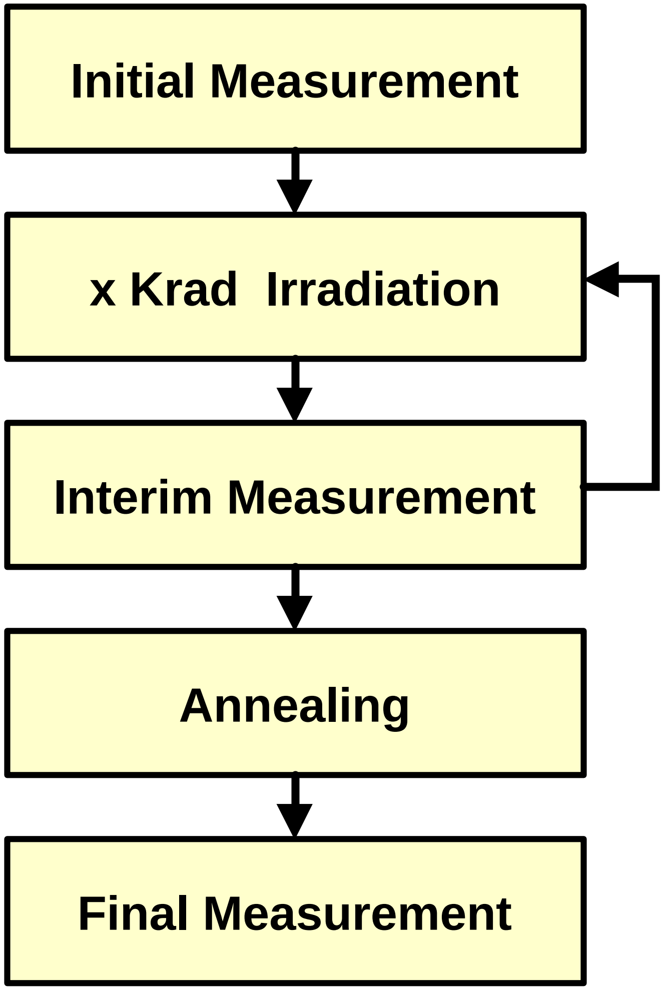
After K LaBel, IEEE TNS vol 45-6, 1998

Sources of Radiation Data

- Available databases:
  - NASA-GSFC: http://radhome.gsfc.nasa.gov
  - NASA-JPL: http://radnet.jpl.nasa.gov
  - ESA: http://escies.org
  - DTRA ERRIC: http://erric.dasiac.com
  - NRL REDEX: http://redex.nrl.navy.mil

- Other sources of radiation data:
  - IEEE NSREC dataworkshop, IEEE Trans. On Nuc. Sci., RADECS proceedings,..
  - Vendors ?

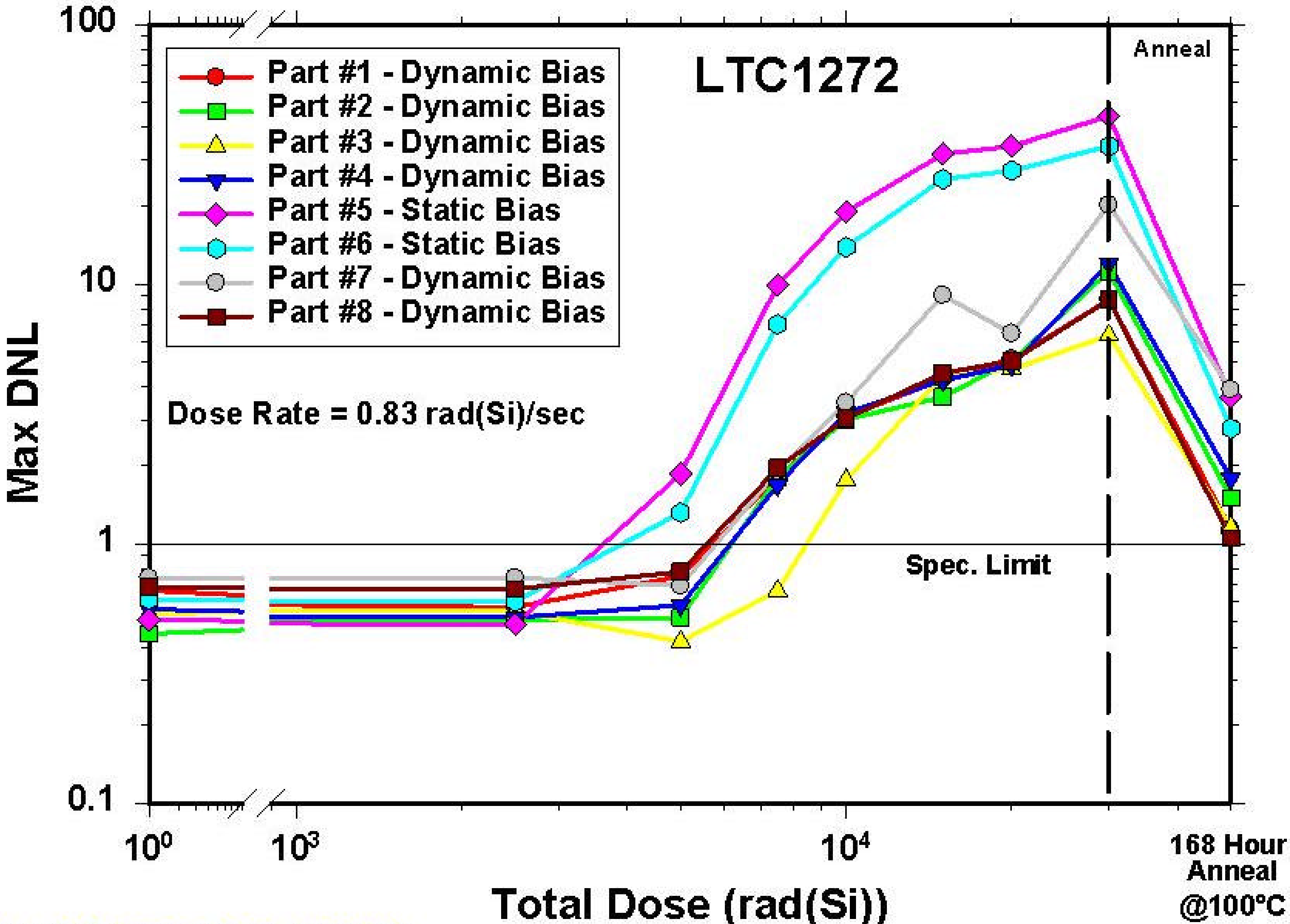
Generic TID Testing



Test standards:
-US MIL-STD1019.5
-ESA/SCC 22900

Test Guidelines:
-ASTM F1892

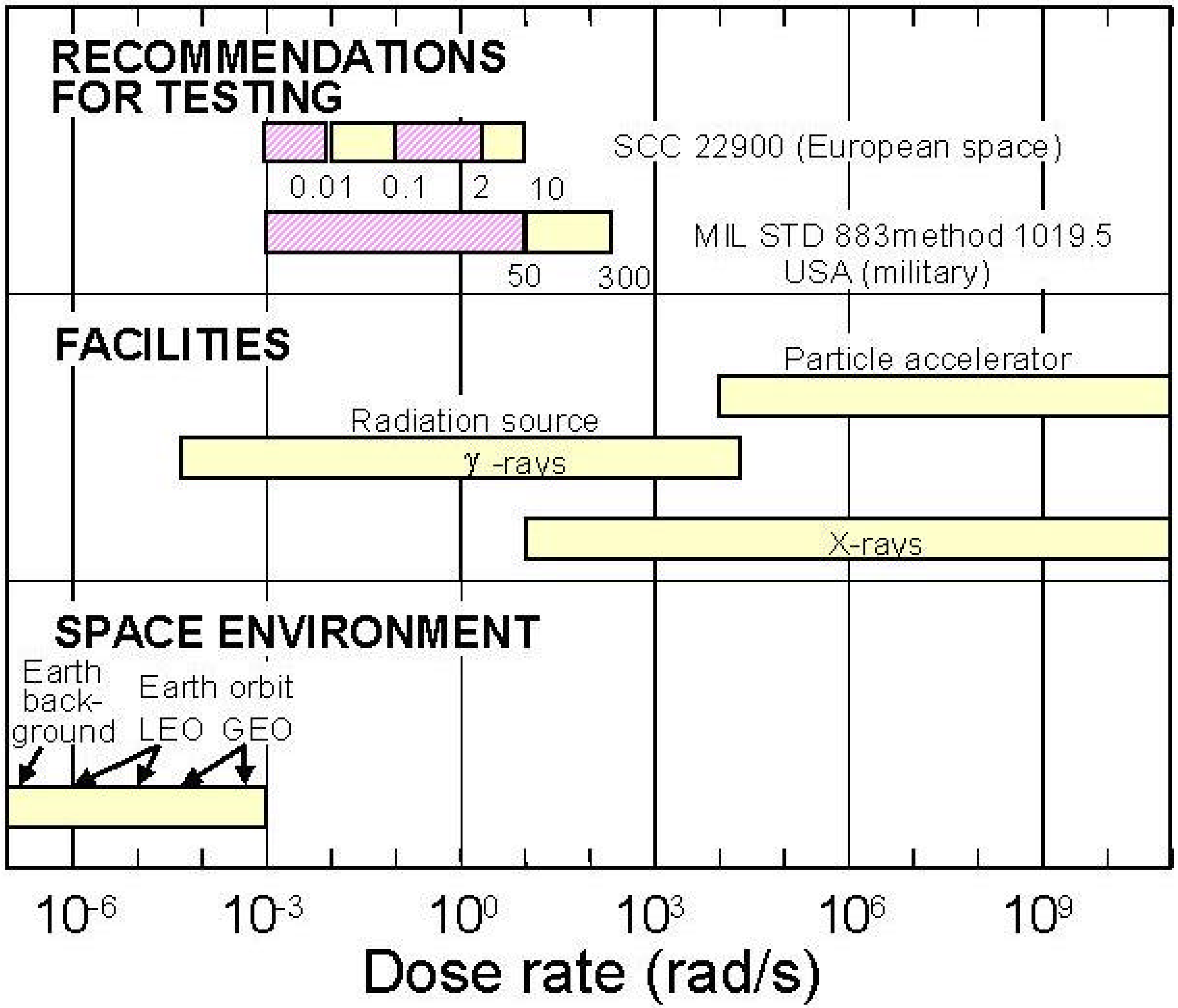
TID Characterization - Example



DNL: Differential Non Linearity

After J Bings, NAVSEA/CRANE test report, 2001

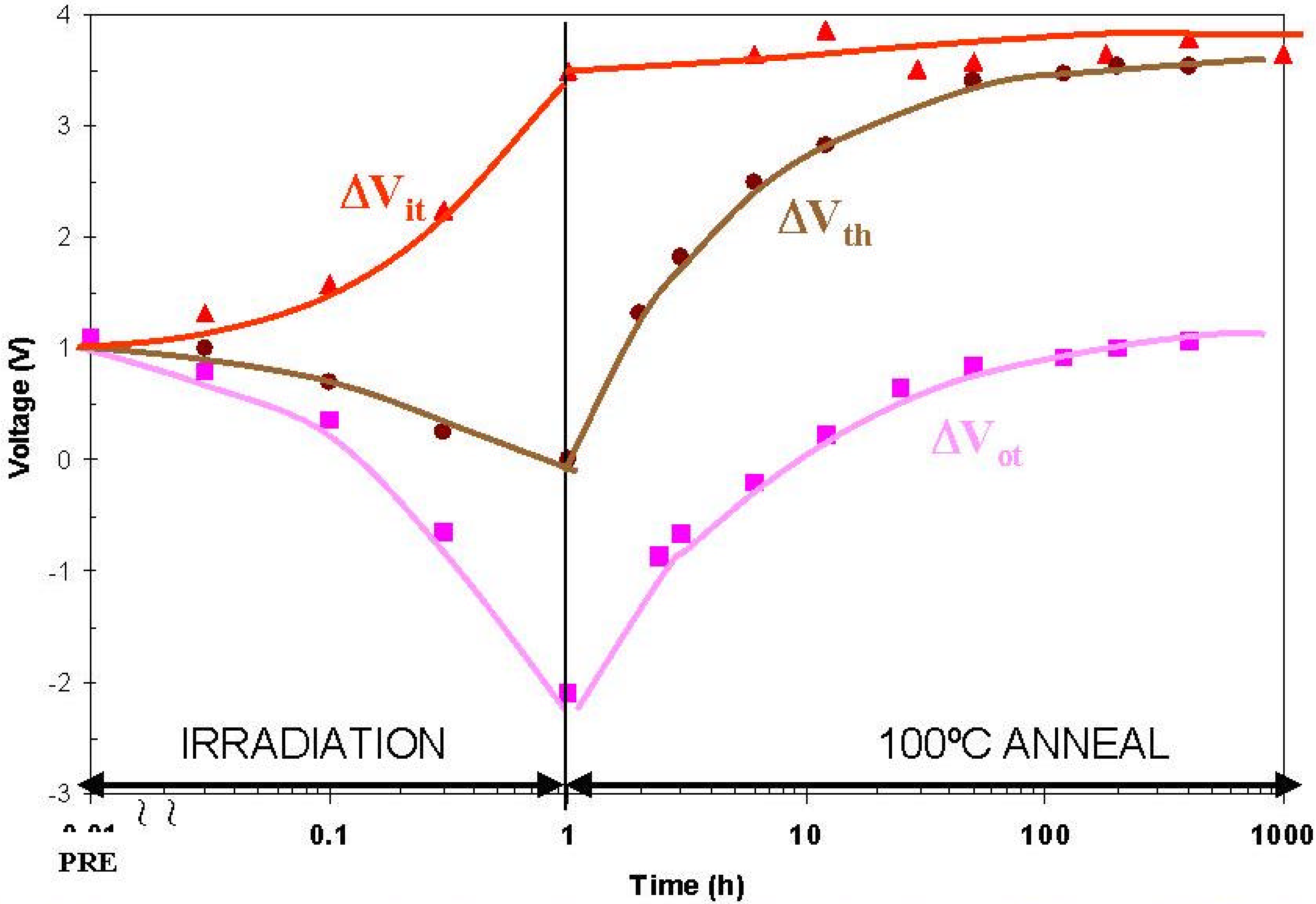
TID - Radiation Sources and Dose Rates



The laboratory dose rates are significantly higher than the actual space dose rates, testing according to test standards gives conservative estimates of CMOS devices TID sensitivity

After A Holmes Siedle and L Adams, Oxford Un. Press, 1993

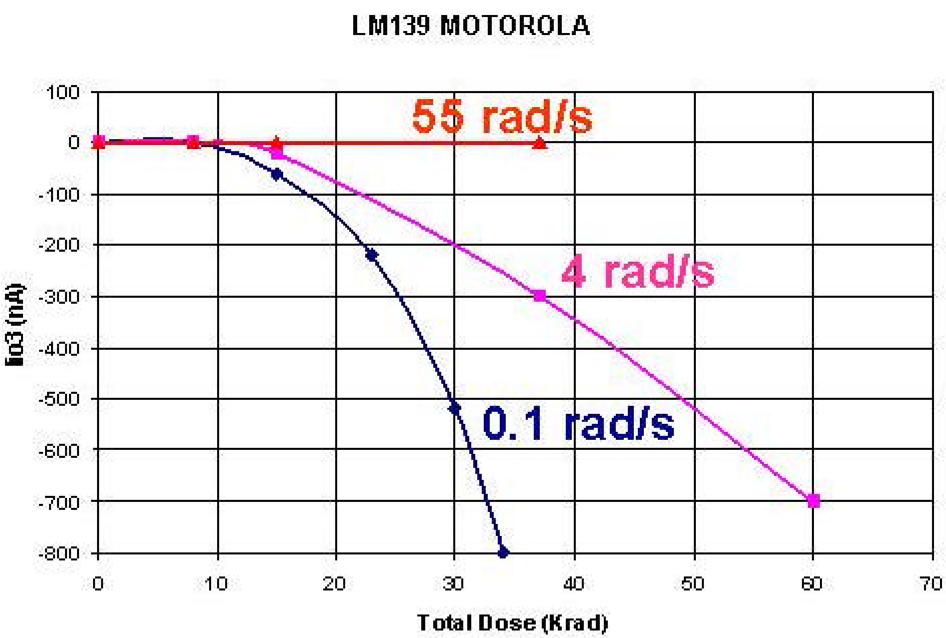
Rebound Effect on CMOS Devices

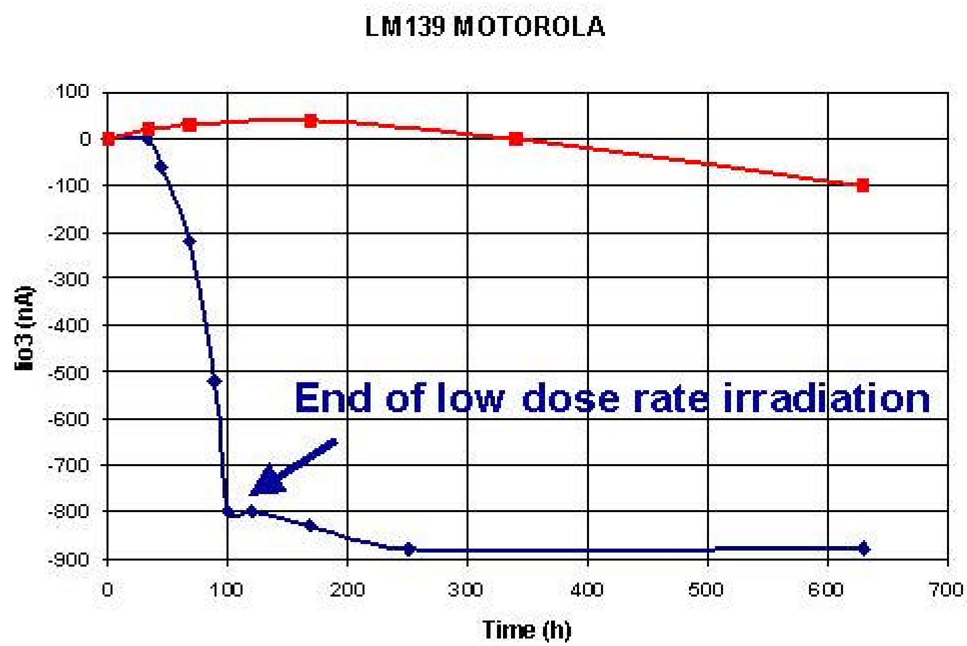


The high temperature annealing is very important to check for rebound effect on CMOS devices

After J Schwank, IEEE TNS vol 31-6, 1983

Current Test Standards do not Allow to Bound the TID Response of Linear Bipolar Integrated Circuits



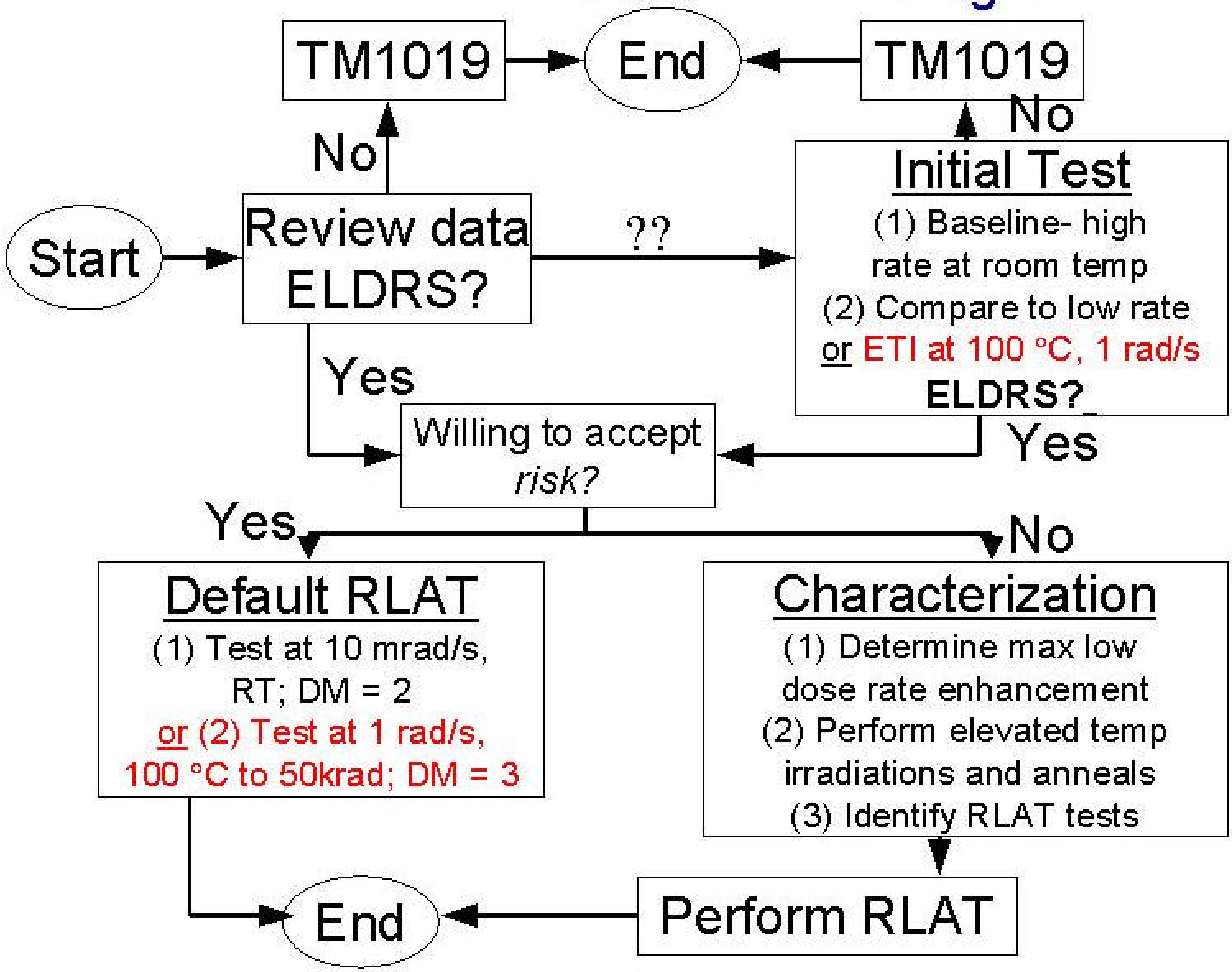


Effect of dose rate

The post irradiation annealing cannot simulate the low dose rate

After T. Carriere, IEEE TNS vol 42-6, 1995

ASTM F1892 ELDRS Flow Diagram

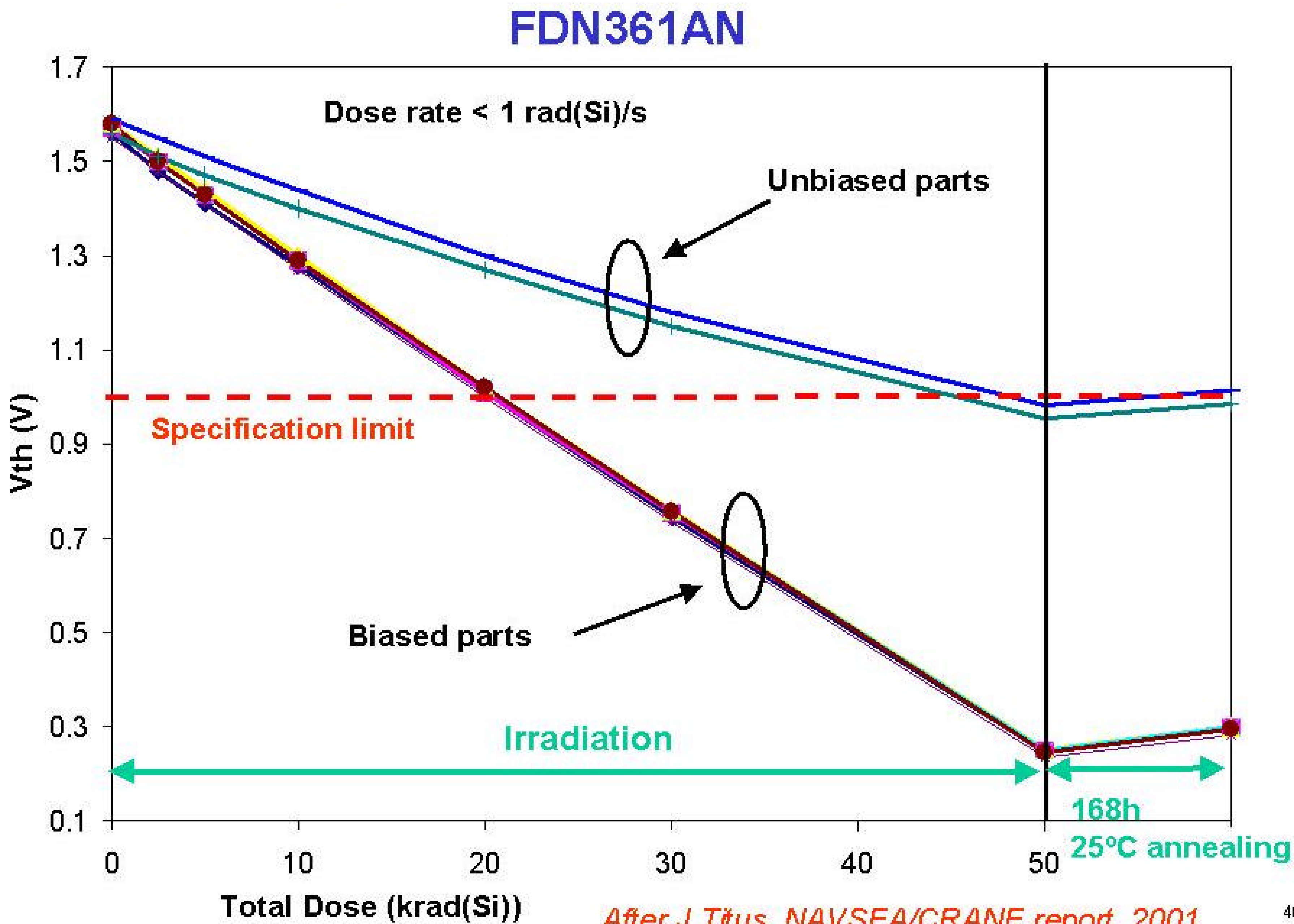


ELDRS: Enhanced Low Dose Rate Sensitivity
ETI: Elevated Temperature Irradiation
DM: Design Margin
RLAT: Radiation Lot Acceptance Test

The Temperature Environment and the Bias Conditions Also Have a Significant Impact on the TID Response

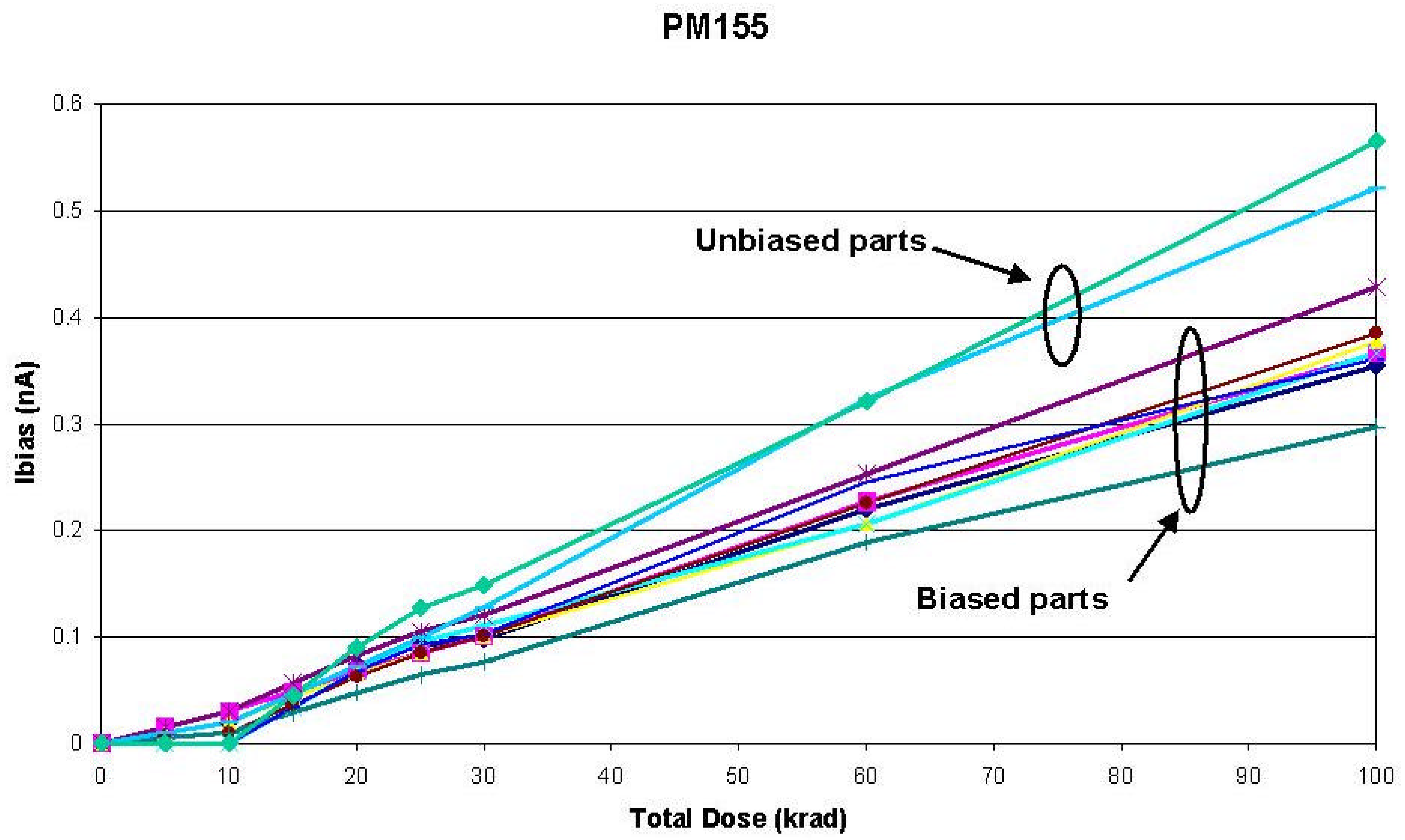
- Application Conditions : Temperature
  - Space : typical temperature between 0 and 70 °C.
  - Laboratory : ambient temperature .
    - *=> In general, the laboratory temperature is a worst case in comparison with application temperature*
- Application Conditions : Bias
  - Space : dynamic bias or OFF
  - Laboratory : Usually worst-case.
    - *=> The bias in laboratory is a worst case or equivalent in regard with the application bias*

TID Testing- Effect of Bias



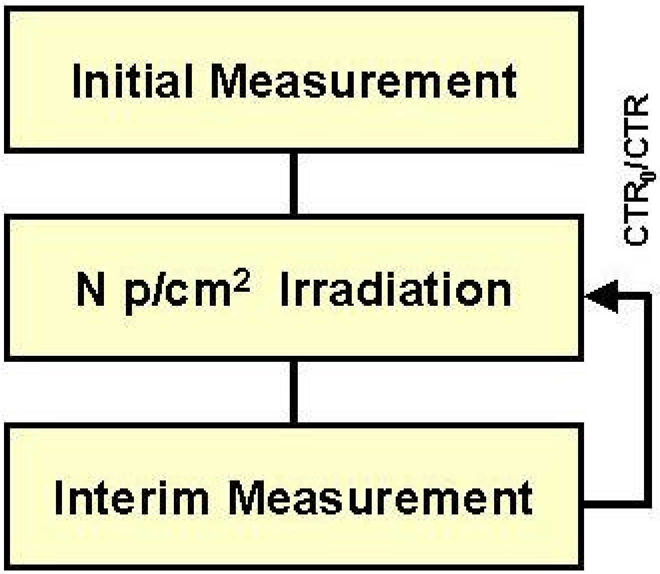
After J Titus, NAVSEA/CRANE report, 2001

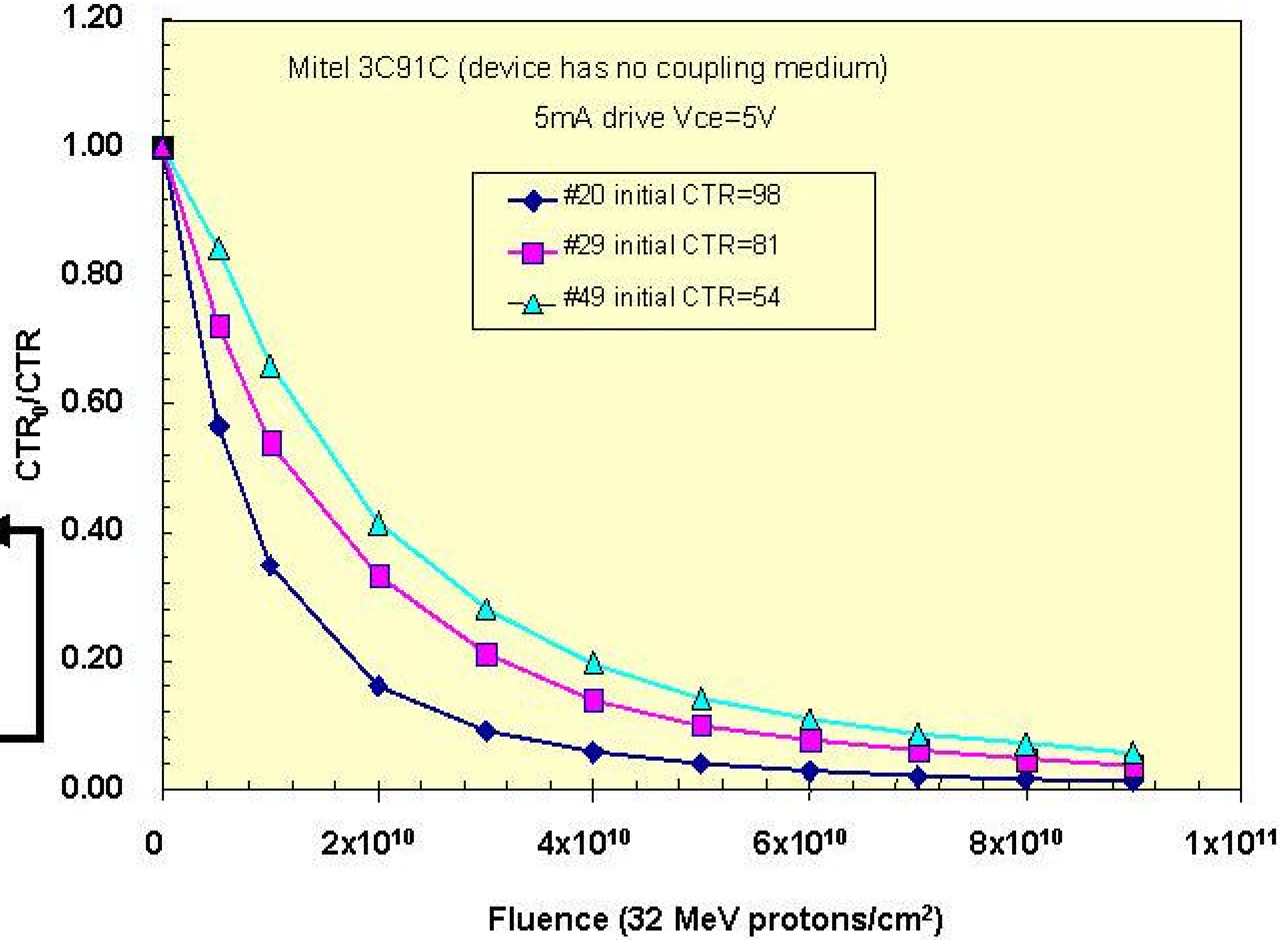
TID Testing- Effect of Bias



After T. Carriere, Astrium report, 1997

Displacement Damage Testing





After R Reed, IEEE TNS vol 48-6, 2001

CTR: Charge Transfer Ratio (Ioutput/Iinput)

Displacement Damage Testing

- Radiation source: Typically protons, one energy
  - on some devices (e.g. optocouplers), due to inconsistencies between experimental determination of damage factors and NIEL calculations, it is recommended to test the parts at multiple energies.
  - Larger Radiation Design Margins may be appropriate.
- Bias conditions
  - In general, less effect than for TID, in most cases parts are unbiased during irradiation.

SEE Testing

Test standards:

•JESD57 (heavy ions only)

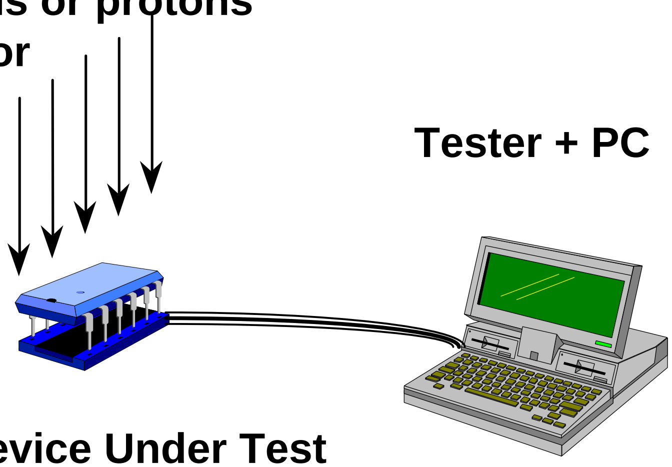
•ESA/SCC 25100 (heavy ions and protons)

Test guidelines:

•ASTM F1192-90 (heavy ions only)

Heavy ions or protons accelerator

Tester + PC

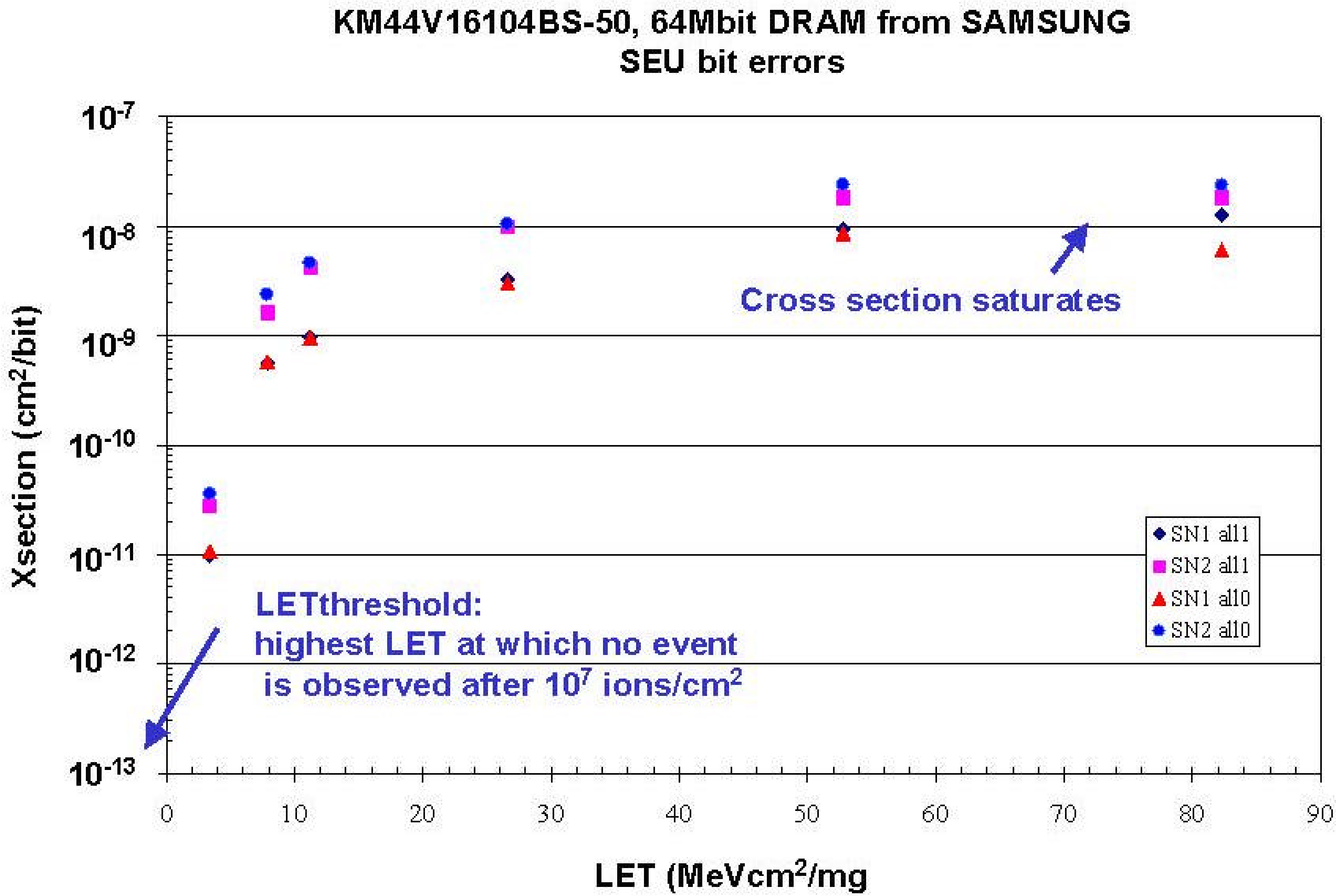


Device Under Test (DUT)

Cross section= number of observed SEE/particle fluence

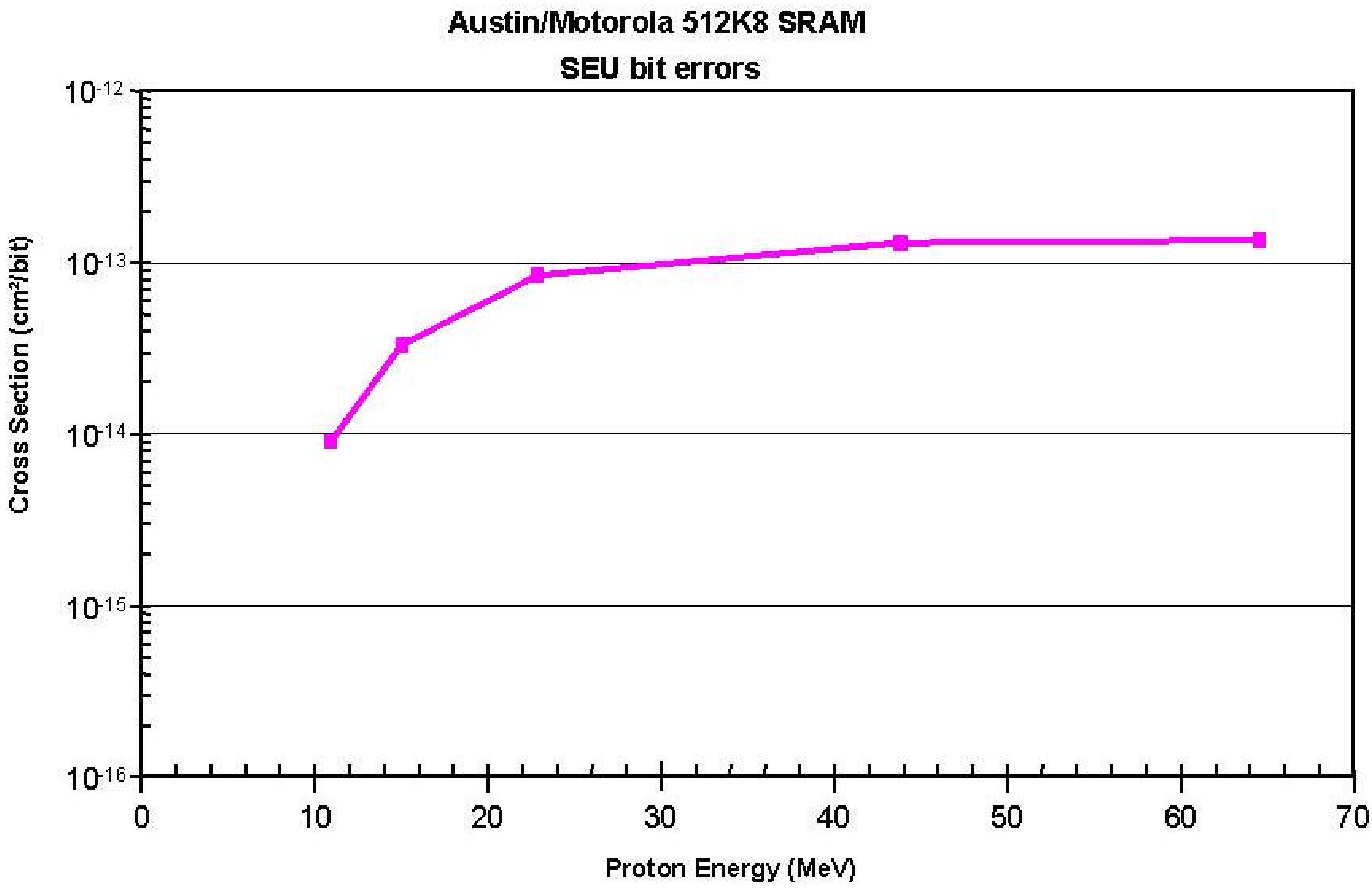
- Particle fluence in #/cm^2
- Cross section in cm^2 (or cm^2/bit)

Heavy Ions Cross Section Curves, Example



After C Poivey, ESA parts conference 2000

Proton Cross Section Curves, Example



After C Poivey, NSREC 1998 data workshop

SEE Testing - Radiation Sources

- Heavy ion accelerator
  - low energy,short penetration range compared to space heavy ions
    - parts are usually delidded for testing.
    - Tests performed under vacuum in most cases.
- Proton accelerators
  - space energy range available on accelerators
    - irradiation performed in Air.
    - parts generally do not need to be delidded.
    - A larger number of particles per test run is often needed for the tests (>10^{10} p/cm^2 compared to 10^7/cm^2 for heavy ions).The dose deposited may be significant.

SEE Testing

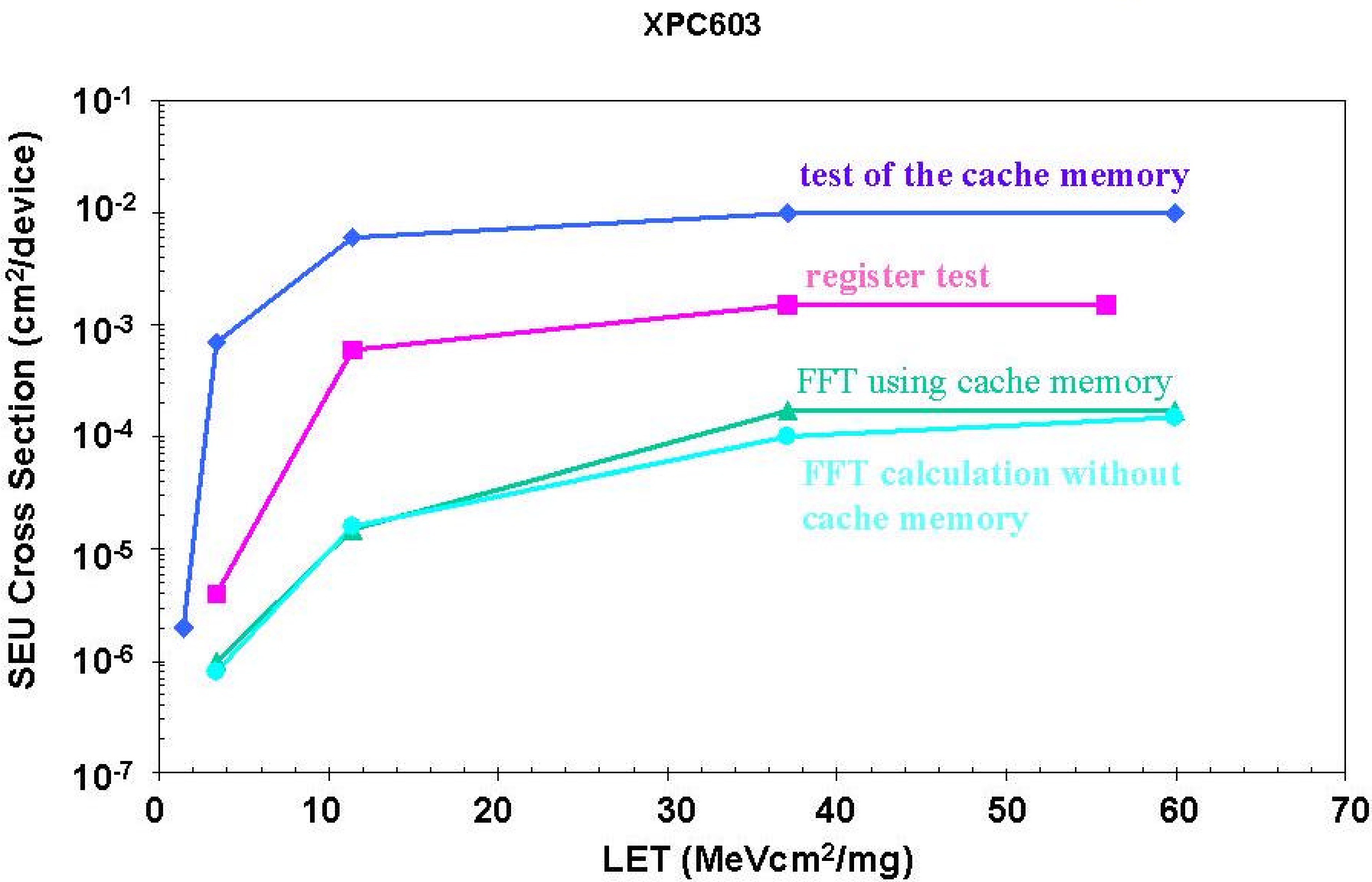
- Application conditions : temperature
  - Space : typical temperature between 0 and 70 °C.
  - SEE testing : ambient temperature .

    => *In general, high temperature is a worst case for SEE testing*
- Application conditions : bias
  - Space : dynamic bias
  - SEE testing : usually worst case, but not always

    => *High supply voltage is a worst case for Single Event Latchup (SEL). Low supply voltage is a worst case for Single Event Upset (SEU).*

    => *The test frequency and the test patterns have a significant impact on the test results.*

Effect of Test Pattern - Example



After F Bezerra, RADECS 1997 dataworkshop

RHA Outline

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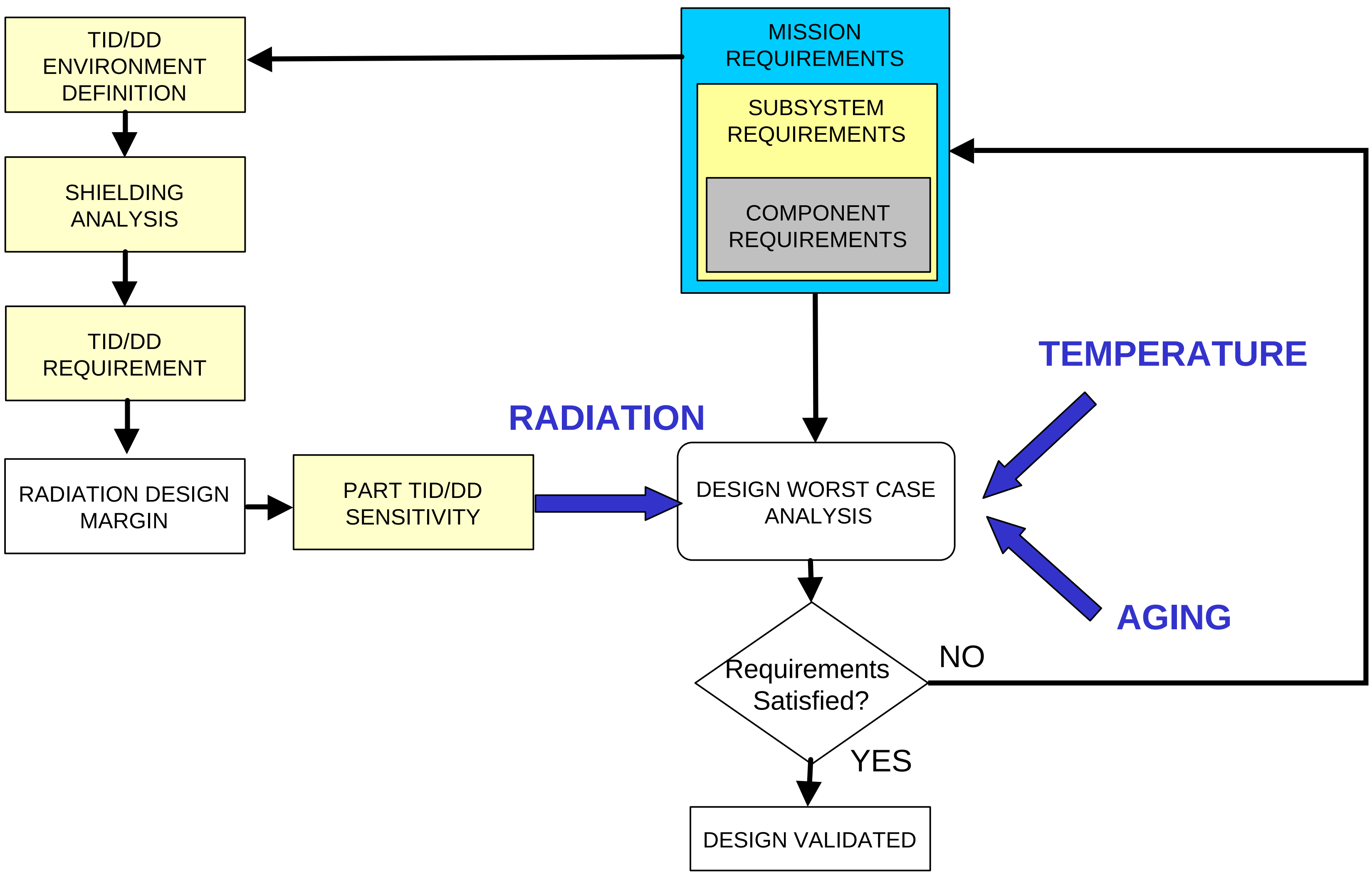
TID / DD - Analysis flow



Design Margin Breakpoint (DMBP)

DM < 1-2	< DM < 10	< DM < 100	< DM
Unacceptable	Hardness Critical-HCC1	Hardness Critical-HCC2	Hardness Non-Critical

- Radiation Lot Testing

Qualitative approach recommended for systems with moderate requirements

After MIL-HDBK814

Part Categorization Criteria (PCC)

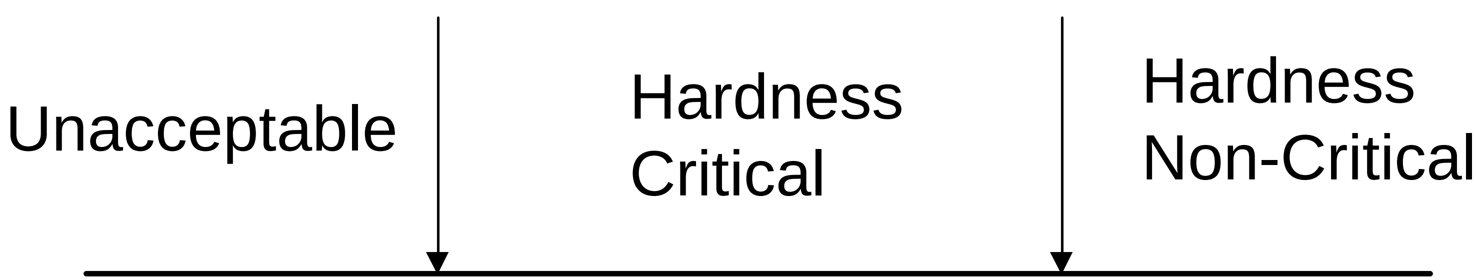
Log normal distribution law

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

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

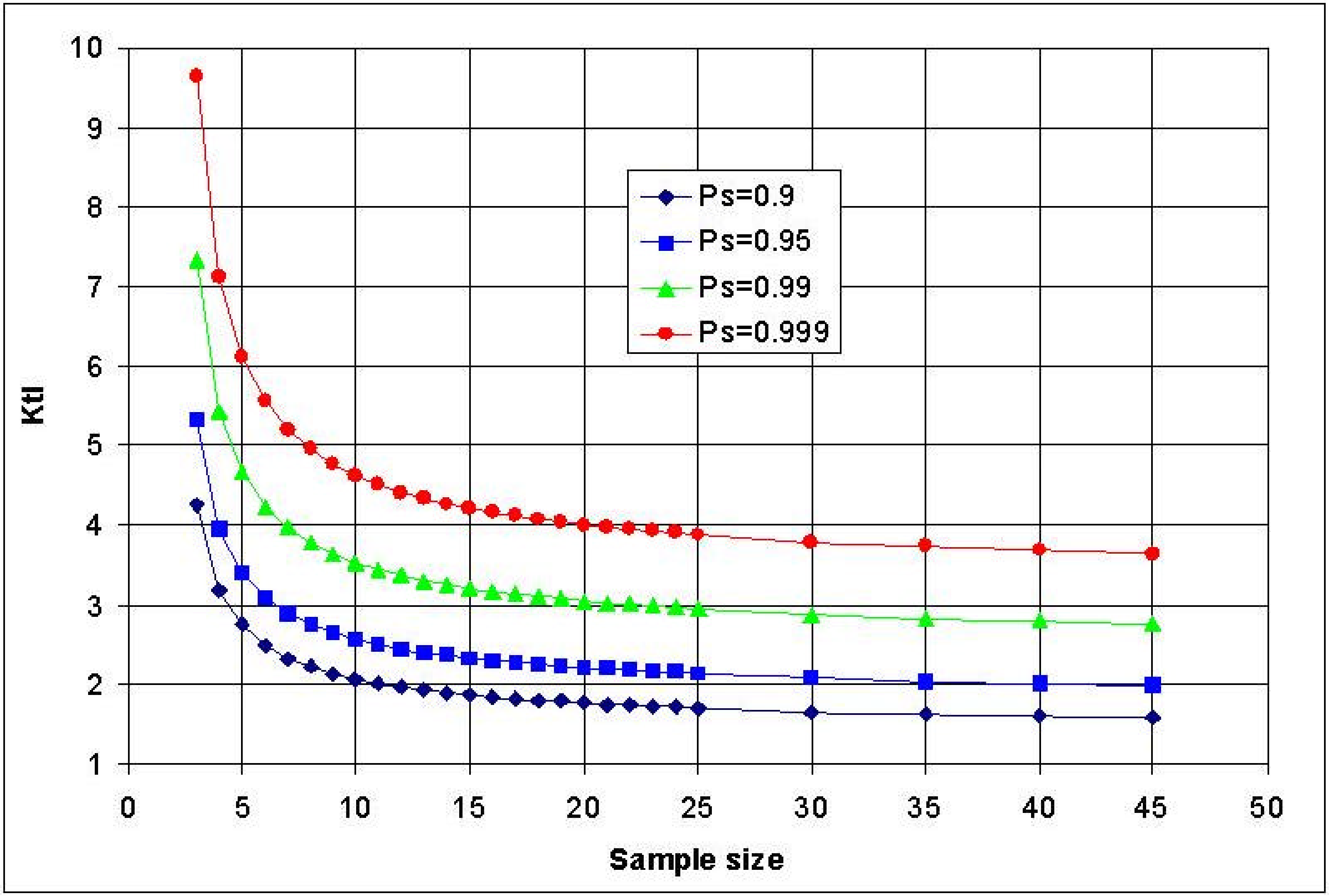
s = standard deviation of sample data

DM < 1-2 < DM < PCC < DM



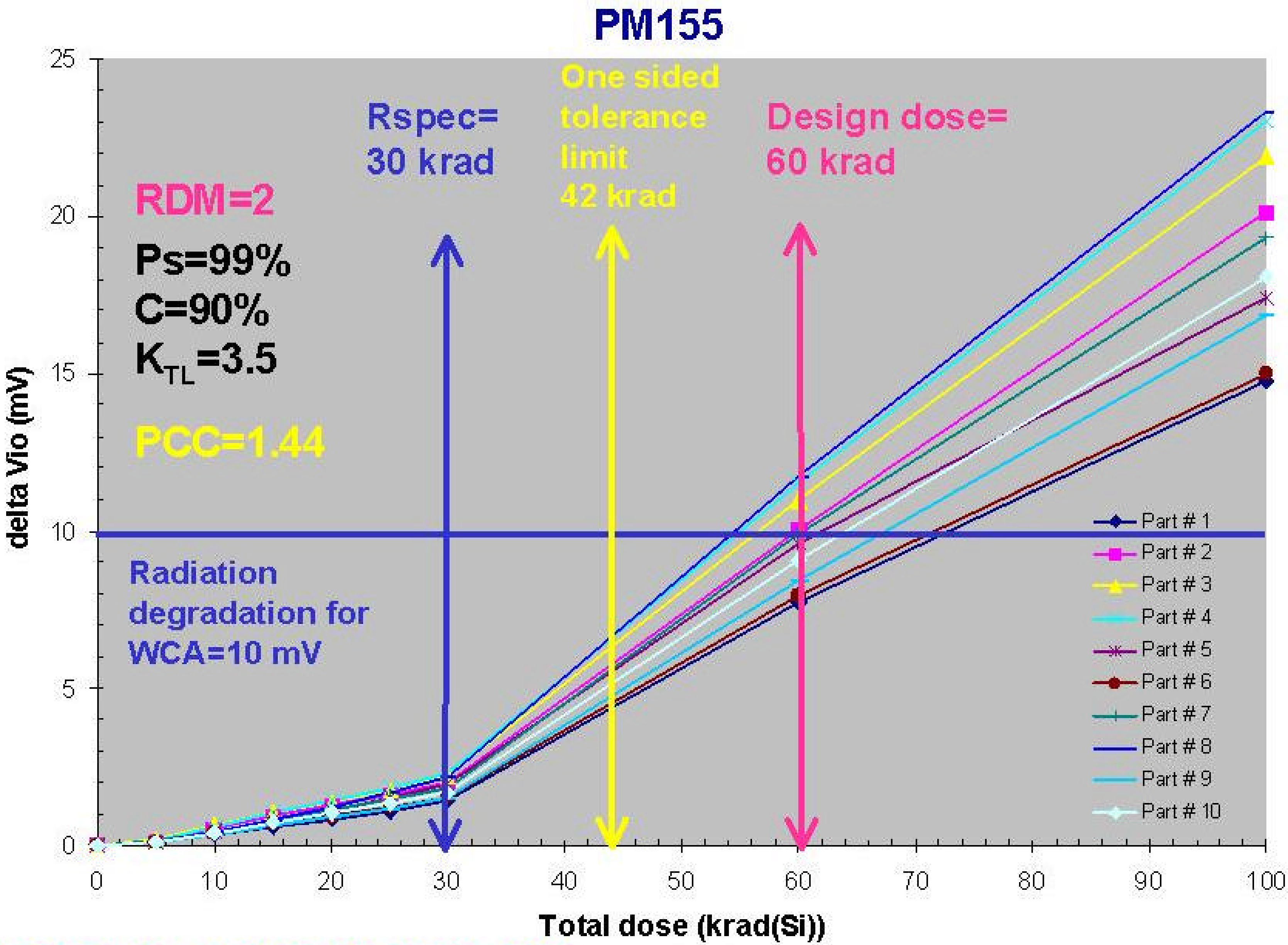
After MIL HDBK-814

One-Sided Tolerance Limits, K_{TL}, for 90% Confidence



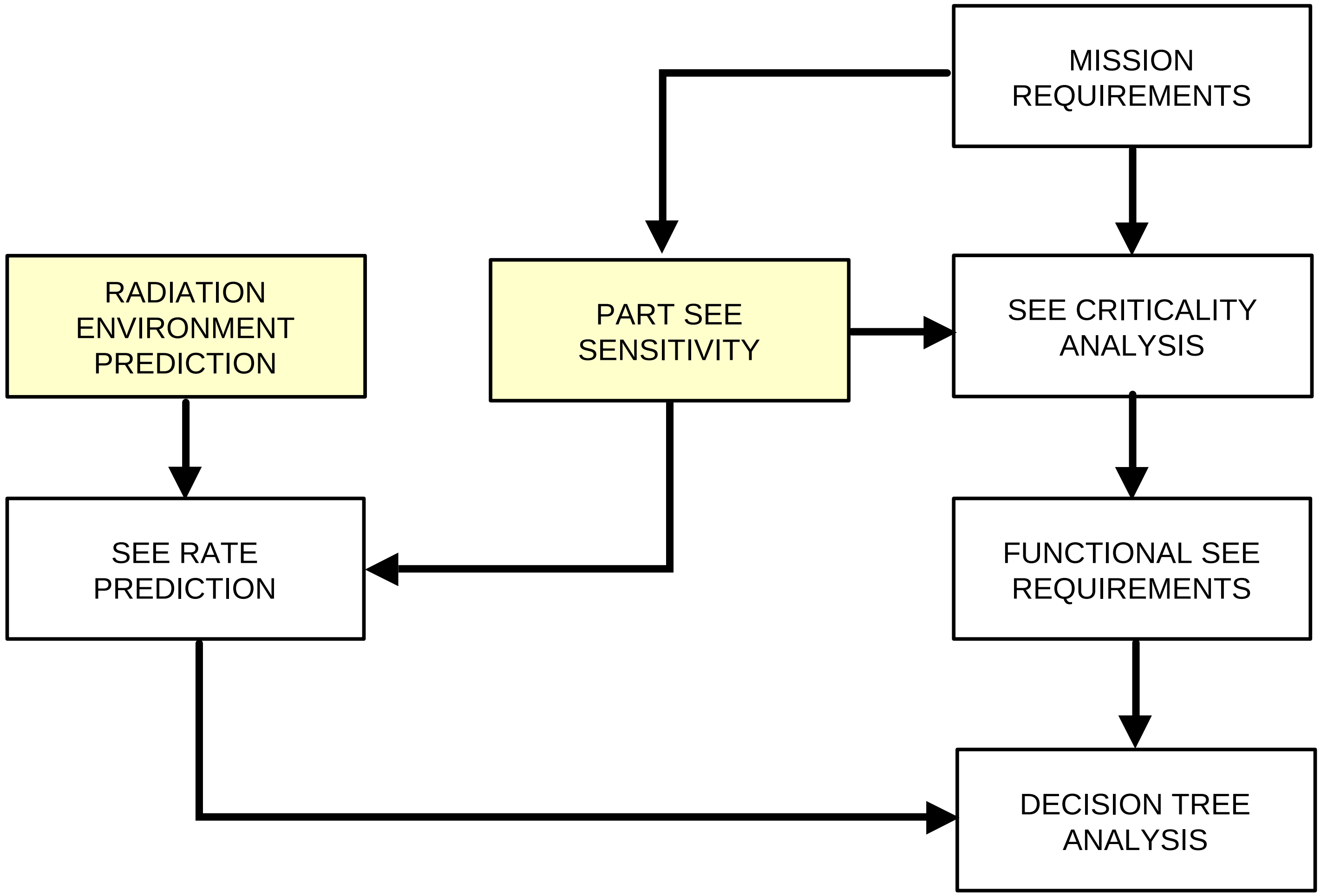
After R Pease, Rad Phys Chem 43, 1994

PCC- Example of Application



After T. Carriere, Astrium test report, 1997

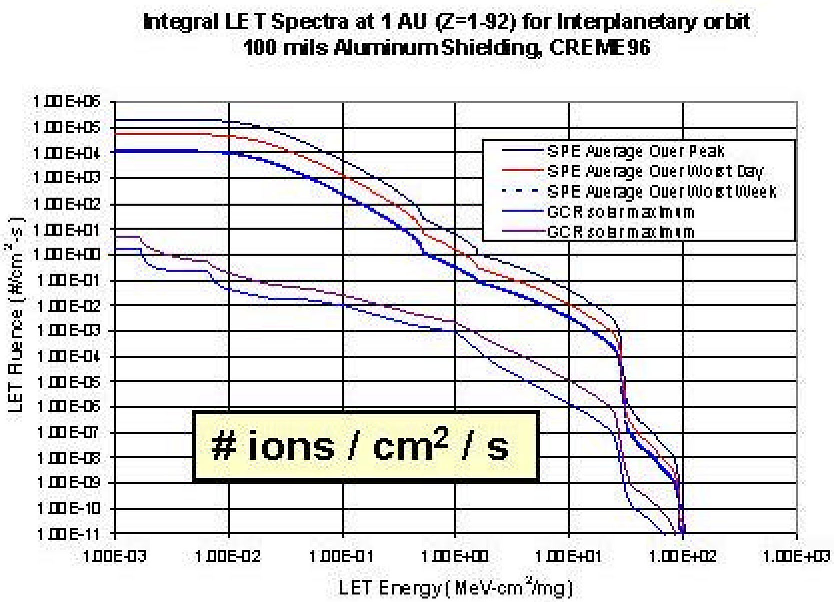
SEE - Analysis Flow

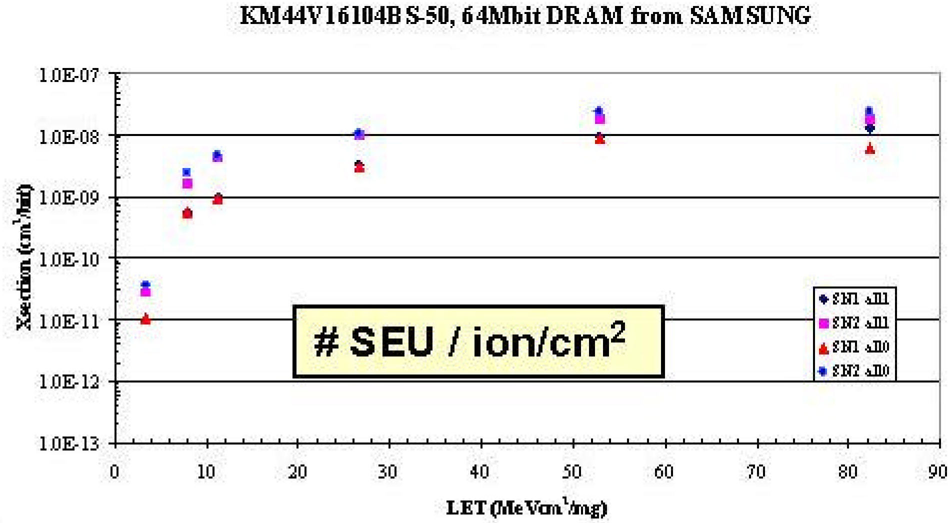


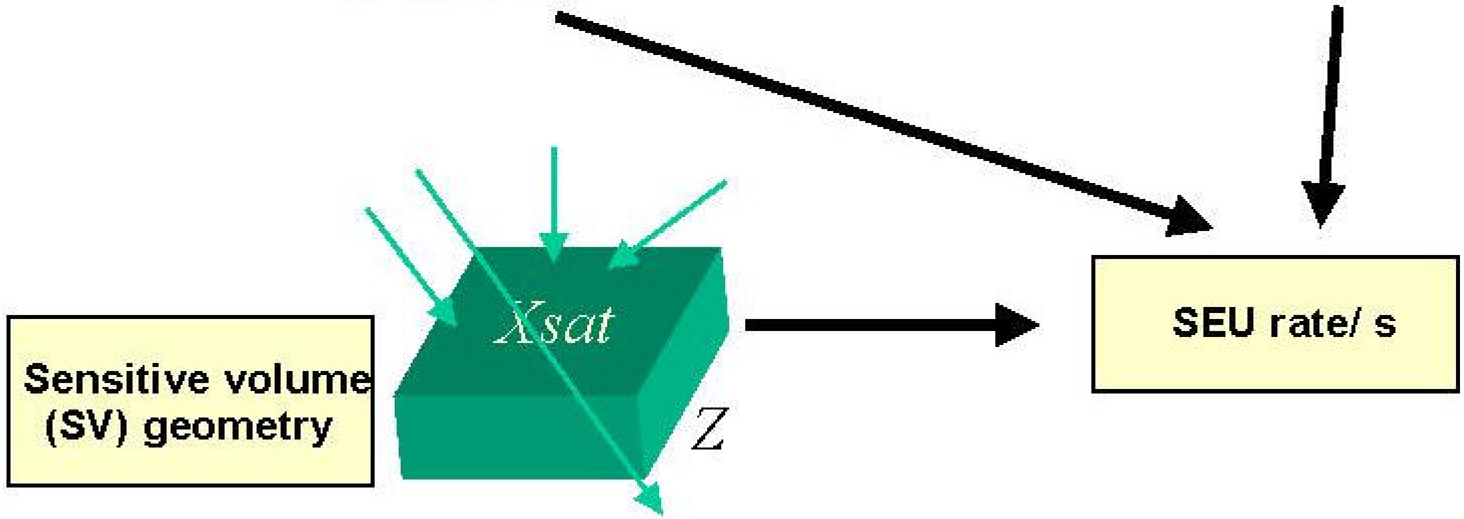
SEE - Analysis Requirement

SEE LET threshold	**Analysis Requirement**
> 100 $MeVcm^2/mg$	SEE risk negligible, no further analysis needed
15 $MeVcm^2/mg < LET_{threshold} < 100$ $MeVcm^2/mg$	SEE risk, heavy ion induced SEE rates to be analyzed
$LET_{threshold} < 15$ $MeVcm^2/mg$	SEE risk high, heavy ion and proton induced SEE rates to be analyzed

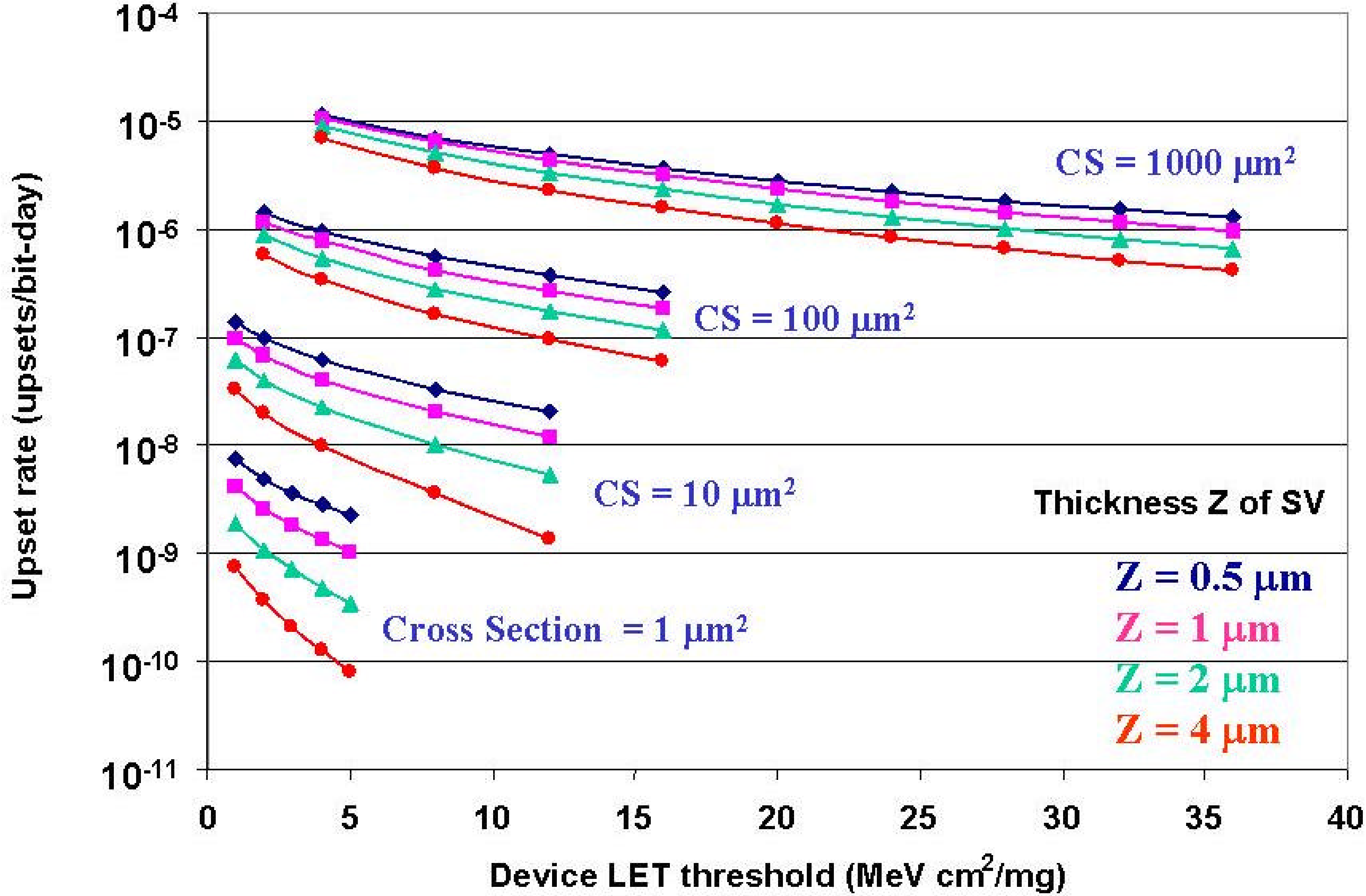
Heavy Ion SEE Rate Calculation
Integral RPP Method







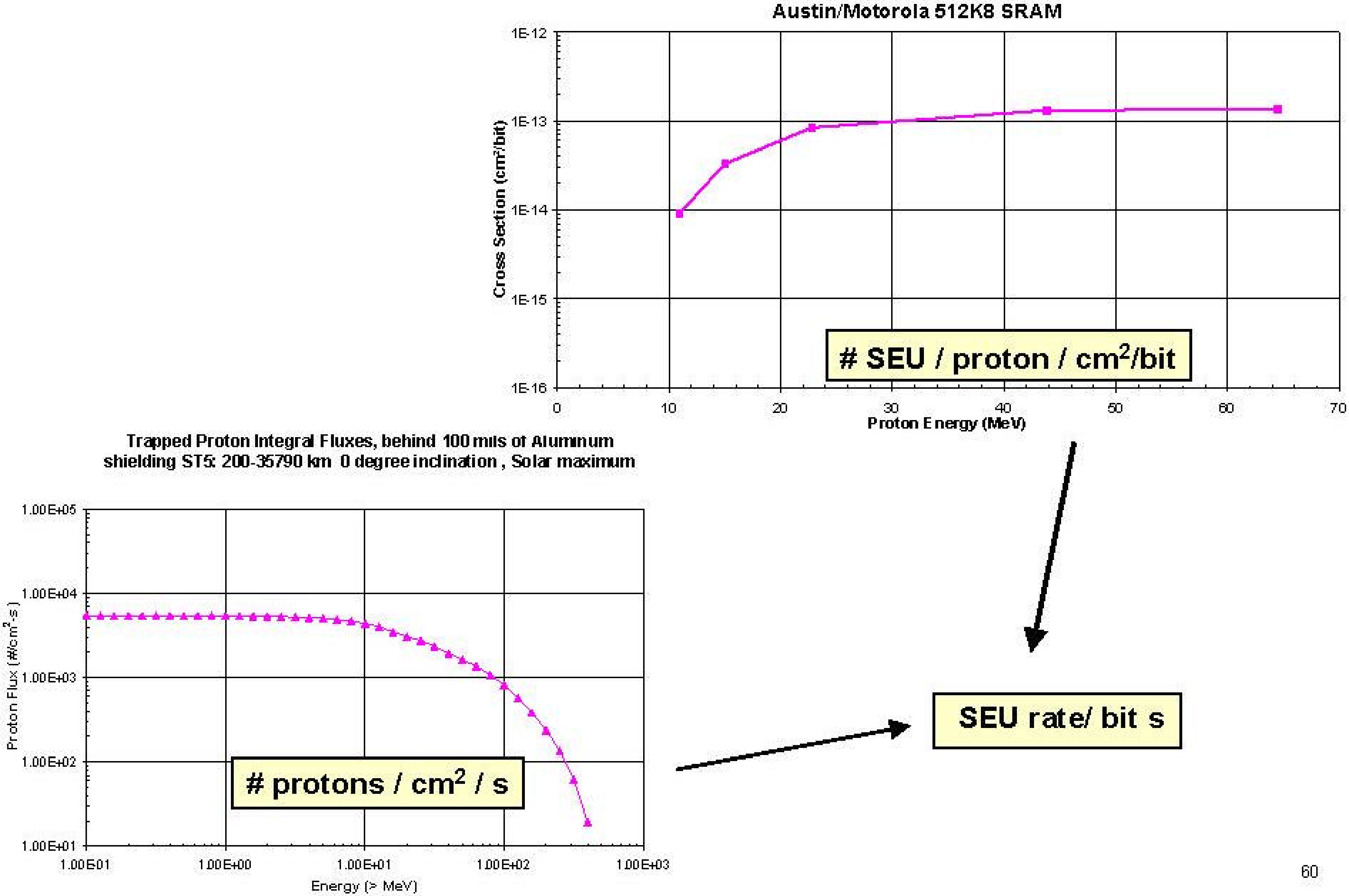
Comparative Upsets Rates Geosynchronous GCR Solar Minimum Environment, CREME 96



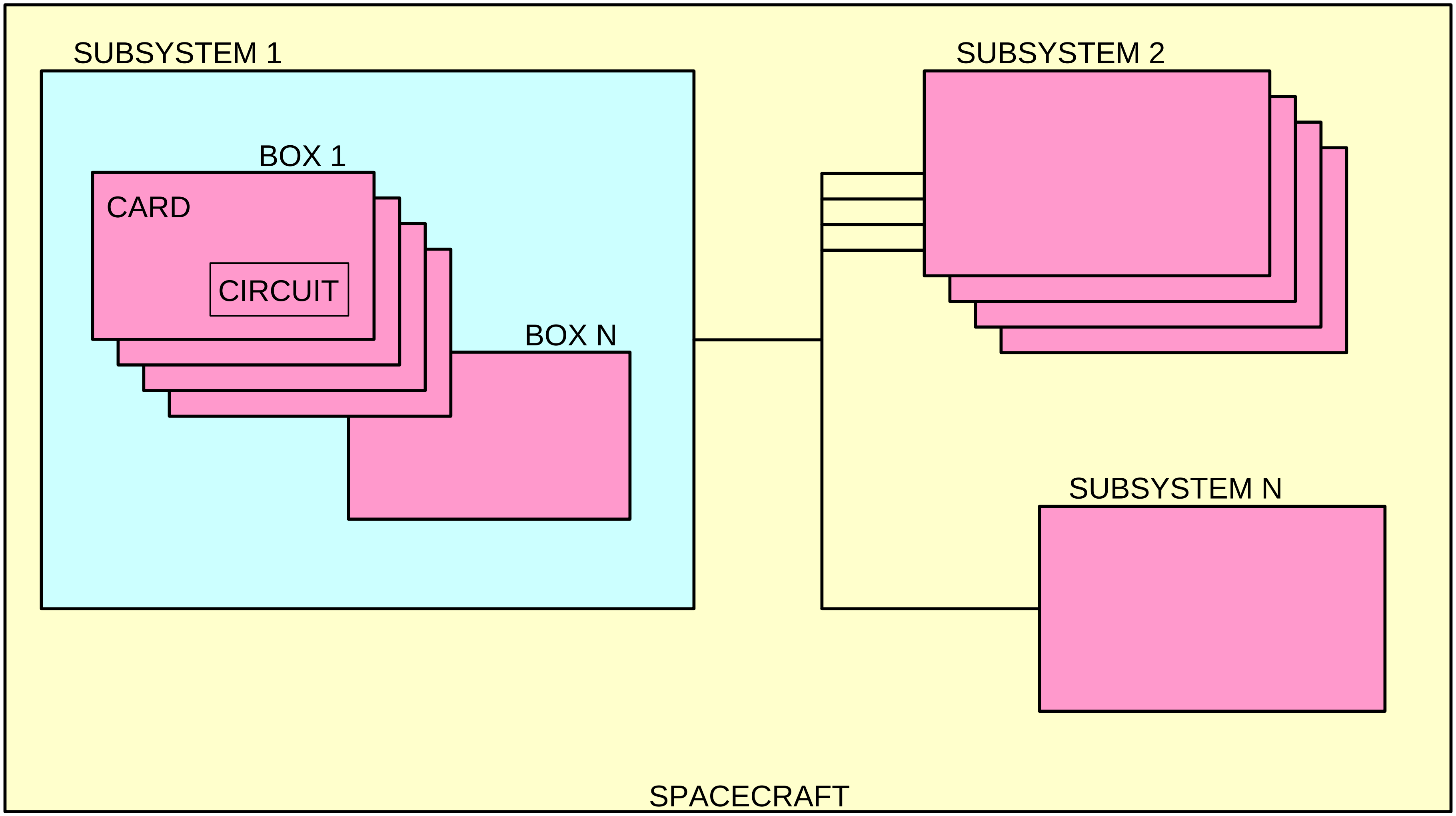
Uncertainties in SEE predictions are significant

After E Petersen, NSREC 1997 short course

Proton SEE Rate Calculation

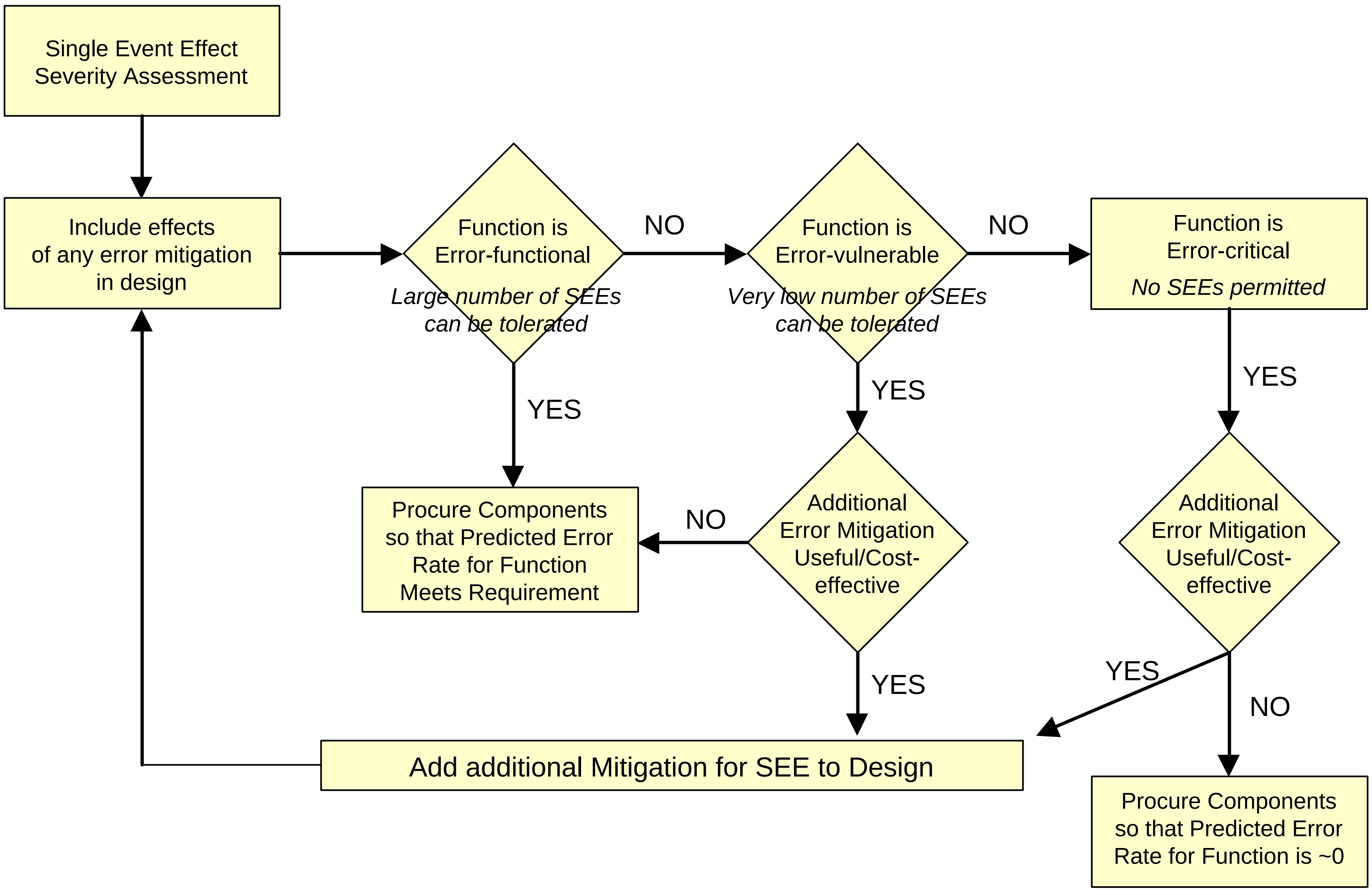


SEE Criticality Analysis (SEECA) Leads to System Performance



From SEECA document NASA-GSFC radhome web page
http://radhome.gsfc.nasa.gov

SEE - Decision Tree



From SEECA document NASA-GSFC radhome web page
http://radhome.gsfc.nasa.gov

Example of SEE Analysis

- Function Description
  - Memory module for Command&Data Handling (C&DH) subsystem processor : 8M*40 bits
  - 5 8Mx8 DRAM K4F660812D
  - SEU mitigation: Hamming (32,8) EDAC (correct one error, detect 2) + scrubbing
- Mission environment
  - 200km-35790 km
  - 0 degree inclination
  - 3 months duration
- Exposed to GCR, solar particles and trapped protons

DRAM: Dynamic Random Access Memory
EDAC: Error Detection And Correction

Example of SEE Analysis

- Heavy ion results
  - No SEL
  - No SEFI
  - No block/column error
  - MBU
  - SEU
- GCR Heavy ion induced SEE rate
  - 0.07 SEU/device day
  - 10^{-4} MBU/device day
- Proton results
  - No SEL
  - No SEFI
  - No block/column error
  - No MBU
  - SEU
- Trapped Proton induced SEU rates
  - 3 SEU/device day

Example of SEE Analysis

- Function criticality analysis& requirement
  - one uncorrected error may cause the C&DH processor to fail, and then to reset
  - error vulnerable class: < 1 failure/mission is allowed

The failure rate is acceptable for this mission,
but a failure could happen the first day of the mission

- Function failure rate for background environment (GCR+trapped protons)
  - MBU ~ 0.04/mission
  - Accumulation of 2 SEU between two consecutive scrubbing of a data word

$\text{Rate/s}=\{1-[e^{-\mu}x(1+\mu)]^N\}/t_i$ *

- t_i=time required to update the total system memory=240s

  μ=mean number of upsets per memory word during t_i=5E-9
- N=total number of system memory word=8M

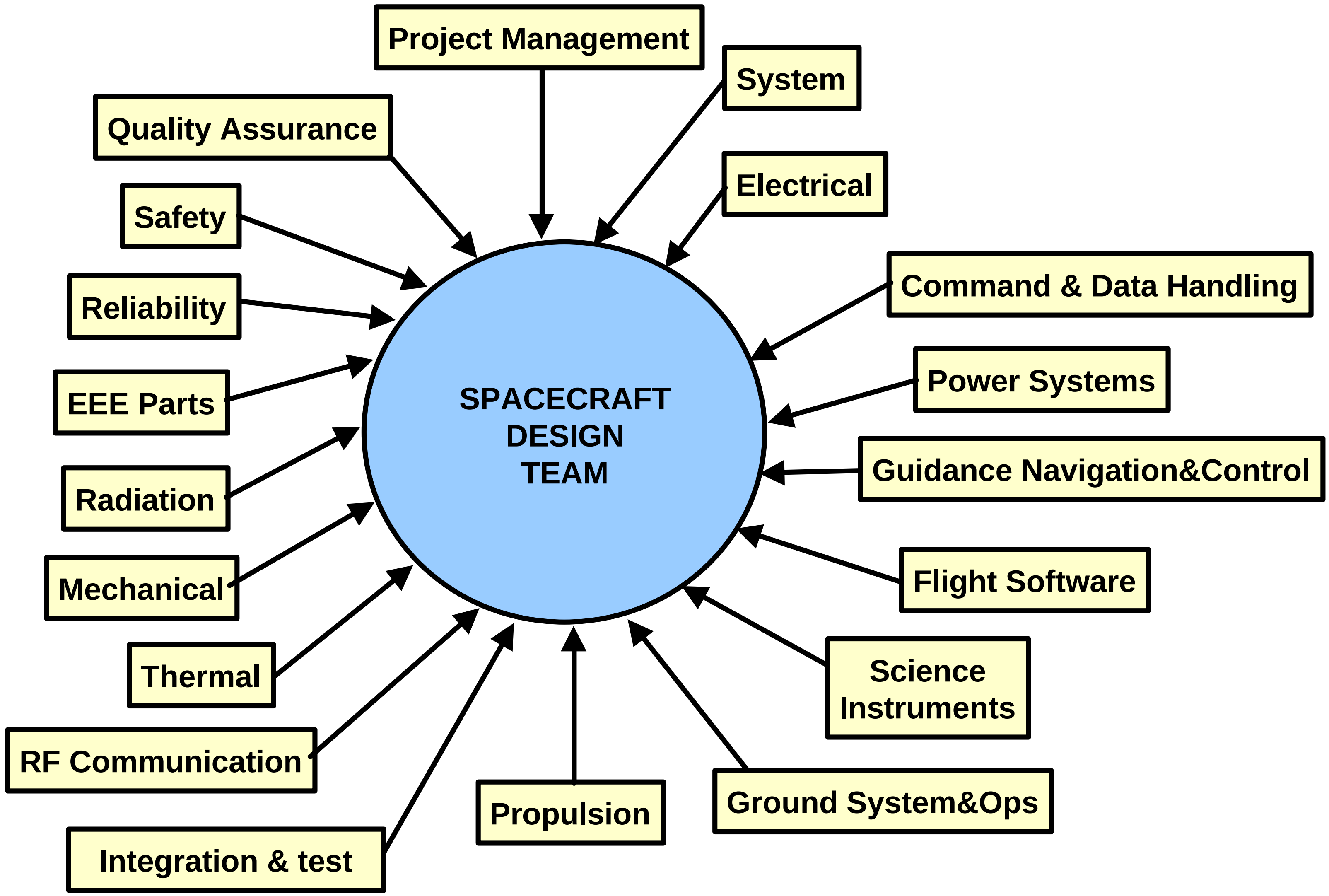
Rate/year~ $4x10^{-6}$/mission

*After JB White, IEEE Trans on Aerospace and Electronics Systems, vol 18-1, 1982

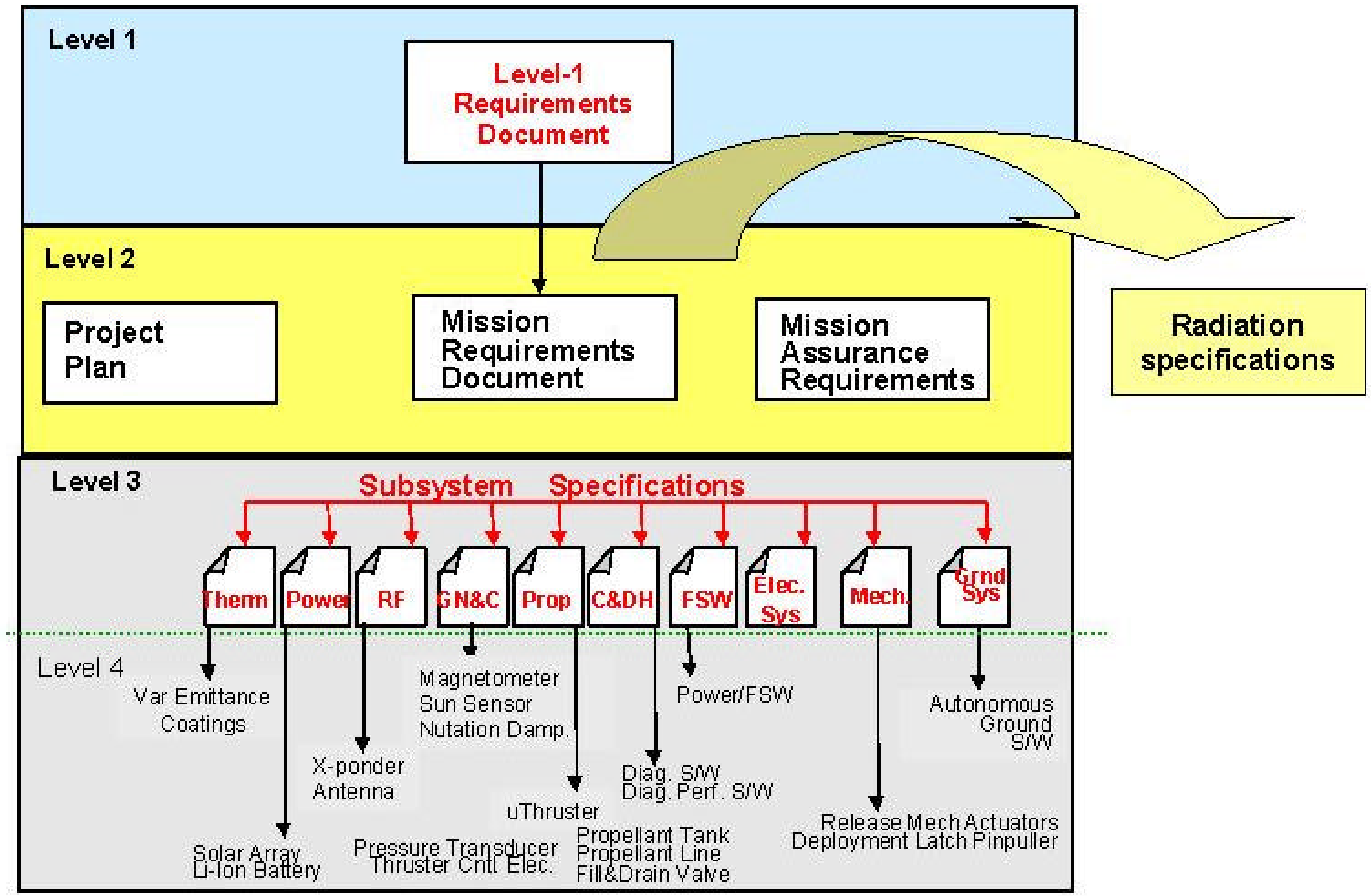
RHA Outline

- Overview
- Define the mission radiation environment
- Bound the part response
- Define the function/subsystem/system response
- Management of RHA
- Conclusion

Management of RHA



Project Requirements Flow-Down



Radiation Specifications

- Environment specification
  - Particle flux, peak and average, shielded and unshielded
  - Mission dose depth curve
- Radiation Hardness assurance specification
  - Mission top level requirements
  - Required design margins
  - Test requirements

Radiation Hardness Assurance During the Program Life

- During the Proposal/feasability Phase
  - Draft Environment definition
  - Draft Hardness assurance requirement
  - Preliminary studies
- At the Preliminary Design Review (PDR)
  - Final Environment definition
  - Electronic design approach, ..
  - Preliminary spacecraft layout for shielding analysis
  - Preliminary shielding analysis
  - Final Hardness assurance requirement definition
- At the Critical Design Review (CDR)
  - Radiation test results
  - Final shielding analysis
  - Circuit design analysis results
- After CDR
  - Radiation Lot Acceptance tests
- After Launch
  - Failure analysis

RHA Outline

- Overview
- Define the mission radiation environment
- Bound the part response
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Conclusion

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

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