NON-VOLATILE MEMORY CHALLENGES FOR THE NEXT GENERATION OF DEEP SPACE MISSIONS

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Agenda

- Introduction
- Deep Space Challenges
  - Power, Mass, Volume
  - Environment
    - Temperature, Radiation
      - Sources and Effects of Radiation
  - Mitigation
- Projected Data Storage Requirements of Proposed Missions
  - Comparison of Data Storage Requirements against ITRS – A Corollary is Developed
- Commercial Challenge: *Quality*
- Conclusion

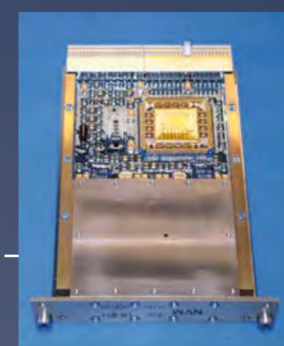
Introduction – Future Missions

- JPL is examining missions which will store unprecedented amounts of data on board and relay specifically requested data packs to Earth via Laser-Optical links

- Missions requiring over 20 Tb of data storage – this is 4 Orders of Magnitude greater than has ever been done.

Introduction – Examination of the Past

- Cassini (to Saturn) was first NASA deep space mission to use Solid State Recorder
  - Previous missions, such as Galileo (Jupiter) and Magellan (Venus) used multi-track tape drives (almost 2 km!)
- Science data capacity drove mission science & mission planning
  - 2 Gb capacity was *de facto* standard
    - This was based upon an inflation of the amount of data that NASA's largest recorder could hold – with 1 ¼ miles of tape!
- Mars Landers & Rovers, Stardust (comet dust sample & return), Genesis (deep space dust), JUNO (Jupiter), …, … all based upon previously developed 2Gb Flash data card – using devices no longer in manufacture



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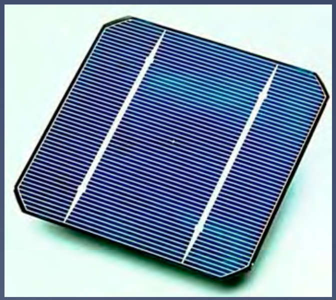
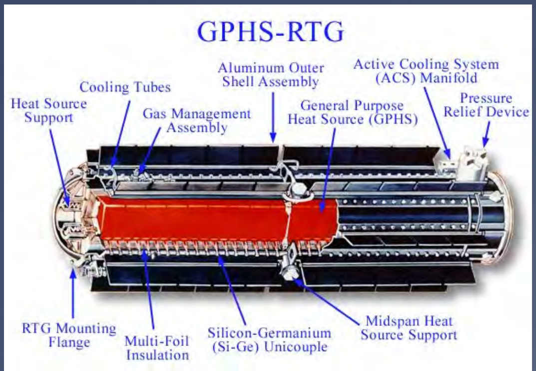
Deep Space Challenges
P M V E

Power

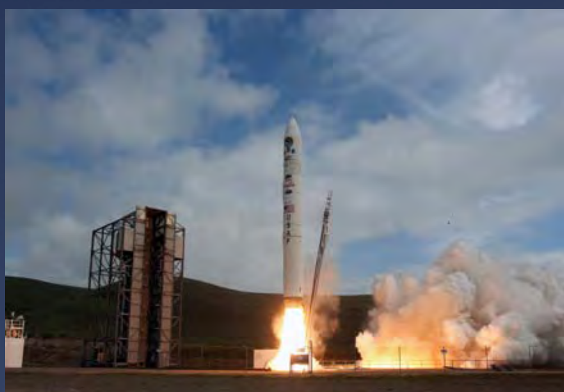
- Three sources of power in spacecraft & satellites
  - Battery
  - Solar
  - Nuclear (radio-isotope)



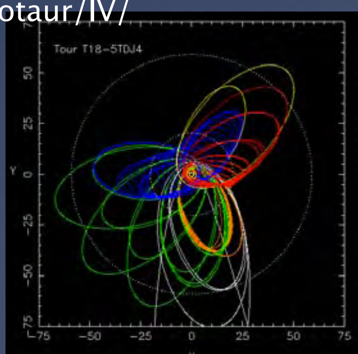


Deep Space Challenges
P M V E

Mass

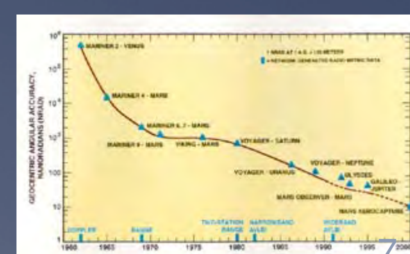


Source: www.orbital.com/SpaceLaunch/Minotaur/IV/



- The successful launch of any mission depends upon the THROW of the vehicle
- The cost of launch depends upon the Mass and Trajectory Required

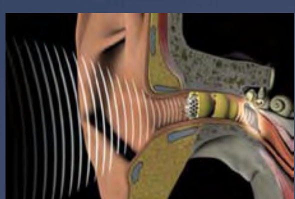
- The Minotaur IV shown here can launch 1000 kg into Polar orbit with a cost of $12.9M



Deep Space Challenges
P M V E

Volume

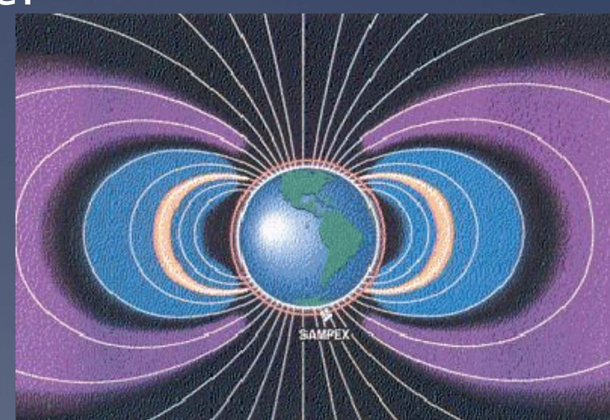
- As with any commodity – from hearing aid to blast furnace – the product must fit within the space allocated
  - Or something must be reduced to permit an oversized unit
    - Less Science? Shorter Mission?



Deep Space Challenges
P M V E

Environment

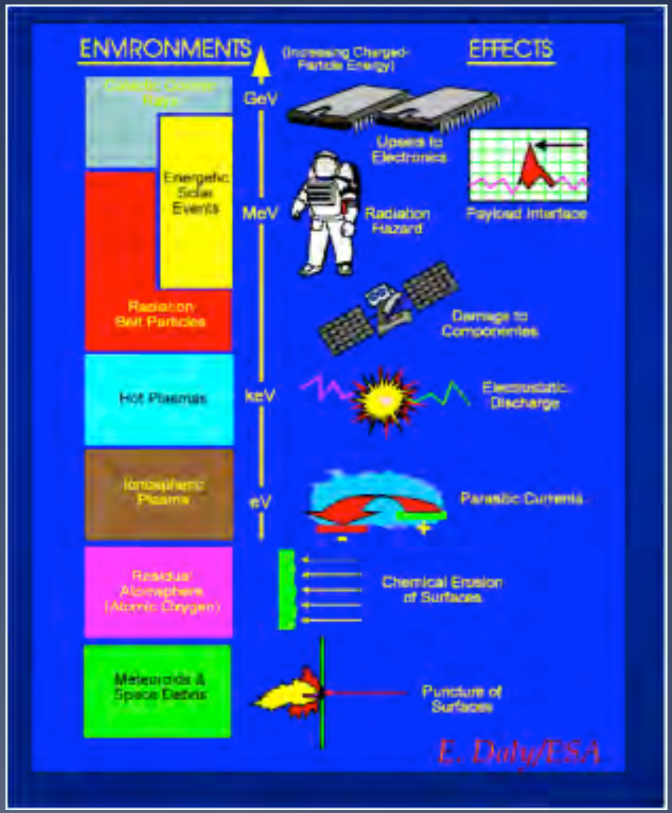
- Perhaps no other Obstacle is so misunderstood, yet so important to mission success than definition of the Environment
  - Low Earth? Deep Space? GeoSynchronous?



Deep Space Challenges

Radiation, Temperature, Power – the three SIGNIFICANT challenges

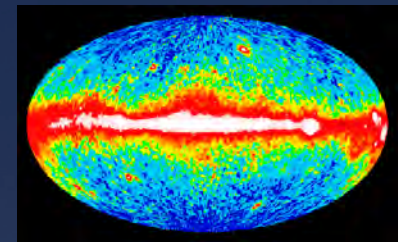
- Radiation – sources are varied and widespread
  - Solar wind, gamma bursts, event horizons, on-board radioistopic generators
  - Magnetic lines of force- entrapment of energetic particles
- Temperature – Control of the Thermal Environment
  - Space is Cold, the Sun is Warm: How to Draw a Line between the Two?
- Power – Solar Cells aren't the only answer



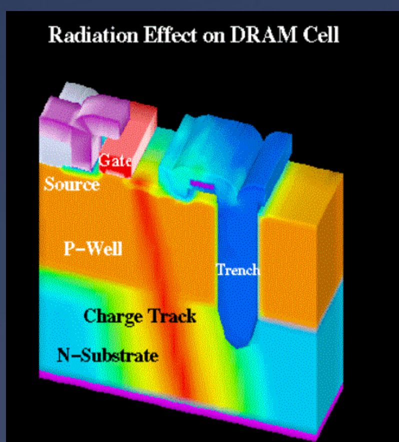
What is a Rad?

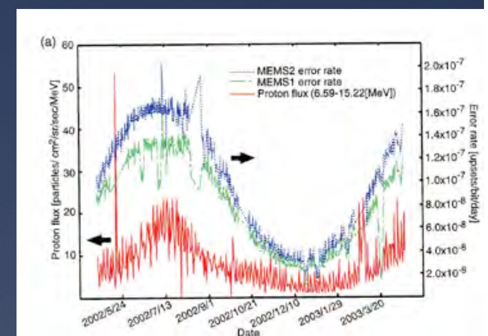
- Energy imparted into MASS
  - 1 Rad = 100 erg/ g
  - 1 Rad = 6.25E7 MeV /g
  - 1 Rad ~ 8.1 x 10^{12} / cm^3 electron-hole pairs (in SiO_2)

Effects of Radiation

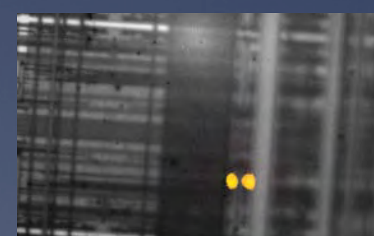


- Gamma Radiation – capture of photons at defect sites <pix Photon strike>
  - Increases leakage, alters voltage threshold

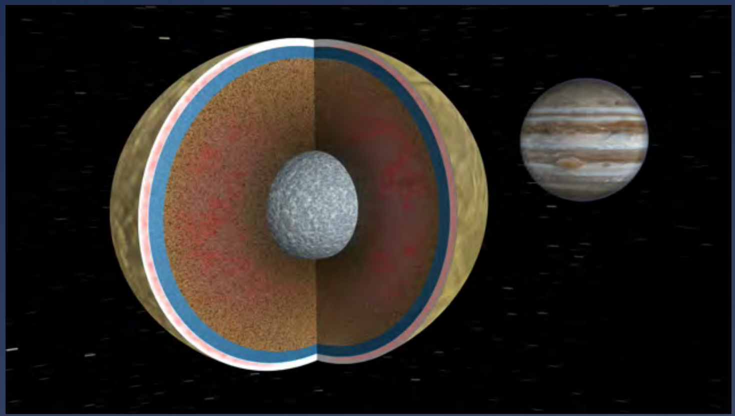




- Ion Strikes – Upsets logic and data states (SEFI)
  - May cause device to short out – destructive latch
- Neutron radiation – May cause destruction or permanent alteration of crystalline structure
  - Upsetting device parameters and operation

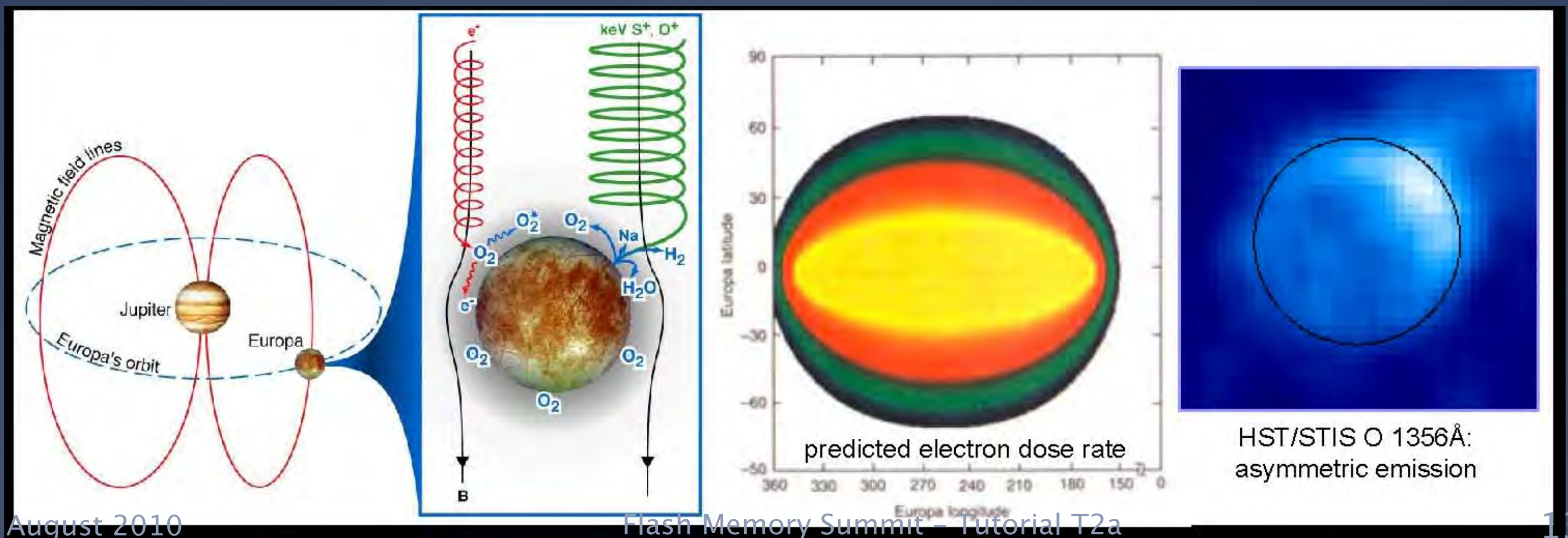


Why Put Up with It?



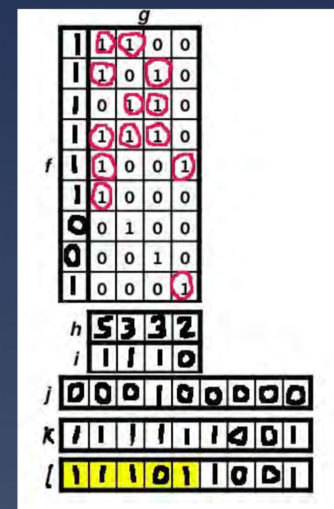
Because We Want to Know MORE

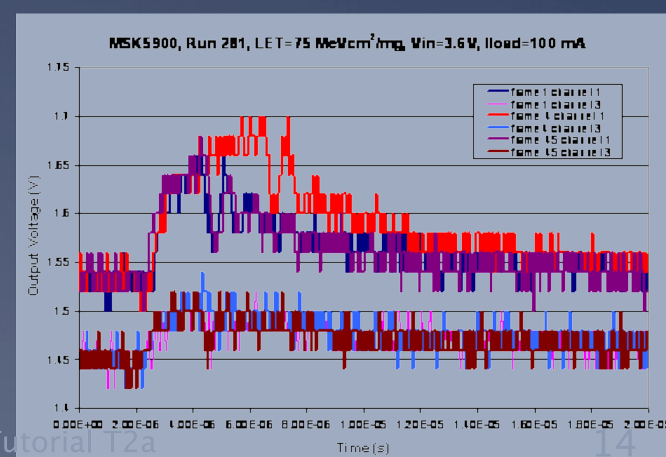
This is a Graphic of Europa – thought to have Liquid Water below its icy crust



Mitigation Against Effects of Radiation

- Gamma radiation
  - Control of processing and doping profiles
  - Design of circuitry to accommodate leakage, Vt shift
  - Sufficient difference in Sense Amp detection levels
- Ion Strikes
  - Data Upset
    - Sufficiently strong EDAC – outside of the chip
    - Sufficient number of electrons storing the information
      - Periodic refresh
  - Logic Upset (SEFI)
    - Sufficiently strong feedback in Flip-flop routes
    - Strong drivers, wide swing receivers
    - Redundant voting systems
- Neutron Radiation
  - Careful processing and device stoichiometry





A Word about ECC

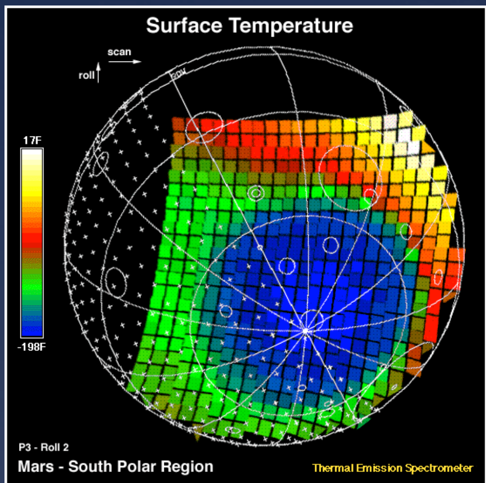
Chips with Built-in ECC

- A plea from a designer at NASA – Stop It
- While it helps your product get over the bumps and hurdles from being dropped or passing through a tunnel, they wreak havoc on End-to-End data system design
- One thing and one thing only comes into play: the acceptable Bit Error Rate of the data stream from the mission, as received on the ground

- Through simulations and testing the “upset rate” of individual data bits can be determined
- The upset rate bounced against the Environment and the Mission Data Loss rate determines the best Error Correcting Code to use
  - Hamming: Cassini, MSL, SMAP
  - Reed Solomon: X2000, MSL, JUNO
  - Viterbi: Magellan
  - BCH: Galileo
  - Fire: X34

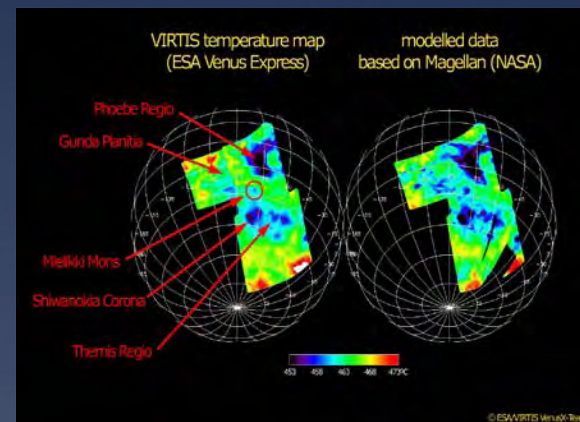
The Upset Rate of a cell is very difficult to determine with ECC mussing up the results!

Temperature



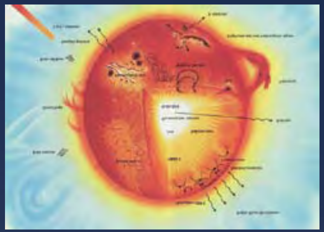
http://tes.asu.edu/

- Surface Temperature of Mars: -107C to -55C
- Surface Temperature of Venus: 480C
- How do Operate in the two Worlds?
  - You don't
  - Mars: requires either insulation (mass); heaters (mass); special device processing (cost)
  - Venus: Active cooling for limited time (mass); special device processing (cost)



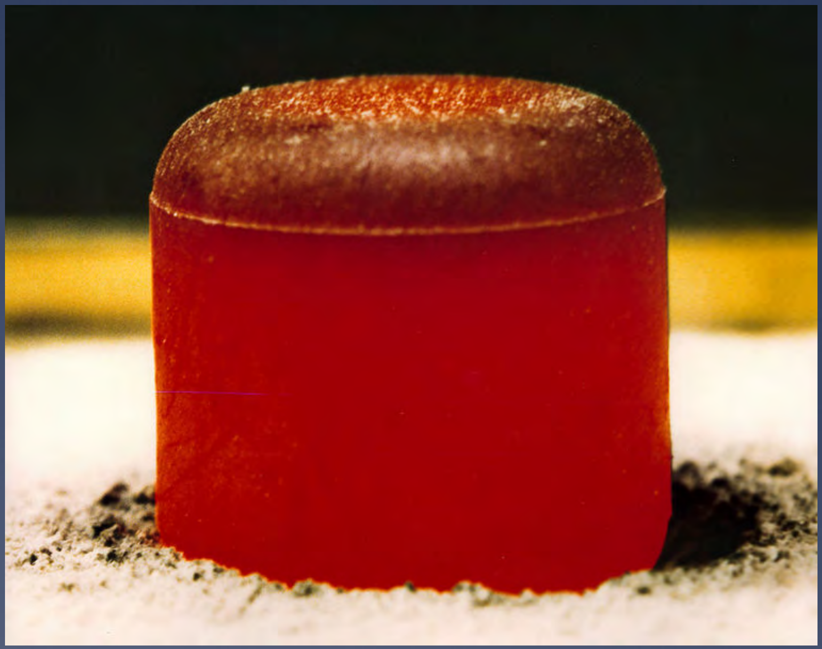
http://www.spacenews.com

Power



Courtesy: Solar Physics Laboratory, University of Montana

- Solar Flux:
  - Earth (1 AU) 340 W/m2
  - Jupiter (5 AU) 13 W/m2
  - Saturn (9 AU) 4 W/m2
- Therefore – solar cells are not effective beyond the orbit of Mars
  - Radioisotope Thermonuclear Generators (RTGs) are required
  - And therefore, back to the same problems caused by the planetary environments themselves!
    - Total Dose, Neutron,… ….



glowing red hot pellet of plutonium-238 dioxide (courtesy Los Alamos National Laboratory)

FLASH TECHNOLOGY

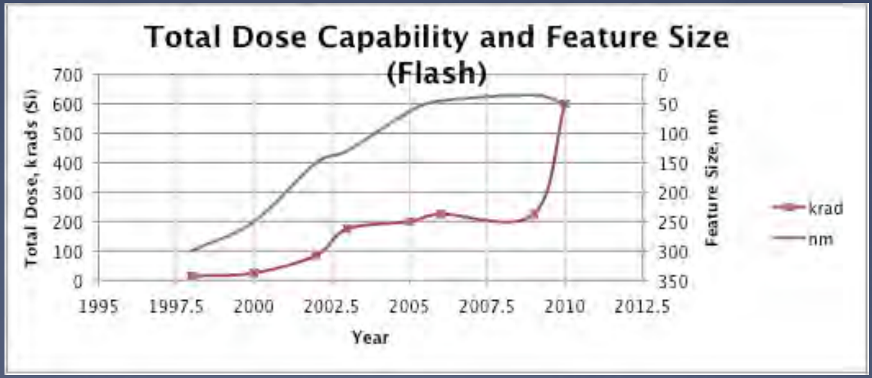
Device capability

Historical & Predicted

Total Dose Capability

- For all products past 32 Mb – the CHARGE PUMP is the most susceptible to radiation damage
  - 90% attributable to high voltages generated and stress upon Cascade capacitors

- HOWEVER: As Feature size shrinks, the overall Total Dose Capability of the device tends to Increase
  - This is merely a matter of Mass – the less amount of Oxide – the less ability of an ion or photon to become trapped at a defect site and induce leakage



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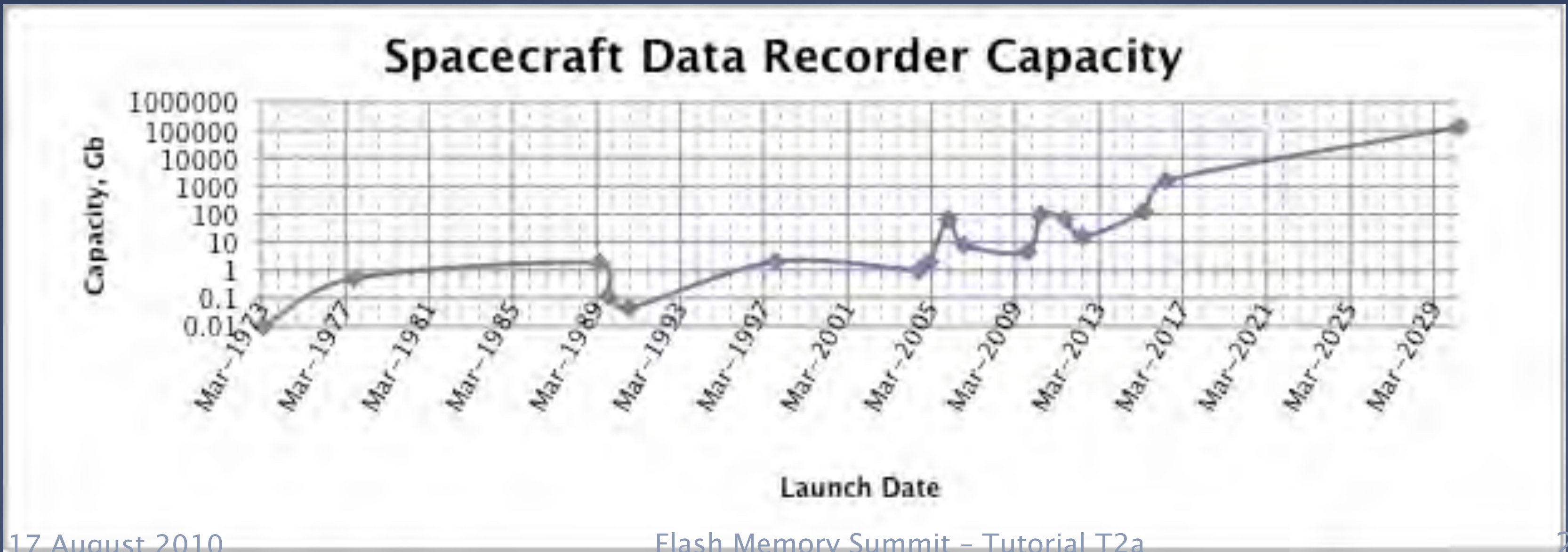
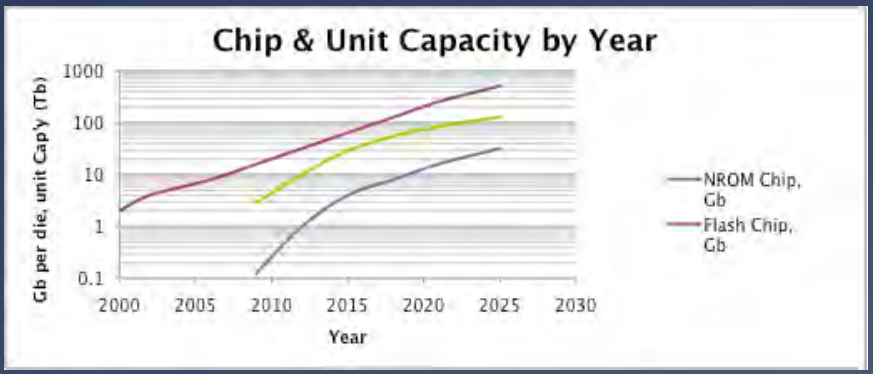
Missions: Historical & Projected

- Earlier missions limited by data storage capacity
  - The amount of Storage defined the Mission
- Projected missions limited by Imagination



Corollary: Mission Demands against ITRS



- Comparison of Projected Mission Demands against *per die* capacity as projected by ITRS shows exact corollary
- The size, mass, power requirements for any recorder can be accurately estimated for any future mission following information readily attainable data in ITRS: the projected necessary data recorder capacities follows exactly the same guide known as Moore's Law.

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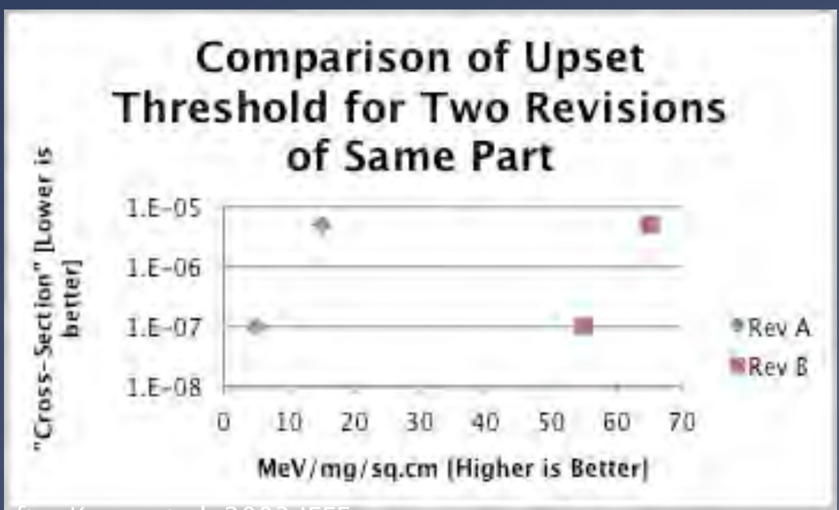
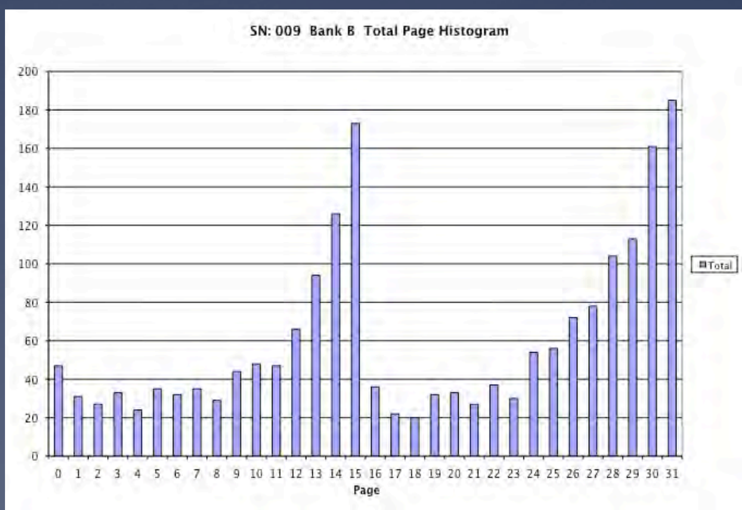
Challenge: Quality

- Process Control: NOT that processes are out of Control
  - That they are changed to improve Yield
    - Sometimes deleterious effects on Sensitivity to Radiation





(after Koga, et al, 2003 IEEE Radiation Effects Data Workshop)

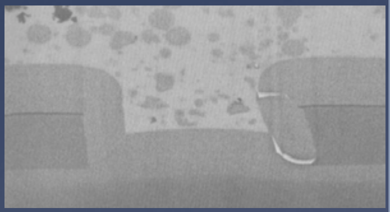
Challenge: Quality

- Packaging: Traditionally hermetically sealed
  - Now accepting epoxy encapsulant

- C-SAM (C-Mode Surface Acoustic Microscopy) used to determine package conformance

Challenge: Quality

Failures



Criteria

- C-SAM and Q-BAM are two non-destructive methods used to determine die attach/packaging voids.
- Concern: Excessive void could become stress point during temperature excursion
- Die stress

Parts Qualification

- Selection of device screening criteria dependent upon mission criteria
  - Cost
  - Duration
  - Sensitivity to Loss of Mission or Data

- MIL-38535 Level V, K, Q – lower?
- Upscreen of Class B to "Pseudo-S"

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Conclusion

- Challenges- The challenges facing designers for deep space missions are many and sometimes contradictory
- For generations, nearly every mission has been limited by the amount of on-board storage
- Missions in planning require unprecedented amounts of storage
- Memory Technologies must be Dense and Radiation Tolerant

Acknowledgement

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SL12-2	Picture Credit: NASA, Compton Gamma Ray Observatory
SL12-3	20th IEEE Sym. On Defect and Fault Tolerance in VLSI Systems
SL12-4	2003 IEEE Radiation Data Effects Workshop, Tucson, AZ
SL12-5	Irom, F.; Catastrophic Failure in Highly Scaled Commercial NAND Flash Memories; Proceedings 2009 NSREC, Quebec, ON

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SL13-2	2007 Europa Explorer Mission Study: Final Report; JPL D-41283, November 2007, Pasadena CA
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SL14-2	Polvey, C.; Single Event Transients on Internal Voltage Pump, Poster, 2006 MAPLD Conference, Washington DC
SL15	http://user88.lbl.gov
SL16-1	tes.asu.edu
SL16-2	spacenews.com
SL17-1	Solar Physics Laboratory, University of Montana
SL17-2	Los Alamos National Laboratory
SL19	Strauss, K.; Memory Technologies and Data Recorder Design, Proceedings, 2009 IEEE Aerospace Conference, Big Sky, MT
SL21	Strauss, K.; Memory Technologies and Data Recorder Design, Proceedings, 2009 IEEE Aerospace Conference, Big Sky, MT
SL22	Strauss, K.; Memory Technologies and Data Recorder Design, Proceedings, 2009 IEEE Aerospace Conference, Big Sky, MT
SL24-1	2003 IEEE Radiation Data Effects Workshop, Tucson, AZ
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