Those Upsetting Ions-The Effects of Radiation on Electronics

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Basic Radiation Concepts

An Overview of Radiation Environments (no chip is spared!)

Basic Radiation Damage Mechanisms

Transient Effects

Trends in Technology

Testing and Mitigation

Some Special Cases

MASSACHUSETTS GENERAL HOSPITAL
RADIATION ONCOLOGY

HARVARD MEDICAL SCHOOL

Acknowledgment of sources:

Handbook of Radiation Effects (Second Edition)

Andrew Holmes-Siedle and Len Adams (Oxford University Press)

SER-History, Trends and Challenges

James F. Ziegler and Helmut Puchner (Cypress)

Space Radiation Effects in Microelectronics

JPL Radiation Effects Group

http://parts.jpl.nasa.gov/docs/Radcrs_Final.pdf

Basic Radiation Concepts I

Types of Radiation and Their Interactions With Matter

There are two basic ways that radiation interacts with matter, interactions with the orbital electrons and interactions with the nucleus itself.

Photons only interact with the electrons, through Compton scattering and photon electron scattering processes.

Similarly, electrons also only interact with the electrons (at least in the energy range with which we are concerned).

Heavier charged particle such as protons and heavy ions can both interact with the electrons through Coulomb forces, as well as undergo both elastic and in-elastic collisions with the nuclei.

Neutrons can only interact directly with the nuclei, but those interactions can produce charged secondaries (such as protons and alpha particles) that can then in turn interact with the electrons.

The interactions with the electrons are what gives rise to ionization and is the primary mechanism in the deposition of energy, and thus dose, in the material.

Elastic collisions with the nuclei can knock the atom out of position, this is known as displacement damage.

In-elastic collisions with the nucleus can fragment the nucleus, producing a local burst of charged secondaries, which deposit dose through ionization. This will also transmute the atom, creating radioactive isotopes.

So, to sum up we have the following:

Particle Species	Interaction Mechanism(s)	Effect on Matter
Photon	Electron Scattering	Ionization
Electron	Coulomb interactions with orbital electrons	Ionization
Proton	Coulomb interactions with orbital electrons, nuclear interactions	Ionization, atomic displacement, creation of isotopes
Heavier Ions	Coulomb interactions with orbital electrons, nuclear interactions	Ionization, atomic displacement, creation of isotopes
Neutrons	Nuclear interactions	Atomic displacement, creation of isotopes and ionization through charged secondaries

Basic Radiation Concepts II
Fluence, Flux and Dose

Fluence = particles/cm^2

Flux = particles/cm^2/sec

Stopping Power (S) = energy loss/particle. S is also known as DE/DX or Linear Energy Transfer (LET) and is typically given in terms of energy/distance (KeV/micron) or (preferably) as energy/areal density, such as MeV/gm/cm^2 (or KeV/mg/cm^2 etc). This is dependant on both the energy of the particle and the target composition.

Dose = energy/mass = Fluence x Stopping power (provided stopping power is expressed as energy/areal density)

SI unit of dose is the Gray (Gy) = 1 Joule/km

I Rad = 1/100 Gy = 1cGy

Example Calculation

Say we have $1x10^8$ P+/cm^2 of energy 160 MeV incident on Silicon.

DE/DX *for each proton* = 4.2 MeV/gm/cm^2 , and thus the energy deposited would be $1x10^8$ P+/cm^2 x 4.2 MeV/gm/cm^2 /P+ , which gives us $4.2x10^8$ MeV/gm.

Since 1 eV = 1.6x 10^{-19} Joule, that gives us $6.72x10^{-2}$ Gy, or 6.72 rads

Radiation Environments:

1.Space

Cosmic Rays (Solar & Galactic)

Trapped Radiation Belts

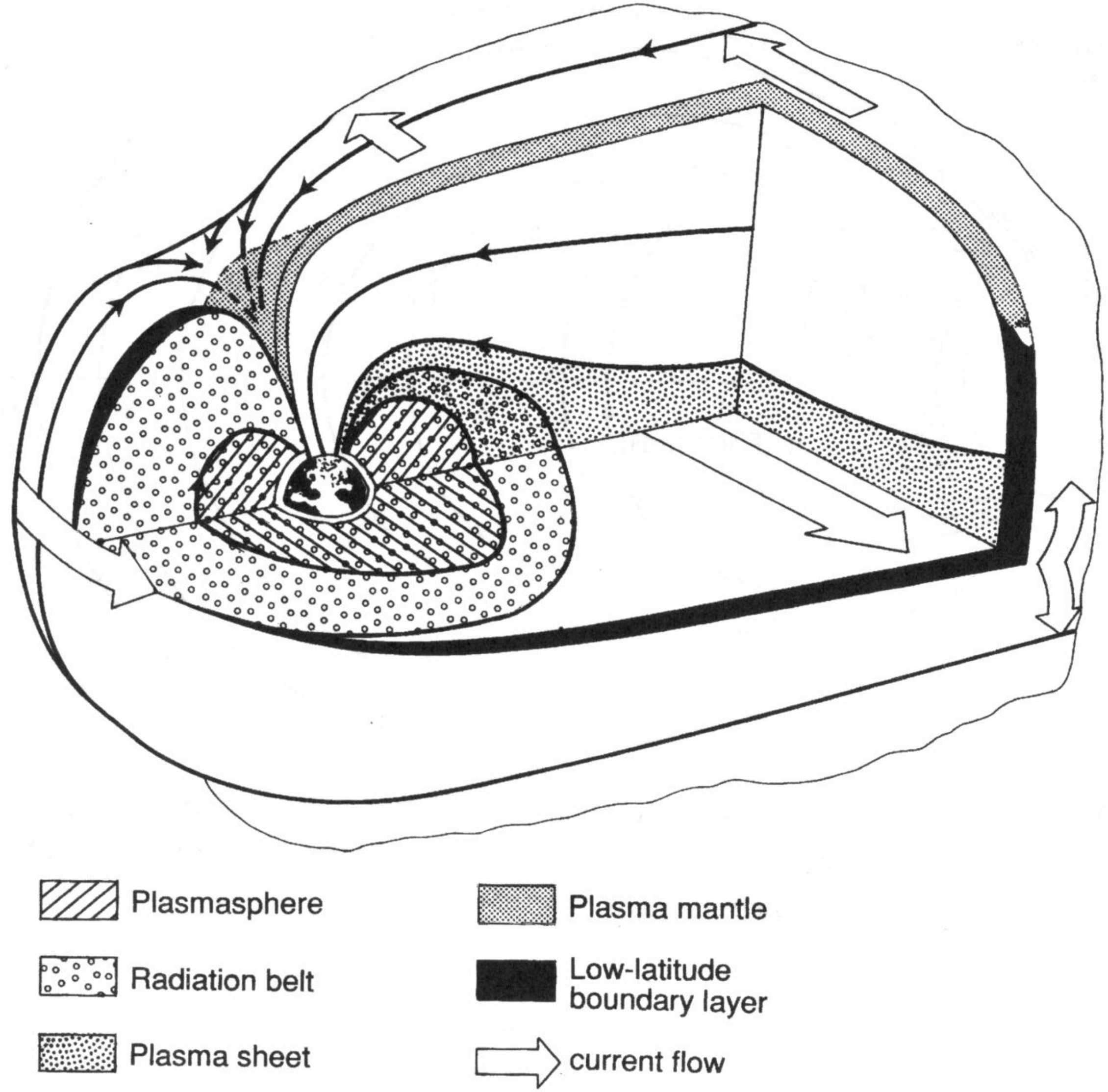
2. Terrestrial

Terrestrial Cosmic Rays (Secondary Particle showers)

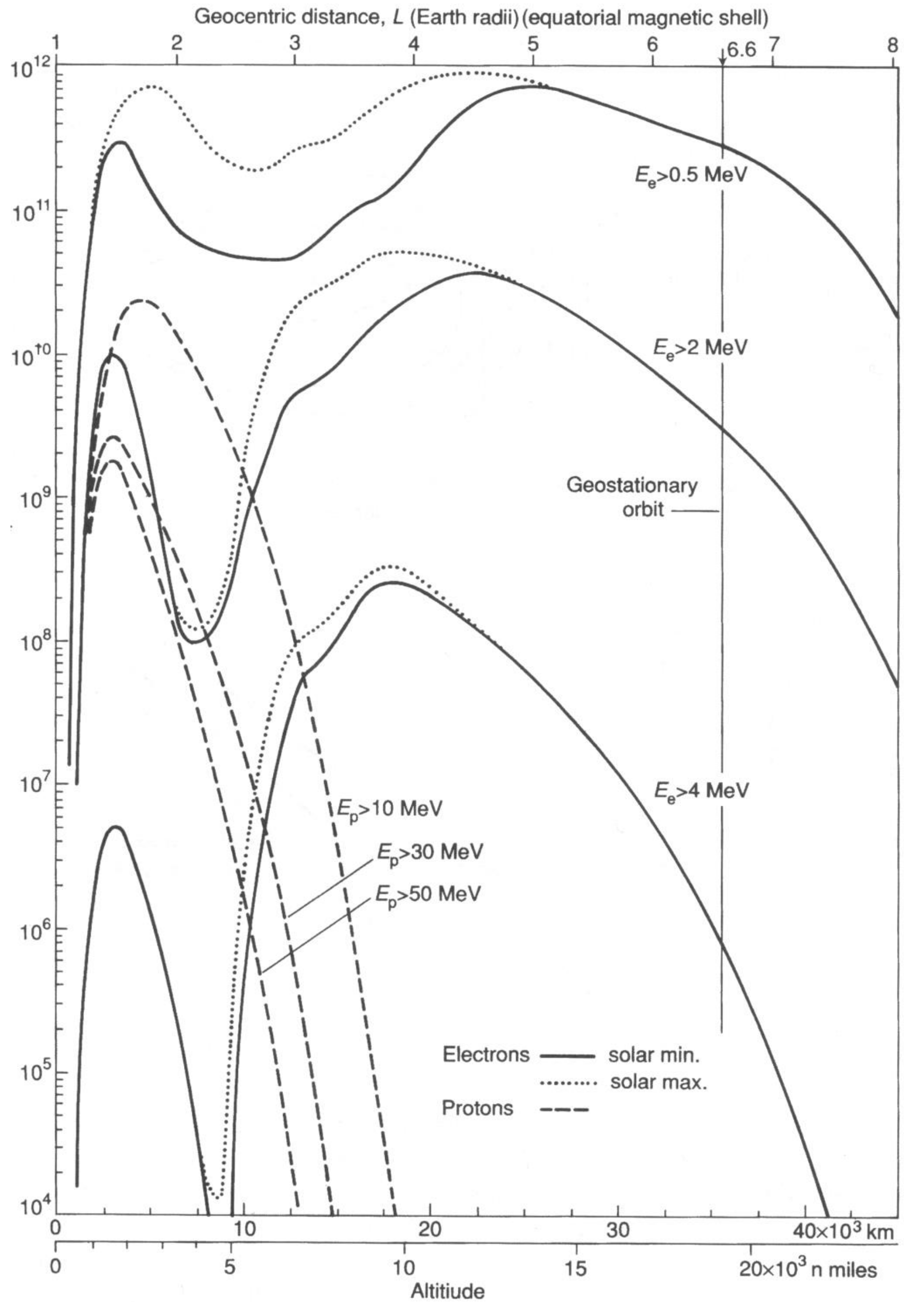
Radioactive Isotopes

Man Made Sources (Particle Accelerators, Medical, etc.)

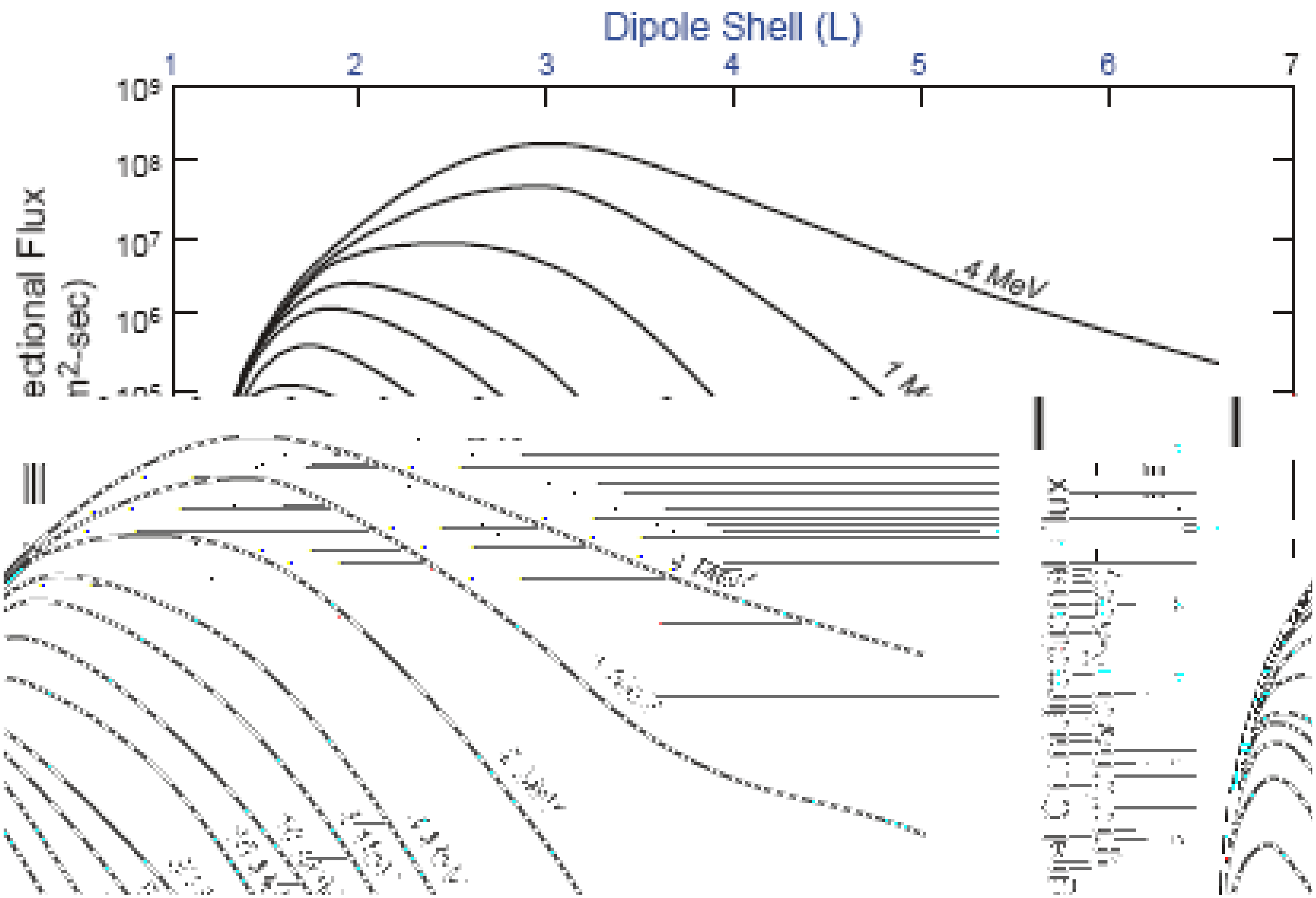
All electronics are in a radiation environment !!


Plasmasphere
Radiation belt
Plasma sheet
Plasma mantle
Low-latitude boundary layer
current flow

Intensity of Radiation by Earth Radii

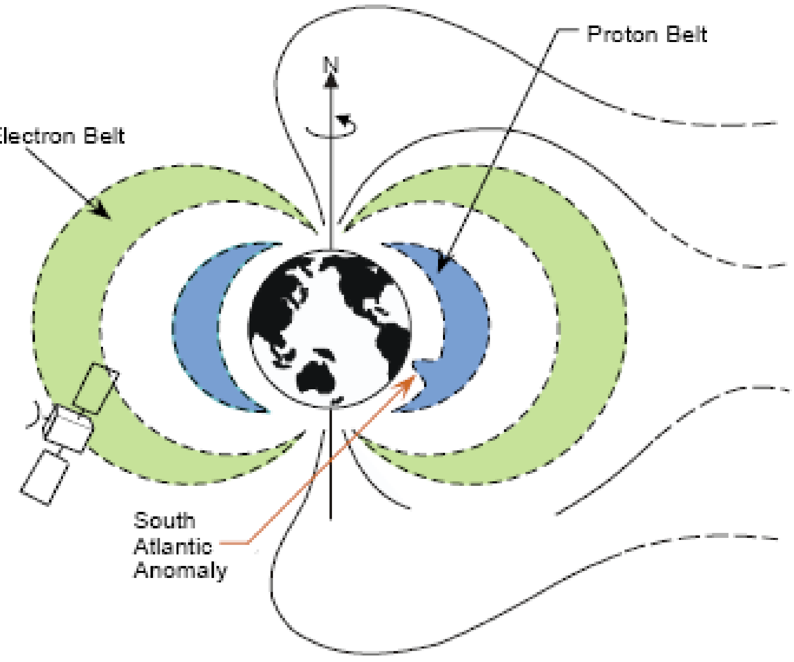


Proton flux by altitude

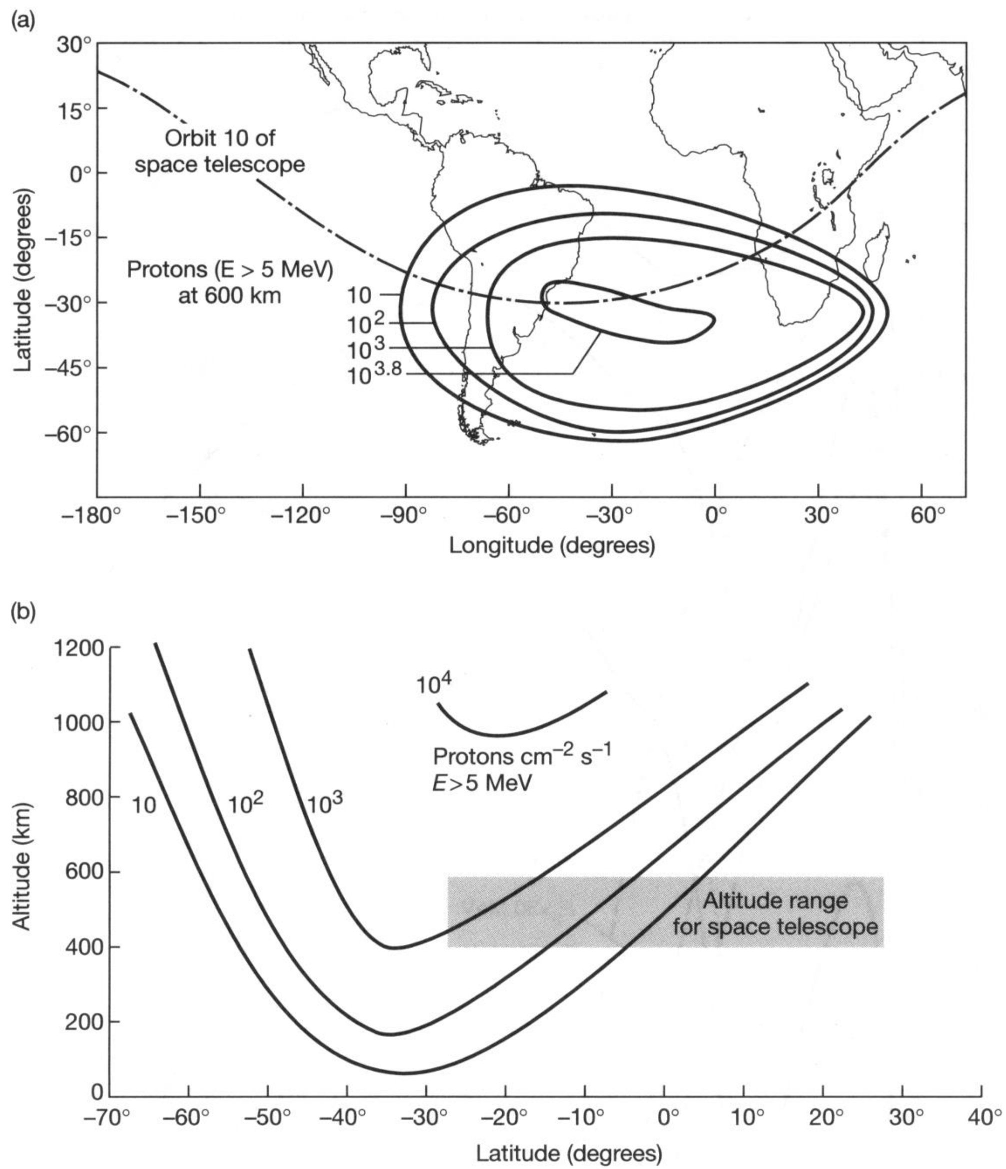


South Atlantic Anomaly (SAA)

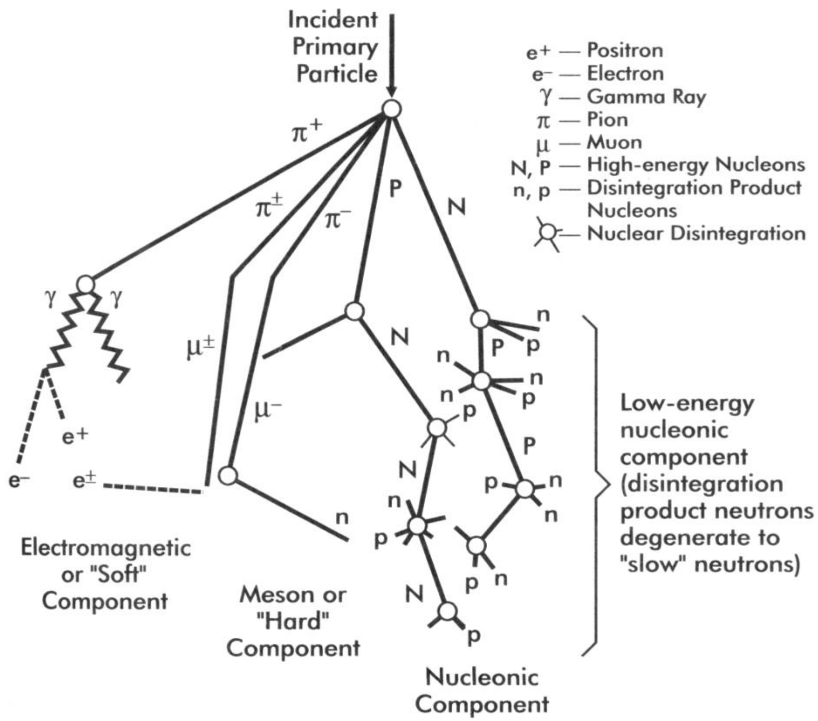
Near Earth TID Environment

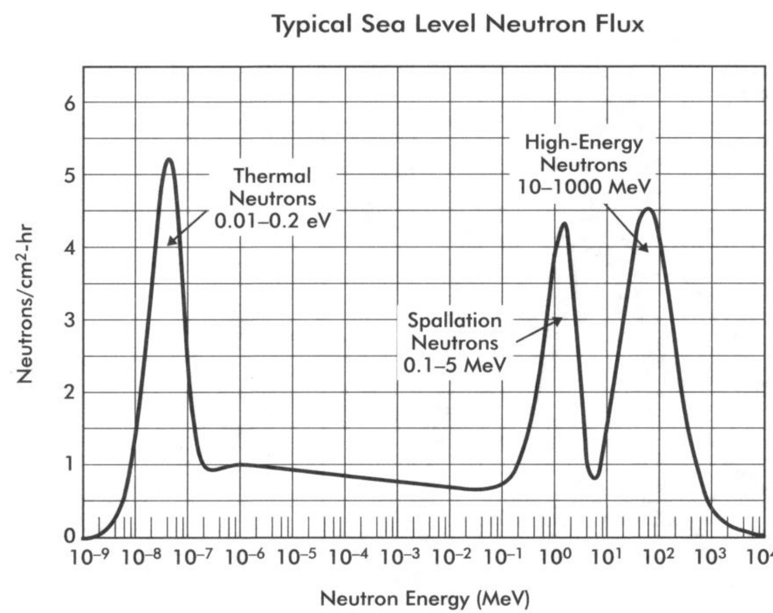


South Atlantic Anomaly (SAA)



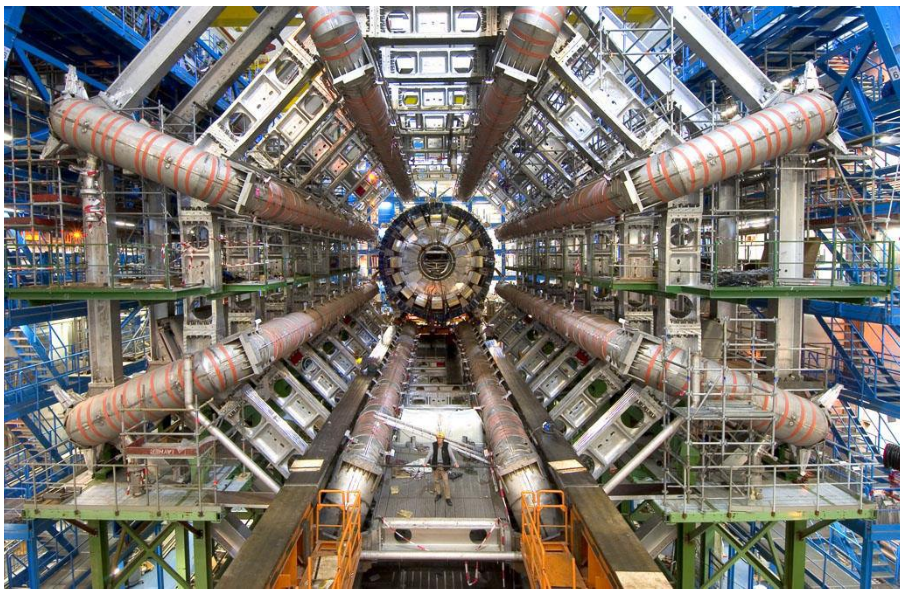
Terrestrial "Cosmic Rays" (i.e. secondary neutrons and protons)





Man Made Environments

Particle Accelerators (Shown Below:ATLAS detector at CERN LHC)



Medical Radiotherapy Machines

Types of Radiation Damage/Effects:

1.Permanent or Long Term **Deterministic**

Displacement Damage

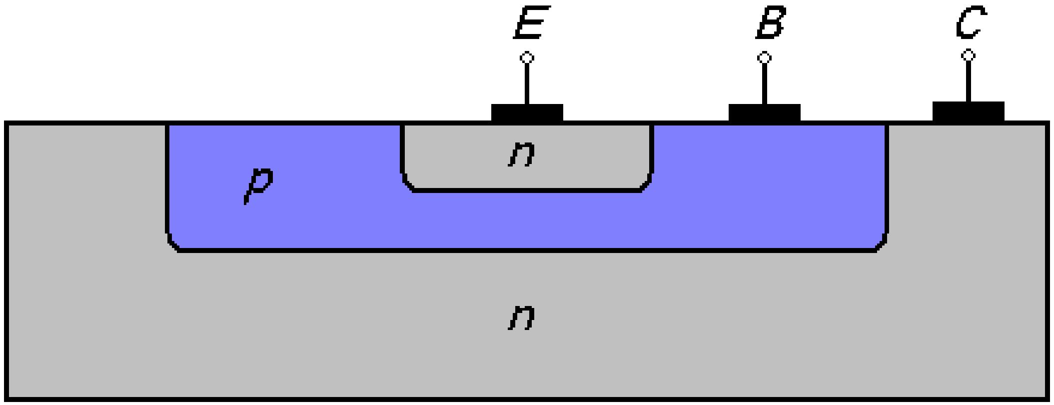
Trapped Charge

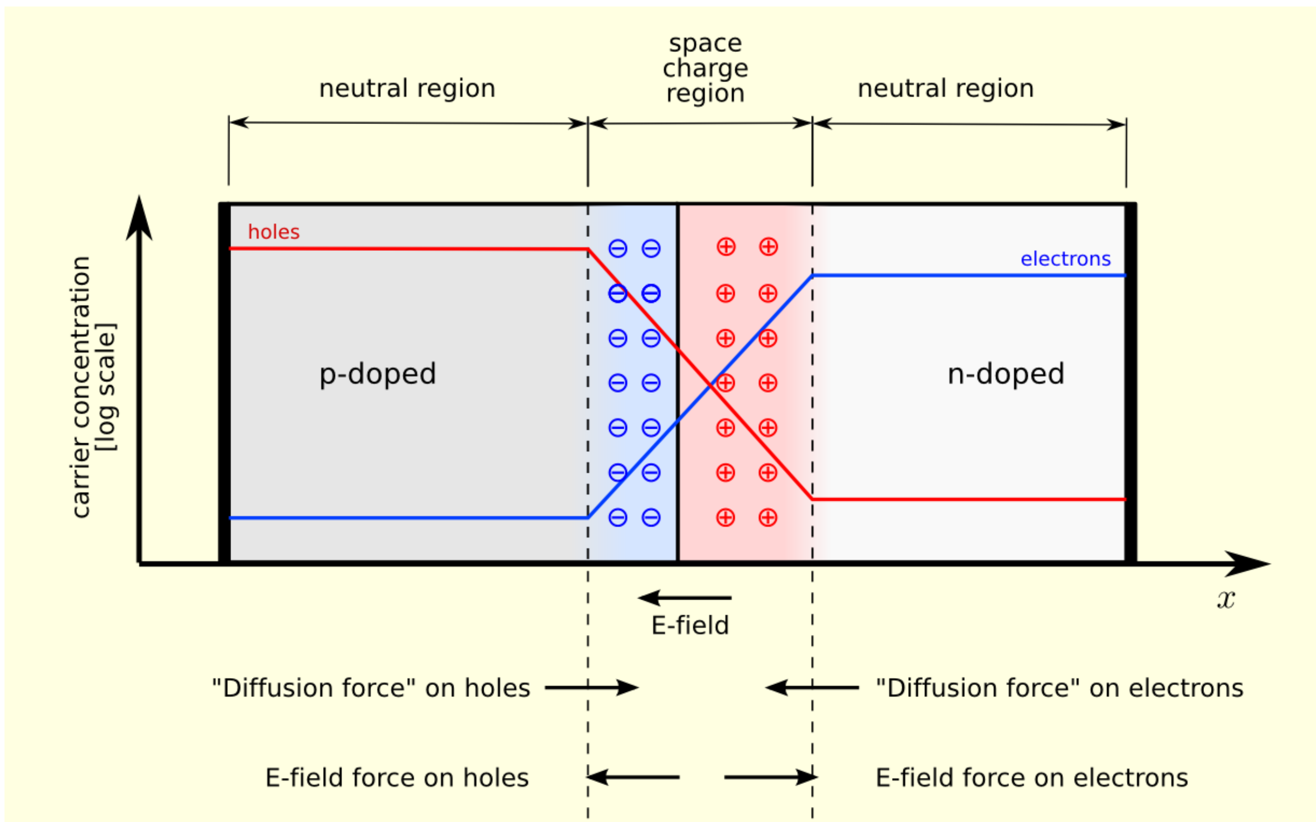
2. Transient **Stochastic**

Single Event Upset (SEU)

Single Event Latch Up (SEL)

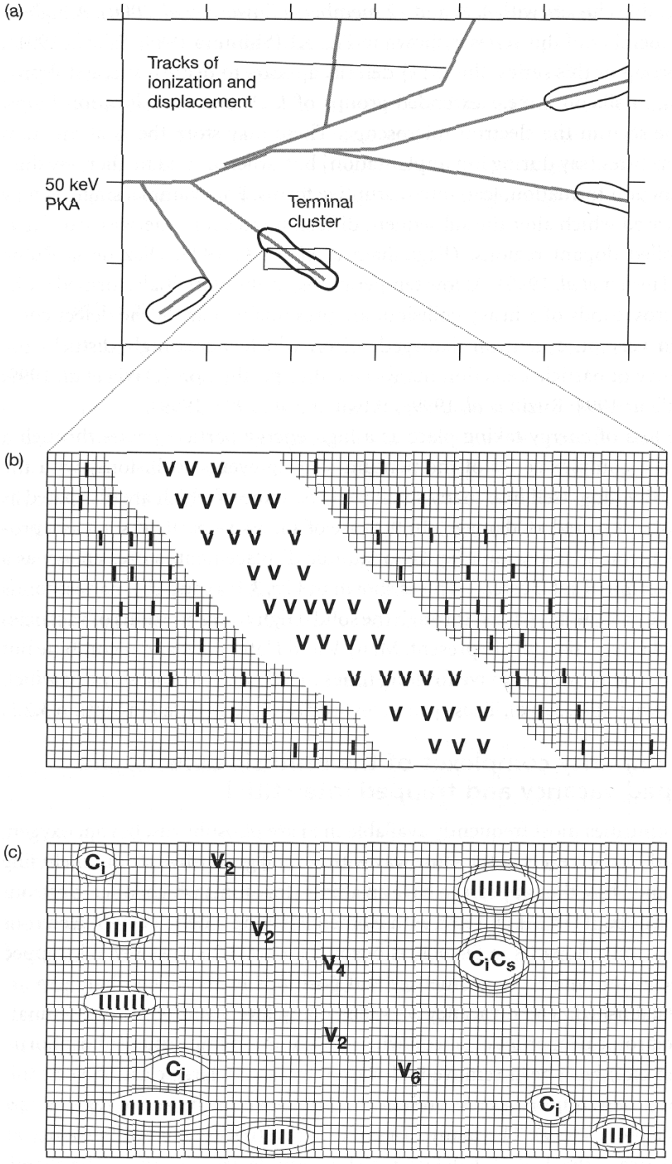
Single Event ____ (Fill in the blank!)


E
B
C
n
p
n


space
charge
region
neutral region
neutral region
carrier concentration
[log scale]
holes
electrons
p-doped
n-doped
x
E-field
"Diffusion force" on holes
"Diffusion force" on electrons
E-field force on holes
E-field force on electrons

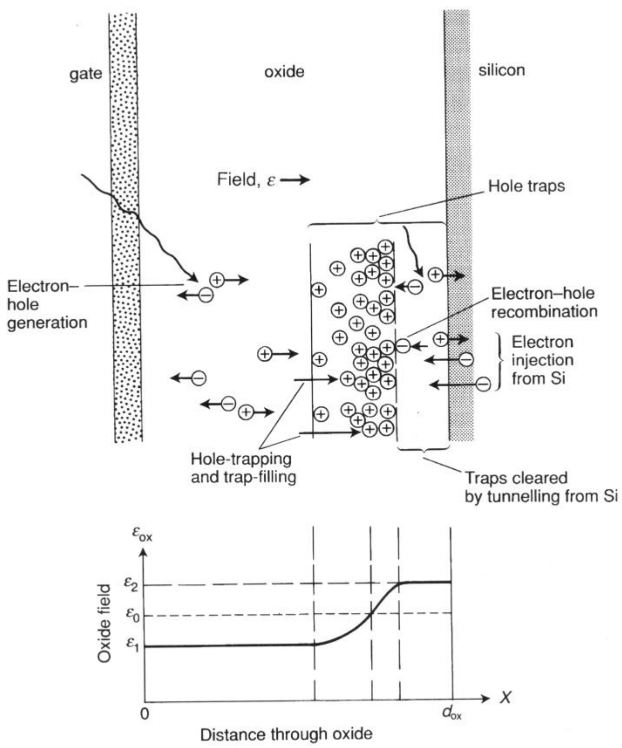
Atomic displacement damage in Si

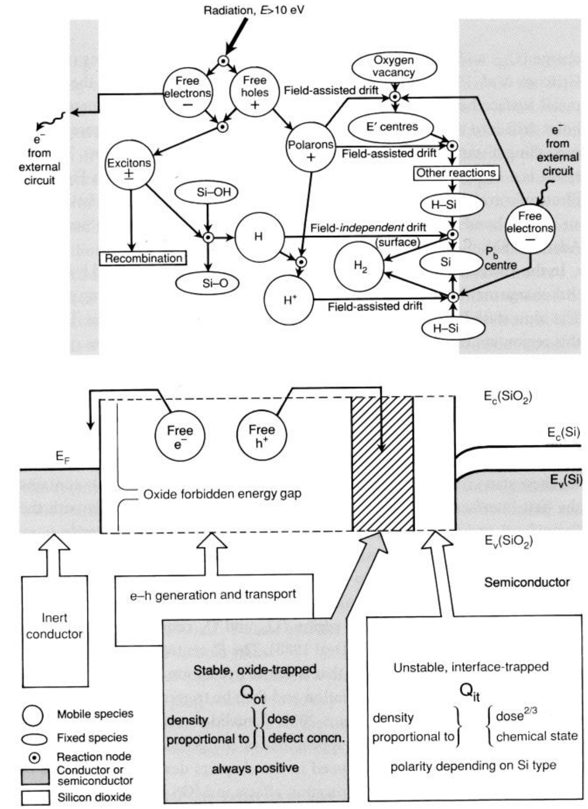
(mostly due to neutrons and Protons)



Minority carrier lifetime and mobility is reduced. This results in gain reduction in bipolor transistors & degradation of performance in LEDs and optical detectors.

Trapped Charge in Oxides





Trapped charge changes/degrades performance

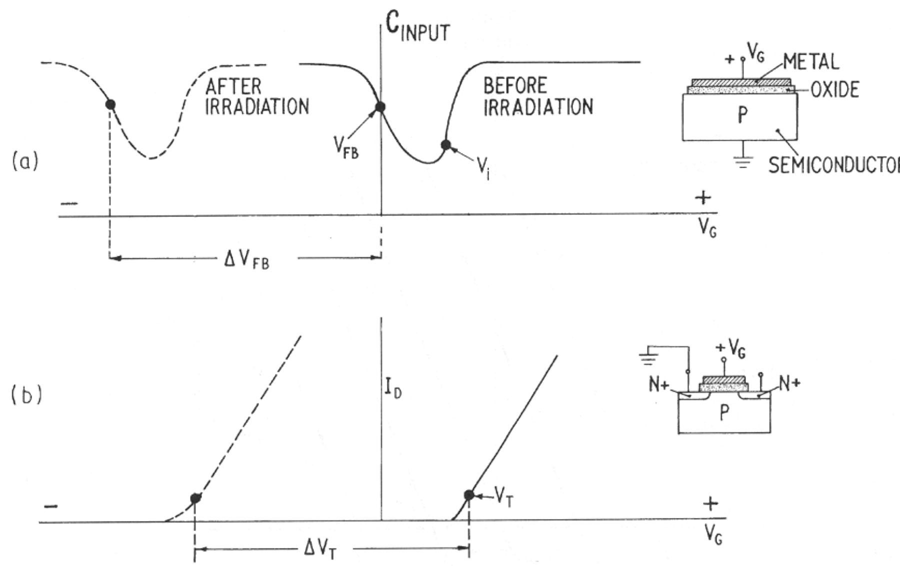
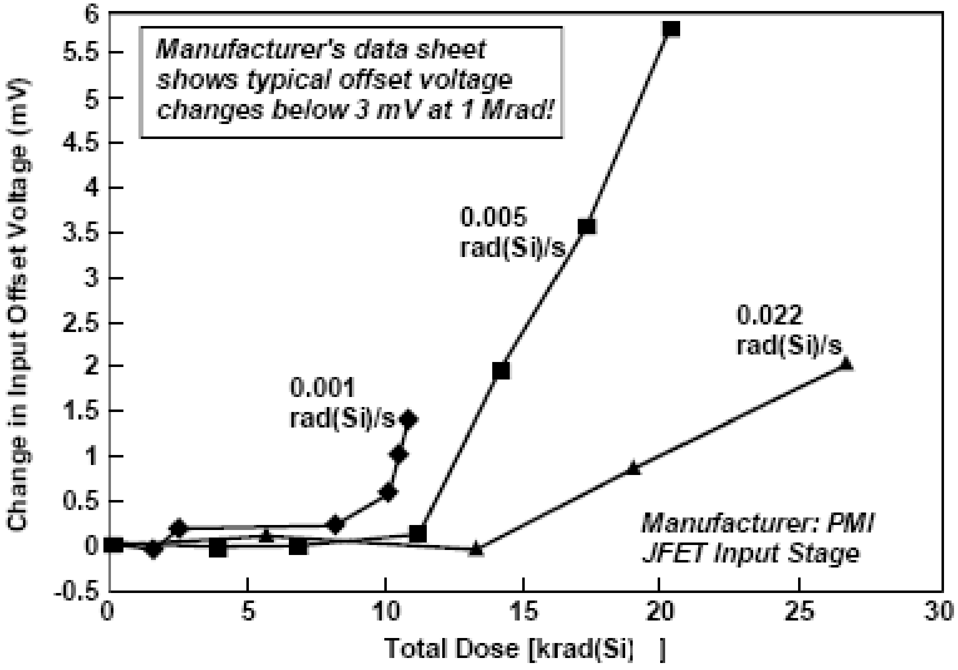
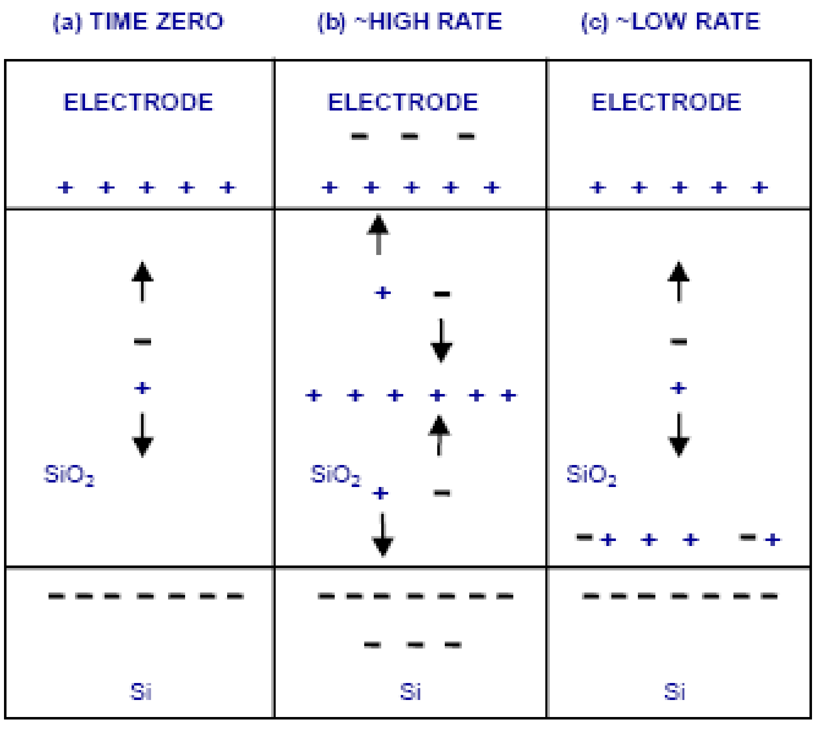


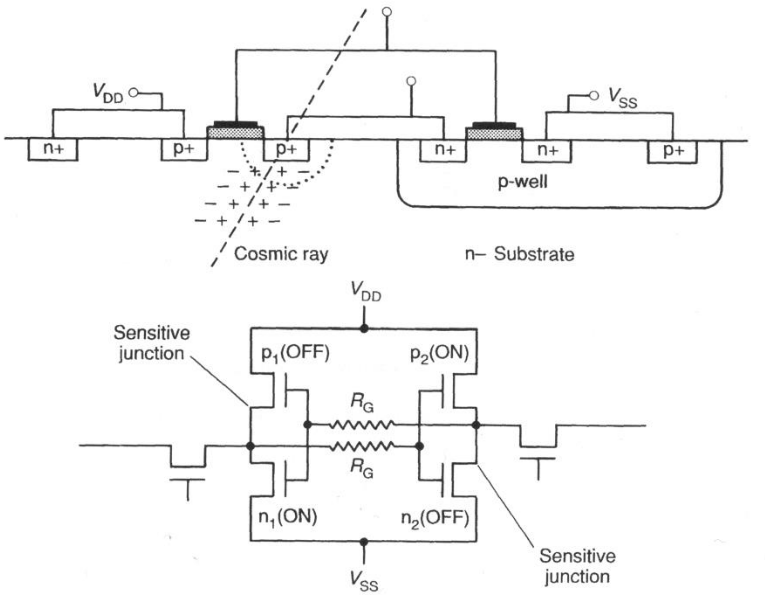
Fig. 4.4 MOS characteristics: typical variation of (a) capacitance and (b) drain current with gate voltage, showing the shifts in flatband and threshold voltages due to trapped charge (no interface states).

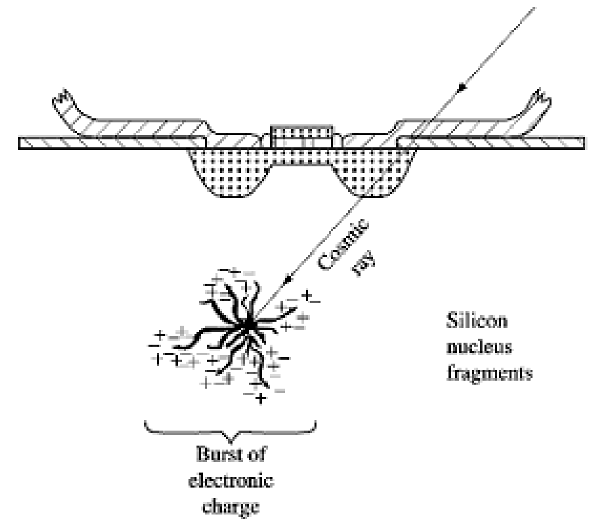
Extremely Low Dose Rate Sensitivity (ELDRS)

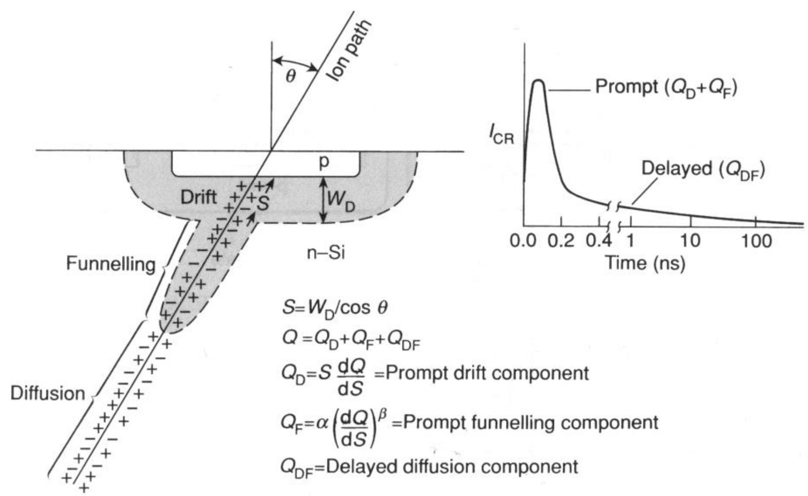




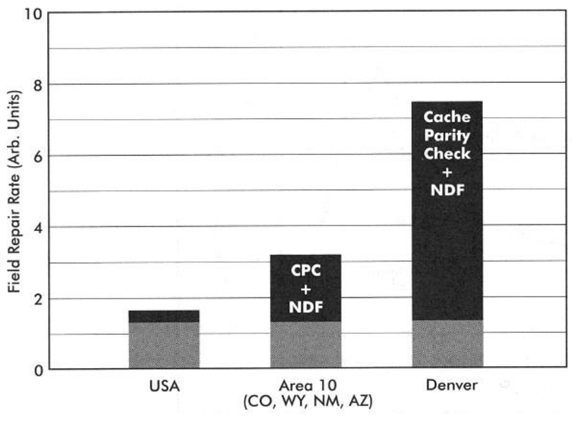
Transient Effects: Single Event Upset

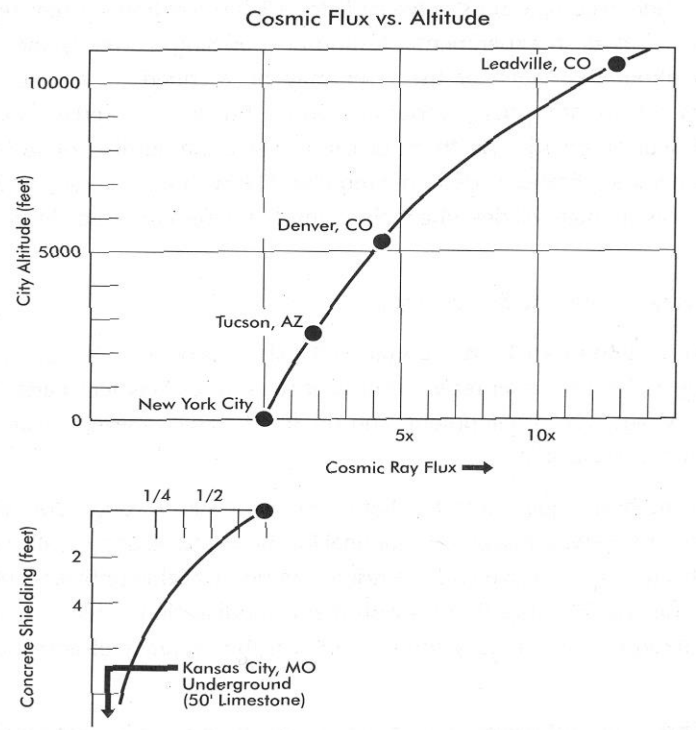






IBM Experiments to show that terrestrial neutrons are a significant source of failures (1984-1988)





Special Case: Thermal neutrons and BPSG

BPSG or Boron Phosphorous Silicon Glass began to be used in the mid 1990s to separate layers in chip manufacture. ^{10}B has a large cross section for this reaction with thermal neutrons (energy < 0.25 eV)

$^{10}B + n \quad Li^7 (0.84\ MeV) + He^4 (1.47\ MeV) + \gamma\ (0.48\ MeV)$

Both the Li^7 and He^4 have sufficient energy to cause an upset

Luckily use of BPSG has been mostly phased out over the last decade, but some legacy parts are still subject to this issue.

Single Event/Soft Error Alphabet Soup !!!

SEU - Single Event Upset

SEE - Single Event Effect

SER - Single Event Response/Soft Error Rate

SEL/SELU - Single Event Latch UP

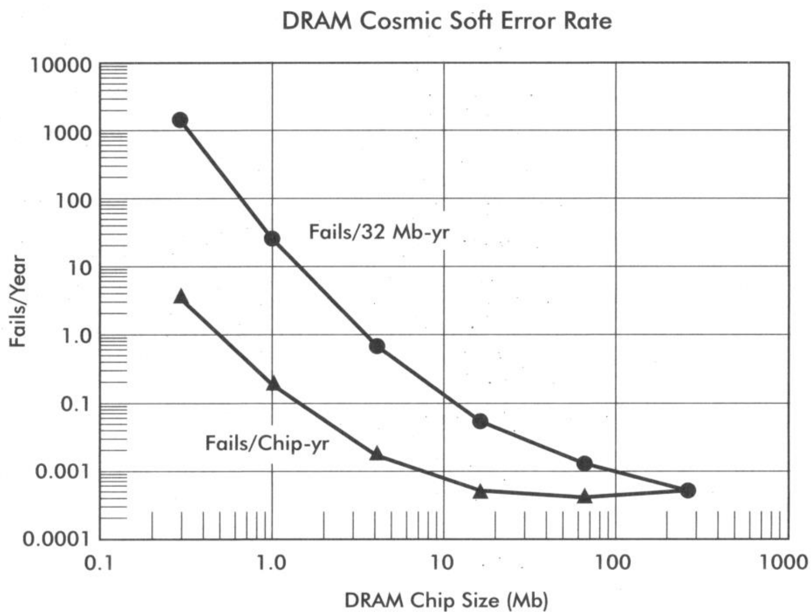
SEB - Single Event Burn Out

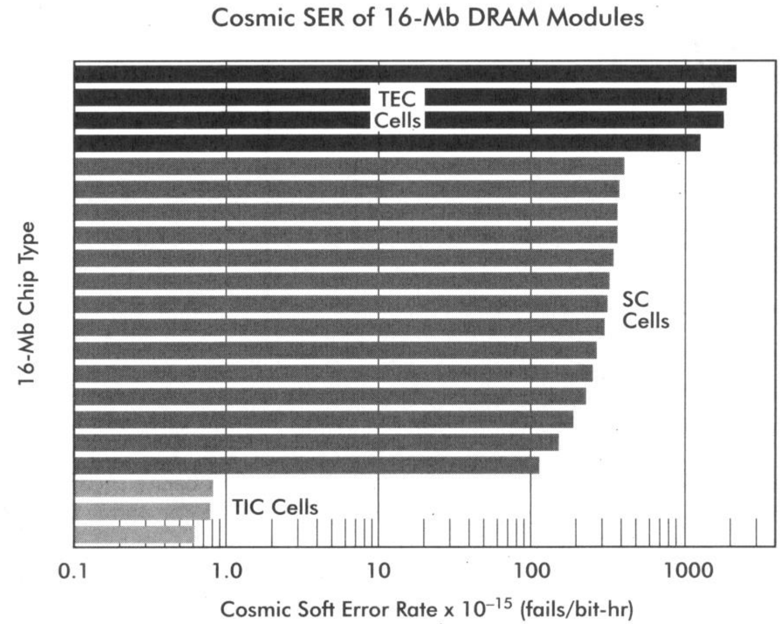
SEGR – Single Event Gate Rupture

SET - Single Event Transient

SEFI – Single Event Functional Interrupt

(And still counting………)

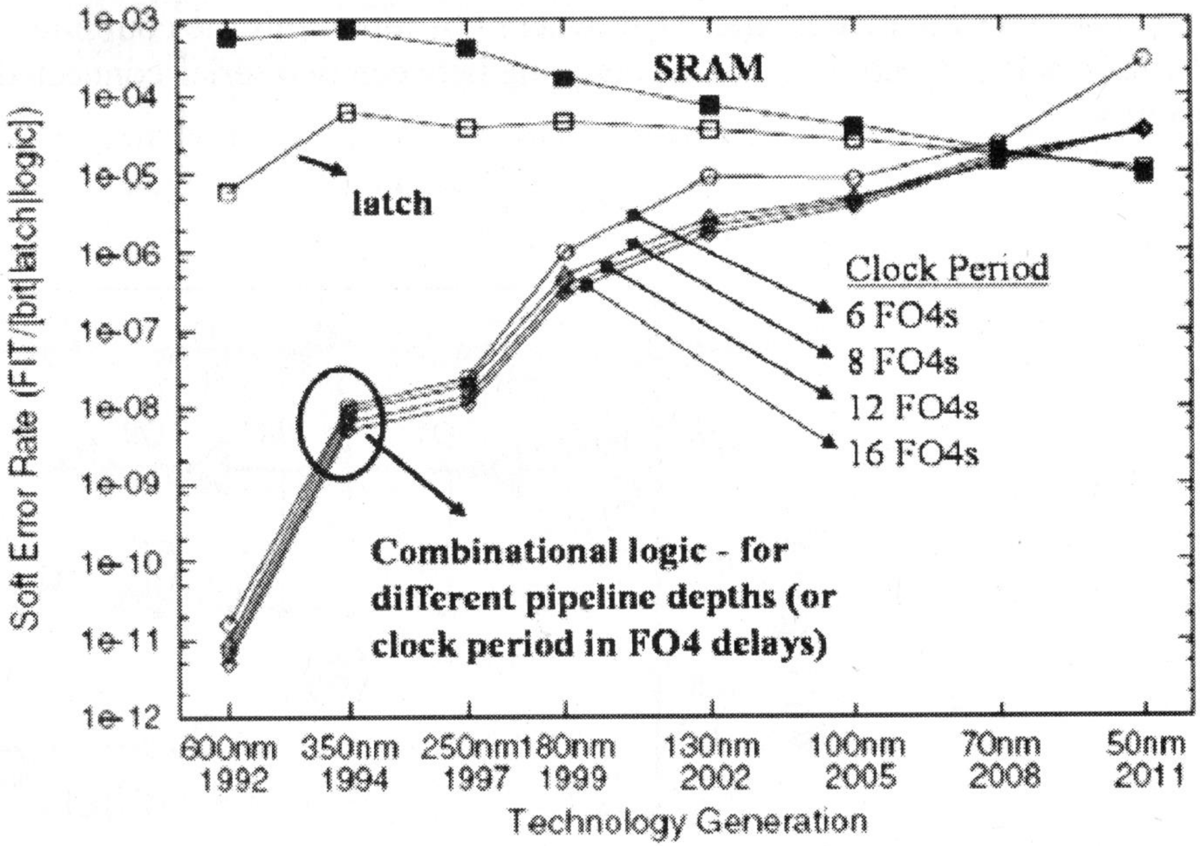




SER Change 1984 -2000

SER by Process Technology

Effect of Increasing Clock Speed on Logic Errors



From Narisimham et al,“The Effect of Negative Feedback on Single Event Transient Propagation in Digital Circuits” *IEEE Trans. Nuc. Sci., vol 53, no. 6, pp.3285-3290, 2006*

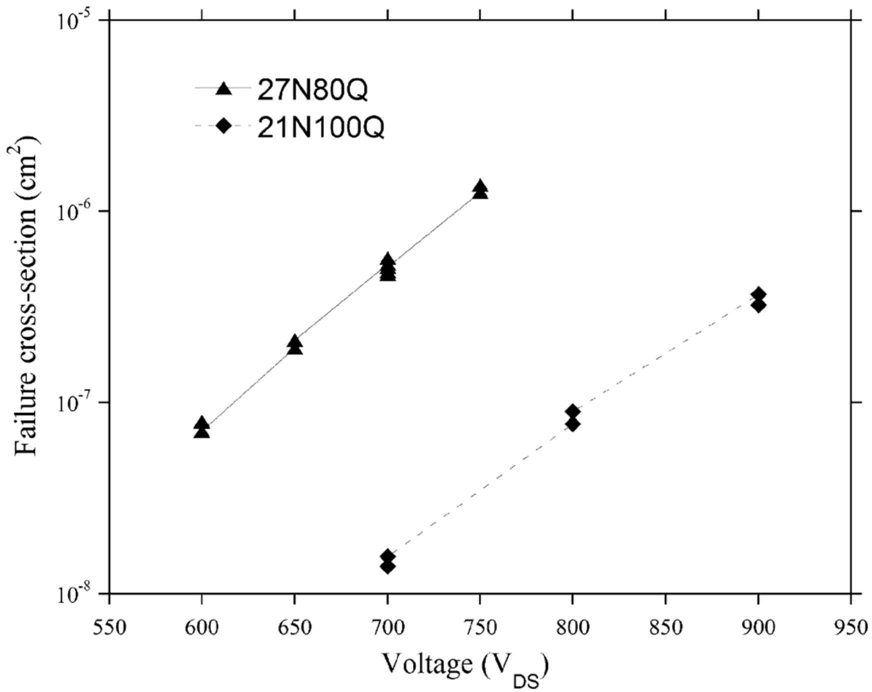
Single Event Burnout (SEB) in Power MOSFETs

This effect was first noticed in high power components used in railway power supplies. The mechanism is described thusly;

"*SEB is triggered when a heavy ion passes through a power MOSFET biased in the off state (blocking a high drain-source voltage). Transient currents generated by the heavy ion turn on a parasitic BJT inherent to the device structure. Because of a regenerative feedback mechanism, collector currents in the BJT increase to the point where second breakdown sets in, creating a permanent short between the source and drain and rendering the MOSFET useless.*" (From G. H. Johnson, J. M. Palau, C. Dachs, K. F. Galloway, and R. D.Schrimpf, "A review of the techniques used for modeling single-event effects in power MOSFETs*," IEEE Trans. Nucl. Sci, vol. 43, no. 2, pp.546–560, Apr. 1996*

The mechanism is essentially the same when triggered by a the charged secondaries produced by a neutron or proton strike on a silicon nucleus.

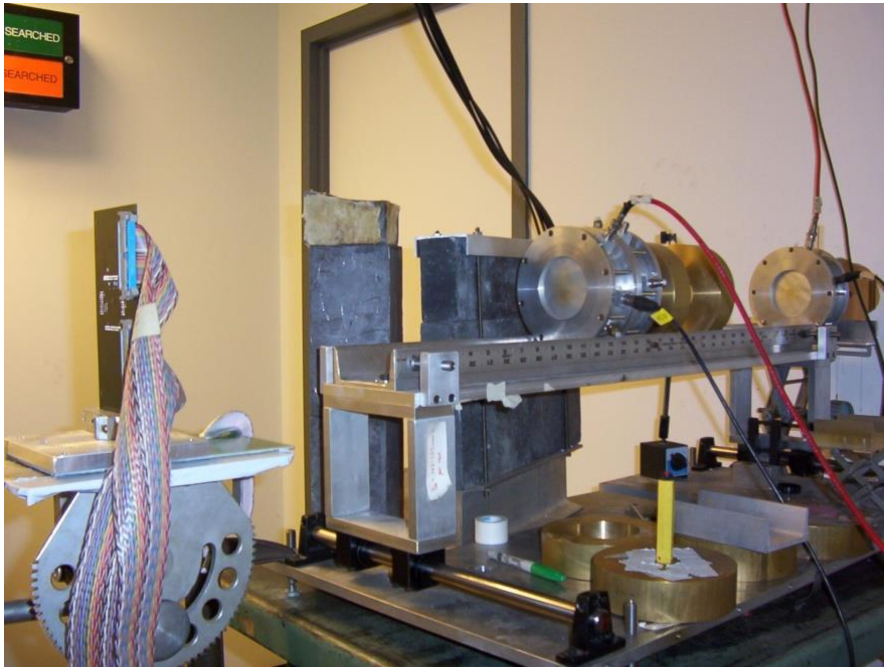
As the use of power MOSFETs is becoming more and more common in power supplies, this is becoming a real problem. The best mitigation strategy is to heavily de-rate the component, running at much lower V_{DS} than the maximum rating. Unfortunately this is not an option when dealing with a commercial device.



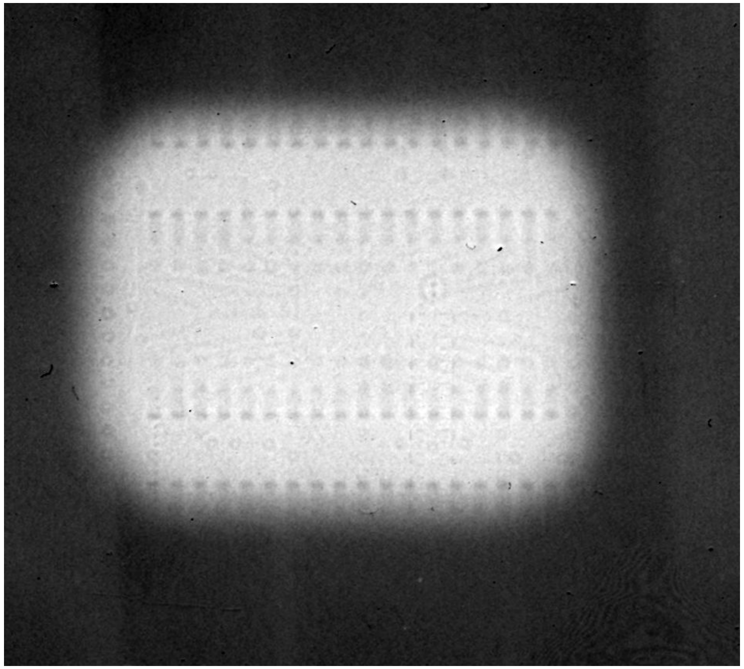
Neutron induced burnout cross-section as a function of V_{DS} for the IXFX 27N80Q and IXFK 21N100Q power MOSFETs.

The 27N80Q MOSFETs in this example are the identical to those installed in an X-ray generator that we purchased for use in one of our treatment vaults. In that unit they are run at a V_{DS} of ~700 V. We concluded that that would results in over 20 failures/day !!

From E. W. Cascio, et al "Single Event Effects in Power MOSFETs Due to the Secondary Neutron Environment in a Proton Therapy Center", *EEE Trans. Nucl. Sci., vol. 59, no. 6*, (2012) Testing is important !! Know what you’re Dealing With !!



Radiation Test Beamline at FHBPTC



Chip under test illuminated by proton beam

Component Level Testing vs System Testing

Component level testing:

Clear and Simple

Convenient

Good Statistics

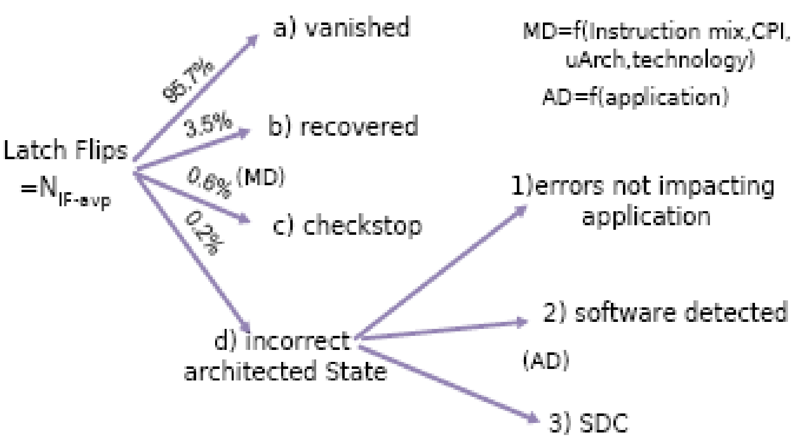
System level testing:

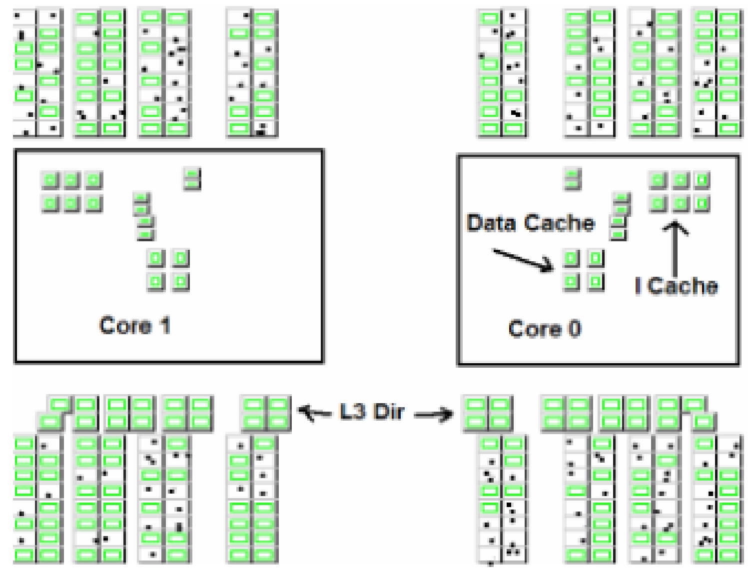
Illuminates Unexpected Failure Modes

Real World Model

Can be Very Difficult and Confusing

A particularly complex example of system level testing.





White Rectangles represent the segments of L2 cache with flipped cells. The flipped cells are shown by dots.

Kellington, et al, “IBM POWER6 Processor Soft Error Tolerance Analysis Using Proton Irradiation”, 2007

Yet Another (smaller) Alphabet Soup !!!

HBP – Hardness by Process

HBD – Hardness by Design

HBS – Hardness by System

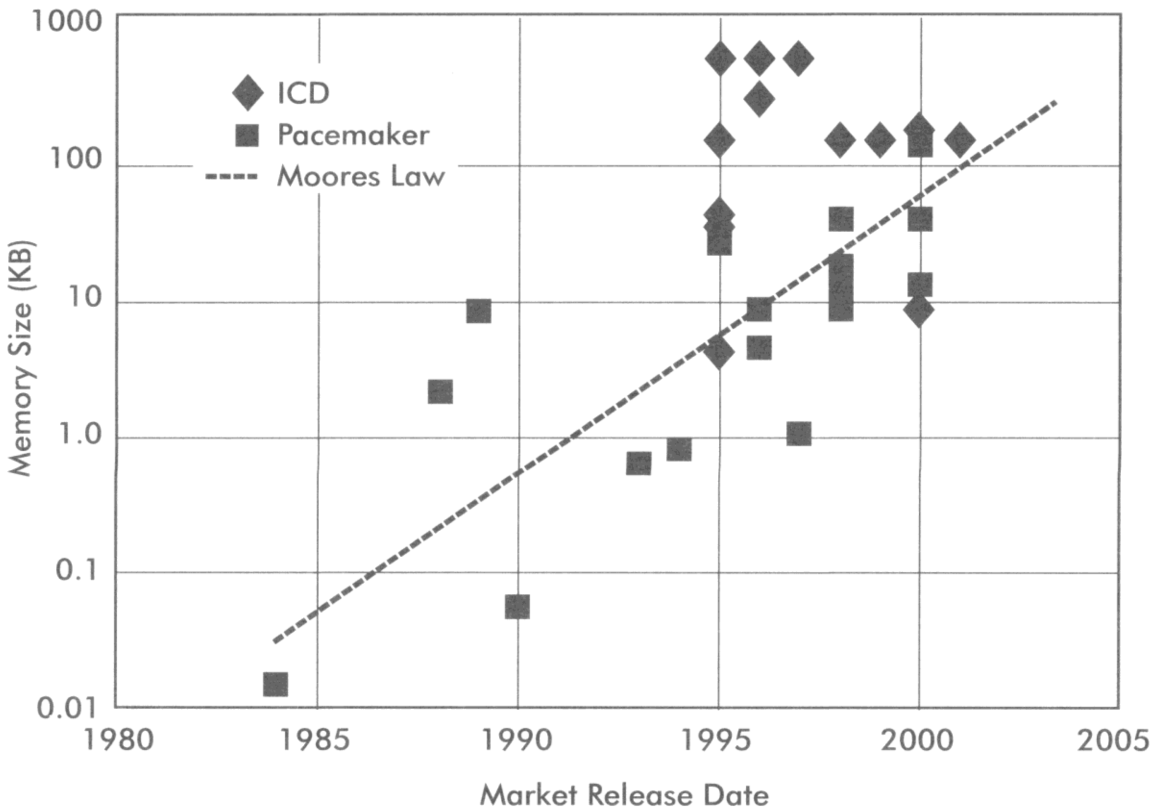
Some Interesting (& Entertaining) Special Cases

Medical Implants

Starfish Prime

The Case of the European Trains

Radioactive Bat Droppings



ICD
Pacemaker
Moores Law
Memory Size (KB)
1000
100
10
1.0
0.1
0.01
1980
1985
1990
1995
2000
2005
Market Release Date

Starfish Prime

High altitude nuclear test performed 9 July 1962

1.4 MegaTon warhead detonated ~250 miles above Johnston Island

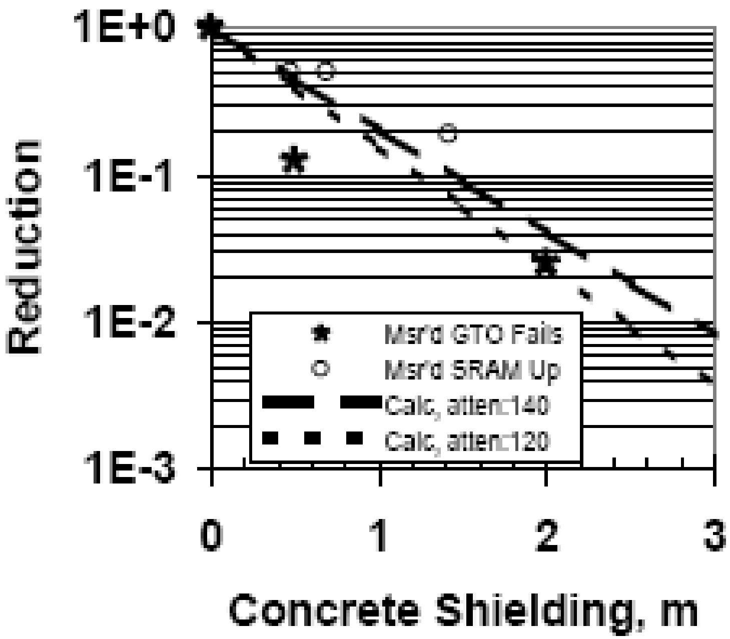
Created artificial radiation belt of high energy electrons which resulted in the failure of 7 satellites (including Telstar)

These elevated levels of electron flux were still apparent years later (~10% of the injected electrons survived 12 months or more)

If there had been manned spacecraft up, the astronauts would have received 5 Rads or more per orbit (based on Skylab-type orbit and typical spacecraft shielding at 1 week after the detonation)

(from Los Alamos report LA-6405, 1976)

In the mid 90s new train engines deployed in Europe were failing due to burnout of high voltage diodes and GTO (gate turn-off) thyristors which were rated at 4500V. This was puzzling, as these components were being operated at 50-60% of their rated voltage, and were designed for ~ 35 year lifetime.



An experiment was performed that showed that these failures were the result of neutron induced burn out from cosmic rays.

The GTOs were operated at 4300V and the failure rate dropped from 6 fails in 700 device-hrs to 1 fail in 4,500 device-hrs with the addition of 2 meters of concrete shielding.

E. Normand et al, “Neutron-Induced Single Event Burnout in High Voltage Electronics”, *IEEE Transactions on Nuclear Science, Dec 1997*

In 1992 a small company in Louisiana that mines bat guano opened a new mine in a bat cave near Jordan Mountain, and this caused a semiconductor factory to shut down for 8 weeks!

This new mine had high levels of radioactive thorium which dissolved in the groundwater, entered the local food chain and ultimately the bat droppings. Guano is a source of phosphates, and one of the mine's customers was a chemical company that produced high-purity phosphoric acid used to etch Al structures in ICs … and so it goes…