Radiation and its Effects on
Components and Systems (RADECS),
September 24-28, 2012

Radiation Testing and Modeling: Practical Challenges and Shortfalls for the Next Five Years

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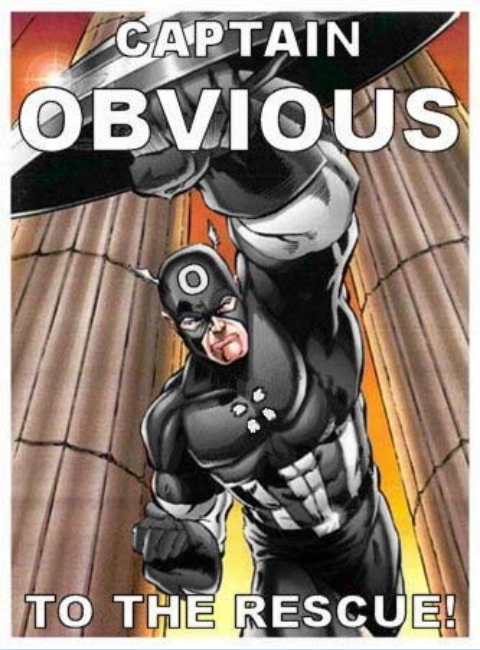
Abstract and Outline

Researchers are often so focused on their research, they fail to see the practical aspects required. In this regard, predictions for near to mid-term challenges for our community are presented incorporating recent aerospace trends and radiation effects research results.

Emphasis will be on single event effect (SEE) issues.

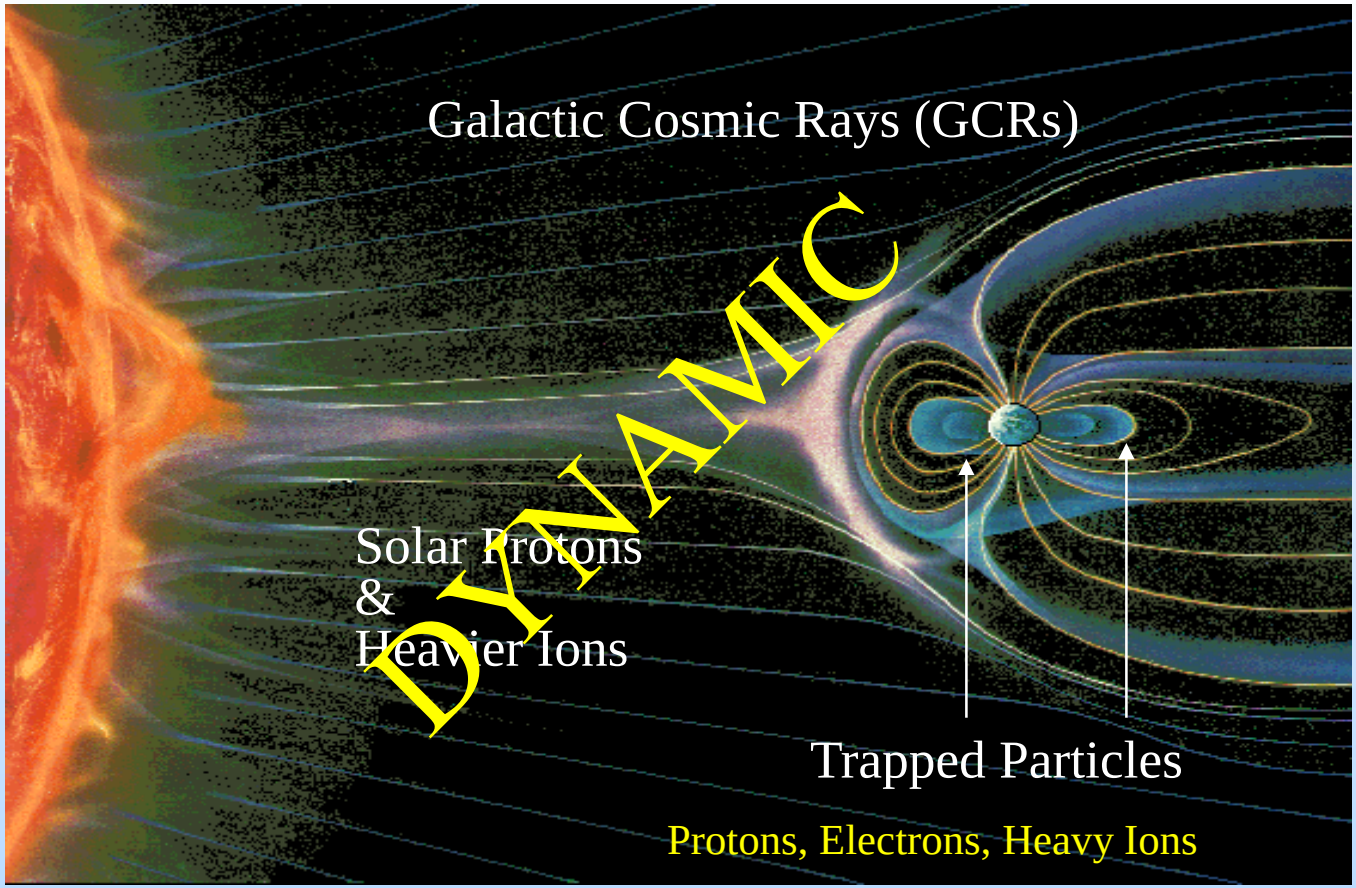
- **Background**
- **Challenges**
  - **Facilities**
  - **Physics of Testing**
  - **Test Setups**
  - **Modeling**
  - **Other**
- **Summary**



http://ktliterary.com/wp/wp-content/uploads/2010/10/captain-obvious-to-the-rescue.jpg

Space Radiation Environment

after
Nikkei Science, Inc.
of Japan, by K. Endo
and NASA, by J. Barth

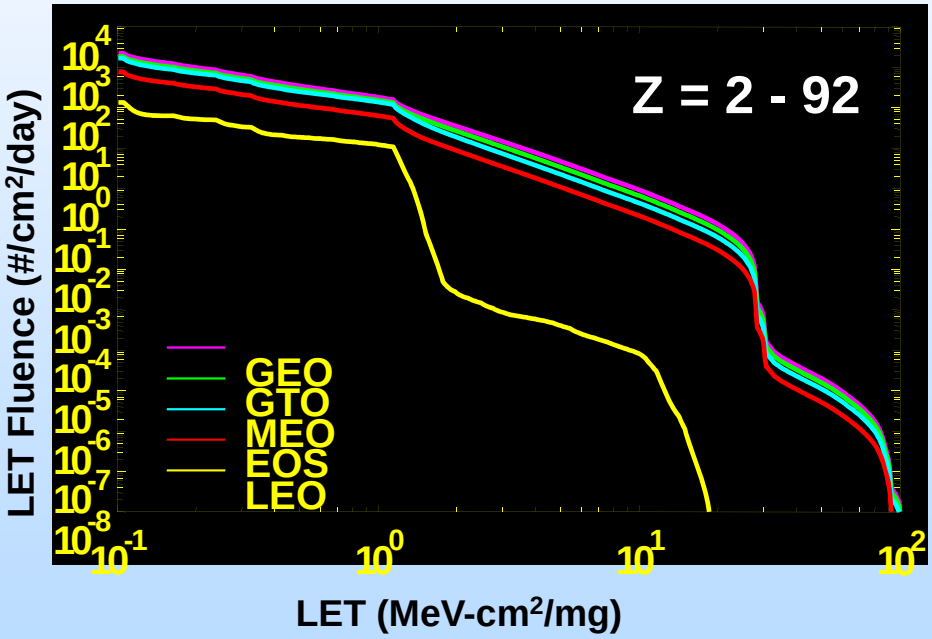


Deep-space missions may also see: neutrons from background or radioisotope thermal generators (RTGs) or other nuclear source
Atmosphere and terrestrial may see GCR and secondaries

Space Hazard:
Galactic Cosmic Rays (GCRs)

- **Definition**
  - **A GCR ion is a charged particle (H, He, Fe, etc) aka *heavy ions***
  - **Typically found in free space (galactic cosmic rays or GCRs) and in some solar events**
    - **Energies range from MeV to GeVs for particles of concern for SEE**
  - **Unit of interest**
    - **How much energy is lost/deposited by the particle as it passes through a semiconductor material. This is known as Linear Energy Transfer or LET (dE/dX).**
    - ***May no longer be only metric of interest! Consideration for total charge collected and ion species issues have been documented.***

CREME 96, Solar Minimum, 100 mils (2.54 mm) Al

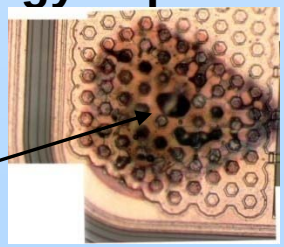


Time

Commercial Technology Sensitivity

Single Event Effects (SEEs)

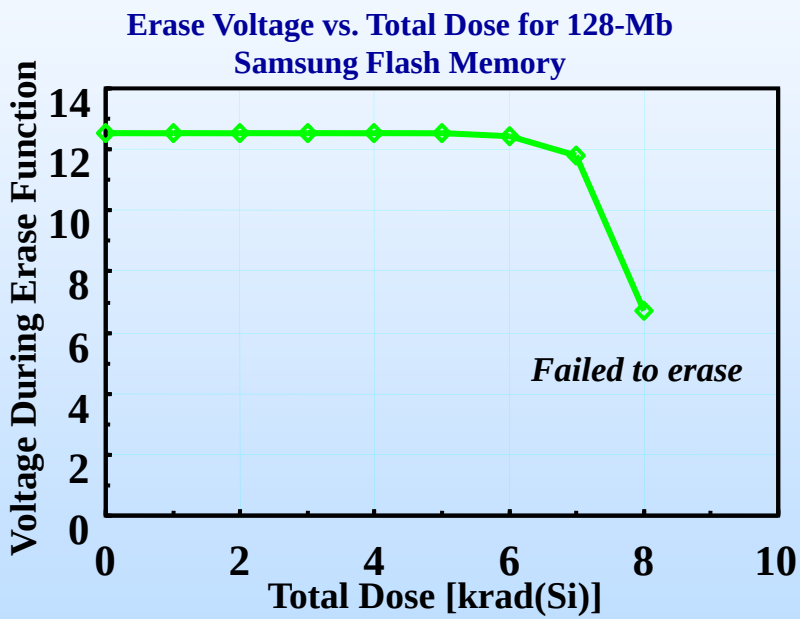
- **An SEE is caused by a *single charged particle* as it passes through a semiconductor material or interacts material**
  - **Heavy ions**
    - **Direct ionization – deposits energy as it goes through device**
  - **Protons for many unhardened devices**
    - **Indirect ionization - reaction products with materials deposit that may be sufficient to cause effects**
    - **Direct ionization with protons a potential for many newer technology devices (low proton energies may cause direct ionization)**
- **Effects on electronics**
  - **If sufficient energy is deposited (critical charge), effects on the device may be observed.**
    - **Soft errors such as upsets (SEUs) or transients (SETs), or**
    - **Hard (destructive) errors such as latchup (SEL), burnout (SEB), or gate rupture (SEGR)**
  - **$LET_{threshold}$ is a metric for determining minimum energy deposition required to cause an effect.**
- **Severity of effect is dependent on**
  - **type of effect and system criticality**



Destructive event in a COTS 120V DC-DC Converter

Total Ionizing Dose (TID)

- **Cumulative long term *ionizing* damage mainly due to protons & electrons**
- **Electronic Device Effects**
  - **Threshold Shifts**
  - **Leakage Current**
  - **Timing Changes**
  - **Functional Failures**
- **Unit of interest is krads(material)**
- **Shielding can reduce (but not eliminate) exposure**
  - **Low energy protons**
  - **Electrons**



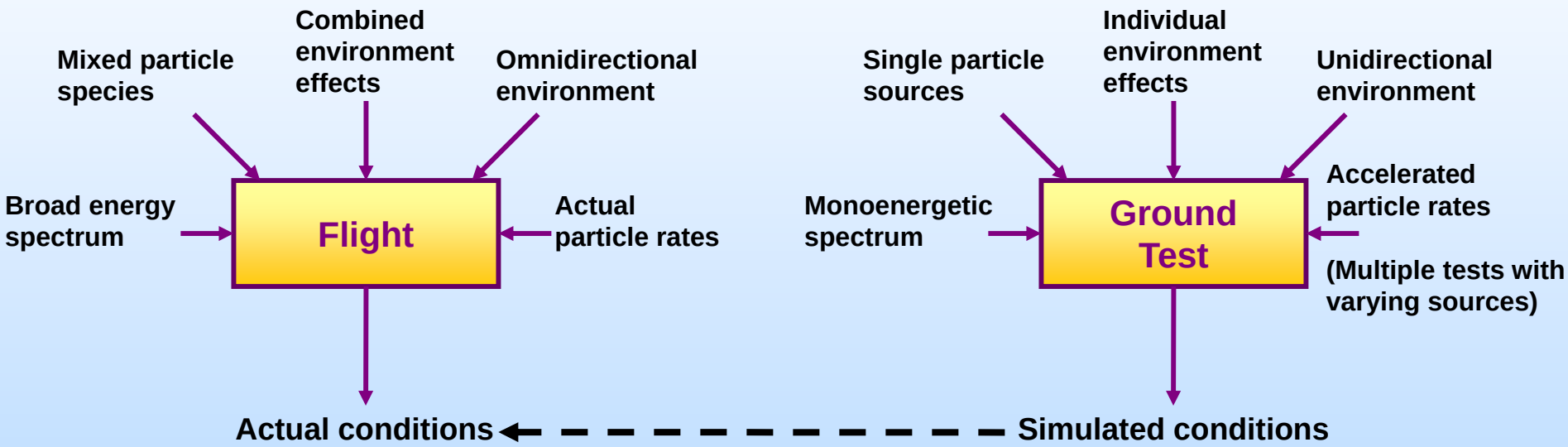
Displacement Damage (DD)

- **Cumulative long term *non-ionizing* damage due to protons, electrons, neutrons, and heavy ions**
- **Effects**
  - **Production of defects which results in device degradation**
  - **May appear similar to TID in device degradation modes**
  - **Optocouplers, solar cells, CCDs, linear bipolar devices**
- **Unit of interest is particle fluence over the mission environment energy spectrum mapped to test energy(ies)**
  - **Non-ionizing energy loss (NIEL) is one means of discussing**
- **Shielding can reduce (but not eliminate) exposure**
  - **Reduce significant electron and some proton damage**

Sample Issues for Radiation Effects Simulation at Cyclotrons and Accelerators

- **Particle**
  - Dosimetry
  - Uniformity
  - Energy mapping to the space environment
  - Particle localization
  - Stray/secondary particles (neutrons, for example)
  - Particle range
  - Flux rates and stability
  - Beam structure
    - Beam spills versus continuous wave (CW)
- **Practical**
  - Cabling
  - Thermal
  - Speed/performance
  - Test conditions
  - Power
  - Mechanical
  - Vacuum

Radiation Test Issues – Fidelity?



How accurate are the ground test condition for predicting Space Performance?

After NASA, by E.G. Stassinopoulos

Two Types of Space Electronics Investigations with Heavy Ions

- ***Research***
  - Investigates the basic response of the semiconductor technology to irradiation for use in developing technology models
  - Investigates the specific technology/circuit parameters that determine the device/technologies radiation tolerance or susceptibility
- Goal is developing proper radiation assurance methods and risk identification

- ***Qualification***
  - Provides the irradiation of (typically) the flight lot of a device in order to determine the device's suitability for a specific mission and/or application
- Goal is to utilize "known" methods and provide risk quantification to a specific flight project (or to a "standard")

Qualification Radiation Tests – Two Types

- ***Piecepart tests***
  - **Provides greatest insight into a device's performance**
  - **All ground radiation tests can be performed**
    - **Heavy ion**
    - **Proton**
    - **Co-60 (TID)**

Ziatech ZT-6500 3U Compact PCI Pentium Board.

- ***Board level tests***
  - **Provides insight as to how the system responds to a single device or system irradiation or accumulated board-level dose**
    - **Useful for system level validation (i.e., verifying fault tolerant architecture response) and limited specific issues and missions**
  - **Facilities**
    - **Co-60 (TID)**
    - **Proton**
    - **Heavy ion tests limited due to penetration ranges of ground-based ions at many facilities without excessive preparation as well as obtaining significant statistical fault coverage**

Challenges

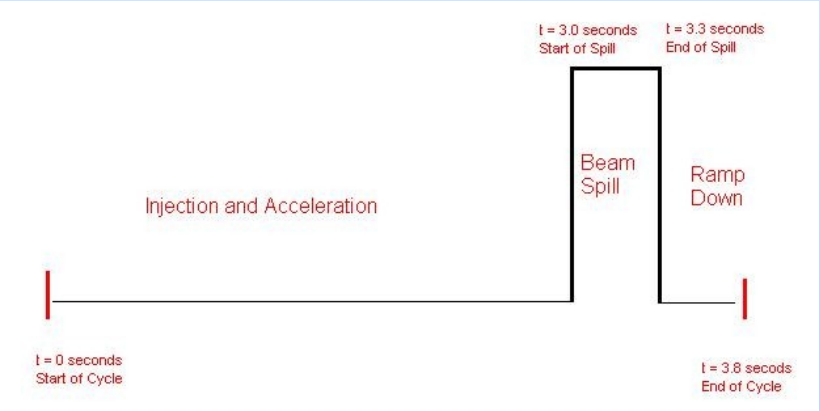
- **Facilities**
- **Physics of Testing**
- **Test Sets and Standards**
- **Modeling and Tools**
- **"Other"**

http://www.sandia.gov/mstc/services/images/heavy-ion-accelerator.jpg

Note: This is NOT an attempt at a complete list of challenges, simply a compendia of selected, perceived, "high value" concerns

Challenge: Facilities

- **Insufficient Beam Time Availability - SEE**
  - **Amount required**
  - **Schedule**
  - **Affordability**
- **Energy Availability - SEE**
  - **Penetration and angular testing**
- **Beam structure - SEE**
  - **“Continuous wave” vs. “Beam spills”**
- **Fault isolation testing**
  - **Microbeams, Millibeam™ , and LASERs**

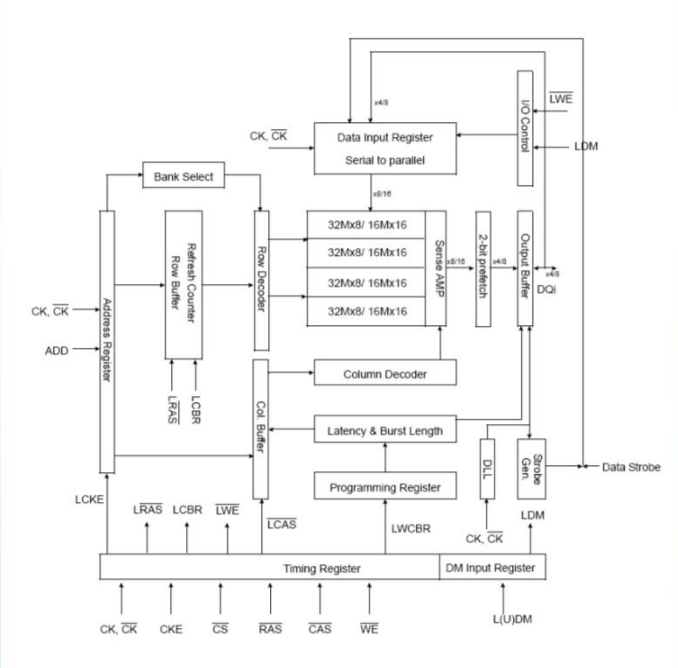


http://www.bnl.gov/medical/NASA/CAD/images/Spill_Schematic.JPG

Not Enough Beam Time Availability at the Existing Heavy Ion Facilities?

- **Multiple factors are driving the shortage of time at our "bread and butter" heavy ion test facilities**
  - **More complex devices require much more time at the facility**
    - **15 years ago a "qual" test on a memory took ~8 hours**
    - **Now, 24-48 hours is "typical"**
  - **More specific conditions are often needed to evaluate**
    - **Angular response,**
    - **Energy/species dependence, …**
  - **More commercial devices are being utilized in space systems**
    - **More devices equals more hours needed**
  - **More research needed to understand the physics and circuit responses on "new" technologies/architecture and to develop appropriate models**
  - **Facilities are "shared" with science groups**

Can we test anything completely?



Sample Single Event Effect Test Matrix

full generic testing

Amount	*Item*
3	Number of Samples
68	Modes of Operation
4	Test Patterns
3	Frequencies of Operation
3	Power Supply Voltages
3	Ions
3	Hours per Ion per Test Matrix Point

Commercial 1 Gb SDRAM
68 operating modes
operates to >500 MHz
Vdd 1.8V external, 1.25V internal

66096 Hours

2754 Days

7.54 Years

and this didn't include temperature variations!!!

Test planning requires much more thought in the modern age as does understanding of data collected (be wary of databases). Only so much can be done in a 12 hour beam run – application-oriented

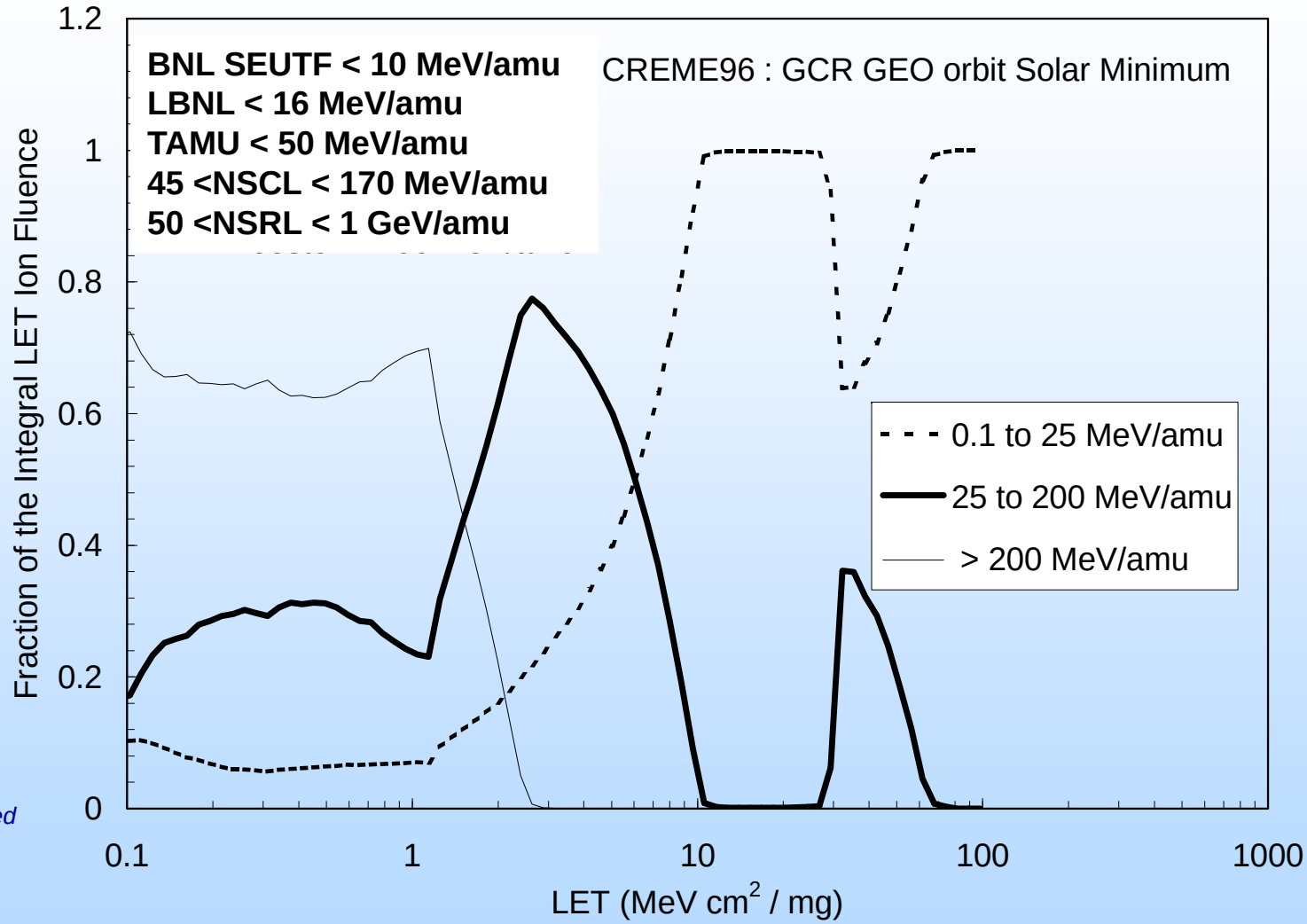
After
NASA, by K. LaBel

Presented by Kenneth A. LaBel at Radiation and its Effects on Components and Systems (RADECS), Biarritz, France, September 24-28, 2012 and published on nepp.nasa.gov.

Improved Access and Affordability to High Energy Heavy Ion Sources

- **Multiple items drive the desire to use a high energy facility**
  - **Higher energy = more ion range (penetration)**
    - **Can test packaged or even stacked devices (3D ICs)**
  - **Ability to perform grazing angle and backside testing**
    - **Important for sub-90 nm devices**
  - **Ability to perform system/board level validation tests**
  - **Improved fidelity to the natural space environment**
- **High energy facilities may also have challenges for beam structure (next slide) and dosimetry/secondaries**
- **Current costs of ~$5K (US)/hour are prohibitive to many potential users**

U.S. Space LET Coverage



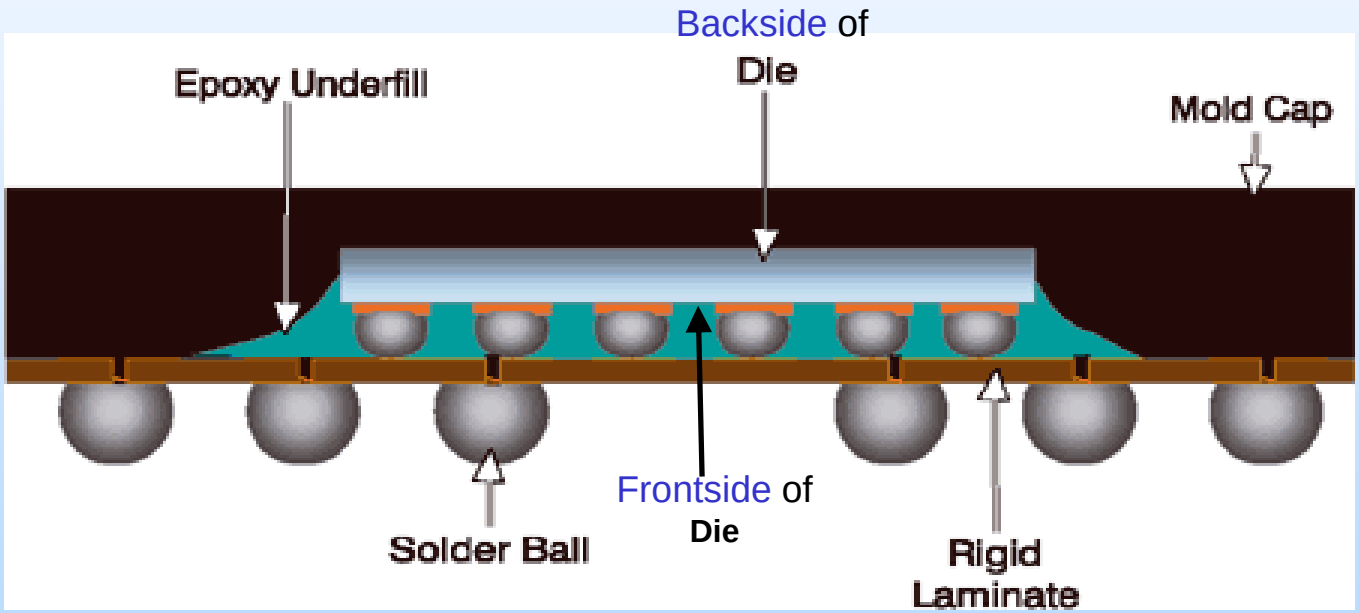
After NASA, by R. Reed

Close to 99% of the space heavy ions that have LETs > 3 MeV cm^2 / mg have energies < 200 MeV/amu

Device Package and Particle Penetration –

Example: Flip-Chip Ball Grid Array (FBGA)

Must remove sufficient amount of material to penetrate to backside of die AND
penetrate to sensitive volumes



Challenges
Thermal
Integrity
Accuracy
Interactions

Heavy Ion Beam Won't Penetrate Through Balls
= Can Not Irradiate Frontside of Die

Beam Characteristics

- In space, the radiation exposure environment may be viewed as a random, relatively continuous exposure (within a given orbital constraint)
- Not all single event test facilities provide this structure
  - Closely approximates:
    - Continuous wave or CW (relatively continuous particle stream within a given frequency range in the MHz) or
  - Not even close:
    - Beam spills (repetitive "spills" of a given fluence with dead time in between such as 300 msec burst followed by 4 seconds of dead time)
      - Depending on the actual flux rate during the beam spills, multiple particle strikes could masquerade as a single particle strike effecting multiple bits – e.g., beam pileup.
- In the old days, this wouldn't have mattered as much. Why?
  - Most testing was done in a static mode, and,
  - Devices, in general, were much simpler and slower in their operational capabilities (and generally were somewhat less sensitive to lower LET particles).

Beam Characteristics vs. Complex Devices

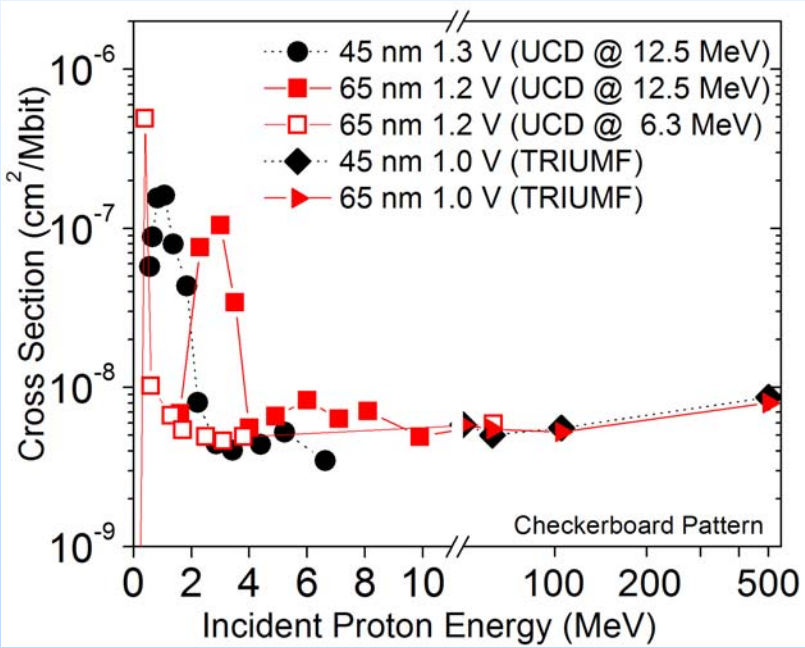
- **In the 90's, the term "sensitive time window" was coined, first in fiber optic link radiation testing, and later, in discussing single event transients (SETs)**
  - **In essence, the particle interarrival time (when the particle arrives at a node relative to clock or data edge) was shown to be important in determining actual device sensitivity relative to the natural space environment.**
  - **Ex., proton SEE testing on a fiber optic link running at a very modest 1 MHz frequency showed an order of magnitude difference in measured cross-sections in comparing data from Crocker Nuclear Labs (CNL) to the beam spill structure of the (now extinct) Harvard Cyclotron Facility (HCF).**
- **This issue is now in effect at some of the heavy ion facilities that offer "beam spills"**
- **Now think of more complex devices, multi-core, GHz operations, embedded IP, and so on…**
  - **Beam spills may well miss many more possible failure modes than a CW unless a significantly more extensive test campaign is undertaken.**

Tools for Identifying Failure Sites

- **In general, there are two kinds of tools we use**
  - **LASERs, and**
  - **Microbeam**
- **As the devices become smaller and more complex, problems such as spot size (10 um spot versus 22 nm transistor, for example) are challenges**
- **There are several LASER sites around the country that are being used as a tool in conjunction with heavy ion exposures**
  - **No test guidelines exist and are needed**
- **U.S.: Current Microbeam at Sandia is low energy (limited penetration into devices)**
  - **Great tool on a unhardened test structure, but not very useful for full devices**
- **Millibeam™ - new tool in place at single site in U.S.**
  - **Requires additional cost for support to use**

Challenge: Physics of Testing

- **Proper metrics for risk quantification - SEE**
  - **Is LET still "king"?**
- **Low proton energy vs. heavy ions**



After Heidel

For Radiation Hardness Assurance (RHA)

Do We Know the Right Factors in Choosing Ions To Test With?

- **This is a very complex issue, but to summarize (published) active research areas**
  - **LET is proposed NOT to necessarily be the correct metric for sub-90 nm technologies (charge collected?), and,**
  - **Data gathered for Power MOSFETs has shown that Ion and Energy need to be taken into account**
- **Need to be clear on understanding the Ion/Energy/LET relationships to bound risk for usage of devices in space**

RHA for Low Energy Protons

- **Okay, let's get the "myth" out of the way: shielding will stop low energy protons from being an issue**
  - **Shielding will reduce the number of low energy protons incident on the shield, however,**
  - **Higher energy protons are attenuated as they go through the shield becoming low energy protons. (i.e., proton spectra on the exterior of a spacecraft does not equal the spectra at the sensitive volume)**
- **Testing with protons has proven to be challenging from**
  - **Finding the right "peak" low energy to the spread of energies going through the device.**
- **Some have proposed using low LET particles as an indicator whether a device is susceptible to low energy protons**
  - **Correlation to space performance?**

Challenge:
Test Setups and Standards

- **State of test standards vs. technology knowledge**
- **Statistical device coverage for complex devices**
  - **SEE**
  - **TID**
  - **Bias configurations for complex devices – TID**
- **"Time-to-test"**
  - **Evaluation boards vs. custom test solutions**

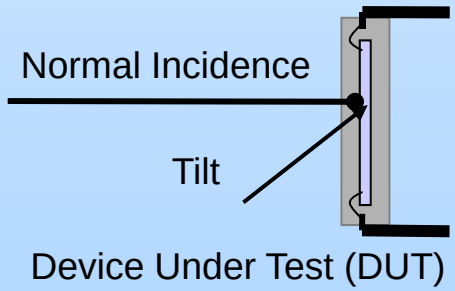
http://nepp.nasa.gov/workshops/etw2012/talks/Wednesday/W01_Berg_SEE_in_FPGA.pdf

SEE Test Standards

- **Given the rapidly changing nature of both technology and the related SEE issues being discovered, it would be nearly impossible to create up-to-date test standards in a timely fashion**
  - **New materials and device architectures**
  - **New mechanisms for upset**
  - **New questions on what the proper test metrics are**
- **Individual test guidelines are in development,**
  - **Winning the battle, not the war**
- **Plans for:**
  - **Field Programmable Gate Arrays (released)**
  - **Low Proton Energy Sensitivity**
  - **Flash Memories (in review)**
  - **DDR Memories, … (in review)**

JESD57 – A Starting Point

- **JEDEC JESD57 is the prime test standard utilized within the US for heavy ion SEE testing**
  - **Developed in the early and mid '90s, it provides a reasonable starting base for planning SEE tests**
- **However, many new SEE-related considerations have forced us to consider some of the advice provided in JESD57. For example:**
  - **Section 3.1.2.1: "The beam angle is normally limited to a maximum of 60 degrees…'**
    - **This doesn't require that you test to 60 degrees, just a recommended normal limit.**
    - ***Grazing angles have been shown to be required for new technologies***
  - **No discussion on asymmetric angular effects (i.e., tilting in both directions as well as changing the roll of the device sample to the incident beam)**



TID –
Too Complex to Test Completely?

- **Consider the more complex devices being built commercially (processors, FPGAs)**
  - **Multi-function, multi-clock domain with a billion transistors**
- **Device manufacturers (mfrs) spends millions of US$ developing test vectors on multi-million US$ automated test equipment (ATE)**
  - **20 years ago we purchased test vectors and utilized in-house ATE – not an option now!**
- **Is functional or in-circuit test with "real" application or "stress" application sufficient?**
- **Utilize step-stress in test chamber and collaborate with the manufacturer for measurements (i.e., dry ice ship to mfr after irradiation)?**
  - **Provides greatest test coverage, but mfr needs to be willing to partner**
- ***How do you determine appropriate biasing for these mixed signal systems on a chip (SOC)?***

SEE and Device State Space

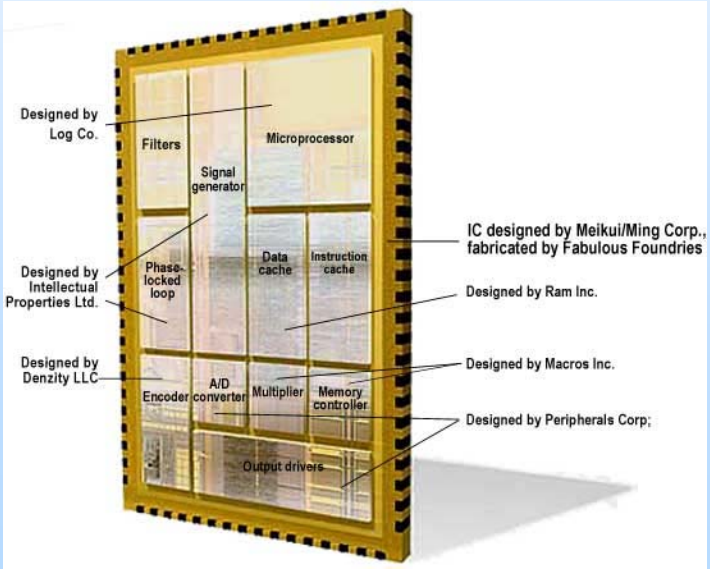
- **This is a more detailed diatribe on "sensitive time windows"**
  - **The example discussed previously was a simple serial path.**
- **Now consider a real complex device with embedded IP, multiple IO paths, clock trees,… and one that is reconfigurable via hardware or software.**
  - **Worst case analysis dictates that you must assume that every single node can take a hit at the worst possible time, but how do you determine how realistic this is?**
- **In other words, two items**
  - **Coverage of complete state space vs. particle hits, and,**
  - **Interpreting test results to an actual user application in a mission environment**
    - **Berg, et al have demonstrated methods for FPGAs that are extensible elsewhere. Evolving "science".**

Trade Space: Above "Board"…

- **Custom device under test (DUT) boards clearly provide improved data gathering to the researching**
  - **Designs for die/angle accessibility, temperature/voltage control, mounting, specific functions, etc… can be built in.**
  - **However, they can be costly (manpower, fabrication, special orders,…) and schedule challenges (how long does it take to design, build, and validate a 28 layer board?).**
- **Evaluation and commercial may not have all the desired features, but they are "off the shelf" (improved cost/schedule, but not testability)**
  - **Key is determining minimum required features for the DUT to be adequately tested and if a commercial option exists**

Challenge: Modeling

- **Rate prediction**
  - **COTS and complex devices vs. "simple devices" – SEE**
- **Model and tool validation**
  - **We can create models but what is really needed to validate?**



http://spectrum.ieee.org/image/1937829

Rate Tool for Use With COTS

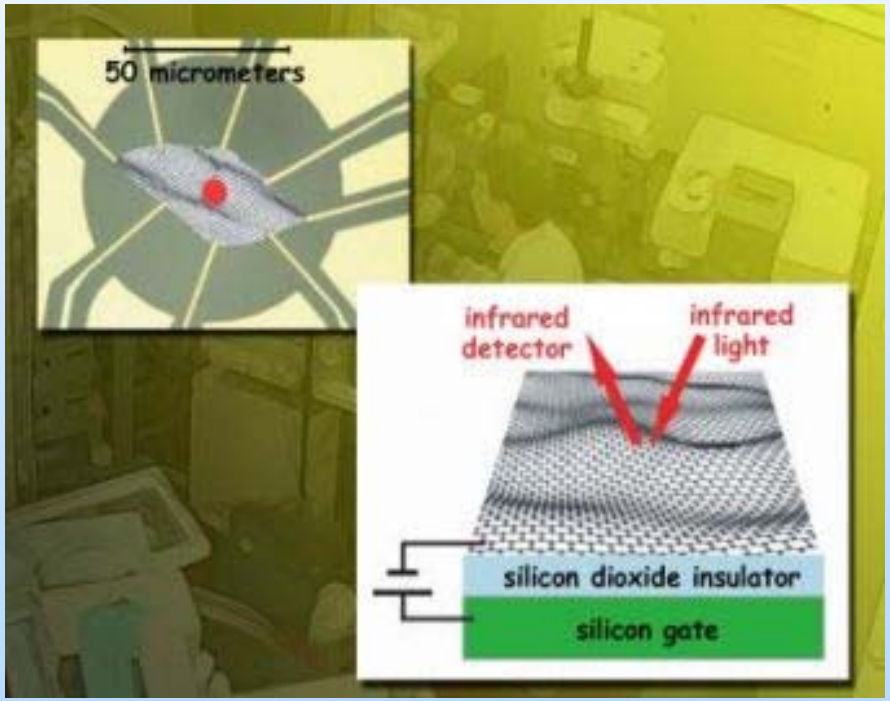
- **For the last 15+ years, CREME96 has been the industry standard to utilize when making rate predictions for space.**
- **In the last few years, newer Monte Carlo-based version have been developed taking into account the import of new mechanisms and improved circuit modeling on sub-90 nm technologies**
  - **Focused on the needs of those building radiation hardened devices, but not the needs of those utilizing COTS electronics**
  - **In other words, it is useful when you have detailed knowledge of the technology and circuit design, but not with a billion transistor COTS device with lots of circuit and technology unknowns**
- **Need to have a *"bounding"* tool using generic technology/device knowledge and device-specific test data for "systems risk analyses"**
  - **Goal is to have a confidence level for a "not to exceed" SEE rate**

How do we PROVE that a model or tool is valid?

- **Once a tool is developed for SEE rate prediction, how do you validate?**
  - **Ground tests:**
    - **Limited to time in beam and single energy, single direction, etc. at a time – however, always a good starting point**
  - **Flight data**
    - **Need harsh enough environment with sufficient number of device samples along with in-situ environment measurement**
      - **Time and money!**
- **I had a summer intern work with me once who on his last day said: "My software just compiled, so it is done." :o)**
  - **Building something is not the same as validating under real conditions.**

Challenge: Other

- **Increasing unknowns**
- **What do we need for next generations of technology?**



http://cdn.physorg.com/newman/gfx/news/2008/surprisinggr.jpg

The more complex a commercial device is…

- **the less we know!**
  - **Proprietary nature of the commercial business**
    - **Process and materials**
    - **Design and layout**
    - **Hidden features…**
  - **This usually means more testing and labor involved to get an "answer"**
    - **It's always easier when you have detailed device information**
- **Now couple this with shrinking budgets**
  - **"Do more for less" defies the laws of finance (and physics, in our case)**
  - **Risk acceptance?**

Ken's Technology Truism

- **Until a manufacturer has "finalized" a product with a new technology, early structure radiation test data is interesting, but not necessarily indicative.**
  - **Hi-K dielectrics were presented as being TID sensitive early on, but they weren't testing what the commercial folks ended up developing (which seems pretty robust)**
- **This doesn't mean that early research is not of value**
  - **It does aid in development, but don't utilize it as a "generic" technology datapoint when a process may still have defect challenges, variability, etc… that need to be solved first**
- **Graphene, carbon nanotubes, beyond FINFETs, …**

Summary

- **Consider this presentation as "food for thought"**
  - **The idea is to think about what you have, but also about what you need**
- **To someone who is a tester, items like higher energy heavy ions have practical test applications as well**
  - **No vacuum required,**
  - **Easier thermal management,**
  - **Improved cabling (no feedthru), and so on.**
- **The current facilities are tremendous assets to the space community and we truly appreciate their efforts to fill our needs.**

Acknowledgements

- **Supporters of this work**
  - **NEPP**
  - **Defense Threat Reduction Agency**
  - **National Reconnaissance Office (NRO)**
- **Thanks to**
  - **Lew Cohn, Bruce Wilson, Jonny Pellish, Ray Ladbury, Melanie Berg, Tim Oldham, and the other usual suspects**
- **Special thanks to**
  - **E.G. Stassinopoulos, without whom, I likely never would have gotten into radiation effects, and,**
  - **Jean Gasiot and Ken Galloway who encouraged me when I was a newcomer to this community (and still do).**