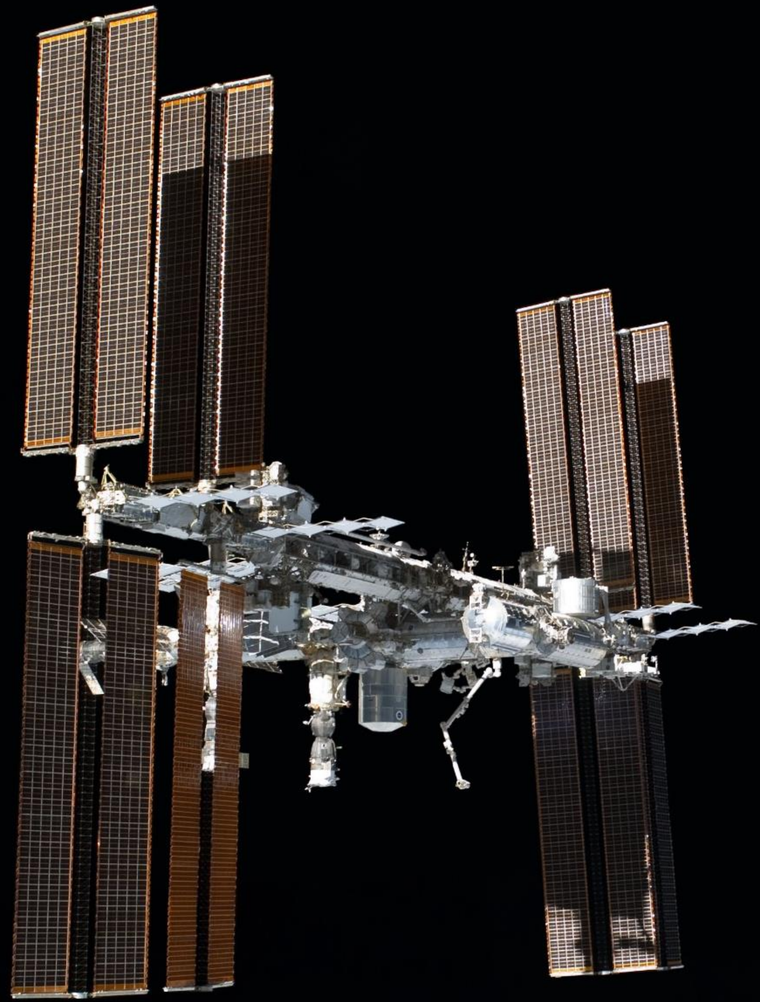

Space Radiation Effects on Avionics Systems:

Single Event Environment (SEE) Effects on Avionics Components and Systems

Hazard Causes

Hazard Effects

Hazard Controls

ES4/Dr. Steve Koontz, ISS System Manager for Space Environments

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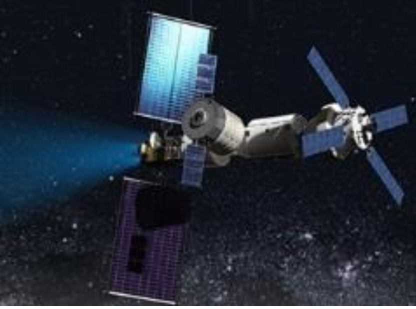
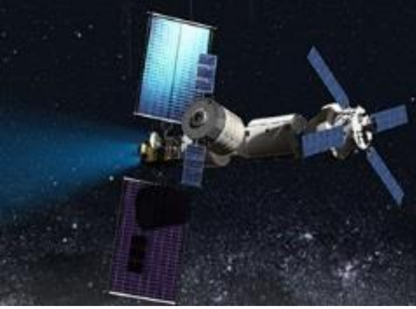


Presentation Outline

Space Radiation Effects
Single Event Effects

- **Why do we care about this?**
  - **Safety Reliability and Mission Success (SRMS)**
  - **Does your hardware meet mission lifecycle SRMS requirements and how can you demonstrate that it does?**
  - **A very brief introduction to Reliability Engineering as applied to spacecraft and sub-system verification processes**
  - **The role of system architecture in mitigating SEE hazards**
- **Single Event Effects (SEE) on Avionics Components and Systems**
  - **Single Event Effects Processes**
    - **Microelectronics as charged particle detectors**
    - **Metal oxide and complimentary metal oxide semiconductor basics (MOS and CMOS)**
    - **Soft errors – Correctable with software/firmware action and/or by power cycling and rebooting**
    - **Hard failures – hardware damage, loss of function, not correctable**
- **SEE Effects Mitigation**
  - **Parts selection and screening tests**
  - **Error Detection and Correction (EDAC), Fault Isolation Detection and Recovery (FDIR)**
  - **Hardware Redundancy**
  - **Flight Rules and Procedures - Manual ground/flight crew intervention for anomaly resolution**

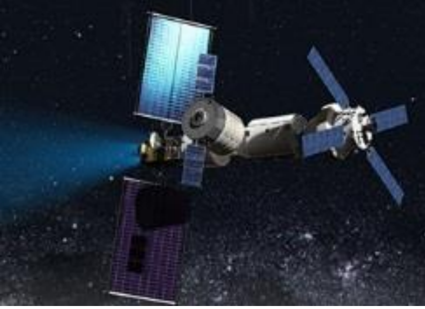


Presentation Outline

Space Radiation Effects

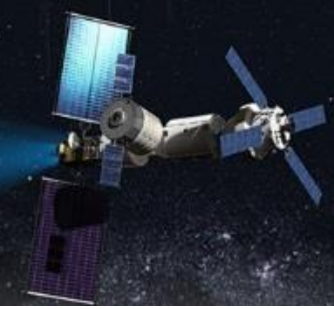
- **SRMS Testing, Analysis, and Verification**
  - **General approach to SEE Testing - – Test like you fly and fly like you test? - well not exactly…**
  - **Program design environments for verification and SEE testing design**
  - **Conventional heavy ion testing of individual parts**
  - **Board/Box level high energy (~200 to 500 MeV) proton testing**
  - **Board/Box level high energy (~ 1 GeV) heavy ion testing**
- **And how well does all of this work?**
  - **ISS LEO – Pre-flight predictions vs. in-flight performance**
    - **ISS Multiplexer De-Multiplexer (MDM) System (up-screened Hi-Rel COTS)**
    - **ISS PCS systems (examples of "consumer" COTS testing and utilization approach)**
  - **Interplanetary GCR Environment, including GEO**
    - **Multiple spacecraft**
    - **Comparing predicted performance with in-flight performance**
  - **Interplanetary Solar Particle Event Environments**
    - **Multiple spacecraft summary**
    - **Comparing predicted performance with in-flight performance**
- **Summary**
- **Back-up and References**

Why do we care about this?



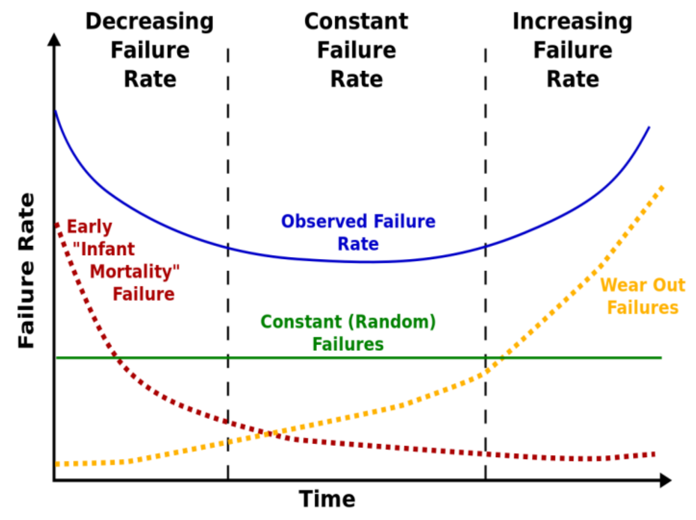
Space Radiation Effects
Safety, Reliability, and Mission Success (SRMS)

- If not accounted for during spacecraft design, development, and test:
  - You may get lucky and operate successfully via workarounds
  - Or you may fail to achieve mission objectives, operational reliability requirements or, in extreme cases loose the entire spacecraft (and possibly the crew)
- The most common hazard effects of the SEE space radiation hazard cause are:
  - Avionics system anomalies
    - Single event effects leading to loss of safety related "must-work must-not-work" functions
  - Electrical power system anomalies
    - Destructive failures of MOS power transistors
- SRMS requirements are levied on almost all major (high cost and high reliability requirement (Hi Rel)) spaceflight programs along with mandatory verification of those requirements documented by some combination of test and analysis prior to flight.
  - Programmatic risk acceptance is the exception not the rule!
    - Risk acceptance depends on the outcome of risk trade studies and program management makes that decision
  - So how do you verify that your spacecraft and it's subsystems meet the program's SRMS requirements?
    - And /or - How do determine if risk acceptance is a viable approach and document that for management?



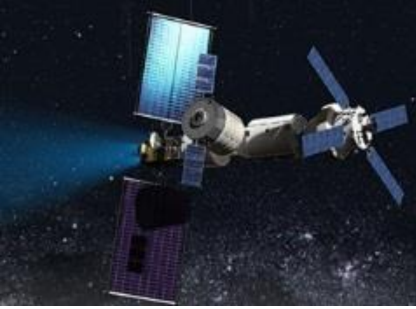
A very brief introduction to Reliability Engineering: The Bathtub Curve

- Observed failure rate as a function of elapsed time, Fail(t), can be represented as the sum of three terms:
  - Infant Mortality Failure = IMF(t)
  - Constant Random Failures = CRF(t)
  - Wear out Failures = WOF(t)
- **Fail(t) = IMF(t) + CRF(t) + WOF(t)**
- In Hi Rel programs, IMF(t) should be close to zero and is made so by:
  - parts and materials selection, screening, and burn-in
  - qualification and acceptance testing
- CRF(t) risk is minimized by:
  - parts selection and screening test
  - residual effects are managed with:
    - system architecture (redundancy and flight spares)
    - Failure Detection Isolation and Recovery (FDIR) and Error Detection and Correction (EDAC) hardware/software
  - Accumulated unrecoverable CRFs can limit the functional life of your flight systems
  - **SEE effects are a CRF(t) phenomena**
- WOF(t) ultimately determines the functional life of your flight hardware and is maximized by
  - Selection of parts and materials with verification by testing and analysis to demonstrate that program longevity requirements are met. (cumulative latent SEE damage is not the same as TID damage – ref "Latch-up")



A very brief introduction to Reliability Engineering: Probability, Randomness and Reliability Estimation

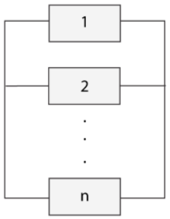
- **Reliability - The probability that a component or system can perform its intended function for a specified time interval, t, under specified conditions**
  - **Reliability = R(t) = (1 – probability of failure) = (1 – F(t)), where F(t) = unreliability**
  - **MTTF** = mean (expected or average) operating time to failure of a non-repairable system
    - Example - test 3 identical systems starting from time 0 until all of them fail.
      - The first system failed at 10 hours, the second failed at 12 hours and the third failed at 13 hours.
      - The MTTF is the average of the three failure times, which is 11.7 hours.
  - **MTBF** = mean (expected or average) operating time between repairable failures (repair time isn't included here)
    - Example - test 3 identical systems starting from time 0 and record total operating time to first repairable failure for each.
      - The first system operated for 15 hours, the second operated for 20 hours and the third operated for 10 hours.
      - The MTBF is the average of the three operating times before failure, which is 14 hours.
  - **Reliability estimates are based on Failure Rate = λ (determined by test and analysis, i.e. time and $$$)**
    - $1/MTTF = \lambda_{MTTF}$ and $1/MTBF = \lambda_{MTBF}$
    - If λ is constant for the time interval of interest, then the following expressions apply;
      - $R(t) = e^{-\lambda t}$ **and** $F(t) = (1 - e^{-\lambda t})$
    - Failure rates for complex assemblies or systems can be calculated using the individual component failure rates combined with the assembly or system architecture models
- **Note that longer "specified time intervals" drive program schedule and budget in a big way**



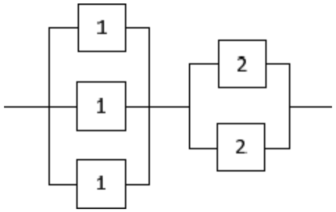
A *very brief* introduction to Reliability Engineering: Redundancy, spares, and overall system reliability (Or how do I build reliable systems with unreliable parts?)

- **Select a system architecture that is robust to part failures**
- So what will it be, serial, parallel, or a little or both?
  - Serial - n component/single string **series** system – if one component fails then the system fails
    - **Serial System Example - Rsys = R1 x R2 x R3 = 0.97 x 0.97 x 0.97 = 0.9127**
  - Parallel - n component/string **parallel** system – the system will still function if only 1 of n strings survives
    - Example for n = 3, R1 = 0.97, R2 = 0.97, R3 = 0.97;
    - **Parallel System Example - Rsys = 1 – $(1\text{-Rn})^3$ = 1 - $(1\text{-}0.97)^3$ = 0.9997**
  - Or a little of both…
    - Series/parallel with cross strapping
- Bottom line:
  - Single string serial systems cannot achieve long-term high reliability even with reliable components , but are often used in systems with short operation times (like launch vehicles and munitions) (what about Galileo?)
  - **Multi-string parallel redundant systems can exceed component reliability**
    - Note - This approach isn't applicable to simple problems that don't admit to serial or parallel architecture reliability analysis , e.g. when reliability is determined by wear-out rates (TID/DDD)

Single string serial system – a single component failure can fail the system



Multi-string string parallel system. If only one string is required for functionality then all the strings must fail to fail the system.



Example of a cross strapped redundant system

Space Radiation Effects

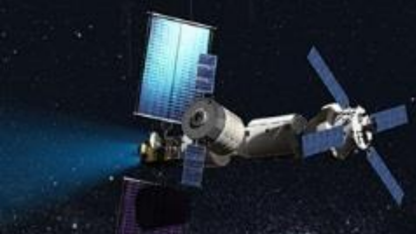
What kind of SRMS requirements will you encounter and how do you meet them?

- **None (well, not really)** - Hi Rel Programs accept the risk only if you can show that there isn't much risk to accept
  - **No hazard control functions and hardware failure isn't a hazard cause (and you will need to prove that via Failure Modes and Effects Analysis (FMEA))**
    - Pre-positioned spares or back-up units available?
    - Limited operating time to minimize failure probability
  - Examples
    - Criticality 3 ISS system hardware
    - Some Commercial Off The Shelf (COTS) crew health equipment on ISS
    - ISS Payloads (show only no failure or combination of failures create a hazard for ISS)
- **System safety and reliability requirements can also be met with Error Detection and Correction (EDAC) and or Fault Detection Isolation and Recovery (FDIR) software combined with operational constraints, redundancy, pre-positioned spares, and flight rules/procedures**
  - Example - ISS Multiplexer De-Multiplexer (MDM) - EDAC, FDIR, spares, and operator intervention
  - Example – ISS PCS (Up-screened COTS Laptops) system - Operational constraints and spares
    - Un-reliability quantified by test and analysis enable operations planning with constraints designed to overcome hardware limitations
- **Hi-Rel Programs increasingly forced to find a way to use "COTS parts"**
  - Class S parts have very small market market volume so they are becoming very hard to find

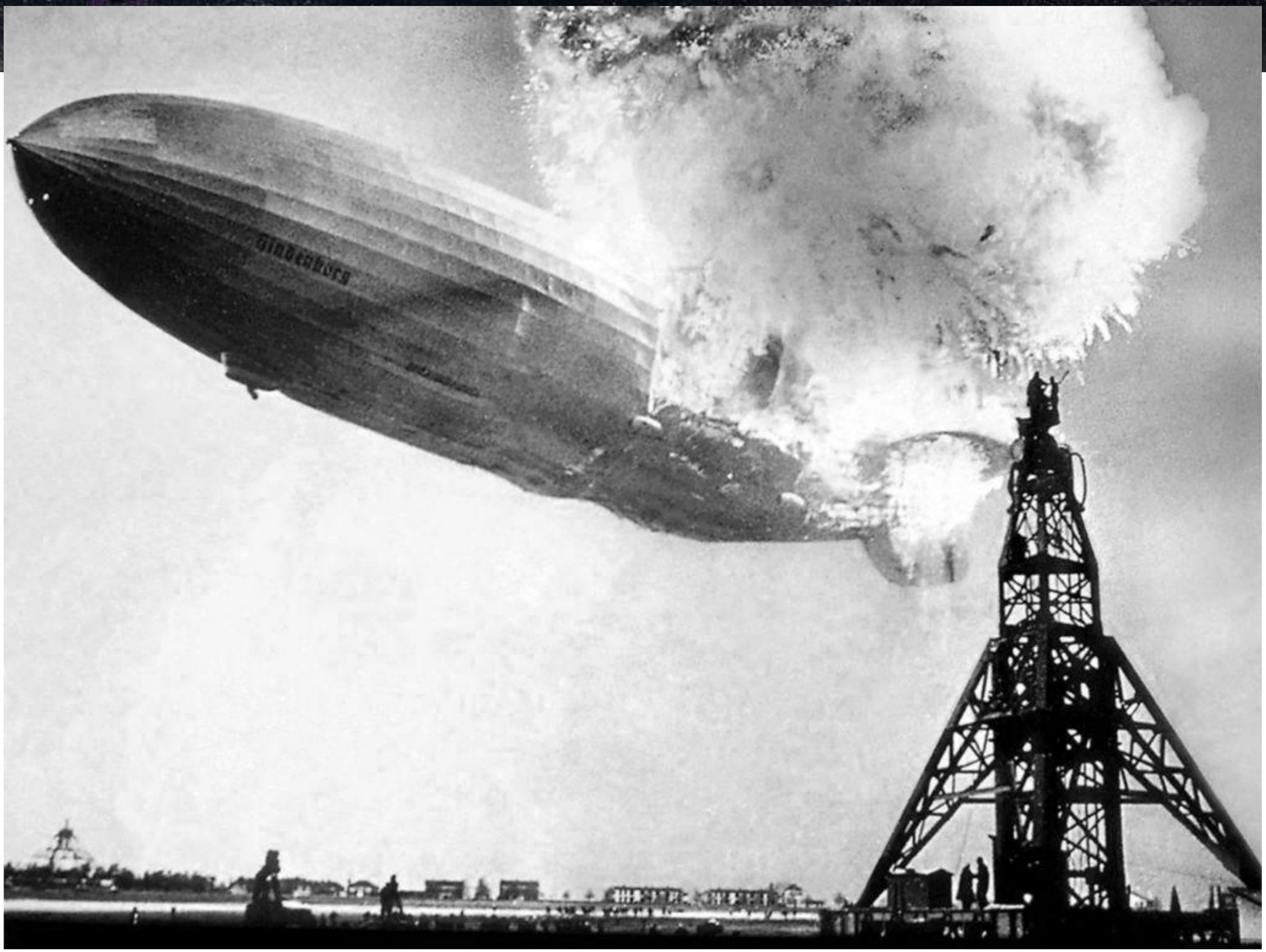
Space Radiation Effects

What kind of SRMS requirements will you encounter and how do you meet them?

- For high Rel program SRMS hardware, there is usually one overarching requirement
  - **It has to work, period!**
  - **So verifiable extreme reliability is mandatory**
  - That has been traditionally accomplished with (allegedly) high reliability (class S) avionics parts and/or Mil Spec parts and components featuring long procurement lead times, extremely high cost, and a lot of ground based testing
  - Other MIL-P or MIL SPEC materials and hardware can be useful, e.g. MIL-883B with up-screening test
- Hi-Rel Programs increasingly forced to find a way to use "COTS parts"
  - DoD attempted to save time and money through "Procurement Reform" to force greater (uncritical) use of COTS in the early 1990s – dramatic increase in equipment failures in the field – DoD returned to a revised version of the traditional Hi-Rel processes applied to non-class S parts
  - **However, not all "COTS" electronics are created equal:**
    - Extremely high volume customers with extreme reliability requirements drove semiconductor manufactures to meet the market needs in the 1980s and 1990's; Example – Texas Instruments Hi Rel electronics parts products
    - Unfortunately the product lot reliability data is often proprietary so you can't document it without repeating the testing yourself in addition to up-screening for space radiation performance
      - Example - ISS MDM Dynamic Access Ram Memory (DRAM)
- **And that is why The bulk of ISS avionics systems (except EPS) are built from <u>up-screened</u> "car parts"!** Example – ISS C&DH MDM System outperforming mostly class S ISS EPS systems with respect to reliability

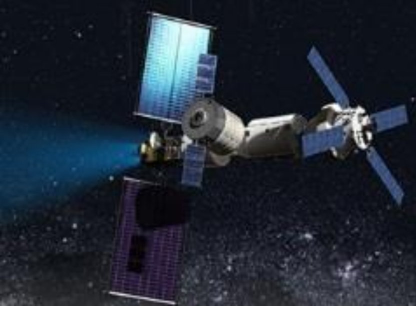


So, if you want to use generic COTS parts without critical evaluation or reliability test and analysis, then you need to ask yourself…

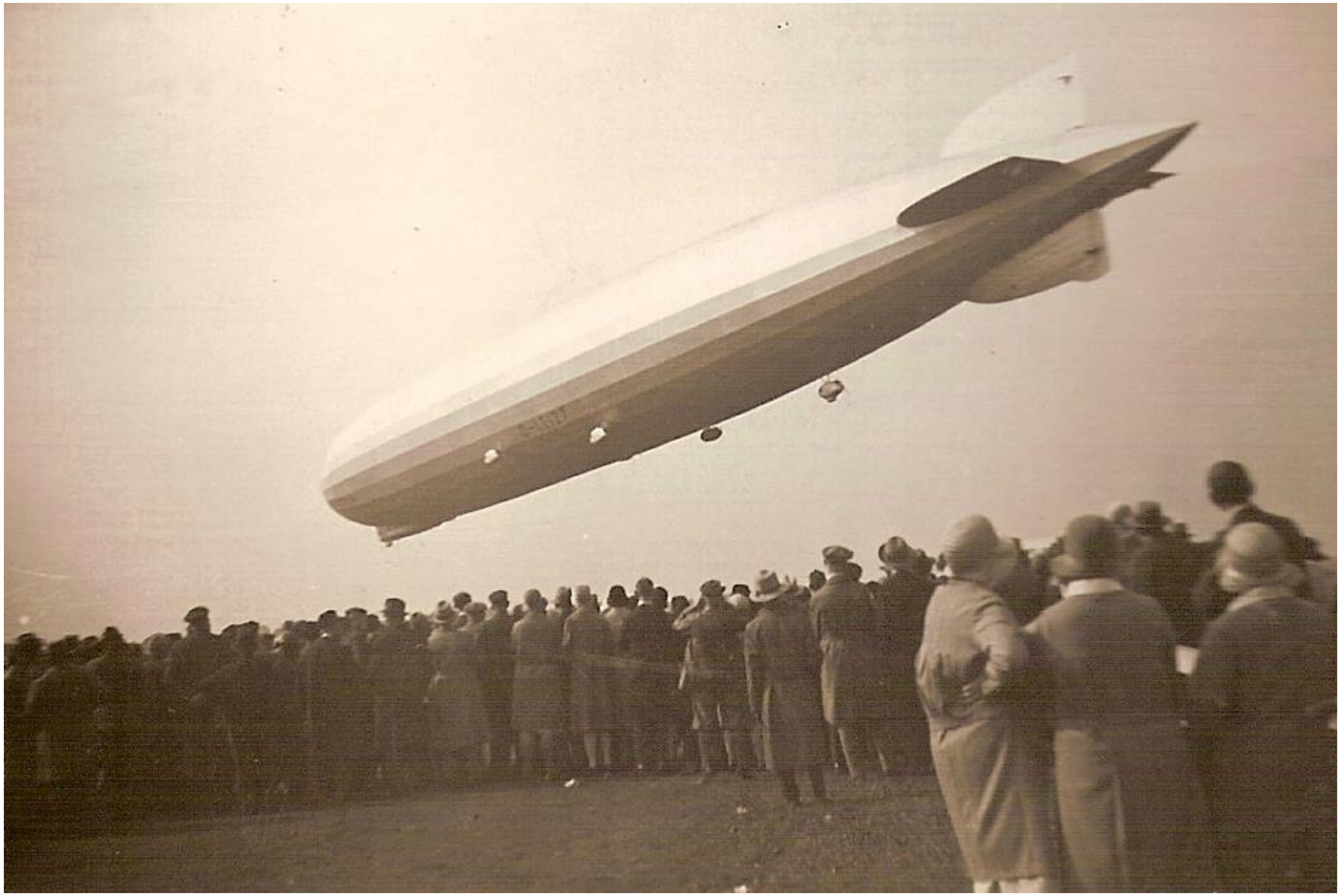


HOW LUCKY DO YOU FEEL?

Just to be clear – this is an example of Murphy's Law, combined with bad materials choices and poor operations planning, in action (and I couldn't find any images of the many failed (due to SEE) spacecraft that were as "motivational")



And least we end this section on too negative a note,



LZ 127 Graf Zeppelin

Role
Passenger/commercial airship

National origin, Germany

Manufacturer, Luftschiffbau Zeppelin

Designer, Ludwig Dürr

First flight, 18 September 1928

Introduction, October 11, 1928

Retired,18 June 1937

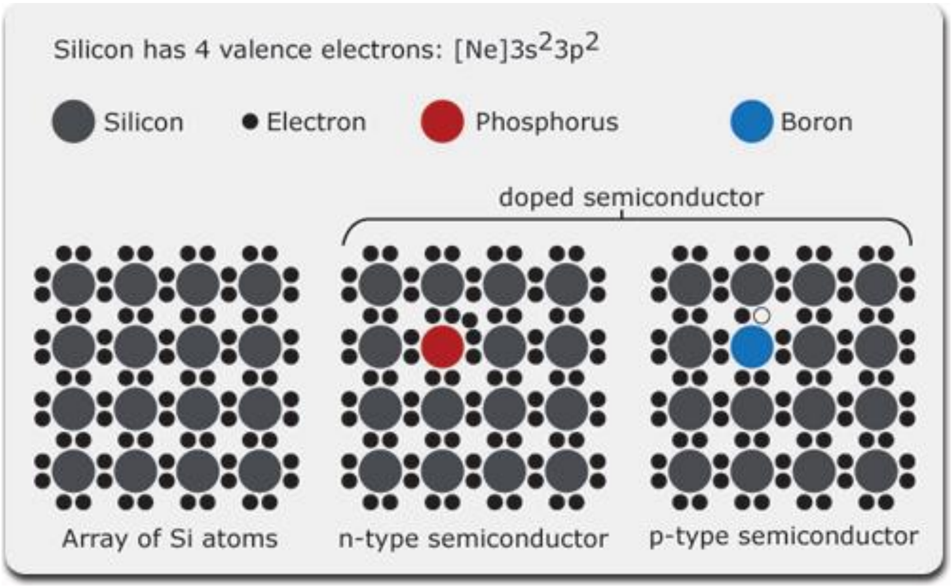
Status, Scrapped March 1940

Primary user, DELAG
Deutsche Zeppelin-Reederei

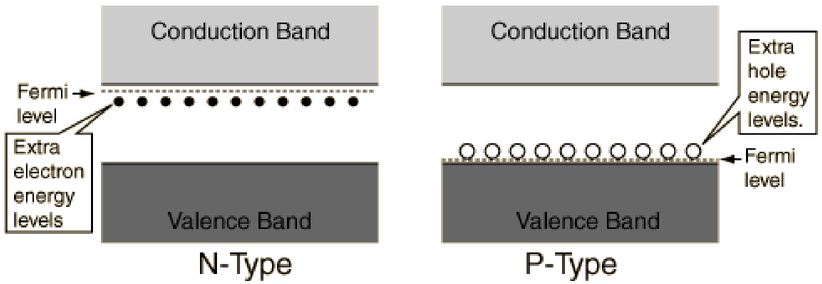
Just to be clear – good design and materials choices along with good operations planning = no problems

Single Event Environment (SEE) Effects on Avionics Components and Systems (Hazard Cause and Component Level Hazard Effects)

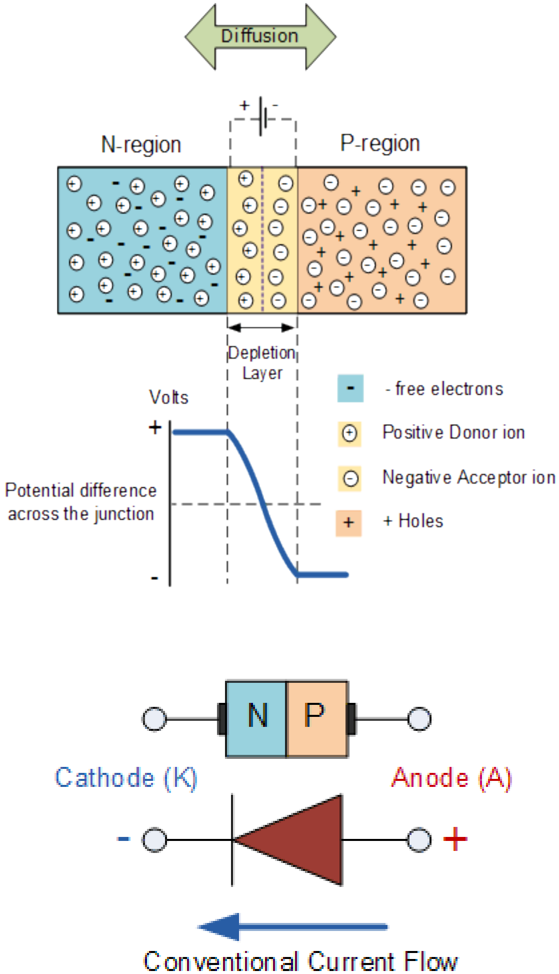
Semiconductor doping, type N and P



- Intrinsic crystalline silicon **5×10^{22} atoms/cm³**
- Intrinsic charge carrier conc. ~ **1.08×10^{10}/cm³** at 300 K
- Typical doping concentration range for silicon semiconductors range from **10^{13}/cm³ to 10^{18}/cm³**
- More than 10^{18} /cm³ => metal like conductivity
- **Bottom line here – energetic charged particles can easily produce transient charge carrier concentrations along the particle flight path through the semiconductor that greatly exceed the nominal carrier concentrations in typical doped semiconductors**



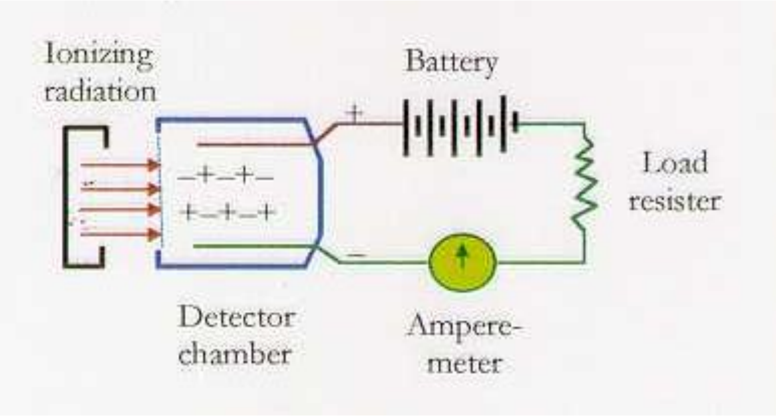
The Semiconductor PN Junction Diode



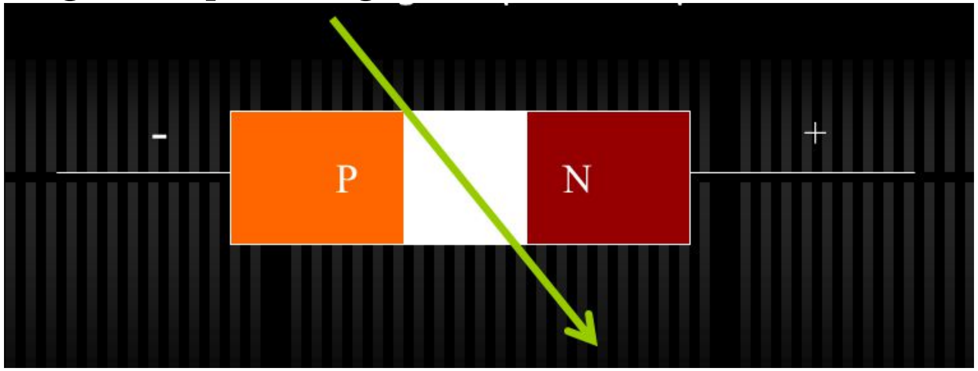
The origin of single event effects – Solid state electronic devices (with "PN" Junctions) are radiation detectors

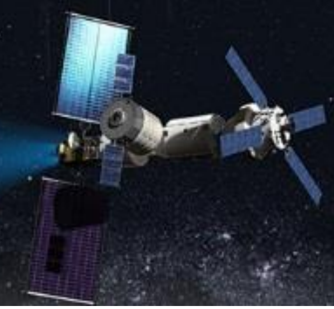
- Consider a reversed bias PN junction with a thick depletion region", i.e. a region with no free charge carriers.
- Ionizing radiation particles passing through the depletion region
  - Generate free charge carriers
  - Producing a current pulse in the external circuit.
- Like a solid state ionization chamber

Basic components of a simple gaseous ionization chamber



A reverse biased PN junction diode. The energetic charged particle produces charge carriers along its track (green arrow) through the depletion region



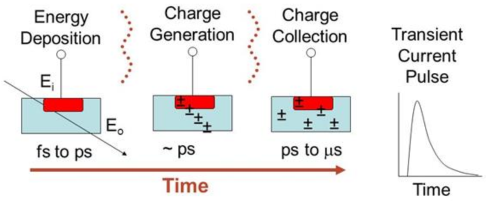


Single Event Effects: Charge production and device SEE threshold

- Charged particle **Linear Energy Transfer, LET**, is a measure of how much ionization the charged particle can produce along a flight path of length, L, through the device
- The ionization produced along the particle track is collected by the device and appears as a current/voltage transient pulse on the outputs as described in the equations and drawing below

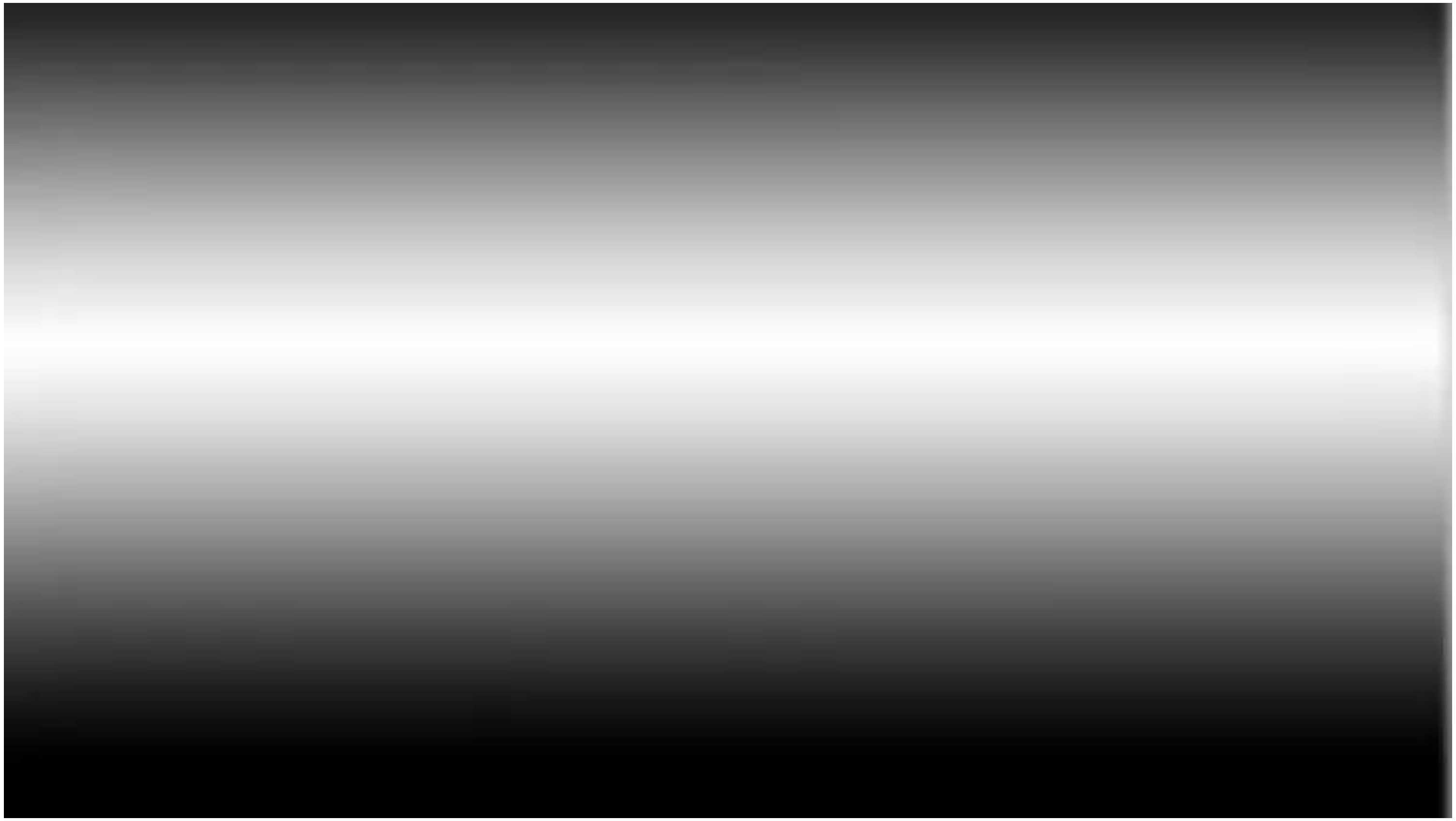
$$I(t) = \frac{Q_{coll}}{\tau_\alpha - \tau_\beta}\left(e^{-\frac{t}{\tau_\alpha}} - e^{-\frac{t}{\tau_\beta}}\right)$$

$$Q_{coll} = 10.8 \times L \times LET$$



  - L is the charged particle path length through the device "sensitive volume (SV)"
    - SV shape and aspect ratio is important here so that L changes with the angle of incidence on the SV in different ways for different shapes (note that "Effective LET" = LET / cosΘ isn't always applicable)
  - LET = dE/dL = a function of **charged particle atomic number, z and velocity, v, [$(z/v)^2$]** as well as **target material electron number density** which depends on density, atomic charge number, and atomic mass number
  - 10.8 eV is the energy needed to generate an electron hole pair in Si
- If the charge produced, Qcoll, is greater than the circuit critical charge , Qcrt, a single event effect is possible, otherwise not
- So for each specific device and SV shape, in an isotropic particle flux, an **LET threshold (LETth) exists so that for LET < LETth no SEE effects are probable**
  - **The device LET dependent SEE cross section, σ(LET), is also related to the SV size and shape and is a measure of SEE event probability**

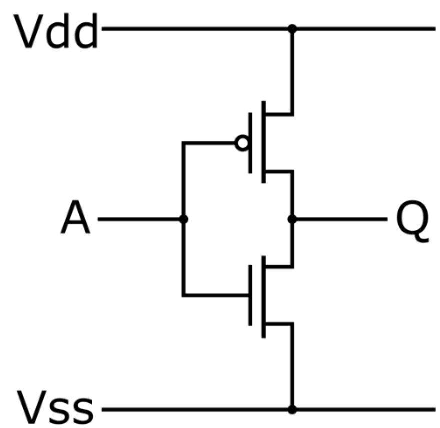
MOSFET Basics

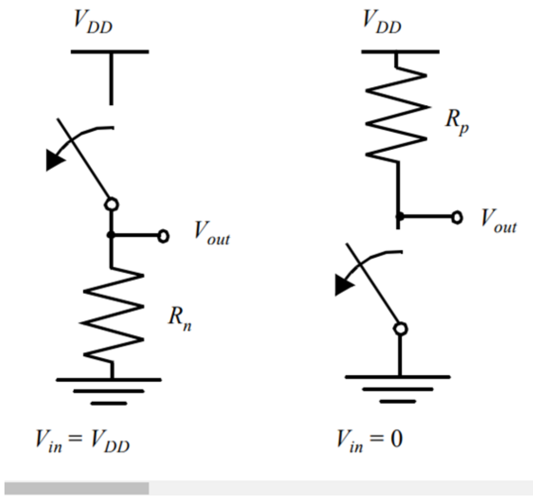


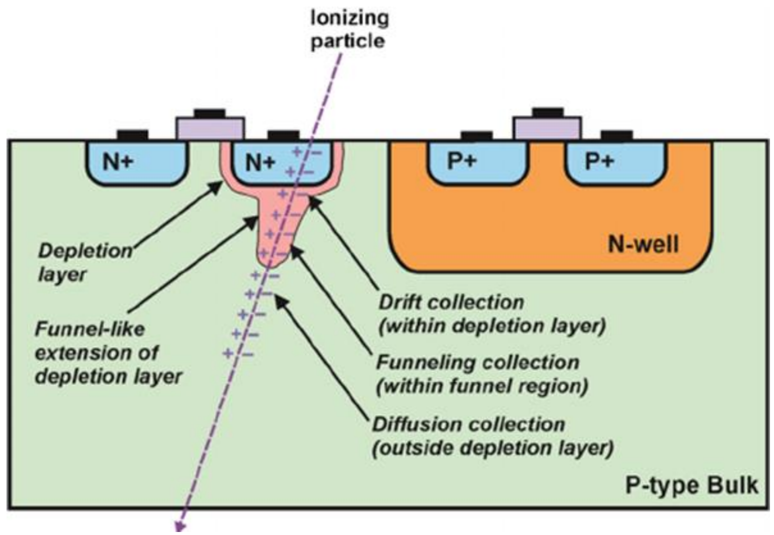
Metal oxide semiconductor field effect transistor (MOSFET)

Complementary Metal Oxide Semiconductor (CMOS) Basics

- Complimentary metal oxide semiconductor (CMOS)
  - Input (A) = Vdd => output (Q) = Low (Vss)
    - Lower transistor ON
    - Upper transistor OFF
  - Input (A) = Vss => output (Q) = High (Vdd)
    - Lower transistor OFF
    - Upper transistor ON
- Heavy ion strikes at sensitive locations in the CMOS inverter structure can cause the output to change

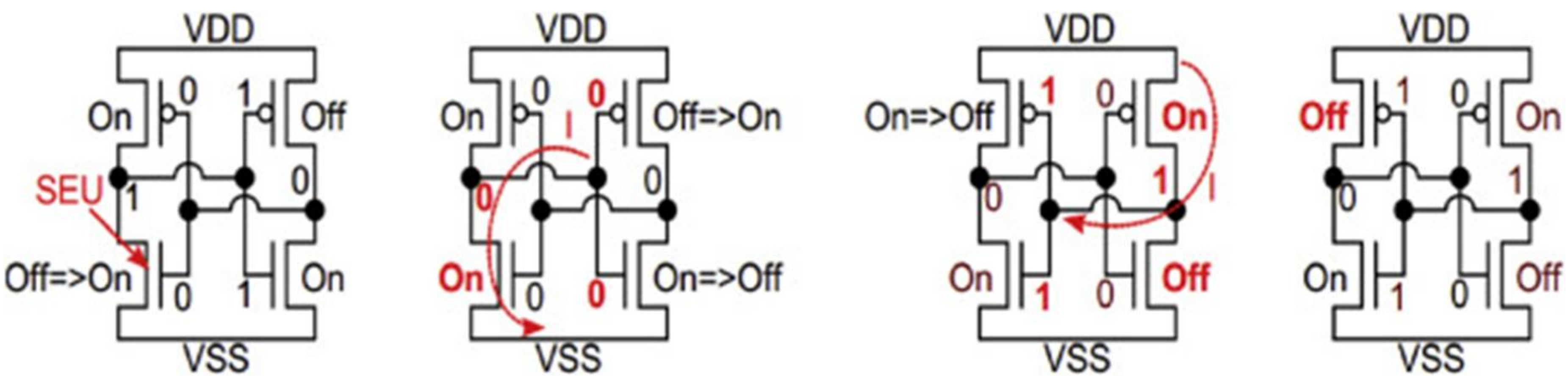






Single Event Upset (SEU) in a CMOS Latch

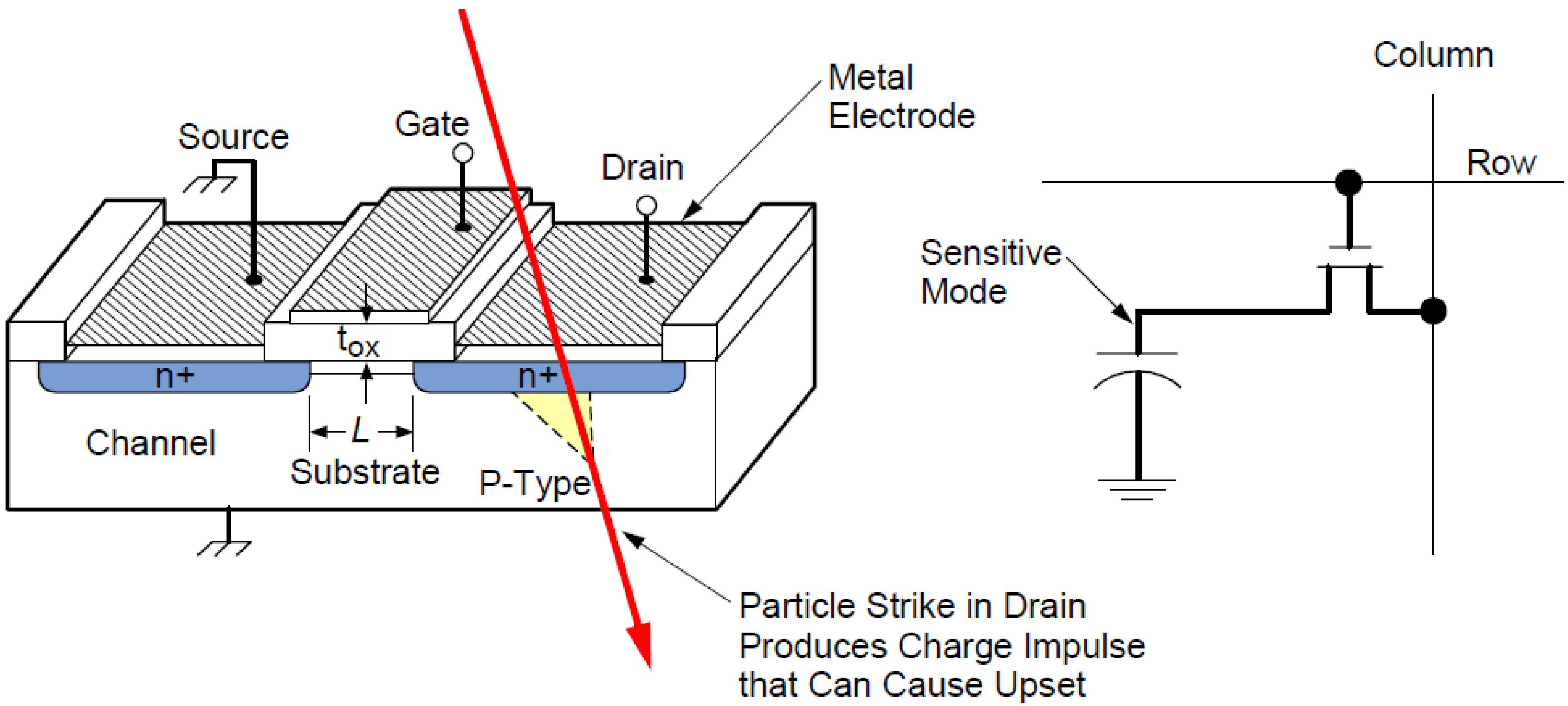
- Cosmic ray strike on an n-mos drain in a CMOS **latch**
  - SEE change of output is possible only if the latch characteristic response time is small enough to respond to the transient currant/voltage pulse
  - In this case, and nearly all others, there are no SEE effects if the device isn't powered



a) Particle hit b) Propagation c) Further Propagation d) Result

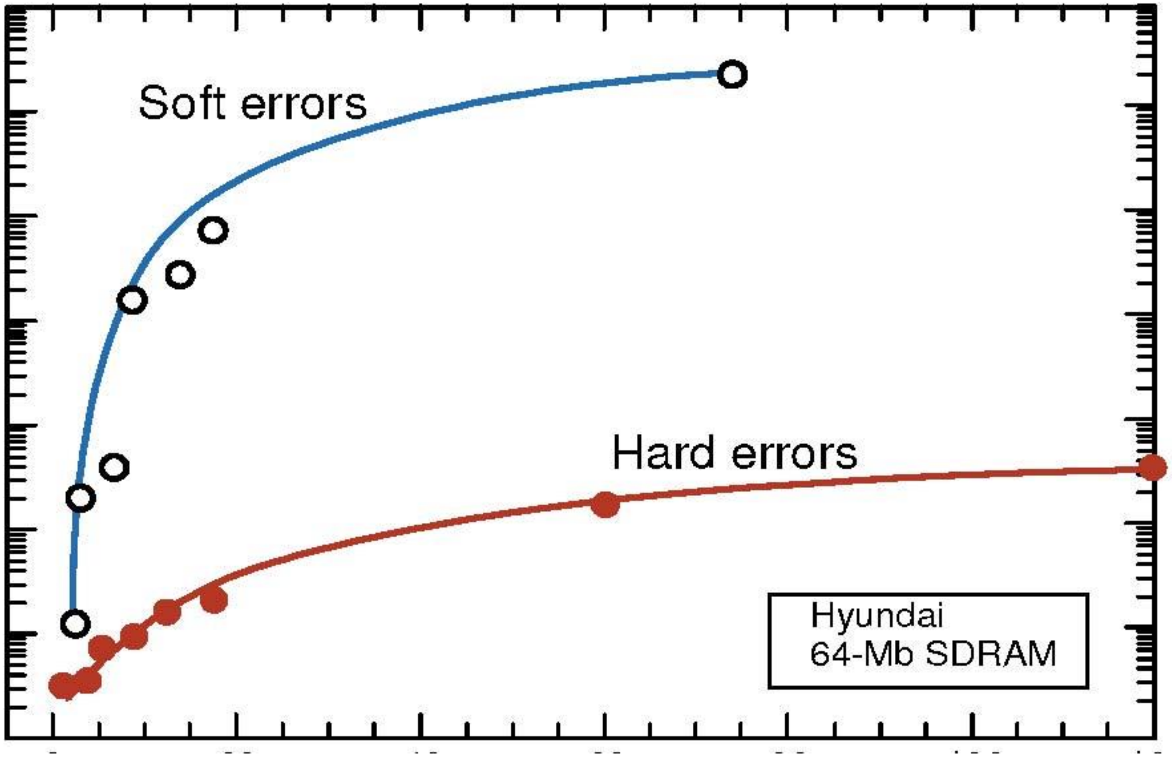
Single Event Upset (SEU) in a MOS DRAM memory cell

- Cosmic ray strike on the drain of a MOS transistor in a DRAM memory cell can lead directly to a change from 0 to 1 or 1 to 0

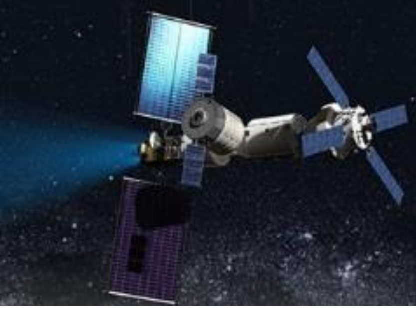


SEE Effects can be destructive (Hard), non-destructive (Soft), or a little of both (latch-up)

- Destructive single event effects (Hard)
  - Hardware function lost and not recoverable
- Non-destructive single event effects (Soft)
  - Recoverable
- Latch-up (features of both)
  - Recoverable (if you power cycle quickly enough) but latent damage may accumulate leading to hard failure later
- Probability (cross section) and threshold of soft events is almost always much greater than probability/threshold of hard events or latch-up



Sammy Kayali ,Jet Propulsion Laboratory, California Institute of Technology, May 14, 2007

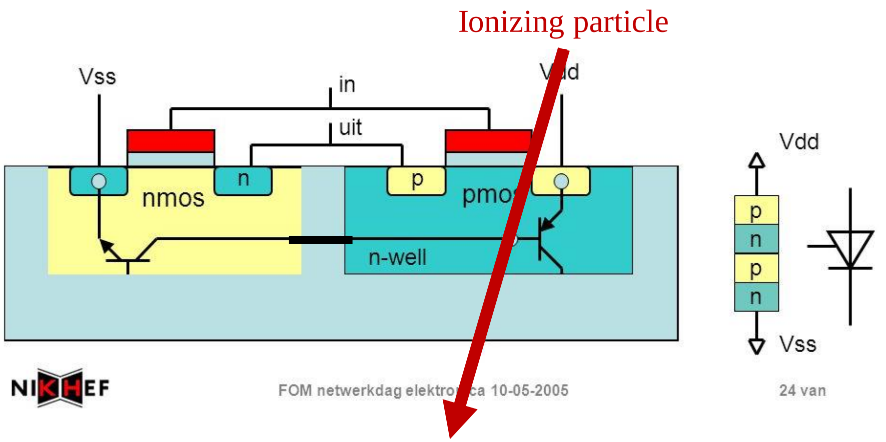


Non-destructive Single Event Effects

- Single Event Transient (SET)
  - Affected device emits current/voltage pulse to downstream circuitry
  - Both analogue and digital devices affected
  - Downstream devices can change state possibly producing SEU and or SEFI
- Single Event Upsets (SEU)
  - Change of state (0-to-1 or 1-to-0) of a data storage element (memory or registers)
  - Both single bit (SBU) and multiple bit upsets (MBU) can happen in a single data word
  - Corrupts data – right number => wrong number => wrong calculation output => bad things can happen
- Single Event Functional Interrupt (SEFI)
  - Event causing temporary (recoverable) loss of device functionality
    - Recovered by reset or power cycle
    - Often caused by an SEU or MBU corrupting data in control circuity registers
    - One effect of latch-ups (a possibly destructive effect) and MBUs

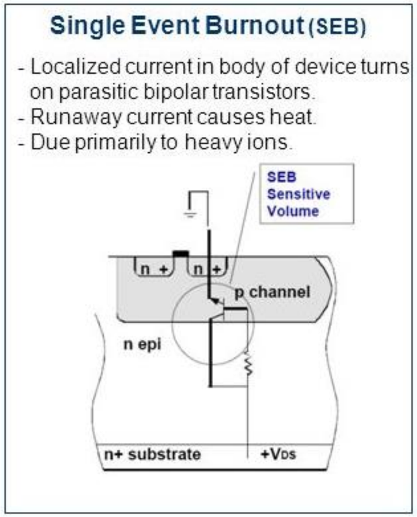
Destructive Single Event Effects Latch-up in CMOS

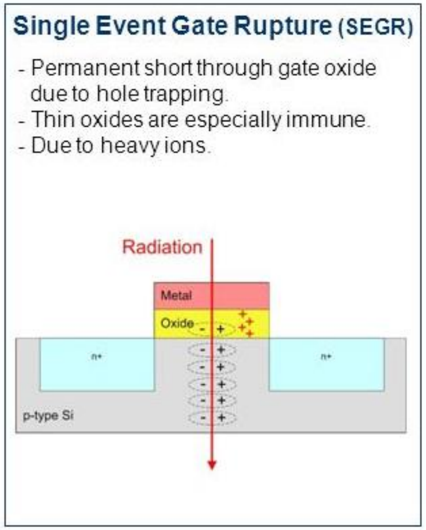
- Single Event Latch-up (SEL) in CMOS
  - Cause – heavy ions, protons, neutrons
  - May lead to hard failure
  - Power cycling may recover the device if it isn't burned out before detection and power cycling
  - Threshold decreases and cross section increases with temperature
  - Modern devices have many different latch-up pathways
- "Bulk" CMOS most susceptible
  - Silicon on insulator (SOI) or epitaxial (epi) technologies more resistant
  - Latch-up resistant device technology (e.g. insulating oxide "trench" around the P and N transistors)
- Some mitigation possible with current limiting devices and "smart fusing"

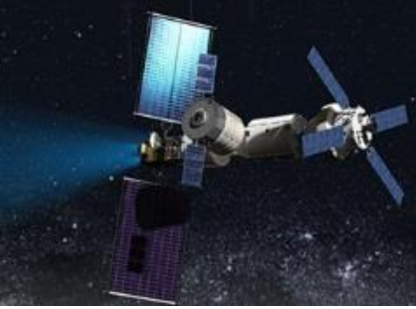


Destructive Single Event Effects Burnout and Gate Rupture

- Single Event Burnout (SEB)
  - Localized current in body of device turns on parasitic bipolar transistor shorting power supply to ground
  - Something like second breakdown in power transistors and functionally similar to latch-up
  - Triggered by heavy ions, protons, and neutrons
  - Always destructive
  - CMOS, Power BJTs, FETs and MOSFETs can be susceptible
- Single Event Gate Rupture (SEGR)
  - Triggered by heavy ions
  - Always destructive
  - Depends on ion angle of incidence
  - Dependent of electric field in gate oxide
  - Synergy with TID and SEE
  - Power MOSFETs are most susceptible

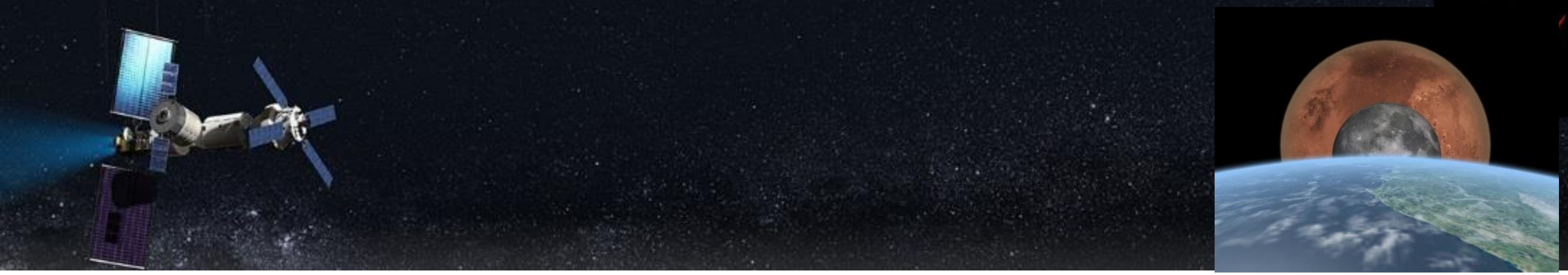




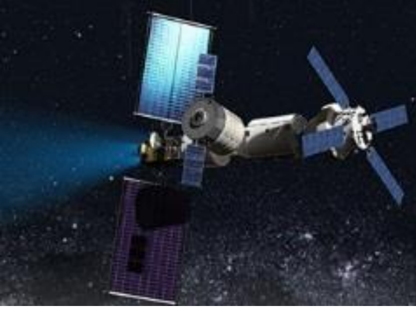


Destructive Single Event Effects – Single event Hard Errors (SHE) and Micro Latch-up

- SHE (Stuck-Bits)
  - Permanent change of state (0-to-1 or 1-to-0) of a data storage element (memory or registers)
    - Believed to be a micro-dose effect – single high LET heavy ion causes large (+) charge in device oxide
    - May exhibit high part to part variability and difficult to identify during testing
  - Not correctable with power cycle and/or reset
  - Typically, the memory block is taken out of service (by FDIR or operator intervention)
- Micro latch-ups can also cause blocks of memory to be unable to change state
    - Not destructive if power cycled before permanent damage occurs



SEE Effects Mitigation
(Hazard Controls)



SEE Effects Mitigations: Or how to build reliable systems with unreliable components

- Your goal is to make the probability of losing any mission success or safety critical system or subsystem functionality meet program requirements, **during the specified time interval, t,** while staying within your schedule and budget guidelines
- So how might you do that for destructive and nondestructive SEE?
  - Make **t** as small as possible – if it isn't needed power it down
  - Select components with such high LET thresholds that they are effectively immune to SEE for the mission SEE environment and the "specified time interval, t"
  - For Latch-up, select component types that a relatively immune to latch-up like silicon on insulator as opposed to bulk silicon CMOS
  - Soft fusing - also for Latch-up - detects latch-up over current in component and power cycles component to clear latch-up
  - De-rate parts – i.e. operate at 30% to 20% of device spec. voltage rating
    - Power transistors
    - Less voltage means less energy available for destructive SEE

SEE Effects Mitigations:
And how might you do that for destructive SEE in general

- Parallel redundancy with TMR , or something like it, for uninterrupted operations on module failure supported by:
- Fault Detection Isolation and Recovery (FDIR) software to:
  - Identify failed modules and take specific actions to recover or isolate depending on module status
  - Power cycle, reboot and re-synch if that is indicated to recover the module
  - All without ground or crew intervention
- Pre-positioned flight rules and procedures to support operator intervention (no automatic FDIR function)
  - Example - Recovery of ISS multiplexer/demultiplexer (MDM) functional interrupts require on the order of 24 hours of mission engineering room (MER) command and data handling (C&DH) console time for recovery of the MDM
  - ISS Lap top hard failure - Find one of the many cold spares - power up – continue the task
- **Module failure rates need to be small enough not to overwhelm the system**
- **Note that in most cases you won’t know if your system has had a destructive event or not until you try to recover it and fail**

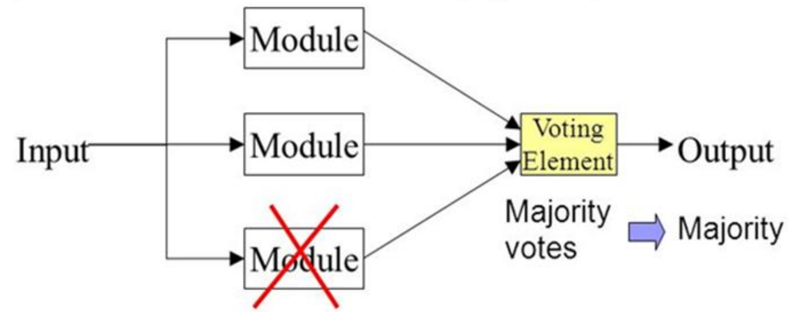
SEE Effects Mitigations:
And how might you do that for non-destructive SEE – Single event data errors - SEUs, MCUs, MBUs, etc.

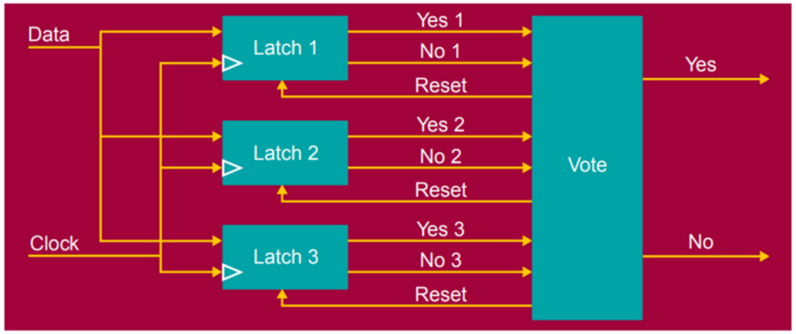
- Select components with such high SEU LET thresholds that they are effectively immune to SEE for the mission SEE environment and the "specified time interval, t"
- Mitigations based on data redundancy Error Detection and Correction (EDAC)
  - Single and multibit error correction possible – single error correction double error detection SECDED or double error correction triple error detection (DECTED)
  - Software/firmware using variations on the "Hamming Code" - for a "walk through" on how this works see the links below – it isn't that complicated really…
    - http://logos.cs.uic.edu/366/notes/ErrorCorrectionAndDetectionSupplement.pdf
    - https://www.youtube.com/watch?v=v_GmF1xJzGo
  - Hamming code inserts check bits into the data word to allow subsequent identification and correction of corrupted bits (data and/or check bits)
    - SECDED is most common because computational overhead grows rapidly with the size of the data word and number of errors per data word you need to detect and correct
- The effectiveness of all this depends on the error rate being small enough so as not to overwhelm the system
  - Implication for physical layout of spacecraft memory - **ideally, no two bits in a single data word should be physically adjacent or a single ion could flip both**
  - Example - Hubble and Cassini solid state recorder data corruption anomalies

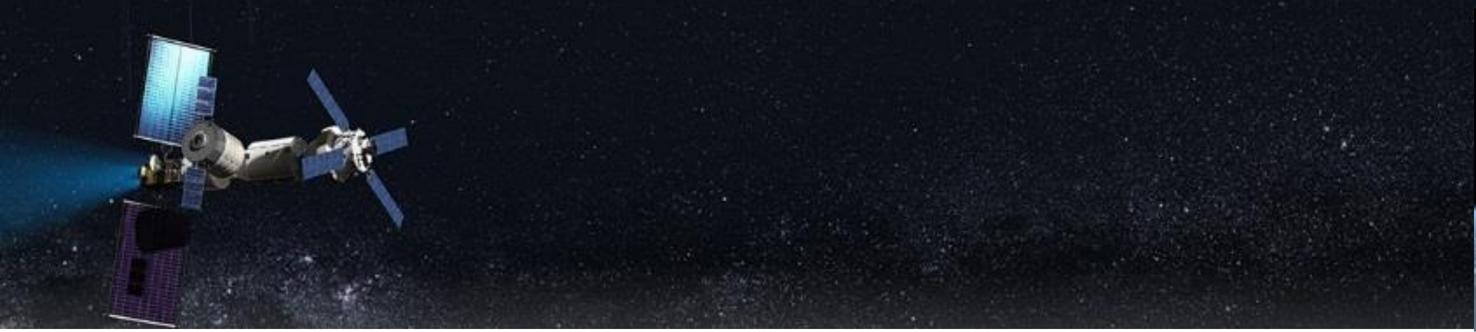
SEE Effects Mitigations:
And how might you do that for non-destructive SEE, in general, including functional interrupt

- Multi-Module Redundancy - TMR is a specific case
  - Nullifies the effects of any SEU bad bits or failures occurring in one of three or more parallel redundant units with multi-module redundancy and voting
  - Voting block needs to be rad/see hard
- System operation continues without interruption
  - **Module failure rate needs to be low enough not to overwhelm the system**
  - Fault Detection Isolation and Recovery (FDIR) software and or ground/crew intervention flight rules and procedures needed to:
    - Identify failed modules and take specific actions to recover or isolate depending on module status
    - Power cycle, reboot and re-synch if that is indicated to recover the module
- System fault tolerance depends on the details of implementation - the basic unit in the sketch to the right is only single-fault-tolerant
  - e.g. Phobos-Grunt failure

Triple Modular Redundancy (TMR)



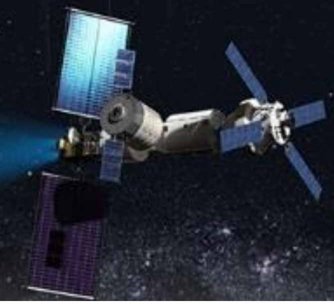





SEE SRMS Verification by Testing and Analysis (Hazard Control)

Test Like you Fly and Fly Like you Test? Well, not exactly

- Why are we doing this?
  - To determine and document the **probability** that a component or system can **perform its intended function** for a **specified time interval, t,** under specified environmental conditions
    - The primary product will be quantitative estimates or measures of **$1/MTTF = \lambda_{MTTF}$ and/or $1/MTBF = \lambda_{MTBF}$** for the integrated spacecraft, it's subsystems, and individual components so that worst-case Loss of Crew/Loss of Mission (LOC/LOM) probabilities can be compared to Program LOC/LOM requirements
    - If program LOC/LOM isn't defined or isn't sub-allocated to the systems an subsystems you may be working to case-by-case system/sub-system reliability requirements
- What does that mean in a practical sense?
  - Depends on hardware criticality
  - Small t and no LOC/LOM consequences on failure implies easy risk acceptance and little or no schedule/budget impact
  - Large t and possible LOC/LOM consequences means schedule and budget impacts that increase exponentially with specified time interval t.

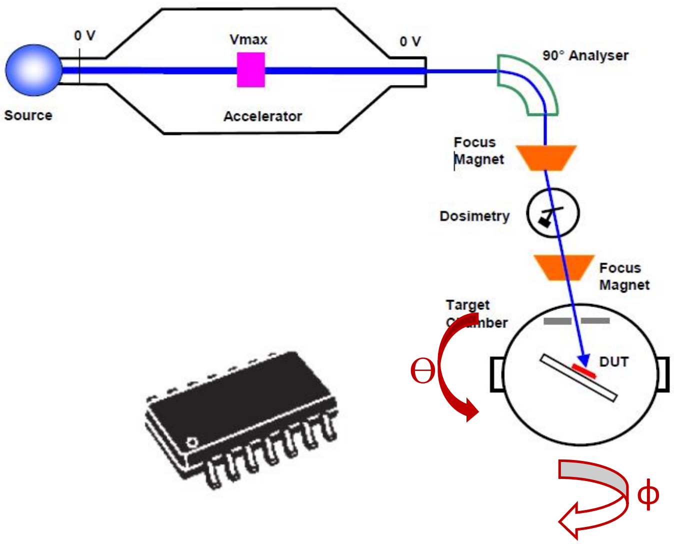


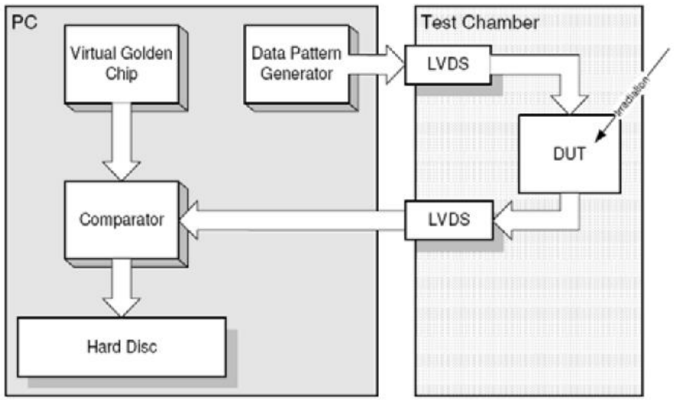
Test Like you Fly and Fly Like you Test? Well, not exactly

- Can we test like we fly and fly like we test?
  - No! Duplicating the isotropic GCR, SPE and trapped radiation flight environments with a ground based particle accelerator system having an accelerated test capability would be outrageously costly
- So what do we do?
  - We use ground based particle accelerators to determine a generic physical property of the electronic devices
    - **The electronic device “cross section” as a function of particle LET, σ(LET)**
  - The σ(LET) function is then used in combination with the LET spectrum expected in the worst-case flight environment(s) to calculate estimated worst-case MTBF and MTTF
  - Expected flight environment LET spectra (including shielding mass effects) can be found in:
    - Program Natural Environments Definition for Design (NEDD) documents (e.g. SSP-30512 or SLS-SPEC-159) and
    - Are also calculated by specific SEE assessment application software packages like CREME-96 https://creme.isde.vanderbilt.edu/

Test Like you Fly and Fly Like you Test? Well, not exactly Traditional Heavy Ion or Proton Testing

- Overview and a simple example of accelerator testing:
  - A 64K bit (8 bit word) memory chip (Nb = 64K bits/chip)
  - Write 0000 0000 into all chip memory locations
  - Irradiate the chip with a known number of particles per square cm (F) at:
    - One particle kinetic energy and LET value
    - One incident angle, θ, WRT chip normal
  - Read out memory to find twenty 8 bit words with 1 upset each (e.g. read 00100000, not 00000000)
    - 20 upsets = (Nu)
- SEU directional cross section at that LET and angle = **$\sigma(LET, \theta) = Nu/(F \times Nb \times \cos\Theta)$**
  - e.g. for $F = 10^3$, Nb = 64K, Nu = 20, $\cos\Theta = 1$ so,
  - $\sigma(LET, \Theta) = 3.13 \times 10^{-7}$ cm^2/bit
- Ideally, repeat over the range of particle LET values (and incidence angles) of interest to obtain the cross section as a function of LET and Θ.
  - Need to do variation of ϕ too, but that doesn't often happen (costs too much money)





Test Like you Fly and Fly Like you Test? Well, not exactly Traditional Heavy Ion or Proton Testing

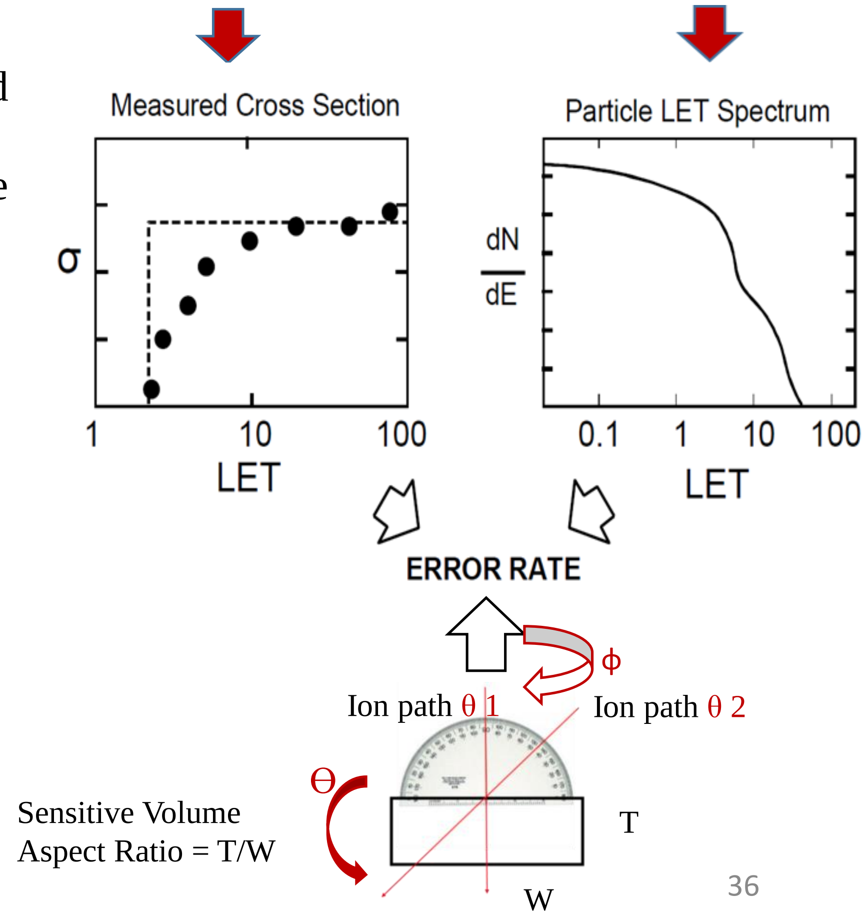
- Next we calculate the estimated chip failure rates, $1/MTTF = \lambda_{MTTF}$ and/or $1/MTBF = \lambda_{MTBF}$, in the flight environment
- The measured σ(LET, θ, ϕ) function, the flight environment charged particle LET spectrum and the estimated shape of the sensitive volume are combined to calculate the estimated λ_{MTTF} and/or λ_{MTBF}
- The equation, called a convolution integral, looks like this:

$$\lambda_{MTTF/MTBF} = \iiint f[LET] \times \sigma(LET,\Theta,\Phi) d(LET) d(\Theta) d(\Phi)$$

  - Angular dependence is often ignored or crudely estimated
    - Costs too much money…
  - But it needs to be included to calculate λ for an isotropic radiation environment impinging on an anisotropic target
- Note – if you have a heavy ion σ(LET) function you can calculate the unique proton σ(K.E.) function directly
  - Unfortunately going from proton σ(K.E.) to heavy ion σ(LET) doesn't give a unique solution (at least we don't know how just yet)
    - J. Barak; "Simple Calculations of Proton SEU cross sections from Heavy Ion Cross Sections," IEEE Transactions on Nuclear Science, Vol. 53, No. 6, Dec. 2006, pp 3336-3342

Note that this σ(LET) is an integral probability distribution function

Note that this (f(LET) is a differential probability distribution function

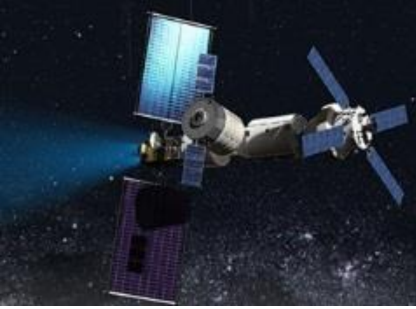


Test Like you Fly and Fly Like you Test? Traditional Heavy Ion or Proton Testing Standards and Guidelines

- European Space Components Coordination (ESCC) basic Specification No. 25100, "Single Event Effects Test Method and Guidelines", October 2015
- ASTM-F1192 - "Standard Guide for the Measurement of Single Event Phenomena (SEP) Induced by Heavy Ion Irradiation of Semiconductor Devices", 2011
- JESD57 - "Test Procedures for the Measurement of Single Event Effects in Semiconductor Devices from Heavy Ion Irradiation"
- JESD89-1A - "Test Method for Real-Time Soft Error Rate"
  - Widely used for SER testing for ground level applications
- MIL-STD750E Method 1080 – Single-Event Burnout and Single-Event Gate Rupture"
  - Specific for SEB and SEGR in power transistors
- JEDEC JESD 234 – "Test Standard for the Measurement of Proton Radiation Single Event Effects in Electronic Devices", October 2013
- Unfortunately, testing standards and guidelines aren't necessarily keeping up with the rate of change of modern microelectronic devices
  - **Are the test methods applicable to contemporary and future devices?**

Test Like you Fly and Fly Like you Test? The times they are-a-changing

- Heavy ion SEE test methods were developed in the 1980’s and 1990’s using the microelectronic technology available at that time…
  - Then ~ 100 micron device design rules
  - Now ~ 100 nanometer (or smaller) design rules, and much higher transistor densities on chip
  - Then - one layer of thin-flat (~1 micron) transistors on chip (“2D”) - “effective LET” ok
  - Now - moving toward thick (> 10 microns) 3D architectures on chip - “effective LET” not ok
    - Particle range limits use of conventional accelerators for testing (see back-up)?
    - Single charged particle track can encompass many transistors (MBU)
  - Then - Test/analysis on “de-lidded” parts/chips (no packaging) to determine device SEE cross section despite limited kinetic energy and range of available (affordable) heavy ion accelerators
  - Now - Assembled article (packaged parts/chips and board/box) level test methods are being developed/used
  - Then - simple devices with relatively simple “State Space”
  - Now - complex “system on a chip” devices with extensive, complex “State Spaces”
- Even partial SEE characterization of a contemporary complex device, like a Field Programmable Gate Array (FPGA) with conventional heavy ion test methods is usually a multi-year, multi-million dollar “science project”



Some new approaches to spacecraft avionics SEE test and verification

- **Wouldn't it be a good thing if we could test assembled avionics articles, running flight like software (including EDAC and FDIR), and produce a more flight like test result?**
  - Yes, but there are no standardized test methods for doing that yet
  - There are however some test methods in development that have been accepted by some programs for flight hardware certification
- **High energy (200 to 500 MeV) proton testing (JSC EV5) – See References in back-up section**
  - Sufficient particle range to test at board or box level
  - Direct measure of rates from proton direct ionization (if any) and in-device proton induced nuclear reaction products
  - LET spectrum of proton induced nuclear reaction products compared to flight environment LET spectrum allows estimate of upper bound on heavy ion (GCR) rates (up to LET ~ 15 (MeV cm^2)/mg)
  - Successful flight history but very limited test method verification/documentation
  - For ISS orbit and 0.1" Al shielding, $MTBF_{HI} \geq 6$ years / (#SEE in 10^{10} protons/cm^2)
    - $P_{success}$= exp -(time / $MTBF_{HI}$); for $MTBF_{HI}$ = 6 and time = 0.1 we have **$P_{success}$ = 0.85**
    - PROTEST Code - O'Neill, 1998
- **High energy (on the order of 1 GEV) heavy ion accelerator testing (JSC EV5) – See References in back-up section**
  - Sufficient particle range to test at board or box level
  - Direct measure of heavy ion (GCR) rates as a function of LET
  - Straightforward determination of LET thresholds for latch-up and gate rupture/burn-out failures
  - Currently only available at Brookhaven National Laboratory (BNL) NASA Space Radiation Laboratory (NSRL)
  - Limited beam time available and high cost are issues

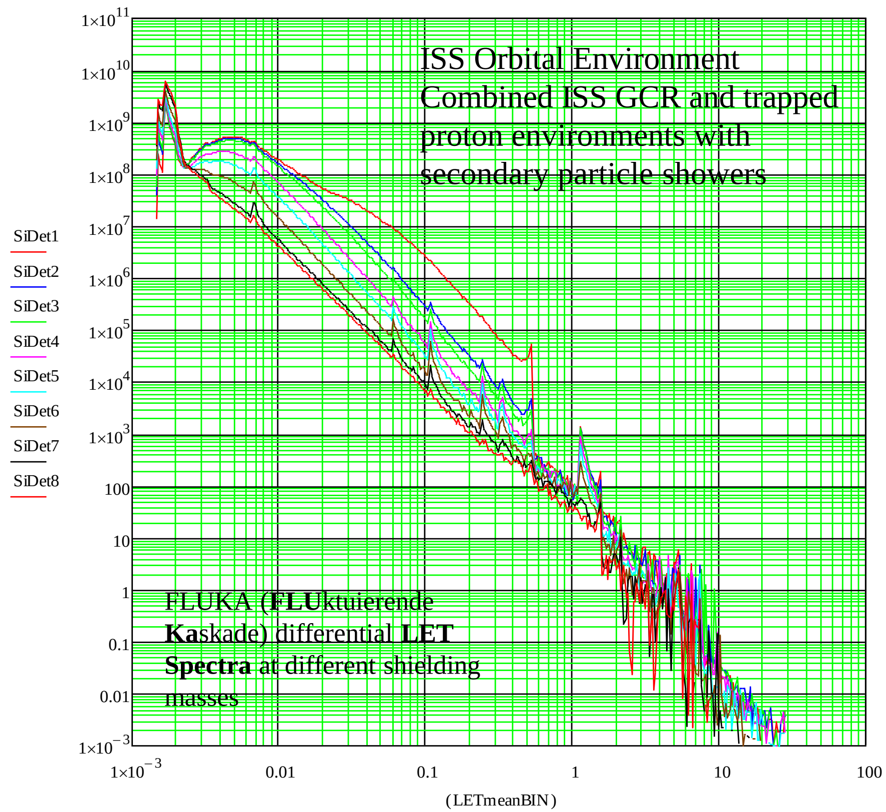

And how well does all this work?

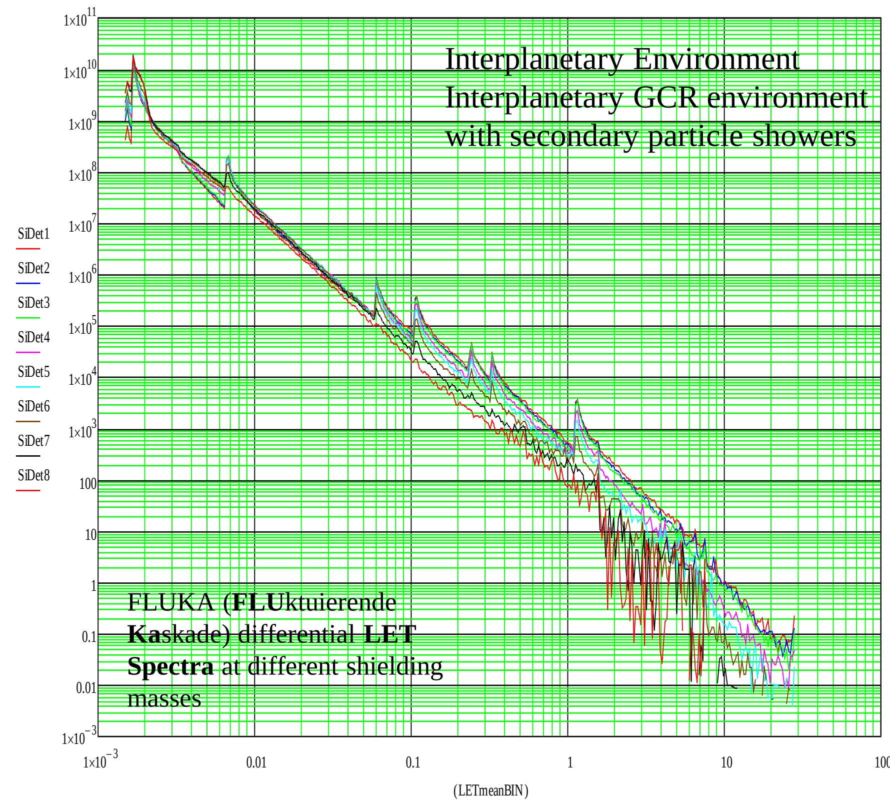
How well does all this work and what constitutes "acceptable" precision and accuracy?

- Typically, how close do the calculated (test and analysis) failure rates come to the observed in-flight failure rates?
  - If calculated (ground test and analysis) and observed (in-flight) SEE rates are within a factor of 2 of each other, that is considered excellent agreement but it doesn't happen that often
  - More typically, the two SEE rates will be within one to two orders of magnitude of each other
    - Petersen. E., L., "Predictions and Observations of SEU Rates in Space," IEEE Transactions on Nuclear Science, 44(6), December, 1997, pp 2174-2287
  - BTW – there isn't a lot of publically available data on this subject – classified/proprietary
- Why is that the case?
  - The vast differences between the real flight environment and the ground based test environments lead to an enormous number of simplifying assumptions and approximations
    - **σ(LET, Θ, ϕ)** test data is often "noisy", complicated, and difficult to interpret, especially when dealing with contemporary complex devices like systems on a chip (SOC) or field programmable gate arrays (FPGA)
  - The limitations imposed by the "affordable testing" mandate
- And we can use the ground based test and analysis products for decision making anyway because???
  - Proven track record of eliminating potential problems before flight in numerous programs
  - In most cases, if you multiply your expected rates by 100 you will find that your system still meets reliability requirements

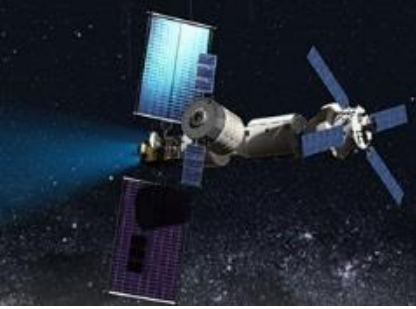
Differential LET Spectra: ISS orbit vs. interplanetary space

[#/(cm^2 week LET)] at various shielding depths in a concentric spherical shell shielding mass model

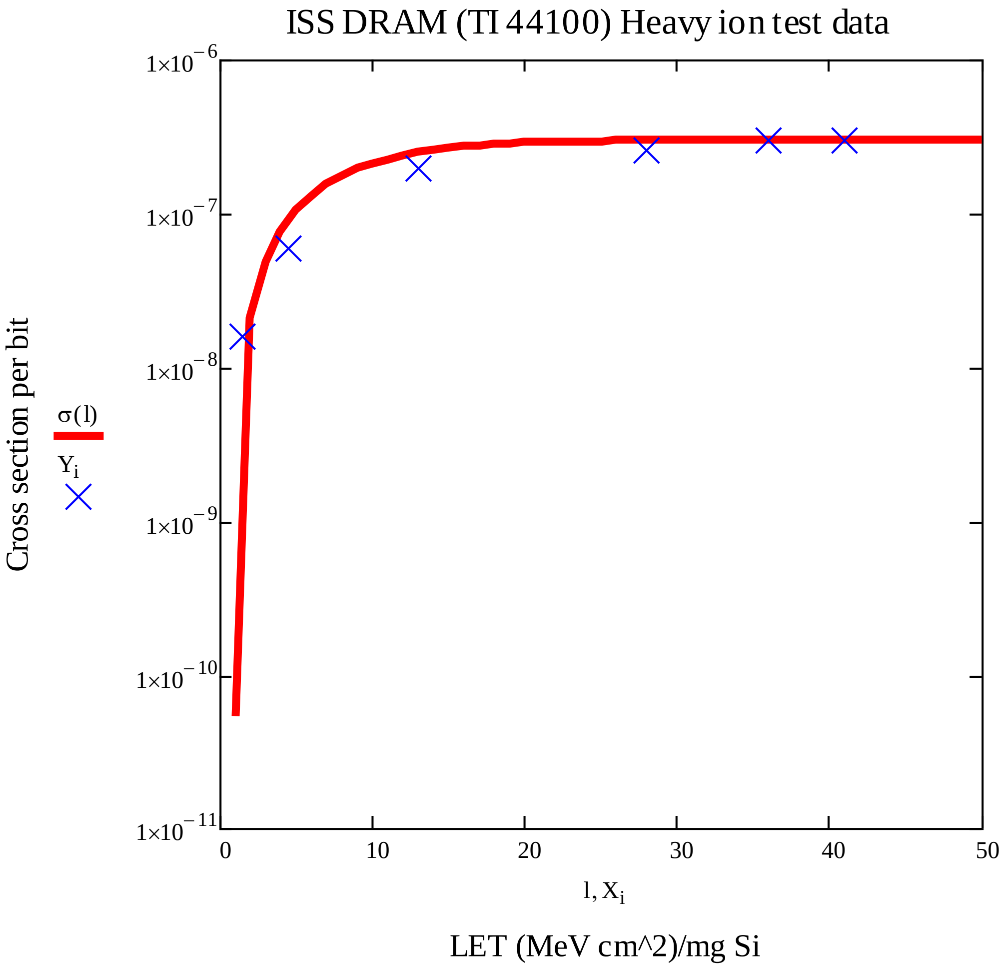




Detector Si Shell	SiDet1	SiDet2	SiDet3	SiDet4	SiDet5	SiDet6	SiDet7	SiDet8
Detector Shell Radius (cm)	5037.4	5037.3	5037.1	5035.6	5033.7	5030.0	5018.9	5000.0
Si Detector Median Al Shielding Mass in g/cm^2	0.15	0.81	1.6	7.9	15.6	31.1	77.5	156.2



ISS MDM DRAM
Integral cross section vs LET curve and Weibull function fit
(TI 44100/TI44400) Heavy ion test data



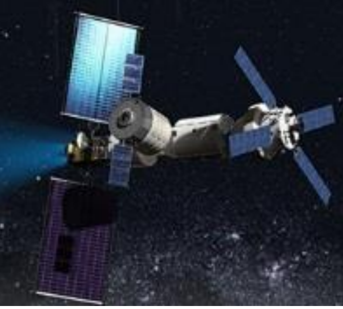
$lo := 0.99 \qquad \sigma sat := 3.00 \cdot 10^{-7} \qquad w := 7.7 \qquad z := 1.3$

$$\sigma(l) := \sigma sat \cdot \left[1 - \exp\left[-\left(\frac{l - lo}{w}\right)^{z}\right]\right]$$

$Y_i :=$	$X_i :=$
$1.6 \cdot 10^{-8}$	1.5
$6 \cdot 10^{-8}$	4.5
$2 \cdot 10^{-7}$	13
$2.6 \cdot 10^{-7}$	28
$3 \cdot 10^{-7}$	36
$3 \cdot 10^{-7}$	41

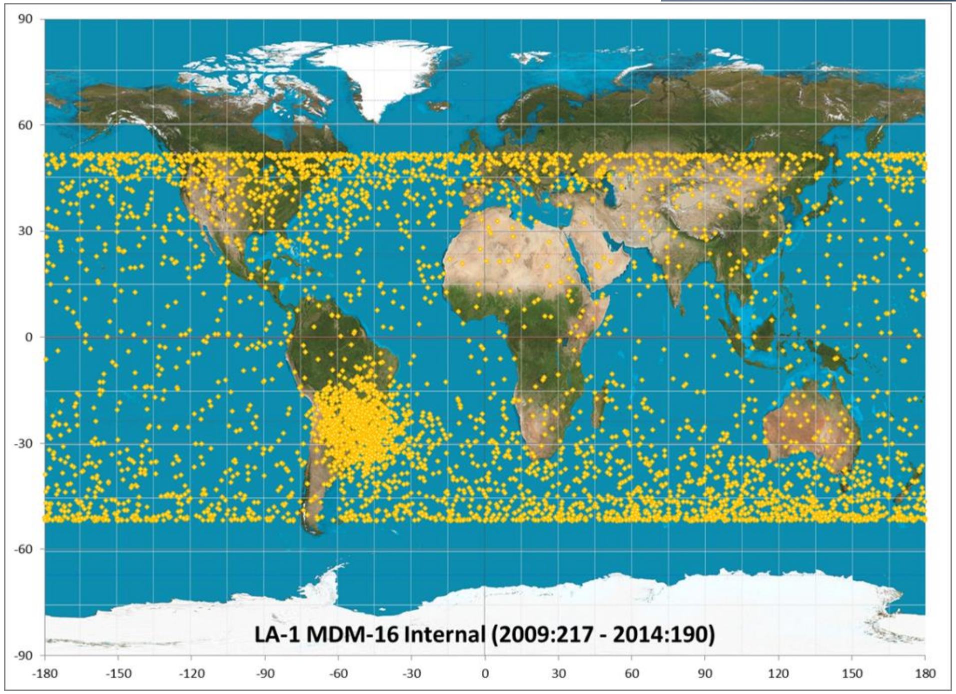
Harboe-Sorensen, R., Muller, R., Daly, E., Nickson, B., Schmitt, J., Rombeck, F. J.; " Radiation pre-screening of 4 M bit dynamic random accessmemories for space application," in RADECS 91, Proceedings of the FirstEuropean conference on Radiation and its Effects on Devices and Systems,09/09/91 to 09/12/91, La Grande-Motte, France, IEEE Catalog Number 91TH0400-2

(check on Weibull Parameters from Boeing ISS (MDC99H761 internal MDM verification report)

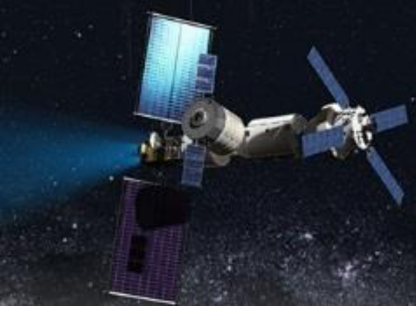


ISS MDM DRAM SEUs
What we see

- SEUs in MDM DRAM are identified and corrected by an EDAC algorithm implemented as part of the normal memory refresh cycle
- Each memory location is refreshed every few micro seconds and SEUs are reported in the telemetry stream along with an ISS time mark
  - SEU bad-bit residence time is less than a few microseconds
  - About 20 % of SEUs happen in the South Atlantic Anomaly and about 70% at high latitudes
  - Very few outside the SAA at low latitude

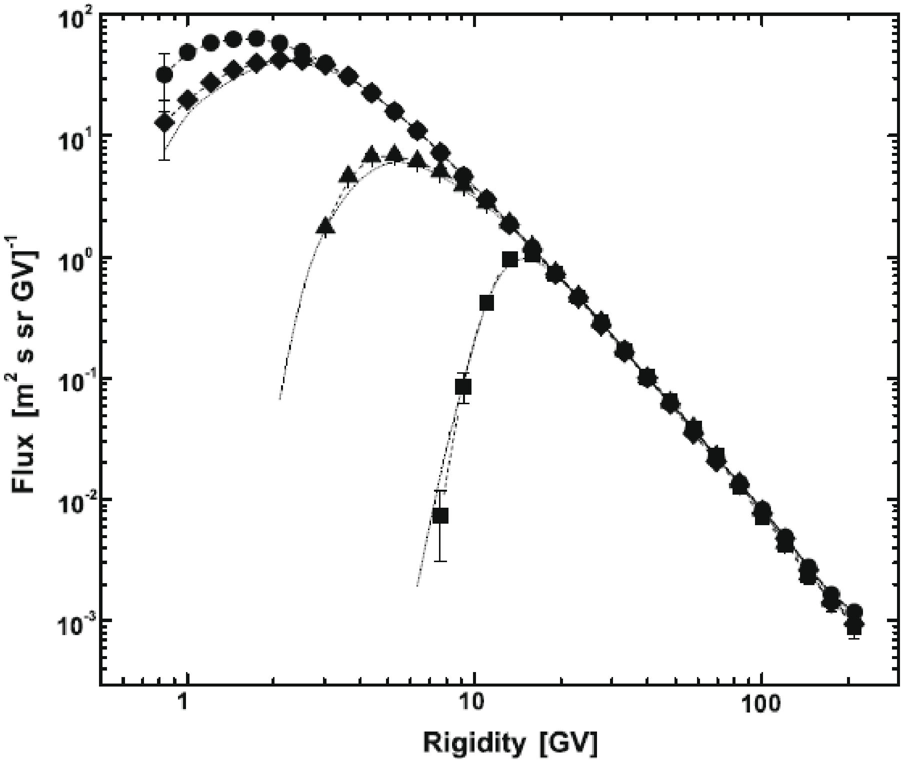


Device	Median Shielding Mass g/cm^2	In-Flight SEU/bit day	FLUKA Predicted SEU/bit day (FLUKA)	CREME-96 Predicted SEU/bit day (CREME)	FOM Predicted SEU/bit day (FOM)
TMS44400	10	8.5×10^{-8}	8.8×10^{-8}	1.1×10^{-7}	2.5×10^{-7}
TMS44400	40	7.0×10^{-8}	7.2×10^{-8}	3.1×10^{-8}	6.8×10^{-8}



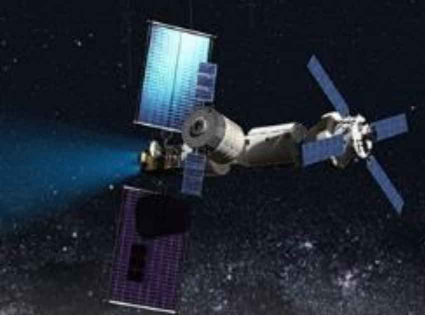
ISS Orbit and Radiation Environments – Latitude dependence of GCR spectra

Latitude dependence of GCR spectrum (He) for ISS orbit - AMS-1/STS-91. Higher magnetic latitude => Reduced geomagnetic shielding and greater similarity to interplanetary GCR environment

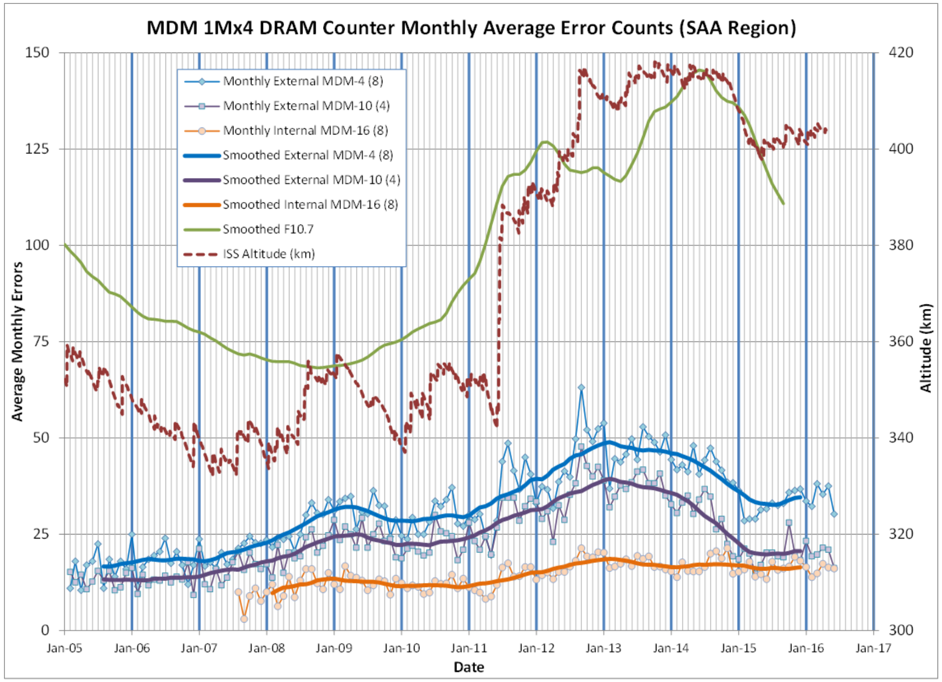


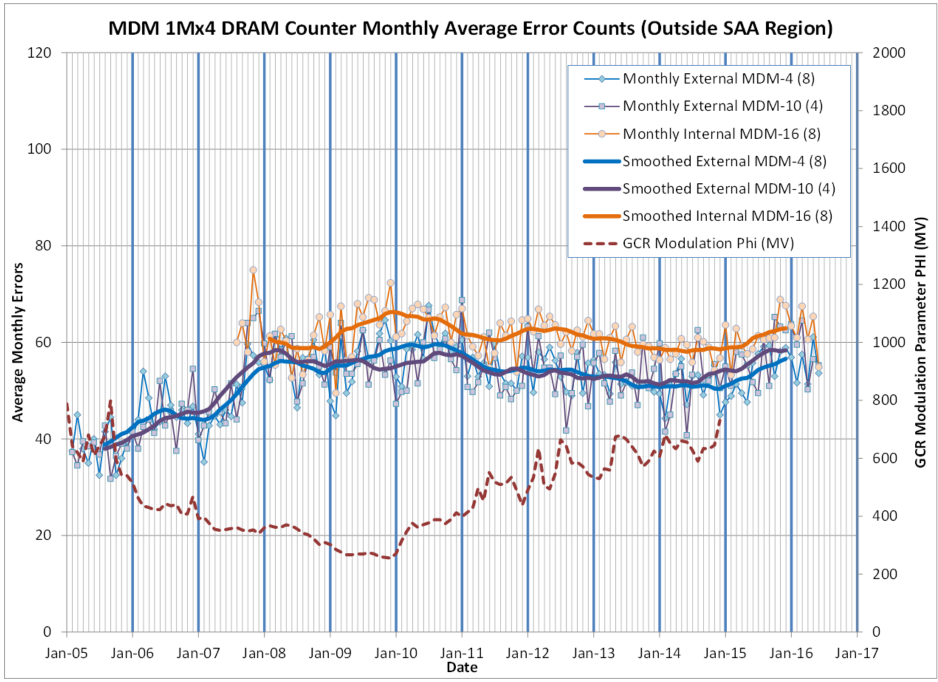
Fluxes of He nuclei inside the magnetosphere. AMS-01 data (symbols) for the three geomagnetic latitude shielding regions. The full-circle data are those at 1 AU outside the magnetosphere.

P. Bobik et al. / Advances in Space Research 43 (2009) 385–393

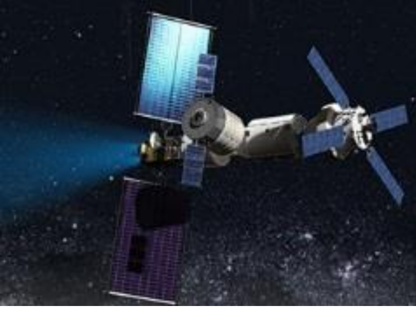


ISS MDM DRAM EDAC SEUs Shielding Mass Effects





- MDM DRAM SEU rates show very different dependences on shielding mass, altitude, and the 11 year solar cycle inside and outside the SAA.
  - Outside the SAA high energy GCRs determine SEU rates which increase with increasing shielding mass (secondary particle shower effects), and show little dependence on altitude, and an expected weak dependence on the solar cycle (GCR modulation factor Phi)
  - Inside the SAA, lower energy trapped protons determine SEU rates which increase with decreasing shielding mass and show a strong dependence on altitude and solar cycle (F10.7)



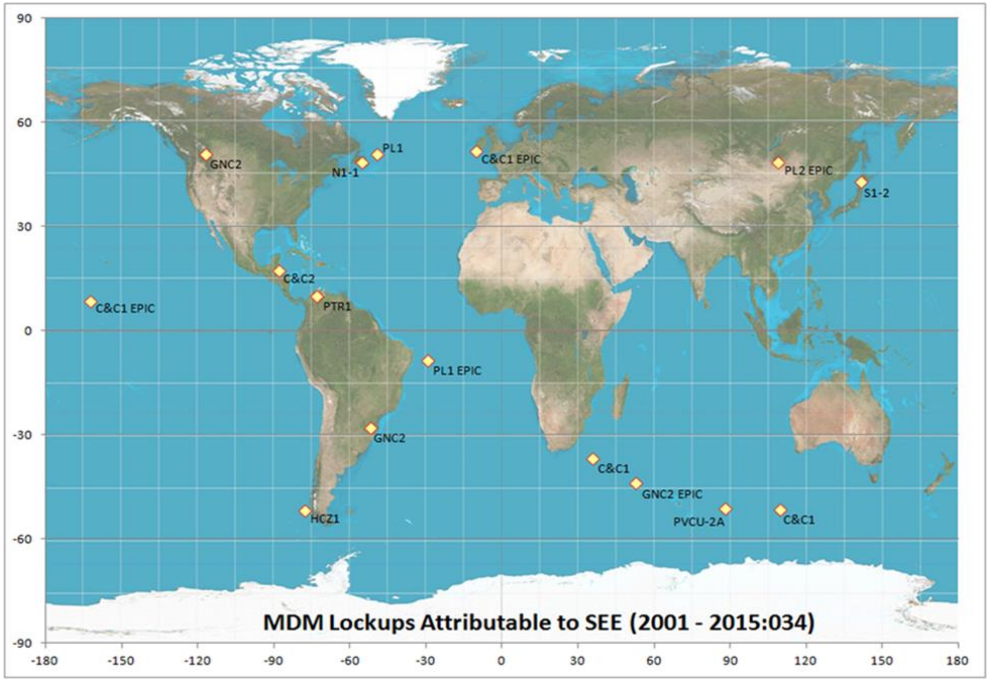
ISS MDM DRAM Upsets Shielding Mass and Geographic Region Dependence

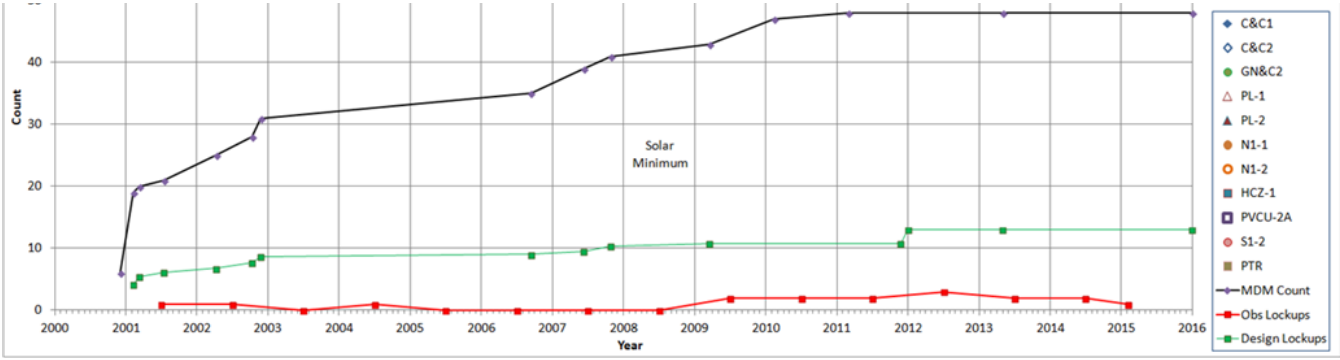
Summary Statistics: ISS MDM DRAM SEU count data by geographic region, 02/2010 through 2017

Statistical Averages for ISS MDMs	All 20 ISS MDMs	8 Internal MDMs	12 External MDMs
Mean SEU count inside SAA (SAA Region) with standard deviation	2671 ± 1112	1412 ± 182	3510 ± 527
Mean SEUs count outside SAA (GCR Region) with standard deviation	5632 ± 403	6030 ± 318	5367 ± 168
% of total counts in SAA Region	31.2 % ± 11%	13% ± 9%	39% ± 4%
% of GCR region total in highest latitude regions (poleward of 40 degrees latitude)	68% ± 4%	64% ± 1%	71% ± 2%

ISS MDM Functional Interrupts Pre-flight "lock-up" predictions vs. in-flight observations

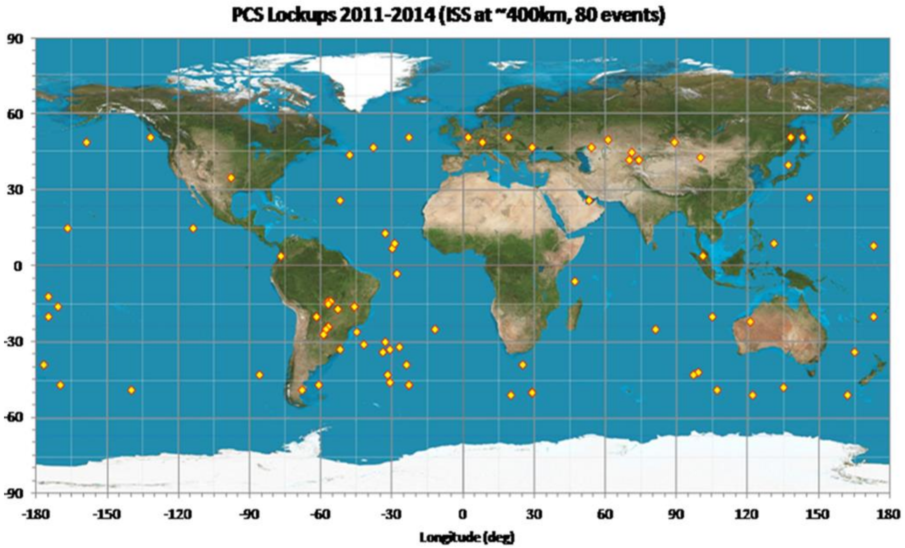
- Specific Program Requirement
  - Mean Time To Recover (MTTR) << MTBF
    - Recovery requires ground intervention and takes ~ 24 hours
- On-orbit MTBF calculated from:
  - Heavy ion test data on all SEE susceptible components
  - ISS SEE design environment (SSP-30512)
  - A reliability engineering functional block diagram of the MDM
- The number of observed lock-ups is between 5 and 10 times smaller than the number of lock-ups predicted
- Flight MDMs are meeting requirements with considerable margin





ISS T61P PCS Lap Top: 200 MeV proton testing result and on-orbit performance

- Geographic distribution of 80 observed T61P PCS on-orbit (@ 400 km) lock-ups and disconnects - 2011 to 2014 - attributed to SEE.
  - Population Size = 7 T61Ps,
  - Shortest time interval between lockups ~ 4.15 hrs. ,
  - Average interval ~304 hrs.,
  - Maximum interval >1800 hrs.
  - Mean MTBF = 82.1 days, standard deviation = 32.2 days
- About half of the events occur at high latitude and between 10-20% of the events occur in the SAA region – no correlation with solar particle events
- There are a number of constraints on using the PCS system for safety critical operations given the expected and observed SEFI rate (JSC 64268, ISS ThinkPad T61p™ Laptop Hardware Project Technical Requirements Specification, Section 6.2, June 2008)



Flight performance vs. JSC board/box level 200 MeV proton test results

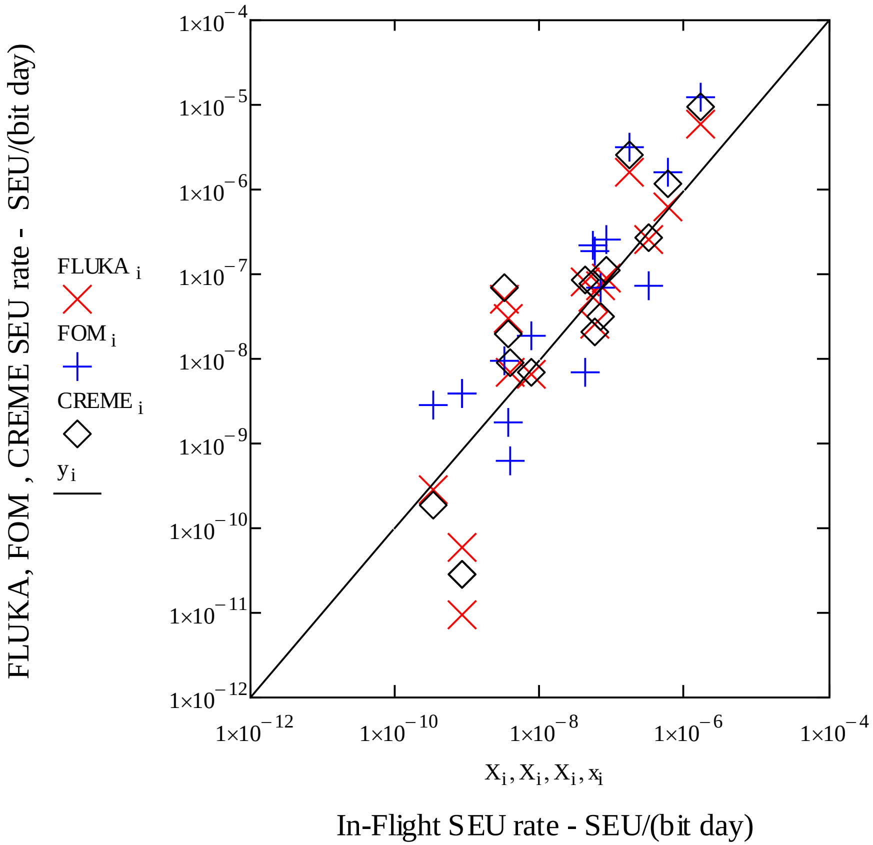
Proton Test	λ_{MTBF} =	5.6×10^{-3} per hr.
In-Flight	λ_{MTBF} =	5.1×10^{-4} per hr.

Predicting on-orbit SEE rates: Multiple spacecraft in LEO, GEO and Interplanetary Space

Using the same device parameters, the FLUKA based rate calculations show the smallest least squares error.

FLUKA, CREME-96 and the Peterson FOM all show overall acceptable performance from a practical perspective

See the data table in the back-up section



$$\sum_i \left[\frac{\left(X_i - FLUKA_i\right)^2}{\left(X_i\right)^2} \right]^{0.5} = 37.881$$

$$\sum_i \left[\frac{\left(X_i - CREME_i\right)^2}{\left(X_i\right)^2} \right]^{0.5} = 50.876$$

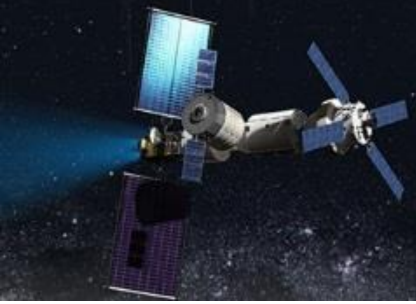
$$\sum_i \left[\frac{\left[\left(X_i - FOM_i\right)^2\right]}{\left(X_i\right)^2} \right]^{0.5} = 53.811$$

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft Single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

Predicting on-orbit interplanetary Solar Particle Event (SPE) Rates: FLUKA Calculations of SPE Upset Rate Increases

Spacecraft/System and Device (ref)	**Nov. 1997 SPE** **Upsets/bit**	**July 2000 SPE** **Upsets/bit**	**Nov. 2001 SPE** **Upsets/bit**	**Oct. 2003 SPE** **Upsets/bit**
Cassini/Solid State Recorder DRAM (16) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no event) daily upset rate	1) $4.4x10^{-7}$ 2) $1.4x10^{-7}$ 3) 0.32 4) $5.8x10^{-8}$	NA	NA	NA
SOHO /Solid State Recorder DRAM (17) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no event)daily upset rate	1) $4.4x10^{-6}$ 2) 2.110^{-6} 3) 0.48 4) $5.9x10^{-7}$	1) $4.7x10^{-5}$ 2) $2.1x10^{-5}$ 3) 0.4 4) $5.9x10^{-7}$	NA	NA
Thuraya/ DSP DRAM (15) 1) Observed event upsets 2) Estimated event upsets 3) Estimated/Observed 4) Quiescent (no event) daily upset rate	NA	NA	1) $2.0x10^{-6}$ 2) $2.8x10^{-6}$ 3) 1.4 4) $5.3x10^{-8}$	1) $1.5x10^{-6}$ 2) $3.8x10^{-6}$ 3) 2.5 4) $5.3x10^{-8}$

Summary



Summary

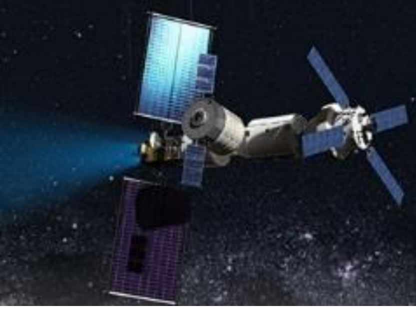
- **Hazard Cause – energetic heavy charged particles (atomic nuclei) and neutrons**
    - GCR, trapped protons, SPE protons, and neutrons
    - Both natural environments primary particles and secondary particle shower products from primary interactions with spacecraft materials
    - Energetic electrons and photons do not contribute to SEE
- **Hazard Effects – Anomalies and failures in spacecraft avionics systems – failure to meet SRMS requirements**
    - Non-destructive SEE
        - SET SEU, MBU, uncorrected latch-up, recoverable Functional Interrupts
        - Data corruption can create LOC/LOM risks
    - Destructive SEE
        - Uncorrected latch-up, SEB, SEGR, SHE
        - Permanent loss of hardware function leading to LOC/LOM risks
- **Hazard Controls - Robust, failure tolerant system design and pre-flight verification of SRMS requirements**
    - Test and analysis to verify expected in-flight system level failure rates meet program SRMS requirements
    - Parallel redundant system architectures, where possible
    - EDAC, FDIR, flight rules/procedures to support recovery from SEE errors, anomalies and failures of safety/mission success critical systems
    - If it isn't needed, power it down!

Back-up and References

Results and Discussion: In-flight vs. calculated spacecraft device SEU rates

Steve Koontz, Brandon Reddell, Paul Boeder: "Calculating Spacecraft single Event Environments with FLUKA, Paper W-33, Proceedings of the 2011 NSREC Radiation Effects Data Workshop, IEEE, July 2011

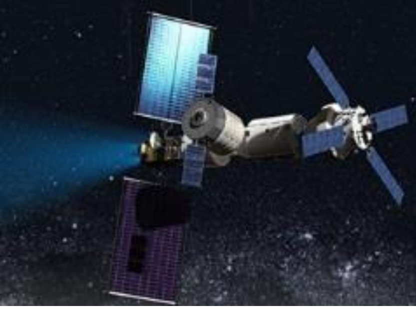
Spacecraft	Flight Env.	Ref.	Device	Median Shielding Mass g/cm^2	In-Flight SEU/bit day (X)	FLUKA Predicted SEU/bit day (FLUKA)	CREME-96 Predicted SEU/bit day (CREME)	FOM Predicted SEU/bit day (FOM)
ISS	ISS	25-27	TMS44400	10	8.5 x 10^{-8}	8.8 x 10^{-8}	1.1 x 10^{-7}	2.5 x 10^{-7}
ISS	ISS	25-27	TMS44400	40	7.0 x 10^{-8}	7.2 x 10^{-8}	3.1 x 10^{-8}	6.8 x 10^{-8}
ISS	ISS	25-27	SMJ416400	10	3.2 x 10^{-9}	5.1 x 10^{-8}	6.8 x 10^{-8}	9.6x 10^{-9}
ISS	ISS	25-27	SMJ416400	40	3.7 x 10^{-9}	3.0 x 10^{-8}	2.0 x 10^{-8}	1.8 x 10^{-9}
ISS	ISS	25-27	KM44S32030T-GL	40	3.3 x 10^{-10}	2.9 x 10^{-10}	1.9 x 10^{-10}	2.8 x 10^{-10}
ISS MISSE-7	ISS	28	V4 XQR4VFX60 - BRAM	0.8	4.2 x 10^{-8}	8.0 x 10^{-8}	8.6 x 10^{-8}	6.8X10^{-9}
ISS MISSE-7	ISS	28	V4 XQR4VFX60 – Config. Memory	0.8	3.8 x 10^{-9}	7.1 x 10^{-9}	9.1 x 10^{-9}	6.2 x 10^{-10}
ISS MISSE-7	ISS	28	V5 LX330T – Config. Memory	0.8	7.8 x 10^{-9}	6.5 x 10^{-9}	7 x 10^{-9}	1.9 x 10^{-8}
Space Shuttle	ISS	29	IMS1601EPI	34	3.1 x 10^{-7}	2.5 x 10^{-7}	2.7 x 10^{-7}	7.4 x 10^{-8}
Thuraya	GEO	30	ASIC 0.25 µ SRAM, IBM SA-12	0.7	5.3 x 10^{-8}	5.3 x 10^{-8}	7.9 x 10^{-8}	2.2 x 10^{-7}
Mercury Messenger	IP	31	ASIC "rad/SEE hard" SRAM	1.0	8.6 x 10^{-10}	5.8 x 10^{-11} (1µ W)	2.9 x 10^{-11}	4.0 x 10^{-9}
Mercury Messenger	IP	31	ASIC "rad/SEE hard" SRAM	1.0	8.6 x 10^{-10}	9.3 x 10^{-12} (no W)	2.9 x 10^{-11}	4.0 x 10^{-9}
Cassini	IP	32	OKI (4Mx1)	3.4	5.8 x 10^{-8}	2.5 x 10^{-8}	2.1 x 10^{-8}	1.9 x 10^{-7}
SOHO	IP	33	SMJ44100	1.0	5.9 x 10^{-7}	6.4 x 10^{-7}	1.2 x 10^{-6}	1.6 x 10^{-6}
SOHO	IP	33	CP65656EV	1.0	1.7 x 10^{-7}	1.6 x 10^{-6}	2.5 x 10^{-6}	3.1 x 10^{-6}
ETS-V	GEO	34	PD4464D-20	5.8	1.7 x 10^{-6}	6 x 10^{-6}	9.3 x 10^{-6}	1.24 x 10^{-5}



SEE Effects Summary

Single Event Upset (SEU)	corruption of the information stored in a memory element	Memories, latches in logic devices
Multiple Bit Upset (MBU)	several memory elements corrupted by a single strike	Memories, latches in logic devices
Single Event Functional Interrupt (SEFI)	corruption of a data path leading to loss of normal operation	Complex devices with built-in state machine/control sections
Single Hard Error (SHE)	unalterable change of state in a memory element	Memories, latches in logic devices
Single Event Transient (SET)	Impulse response of certain amplitude and duration	Analog and Mixed Signal circuits, Photonics
Single Event Disturb (SED)	Momentary corruption of the information stored in a bit	combinational logic, latches in logic devices
Single Event Latchup (SEL)	high-current conditions	CMOS, BiCMOS devices
Single Event Snapback (SESB)	high-current conditions	N-channel MOSFET, SOI devices
Single Event Burnout (SEB)	Destructive burnout due to high-current conditions	BJT, N-channel Power MOSFET
Single Event Gate Rupture (SEGR)	Rupture of gate dielectric due to high electrical field conditions	Power MOSFETs, Non-volatile NMOS structures, VLSIs, linear devices …

http://space.epfl.ch/webdav/site/space/shared/industry_media/07%20SEE%20Effect%20F.Sturesson.pdf



Useful Links

Avionics SEE/TID data and technical support

http://www.fluka.org/fluka.php The home page for the FLUKA nuclear reaction and transport code

https://creme.isde.vanderbilt.edu/ CREME-96 web page at Vanderbilt University

https://parts.jpl.nasa.gov/organization/group-5144/ NASA JPL Radiation effects Group

https://nepp.nasa.gov/ NASA Electronics Parts and Packaging Program – microelectronics reliability including space radiation effects – note the annual workshop meeting

http://www.aerospace.org/education/conferenceproceedings/2017-mrqw-proceedings/ Proceedings of annual Aerospace Corporation Microelectronics Reliability and Qualification Working (MRQW) Meeting, 2016 and 2017.

http://www.sandia.gov/mems/rad-hard/index.html Sandia National Laboratories Rad Hard Electronics and Trusted Services

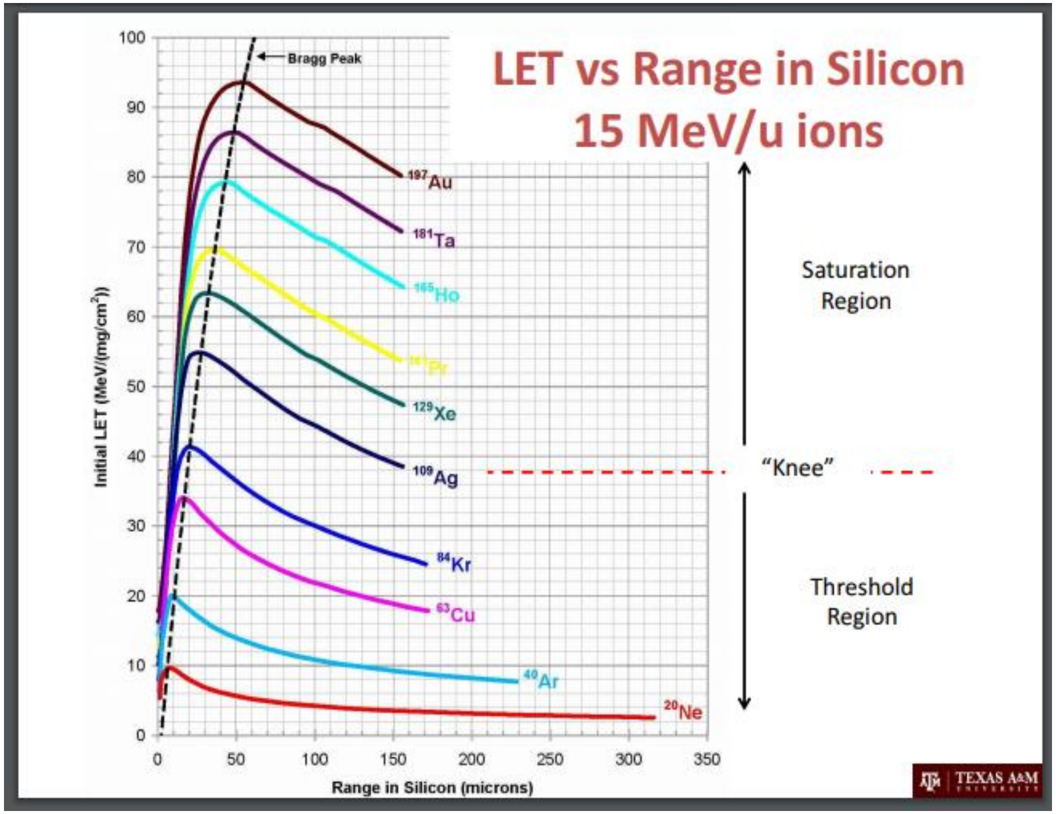
http://www.radecs2016.com/joomla/images/RADECS-2016_Jupiter_10_Steve_McClure.pdf JPL EEE Parts and Materials Verification Program for Jupiter Missions (including radiation effects)

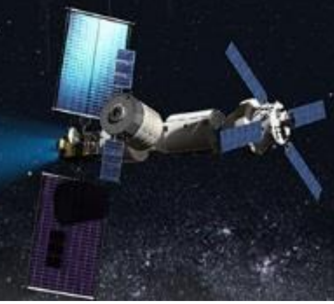
http://www.aerospace.org/wp-content/uploads/conferences/MRQW2016/7E_LaBel.pdf - Facilities listing for high energy proton testing

Spacecraft Avionics SEE/TID "textbook"
L.D. Edmonds, C.E. Barnes, L.Z. Scheick; An Introduction to Space Radiation Effects on Microelectronics, JPL Publication 00-06, NASA Jet Propulsion Laboratory, Pasadena, California, May 2000

Conventional Heavy Ion SEE Test Facilities:

- Conventional heavy ion SEE test accelerators
  - Texas A&M Cyclotron Facility
    - https://cyclotron.tamu.edu/ref/
  - Laurence Berkeley Lab (DoE) 88” Cyclotron Facility
    - http://cyclotron.lbl.gov/base-rad-effects
  - Brookhaven National Laboratory (DoE) Tandem Van de Graph
    - https://www.bnl.gov/tandem/capabilities/seu.php
- Kinetic energy range - 5 to 40 MeV/amu
- LET at normal incidence 0.1 to 80 (MeV cm^2)/mg (Si)
- Limited range and rapid change in LET after entering the surface of the test device (what is the LET in the device sensitive volume?)





High Energy (relativistic) Heavy Ion Accelerator Test Facilities

- Michigan State University Cyclotron Facility
  - http://www.nscl.msu.edu/
- NASA Space Radiation Laboratory at Brookhaven National Laboratory
  - https://www.bnl.gov/nsrl/
- Le Grand Accelerateur National d'Ions Lourds (EU/France)
  - https://www.ganil-spiral2.eu/
- GSI Helmholtzzentrum für Schwerionenforschung (EU/Germany)
  - https://www.gsi.de/en/researchaccelerators/accelerator_facility.htm
- Issues with using these
  - No standard methods yet so it always becomes a “Science Project”
    - No dedicated facilities (except NSRL) for spacecraft avionics SEE qualification
  - If you can get access, the beam time can cost on the order of $5K to $10K per hour

High Energy Proton Accelerator Test Facilities

Proton Facility Status (200 MeV – North America)

	Facility	Location	Hourly Rate	Type	Access/ Annual Hours	Expected Avail.	Shakeout Test
Future Facilities	Northwestern Medicine Chicago Proton Center	Warrenville, IL		Cyclotron	2 hrs – weeknights 8-16 hrs Saturdays	Now	Yes
Future Facilities	Scripps Proton Therapy Center	La Jolla, CA		Cyclotron	Up to 500 hrs	Now	Yes
Future Facilities	Seattle Proton Center	Seattle, WA		Cyclotron	TBD	On hold until CY16	Yes
Future Facilities	Hampton University Proton Therapy Institute (HUPTI)	Hampton, VA		Cyclotron	TBD weekends (up to 30 hrs?)	Awaiting update	Yes
Future Facilities	OKC ProCure Proton Therapy Center	OKC, OK		Cyclotron	Weekdays 6 hrs + possible shared time Saturdays 5-8 hrs	On hold	Change of management – no current interest
Future Facilities	University of Florida Health Proton Therapy Institute (UFHPTI)	Jacksonville, FL		Cyclotron	Weekend days (possibly shared with quality assurance)	CY16	Spring CY16
Future Facilities	Provision Center for Proton Therapy	Knoxville, TN		Cyclotron	TBD	Unknown	Unknown
Future Facilities	Dallas Proton Treatment Center	Dallas, TX		Cyclotron	TBD	On "pause"	TBD
Future Facilities	University of Maryland Proton Treatment Center	Baltimore, MD		Cyclotron	TBD	CY16	Summer CY16
Existing Facilities	Tri-University Meson Facility (TRIUMF)	Vancouver, CAN		Cyclotron	4x/year	Yes	Yes
Existing Facilities	Slater Proton Treatment and Research Center at Loma Linda University Medical Center (LLUMC)	Loma Linda, CA		Synchrotron	~1000	Yes	N/A
Existing Facilities	Mass General Francis H. Burr Proton Therapy (MGH)	Boston, MA		Cyclotron	~800 hours 12hr weekend days, 3 of 4 weekends – 6 month+ lead time	Yes	Yes
Existing Facilities	NASA Space Radiation Lab (NSRL)	Brookhaven, NY		Synchrotron	~1000 hours	Yes	N/A
	Indiana University Cyclotron Facility	Bloomington, IN		Cyclotron	2000 hours	No	N/A

Kenneth A. LaBel - The 2016 MRQW Microelectronics Reliability and Qualification Working Meeting, El Segundo, CA, February 9-10, 2016.

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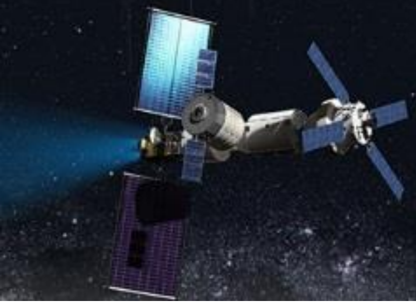

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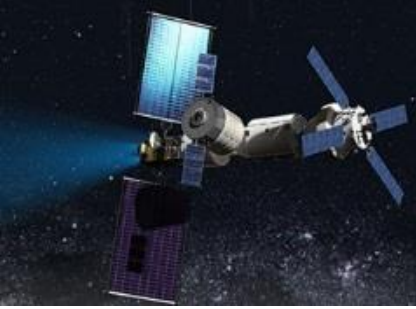

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