Using COTS at the LHC: Building on Space Experience

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Presentation Outline

- Introductory Remarks
- Environment Comparison
- Basic Effects in COTS
- COTS Issues
- Hardness Assurance
- Mitigation Strategies

What is COTS?

Competing Definitions

- Anything you can buy from a catalog
  - If it has a part number and a data sheet, it’s COTS
  - No special requirements or added specifications
- Systems and components not specifically designed for mil/aero applications
  - Emphasizes high volume manufacturing and commercial electronics or automotive use
  - COTS are those things we couldn’t use before

COTS In This Talk

COTS are:

- Standard items available from a manufacturer
- Not designed for radiation environment, but may have some specified tolerance
- Usually “black boxes” to the user
- Not tweaked or modified for the user

Space Experience

Marketplace Changes

- Spacecraft are becoming commodities
- Emphasis is reducing cost
  - More science
  - Stimulate space business ventures
- Cost savings from:
  - Cheaper vehicles
  - Smaller, more capable systems
  - Simpler operations

Space Experience

Dilemma:

- Demand for spacecraft components is flat
- Consumer electronics market offers higher profit per man-year of labor
- Result is fewer devices available which are designed for the space market

Yet the need for high performance systems in space is higher than ever!

Space Experience

COTS Cases

- Choice between hard part and related unhardened commercial device
  - Survivability vs. performance
- COTS sometimes provide mission-enabling performance
  - Usually no radiation tolerant alternative
- COTS vs. equivalent mil/aero part
  - Traditional hard military part often cheaper when qualification costs are considered

Space Experience

Example: Microprocessors in space

- COTS processors usually 3 generations or so ahead of “rad-hard” mil-aero technology
  - Clones of existing commercial processors usually aren’t exact copies
- Advanced commercial tools usually not available for hardened technology
- SEE mitigation for COTS is complex
  - EDAC, watchdog circuits, triple voting, etc.

Space Experience

Risk Elimination

- “No risk is acceptable”
- Usually managed at the lowest level
  - Example: environmental risk in ICs
- Often driven to proven technology
  - Demands technology demonstration flights
- Can be mission or capability limiting
- Upside - systems generally work

Space Experience

Risk Management

- “Mission must not fail - all else is negotiable”
- Low levels may be risky, but risks are mitigated at next higher level
- Often provides mission enabling technology
- Reality: not a new idea
  - We can never eliminate risk, and so these ideas have been used in every piece of engineering

Space Experience

Risk Management Methodology

- State the problem and proposed solutions
- Quantify the risk, if possible
- Know the impact of the risk
- Decide if the risk is acceptable
  - Mitigate?
  - Eliminate?
- Implement the optimum solution

LHC Experience

COTS Use

- Many of the same problems
  - Small market
  - Specialized needs, especially radiation
  - Need for high performance
- Unique Issues:
  - Many different independent groups
  - Wide variety of parts and subsystems
  - No equivalent of a prime contractor?

Environment Comparison

	Space	Aircraft	LHC
Radiation	Charged particles TID, SEE, Displacement	Neutrons Neutron SEE	Neutrons, gamma TID, Neutron SEE, Displacement
Physical Char.	-55 to 125 C Launch vibration	Controlled, 0-70C Some vibration	Controlled, 0 - 70 C No Vibration
Repair/Upgrade	Usually, none	Cost driven	Undesirable

LHC Radiation

Total Ionizing Dose

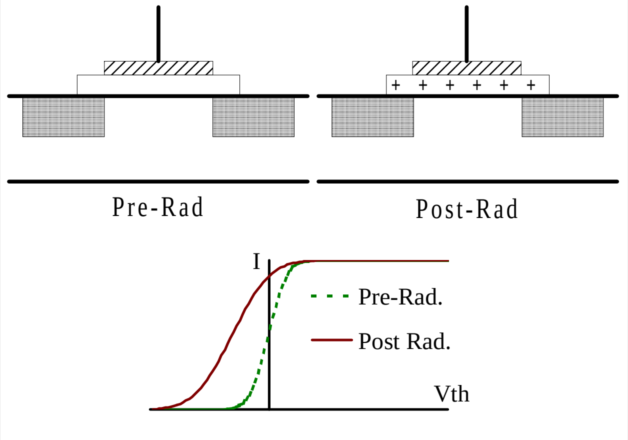
- 10 krad - 10 Mrad, depending on location
- Mostly gamma dose

Neutron Exposure

- 10^{11} - 10^{12} n/cm^2
- Single event effects
- Displacement damage

Basic Mechanisms and Macroscopic Effects

Total Dose in COTS

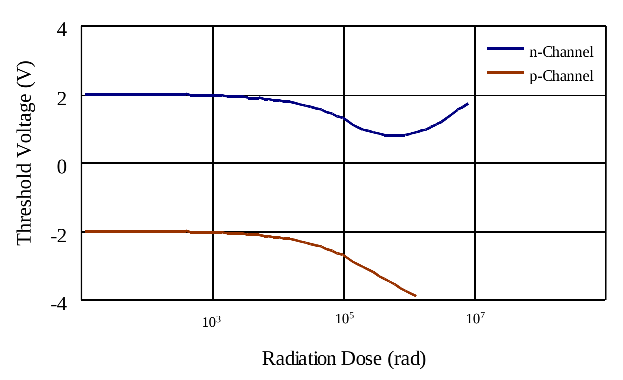


Total Dose in COTS

ELDRS Effect

- Hardness is dose rate dependent
  - Lateral PNP transistors are more sensitive than others at low dose rate
  - At space rates, lateral PNPs are softer than at test chamber rates
  - Temperature confounds the effect
- Serious implications for test fidelity in space applications

Total Dose in COTS



Total Dose in COTS

Microscopic Effects

- Slower gate switching speeds
- Increased leakage currents
- Threshold voltage shifts

Total Dose in COTS

Macroscopic Effects

- Analog and Mixed-Signal Parts
  - Supply current, leakage currents increase
  - Offset voltage increases
  - Gain decreases
  - Converter non-linearity increases
  - PSRR, CMRR increases
  - Reference voltages change

Total Dose in COTS

Macroscopic Effects

- Digital Parts
  - Supply currents, input leakage increase
  - Timing slows down
  - DRAM data retention time decreases
  - Charge pumps fail
  - Transistor threshold voltages shift, so logic gates get stuck in one state

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Total Dose in COTS

Macroscopic Effects

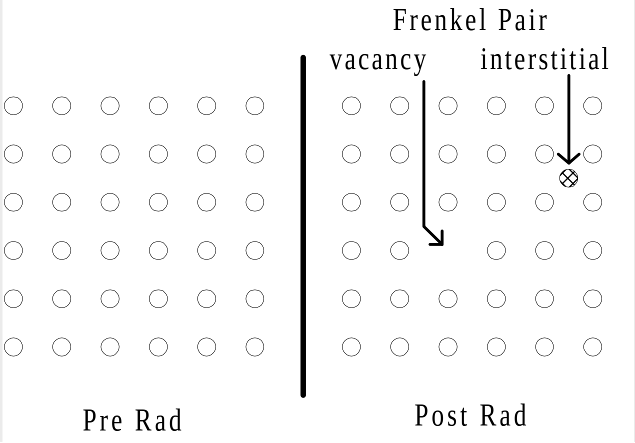
- Digital CMOS
  - Typically 1 - 50 krads
- Analog MOS
  - 1- 30 krads (depending on application)
- Bipolar
  - 10 - 100 krads
  - ELDRS effect may not be an LHC issue

Total Dose in COTS

Macroscopic Effects

- Boards and Systems
  - Strongly dependent on board design
  - Often observe increased supply current
  - In many cases, board works until it just quits
  - May be possible to find reduced operation that continues to work at higher doses.

Displacement in COTS



Displacement in COTS

Microscopic Effects

- Neutron interacts with silicon nucleus
- Dislocates atom
- Formation of a Frenkel Pair which can be thought of as a recombination center
- Vacancy and interstitial cause unwanted quantum states in band gap
- Changes carrier flow

Displacement in COTS

Macroscopic Effects

- Mostly an issue for photonic or optoelectronics
  - Lasers, LEDs
  - Opto-isolators, including DC-DC converters
  - CCDs, similar detectors
  - Bipolar electronics
- Decreases output power of light sources
- Reduces charge collection in receivers
- Increases leakage (or “dark) current

Displacement in COTS

Damage Equivalence

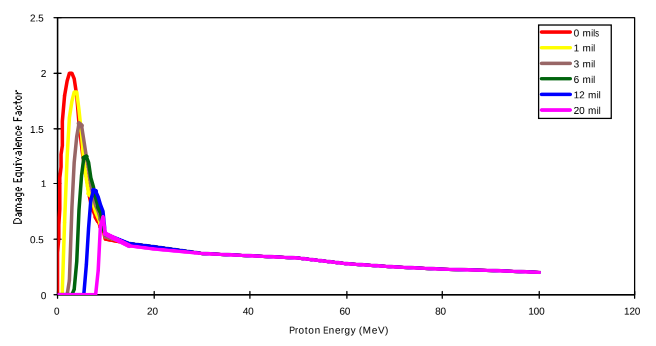
- Test data usually taken with mono-energetic, unidirectional beams
- We need a way to convert a spectrum into a single equivalent fluence of a “standard” particle

$$\Psi_e = \int K(E)\Psi(E)dE$$

Displacement in COTS

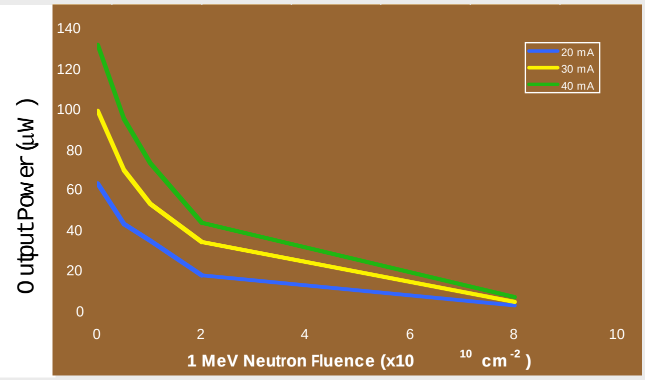
Damage Equivalence Factors in Si

Omnidirectional Proton to Unidirection 10 MeV Proton



Displacement in COTS

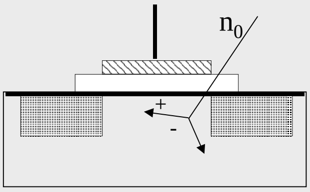
Neutron Irradiation of LEDs



SEE in COTS

Microscopic Effects

- Neutron interacts with silicon nucleus
- Charged secondaries deposit charge
- Collected charge pulse causes effect
- Fundamentally a statistical process



SEE in COTS

Macroscopic Effects

- Destructive Effects
  - Latchup, gate rupture, burnout
  - Neutrons do not generally cause these
- Non-Destructive Effects
  - Upset, functional interrupt, transient
  - Most likely neutron effects

SEE in COTS

Single Event Upset

- Change in state of a memory element
- System-level manifestations depend on application

Single Event Functional Interrupt

- Upset places device in an ill-defined condition
- Sometimes requires power cycle to clear

SEE in COTS

Example: DRAM

- Upset Modes
  - Cell upset
  - Address error
  - Data latch error
- Functional Interrupt Modes
  - Spare memory area
  - Built-in test mode

SEE in COTS

Example: Microprocessor

- Upset Modes
  - Data error
  - Program error
- Functional Interrupt Modes
  - Built-in self test
  - Invalid instruction
  - Bad memory fetch

SEE in COTS

Example: Field Programmable Gate Array

- Non-SRAM Device
  - Dielectric rupture
  - Data errors
- SRAM-Based Device
  - Data errors
  - Inadvertent reprogramming
  - Functional interrupt in state machine

SEE in COTS

Boards and Systems

- Several (sometimes many) devices may be sensitive to effects
- Unpredictable results
  - Depends on type of error and system design
  - Very little visibility to diagnose problems
  - Can’t depend on a system to completely police itself

COTS-Specific Issues

COTS Issues

Lot-to-lot Variation

- Parameters which determine total dose hardness aren’t closely controlled by manufacturers
  - Hardness can vary widely across wafers and manufacturing runs
  - Example: LM108 OpAmp - tested devices hard to as little as 5 krads and as hard as 80 krads
- SEE sensitivity determined by architecture, and so less variable across lots

COTS Issues

Architecture Changes

- SEE susceptibility determined by architecture
- Manufacturers revise die without warning
- Usually invalidates past SEE testing
- Related issue - product obsolesence
    - By the time you find a product you can use, the manufacturer has replaced it with something you can't use!

COTS Issues

Boards and Systems

- Manufacturers change components frequently
    - Cheaper product
    - Performance improvement
    - Obsolesence
- Especially difficult with hybrids
    - No part numbers to check!

Testing and Procurement

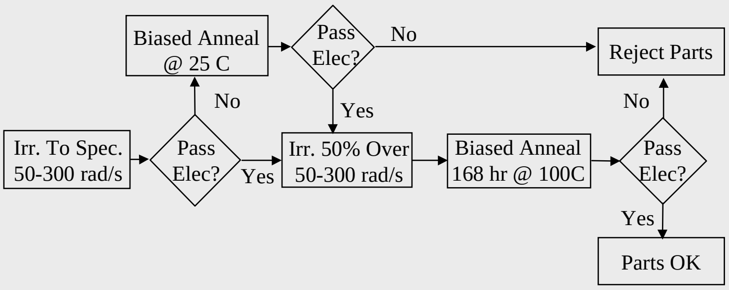
Hardness Assurance

Steps To Hardness Assurance

- Determine requirements
  - Mostly determined by position
- Test components of interest
- Mitigate or circumvent damage effects
- Manage the supply of chosen parts

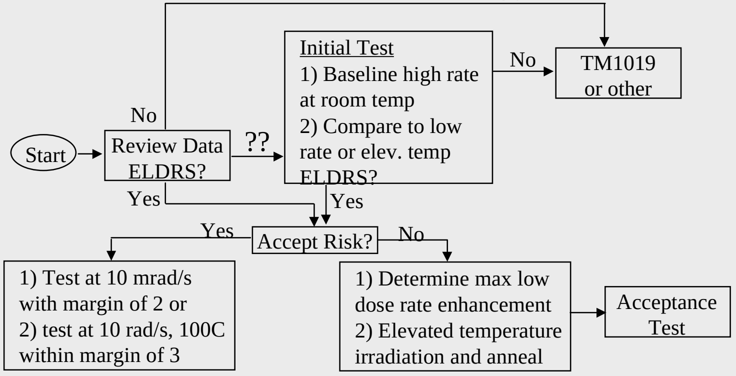
Total Dose Effects

Total Dose Test Methodology



ELDRS Effect

ELDRS Effect Test Methodology



SEE Effects

Event Rate Requirements

- From performance requirements
  - Highly application dependent
- Determination process is iterative
  - Requirements are given at system level
  - More sensitive devices can be used with mitigation if overall rate meets requirement

SEE Effects

Testing Issues

- Purpose: to measure the event cross-section and study external effects
  - Characterization of what happens to a device is necessary for mitigation design
- Quality of test impacts uncertainty
  - Dead time, beam measurement, etc.
  - Number of events detected
  - Fidelity of test

Displacement Effects

Testing Issues

- Data similar to TID Testing
  - Cumulative changes in device behavior as a function of fluence
- Execution similar to SEE testing
  - Beam issues of primary concern
  - Should simulate application as closely as possible

Procurement Issues

Common Buys

- "Frequently Used Parts"
  - Saves on qualification costs
  - Requires high degree of co-ordination
  - Need a centralized distribution system
  - May not help for systems

Procurement Issues

Data Sharing

- Database entries are often incomplete, making it difficult to apply results
  - Record as much info about the test as possible
  - Agree beforehand on how to do tests
- TID
  - Bias circuit, dose rate, anneal times
- SEE
  - Circuit, full cross-section curve, external effects

Mitigation Strategies

Total Dose Mitigation

Three Schemes

- Reduce the dose
  - External shielding
  - Advanced packaging
- Reduce the damage
  - Cold sparing
  - Intentional annealing
- Accommodate the effects
  - Design for end-of-life behavior

Displacement Mitigation

Two Schemes

- Reduce the fluence
  - Shielding
  - Advanced packaging
- Accommodate the effects
  - Design for end-of-life behavior

Displacement in COTS

Example: DC-DC Converters

- Often use optocouplers for isolation
- Mitigation
  - Use least sensitive components
  - Shielding or advanced packaging to reduce fluence
  - Accommodate power MOSFET threshold voltage shifts in design

SEE Mitigation

EDAC Method	**Capability**
Parity	Single bit detect
CRC	Any errors in given structure
Hamming Code	Single bit correct, double bit detect
Reed-Solomon	Errors within symbol
Convolutional Encoding	Burst noise in data stream
Overlying Protocol	System designed to correct errors (i.e., data packet retransmission

SEE Mitigation

Method	**Description**
Watchdog Timer	If not reset within some time interval, reset system
Redundancy	Equivalent systems operate on data.
Lockstep	Two devices are clocked simultaneously.
Voting	Three or more device provide function, which must agree
Repetition	System provides same data more than once
Scrubbing	Rewrite critical memory locations at regular intervals

Resources

Resources

Device Data

JPL	nppp.jpl.nasa.gov	TID/SEE
GSFC	flick.gsfc.nasa.gov	SEE
ERRIC	erric.dasiac.com	Variety
ESA	www.spurelec.demon.co.uk	TID/SEE
NRL	redex.nrl.navy.mil	TID/SEE
Data Workshop	IEEE NSREC	Variety

Resources

General Info

- IEEE Transactions on Nuclear Science
- Journal of Spacecraft and Rockets
- Conferences/Seminars
    - NSREC
    - NSS
    - RADECS
    - Space Parts Working Group
    - GOMAC/HEART