The View from 10,000 ft – what is happening and what it means for flight electronics

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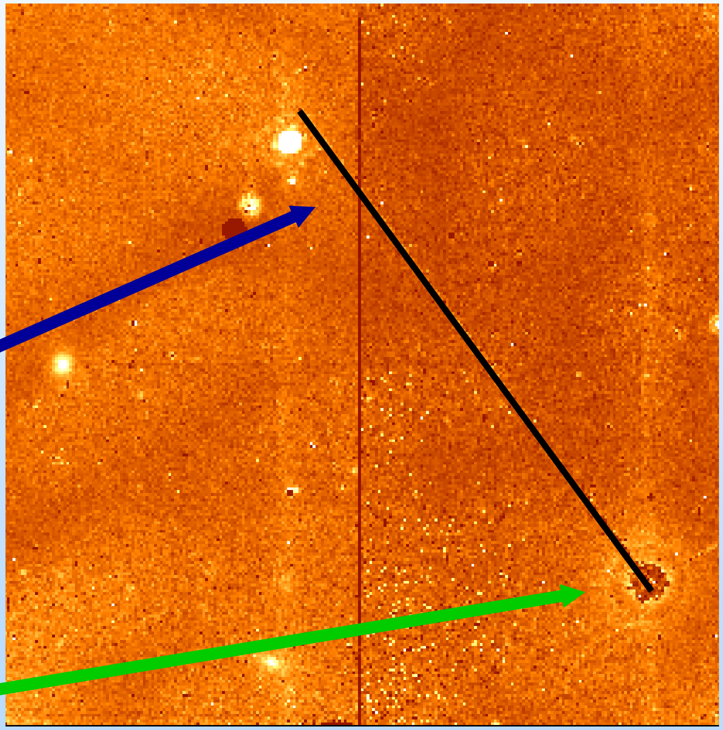
Outline

- What's New with Electronics
- What's Unique About Space and Electronics
- How is NEPP Approaching the Problem



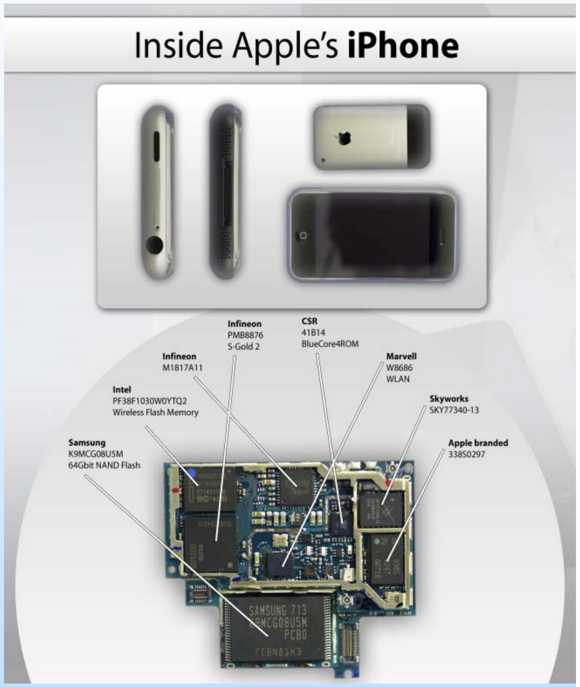
Atomic Interactions
  - ***Direct Ionization***

Interaction with Nucleus
  - ***Indirect Ionization***
  - ***Nucleus is Displaced***

–http://www.stsci.edu/hst/nicmos/performance/anomalies/bigcr.html

The Amazing Progression of the Integrated Circuit (IC)

- **We have been eyewitnesses to the revolution that's taken place in the semiconductor industry**
  - **What was once inconceivable is now the ordinary**
- **Several factors have been at the forefront of this movement**
  - **Integration**
    - **Increasing functionality in decreased space**
  - **Material science**
    - **Using science to modify the silicon transistor and it's package**



Inside a Apple iPhone™ player

Note: this talk has a bit more radiation focus than reliability due to my background

The Growth in IC Availability

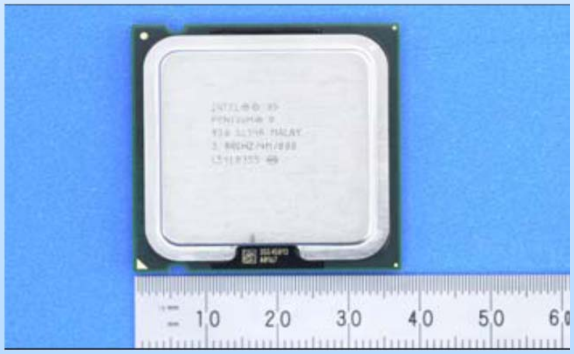
- The semiconductor industry has seen an explosion in the types and complexity of devices that are available over the last several decades
  - The commercial market drives features
    - High density (memories)
    - High performance (processors)
    - Upgrade capability and time-to-market (FPGAs)
    - Wireless (RF and mixed signal)
    - Long battery life (Low-power CMOS)

Integrated Cycling Bib and MP3

Zilog Z80 Processor

circa 1978

8-bit processor



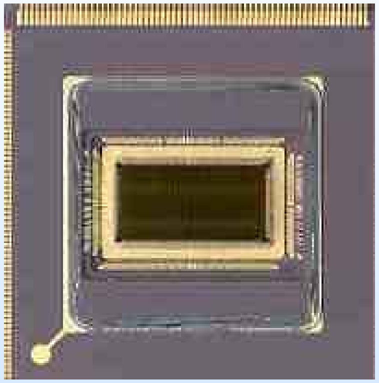
Intel 65nm Dual Core Pentium D Processor

circa 2007

Dual 64-bit processors

Types of Electronic Parts for Space

- One may view electronic parts for space as meeting needs in three categories
  - Standard electronics
    - E.g., capacitors
      - Basic components
  - Standard building blocks
    - E.g., Field Programmable Gate Arrays (FPGAs)
      - Widespread usage in most systems
  - Custom devices not available as “off-the-shelf”
    - E.g., nuclear power or EVA
      - Needed for a specific application - ASIC
- Note: Commercial-of-the-shelf (COTS) assemblies (e.g., commercial electronic cards or instruments) also may be considered
  - Screening is more complicated than ever before!



ACTEL RTSX72S FPGA

A part that passed “standard” qualification, but requires more complex testing

A Critical Juncture for Space Usage – Commercial Changes in the Electronics World

- **Scaling of technology**
  - Increased gate/cell density per unit area (as well as power and thermal densities)
  - Changes in power supply and logic voltages (<1V)
    - **Reduced electrical margins within a single IC**
  - Increased device complexity, # of gates, and hidden features
  - Speeds to >> GHz (CMOS, SiGe, InP…)
- **Changes in materials**
  - Use of antifuse structures, phase-change materials, alternative K dielectrics, Cu interconnects (previous – Al), insulating substrates, ultra-thin oxides, etc…
- **Increased input/output (I/O) in packaging**
  - Use of flip-chip, area array packages, etc
- **Increased importance of application specific usage to reliability/radiation performance**

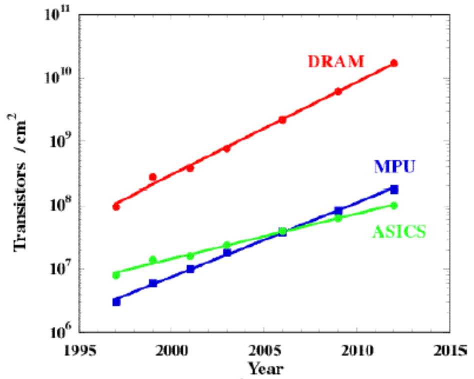
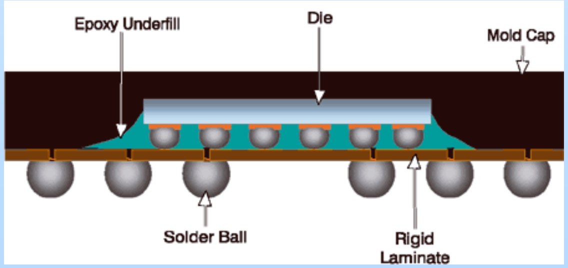


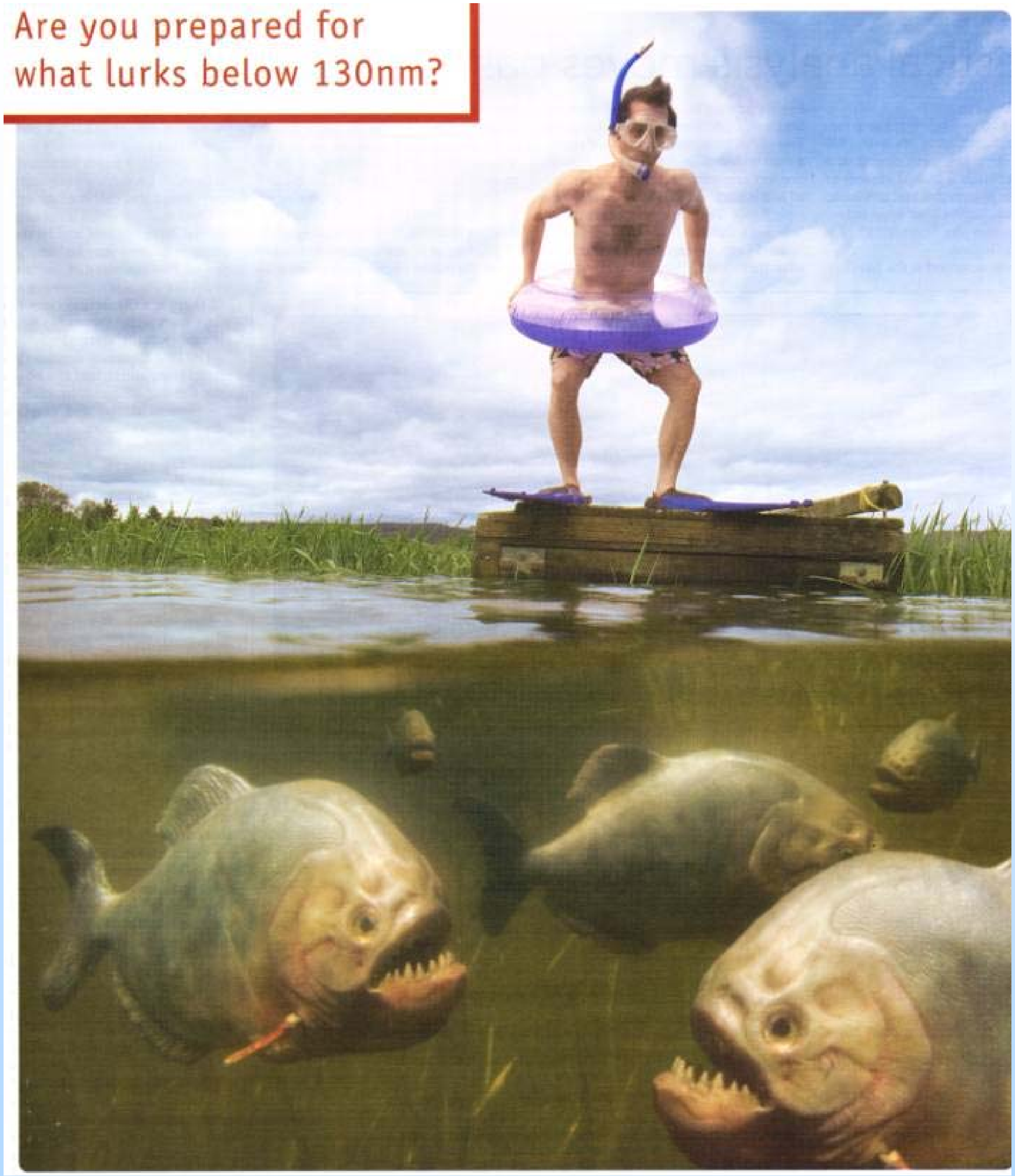
Figure 1.2:- The number of transistors per cm² plotted against the year of first manufacture.



The Changes in Device Technology

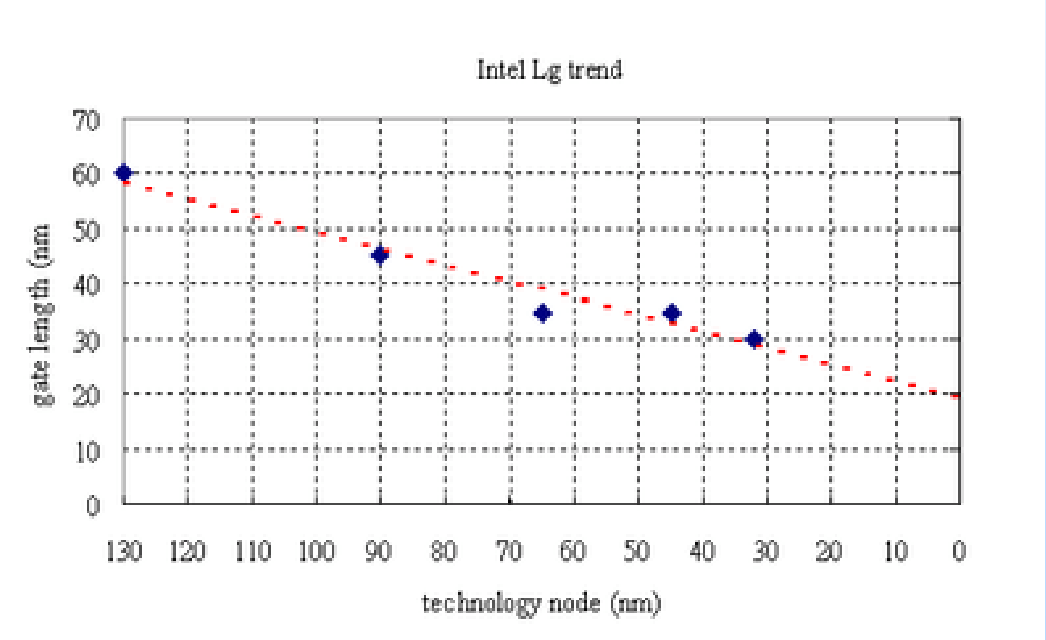
- Besides increased availability, many changes have taken place in
  - Base technology,
  - Device features, and,
  - Packaging
- The table below highlights a few selected changes

Feature	circa 1990	circa 2007
Base technology	bulk CMOS/NMOS	CMOS with strained Si or SOI
Feature size	> 2.0 um	65 nm
Memory size - volatile (device)	256 kb	1 Gb
Processor speed	64 MHz	> 3 GHz
FPGA Gates	2k	> 1M
Package	DIP or LCC - 40 pins	FCBGA - 1500 balls
Advanced system on a chip (SOC) features	Cache memory	>Gbps Serial Link, Serdes, embedded processors, embedded memory


Are you prepared for
what lurks below 130nm?

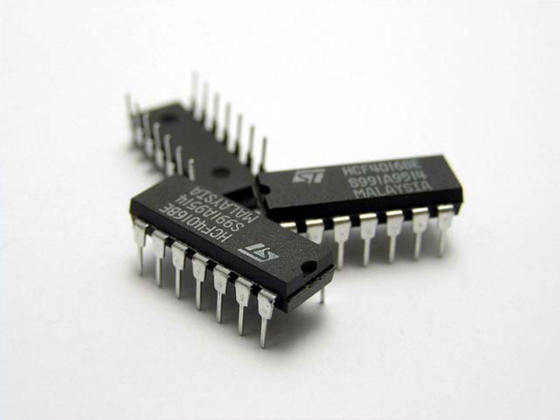
What is a Scaled CMOS anyway?

- **It's all about transistors and sizing (known as gate or channel lengths) and the desire to pack as many transistors on a chip as possible**
  - **Transistor node space is now commercially at 32nm (and 25nm is sampling!)**



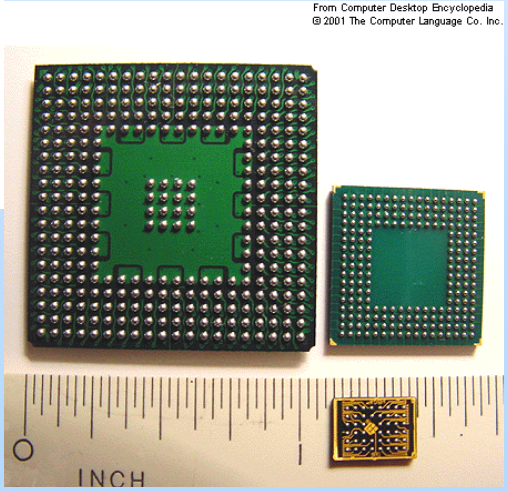
Package Complexity - Evolution

Dual in-line Package (DIP)
10’s of pins
Wirebonded, through hole



Quad Flatpack (QFP)
100’s of pins
Wirebonded, surface mount

Area Array Package
1000’s of pins
Bump bonded,
surface mount or columns added


From Computer Desktop Encyclopedia
© 2001 The Computer Language Co. Inc.

The Challenge for Selecting ICs for Space

- **Considerations since the "old days"**
  - **High reliability (and radiation tolerant) devices**
    - **Now a *very* small market percentage**
  - **Commercial "upscreening"**
    - **Increasing in importance**
    - **Measures reliability, does not enhance**
  - **System level performance and risk**
    - **Hardened "systems" not devices**

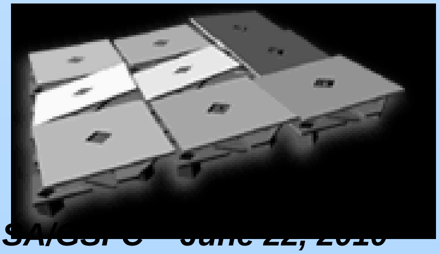
ADCs?
SerDes?
SDRAM?
Processor?
ASICs?
DSPs
FPGAs?
Flash?

System Designer

Trying to meet high-resolution instrument requirements AND long-life in a space environemnt

Microelectronics: Categories

- **Microelectronics can be viewed several ways**
  - **Digital, analog, mixed signal, other**
  - **Complementary Metal Oxide Semiconductor (CMOS), Bipolar, etc...**
  - **Function (microprocessor, memory, …)**
- **There are only two commercial foundries (where they build devices) in the US dedicated to building radiation hardened digital devices. Several others have “foundryless” options.**
  - **Efforts within DoD to provide alternate means of developing hardened devices**
    - **Hardened-by-design (HBD)**
    - **Provides path for custom devices, but not necessarily off-the-shelf devices**
  - **Commercial devices can have great variance in radiation tolerance from device-to-device and even on multiple samples of same device**
    - **No guarantees!**
  - **Analog foundry situation is even worse**
- **New technologies have many unknowns**
  - **Ultra-high speed, nanotechnologies, microelectromechanical systems (MEMS and the optical versions – MOEMS), …**



A MOEMS in action

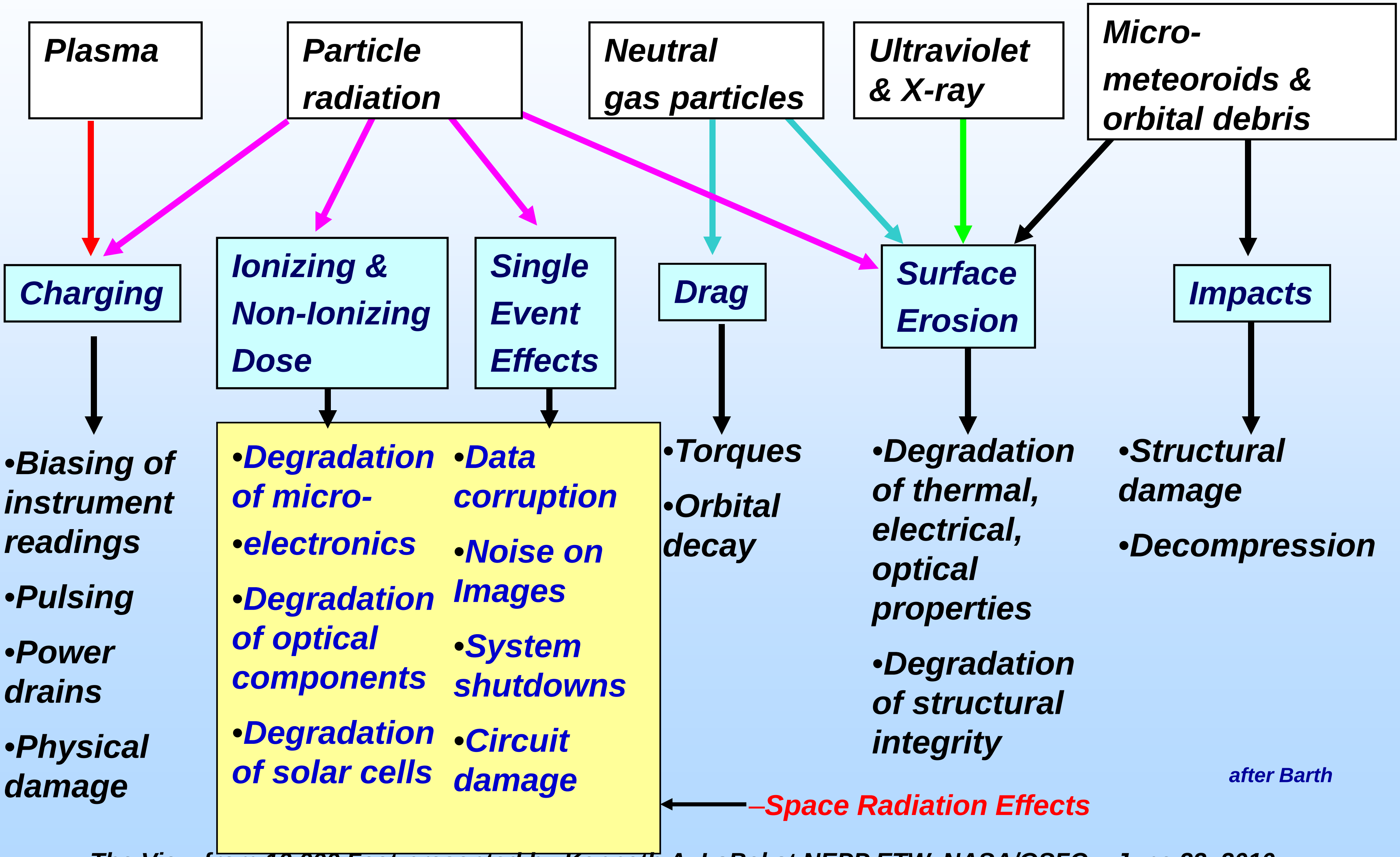
NEPP:

If we used strictly commercial parts

	Terrestrial	Space
Lifetime	1-3 years, then replaced or thrown out	1-20 years and rarely replaceable
Thermal	0-70C	-55 to +125C with extremes much higher and lower
Shock	Oops! I dropped it. Time to get an upgrade anyway…	Launch vibration
Anomaly	Reboot or power cycle or return to dealer	Anomaly or failure
Radiation	Is the microwave on?	Protons, electrons, cosmic rays, …

- NEPP is the only entity at NASA that
  - Trains young engineers in the difference and provides a growth path for developing project parts and radiation engineers
  - Develops and validates qualification methods
  - Provides knowledge that allows insertion of modern devices into our space systems
  - Shares and gathers knowledge with all the industry
    - If the flight projects don't know there's a problem…

Space Environments and Related Effects



Plasma

Particle radiation

Neutral gas particles

Ultraviolet & X-ray

Micro-meteoroids & orbital debris

Charging

Ionizing & Non-Ionizing Dose

Single Event Effects

Drag

Surface Erosion

Impacts

- Biasing of instrument readings
- Pulsing
- Power drains
- Physical damage

- Degradation of micro-
- electronics
- Degradation of optical components
- Degradation of solar cells

- Data corruption
- Noise on Images
- System shutdowns
- Circuit damage

- Torques
- Orbital decay

- Degradation of thermal, electrical, optical properties
- Degradation of structural integrity

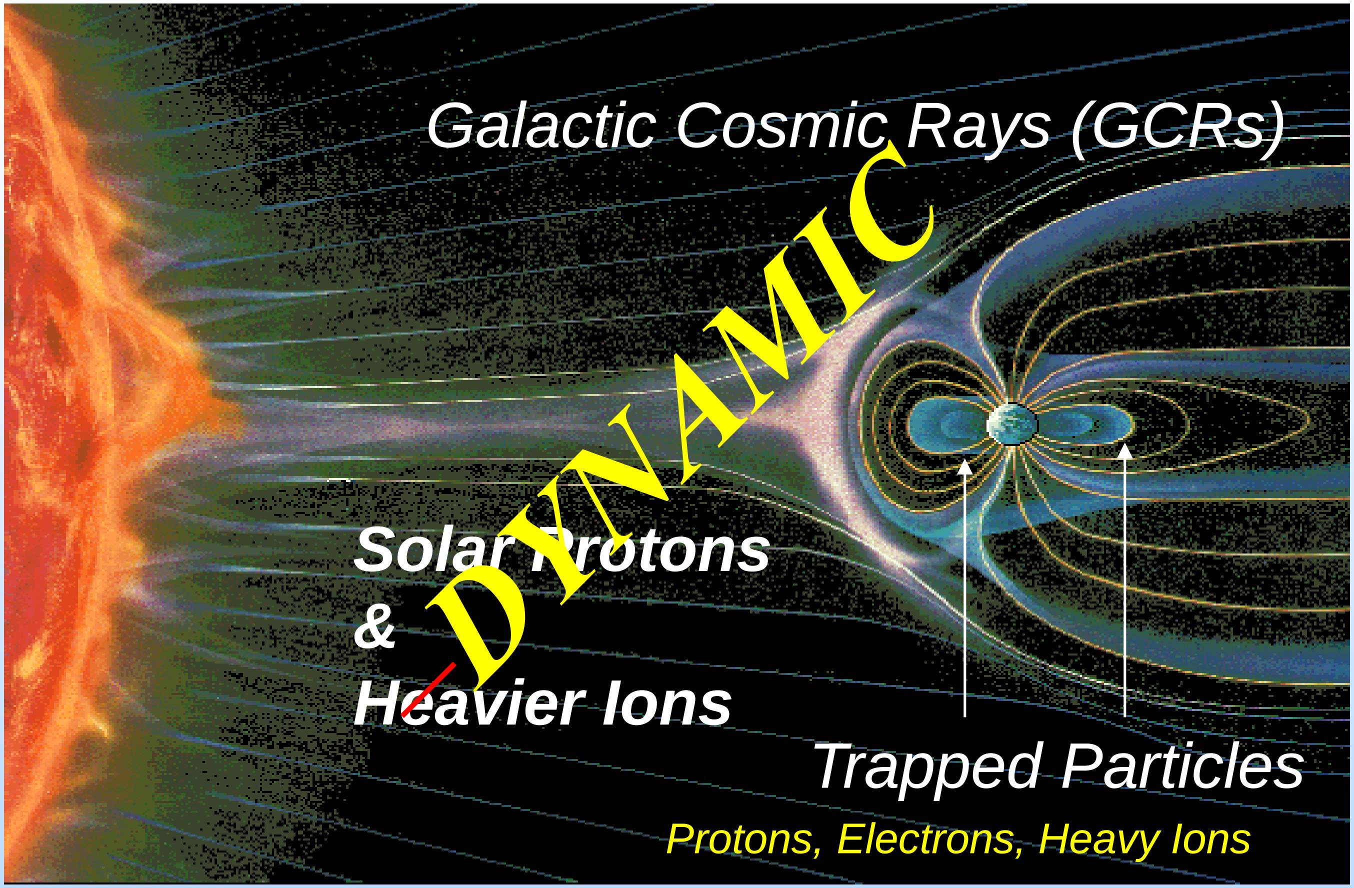
- Structural damage
- Decompression

after Barth

–Space Radiation Effects

Space Radiation Environment

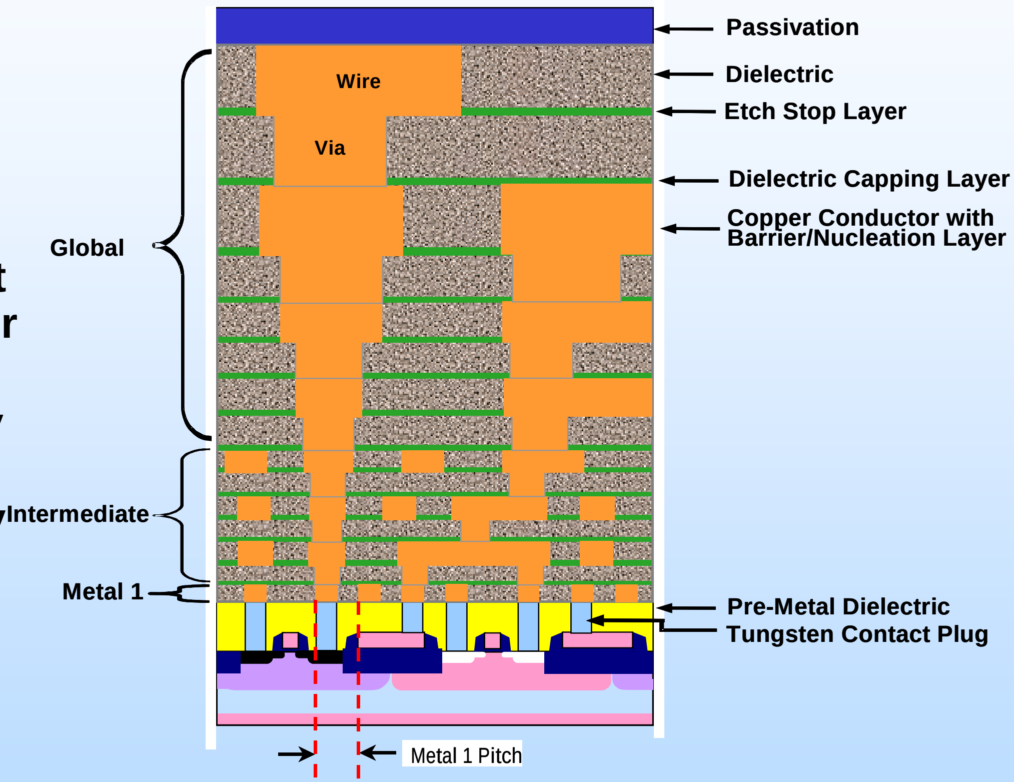
after
Nikkei Science, Inc.
of Japan, by K. Endo



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

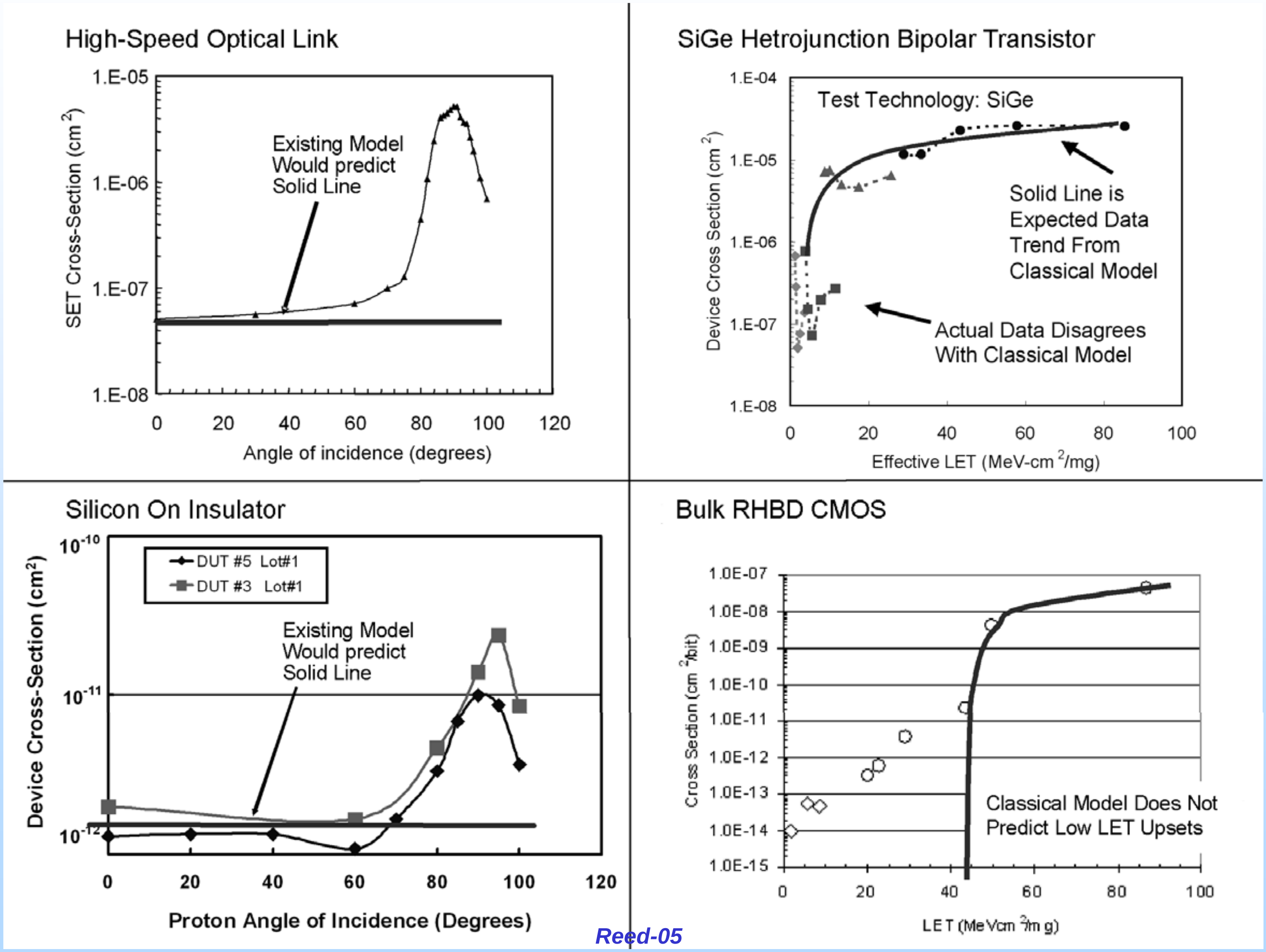
Implications for Electronics in Space

- With all these changes in the semiconductor world, what are the implications for usage in space? Implications for test, usage, qualification and more
  - Speed, power, thermal, packaging, geometry, materials, and fault/failure isolation are just a few for emerging challenges for radiation test and modeling.
    - Reliability challenges are equally as great
  - The following chart (courtesy of Vanderbilt University) looks at some of the recent examples of test data that imply shortfalls in existing radiation performance models.
    - Technology assumptions in standard tools such as CREME96 are no longer valid



Typical device cross-section. Current generations of digital devices take over 1500 processing steps.

Sample Radiation Modeling Shortfalls



High-Speed Optical Link

Existing Model Would predict Solid Line

SiGe Hetrojunction Bipolar Transistor

Test Technology: SiGe

Solid Line is Expected Data Trend From Classical Model

Actual Data Disagrees With Classical Model

Silicon On Insulator

Existing Model Would predict Solid Line

Bulk RHBD CMOS

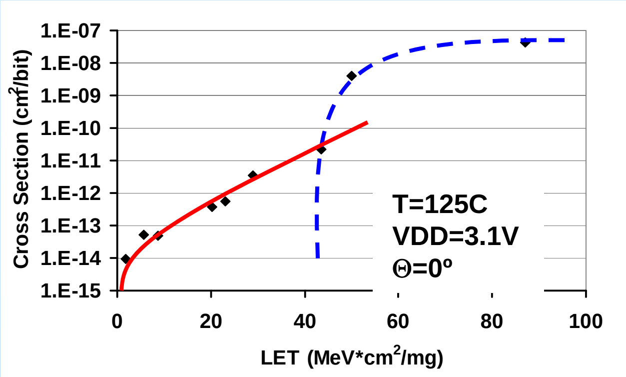
Classical Model Does Not Predict Low LET Upsets

Reed-05

Where we are –

Radiation test methods and what has changed in the world

- Existing test methods
  - SEE
    - JEDEC JSD 57
    - ASTM, F1192-00
  - TID
    - MIL-STD-883B, Test Method 1019.8
    - ASTM, F1892-06
- All had prime development in the mid-90s with some updates since, however, many new issues have been discovered that may not be covered adequately



Courtesy ISDE, Vanderbilt University

- Examples: Recent SEE Phenomena
  - Angular effects in SOI technologies
  - Role of single event transients (SETs) and commensurate speed-related issues in both analog and digital circuits
  - Ion penetration and range issues in power and packaged components
  - Approaches to die access
  - Impact of application and reconfigurable approaches to SEE performance
  - Role of nuclear reactions from heavy ion particle interactions

Reliability testing has had commensurate complications

Hypothetical New Technology Part Qualification Cost Circa 2008

Item	*Cost*	*Note*
Parts Procurement **(500-1000 devices for testing only)**	**$25-1000K**	**Individual device costs can run from cents to tens of thousands**
“Standard” Qualification Tests	**$300K**	
Radiation Tests and Modeling	**$400K**	**Assumes total dose and single event (heavy ion) only**
Failure Modes Analysis	**$300K**	**Out-of-the-box look at the “hows and whats” for non-standard research required for qualification**
Additional Tests, Modeling, and Analysis based on Failure Modes	**$500K**	
Total cost for one device type	**$1.5-3M**	**Not all new technologies will meet standard qualification levels: technology limitations document**

Assumption: 12-24 months to develop sufficient data for technology confidence

Device Complexity Drives Cost and Schedule!
- Ex., Standard Memory

1996 SEE Test of a 4M SRAM				
Description	**Man-weeks or units**	**Cost in $**	**Total**	**Note**
Heavy Ion at BNL SEUTF				
Test plan	0.20	$4,000.00	$800.00	Includes eng, rad, other to define what needs to go into test set with project.
Device procurements	10.00	$50.00	$500.00	
Misc parts	1.00	$250.00	$250.00	Sockets, connectors, etc...
Device delidding	0.05	$3,500.00	$175.00	
Test board design - electrical and layout	0.40	$4,000.00	$1,600.00	
Board fab and population	1.00	$3,500.00	$3,500.00	In-house board build
Board/tester debug	0.50	$4,000.00	$2,000.00	
Rad expert (test oversight and plan)	0.40	$5,000.00	$2,000.00	
Heavy ion test performance - contractor	2.00	$1,500.00	$3,000.00	
BNL Beam	6.00	$700.00	$4,200.00	Simple data: bit flips, latchup
Data analysis	1.00	$3,500.00	$3,500.00	
Test report (eng, rad expert, rad lead)	0.50	$4,000.00	$2,000.00	
			Total:	**$23,525.00**

2006 SEE Test of SDRAM				
Description	**Man-weeks or units**	**Cost in $**	**Total**	**Note**
Heavy Ion at TAMU				
Test plan	1.00	$4,000.00	$4,000.00	Includes eng, rad, other to define what needs to go into test set with project.
Device procurements	10.00	$75.00	$750.00	
Misc parts	1.00	$1,000.00	$1,000.00	Higher speed drives cost
Device thinning and package processing	10.00	$350.00	$3,500.00	Assumes FBGA package; If this does not work, more expensive test facility like NSCL needed: >$100K delta
Daughterboard Board design - electrical	0.40	$4,000.00	$1,600.00	
Daughterboard Board design - PCB	0.50	$3,500.00	$1,750.00	
Test Boards	10.00	$500.00	$5,000.00	
Board population	0.40	$3,500.00	$1,400.00	
Board/tester debug	0.50	$4,000.00	$2,000.00	
Tester VHDL development	3.00	$4,000.00	$12,000.00	
Technician	1.00	$3,500.00	$3,500.00	
Rad expert (test oversight and plan)	0.60	$5,000.00	$3,000.00	
Heavy ion test performance - contractor	2.00	$2,000.00	$4,000.00	
TAMU	16.00	$750.00	$12,000.00	2X time required: more data, more error types, more complex results
Data analysis	3.00	$3,500.00	$10,500.00	
Test report (eng, rad expert, rad lead)	1.00	$4,000.00	$4,000.00	
			Total in	**$70,000.00**

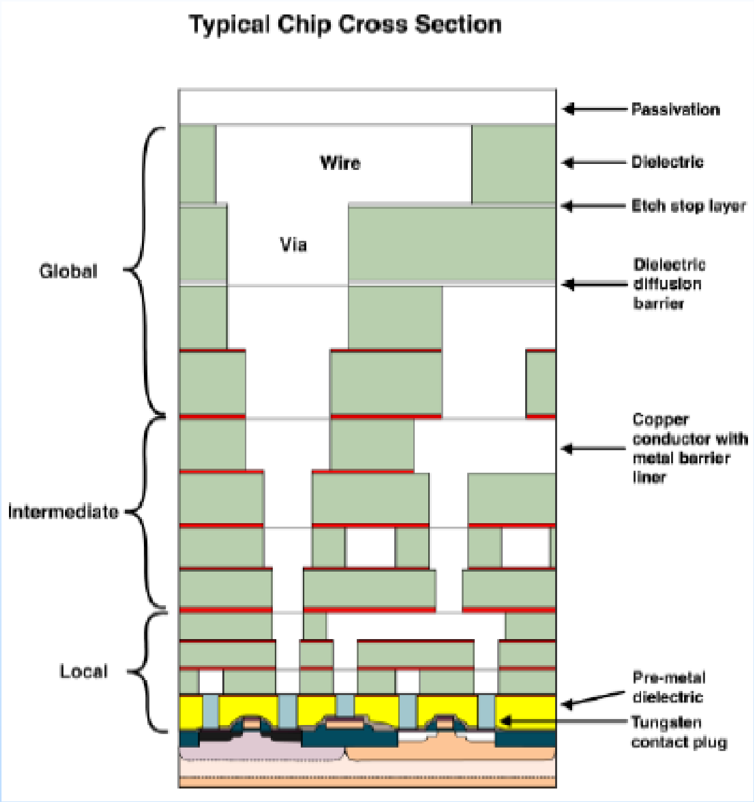
1996 vs 2006 a 3X Cost Delta

Now >> $100K

Other test costs (radiation and reliability) have increased commensurately with ~3X schedule increase as well!

NEPP Mission

- To provide guidance to NASA:
  - Selection and application of microelectronics technologies
  - Improved understanding of risks related to the use of these technologies in the space environment
  - Appropriate evaluations to meet NASA mission assurance needs for electronic systems
- NEPP evaluates new* and emerging** electronic parts technologies and provides assurance support for technologies in current use in NASA spaceflight systems


Typical Chip Cross Section

New – Recently marketed, commercially available

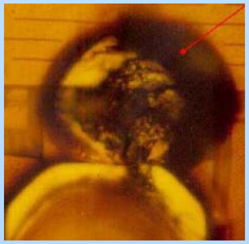
*** Emerging – Available in limited quantities for evaluation, on path to commercial products*

NEPP Overview

- **NEPP supports all of NASA for >20 years**
  - **7 NASA Centers and JPL actively participate**
- **The NEPP Program focuses on the reliability aspects of electronic devices**
  - **Three prime technical areas: *Parts (die), Packaging, and Radiation***
- **Alternately, reliability may be viewed as:**
  - **Lifetime, inherent failure and design issues related to the electronic parts technology and packaging,**
  - **Effects of space radiation and the space environment on these technologies, and**
  - **Creation and maintenance of the assurance support infrastructure required for mission success.**

Electrical overstress failure

in a commercial electronic device

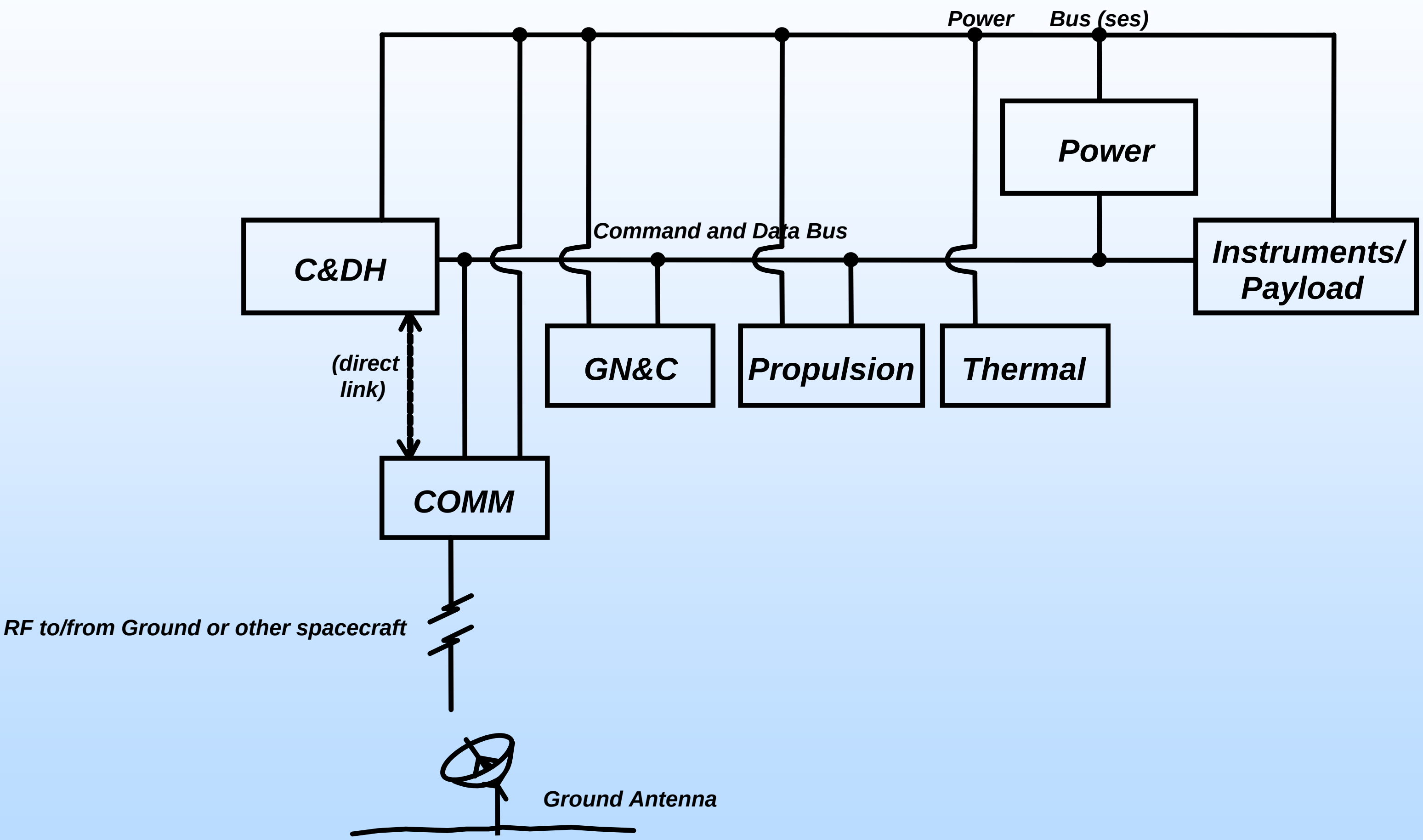


NEPP Works Two Sides of the Equation

- Assurance
  - *Issues that are applicable to space systems being designed and built (i.e., currently available technologies)*
  - Examples
    - Cracked capacitors
    - DC-DC converter reliability
    - Enhanced Low Dose Rate Sensitivity (ELDRS)
  - Communication infrastructure via website and working groups
    - NASA Electronic Parts Assurance Group (NEPAG)
  - Audit and review support

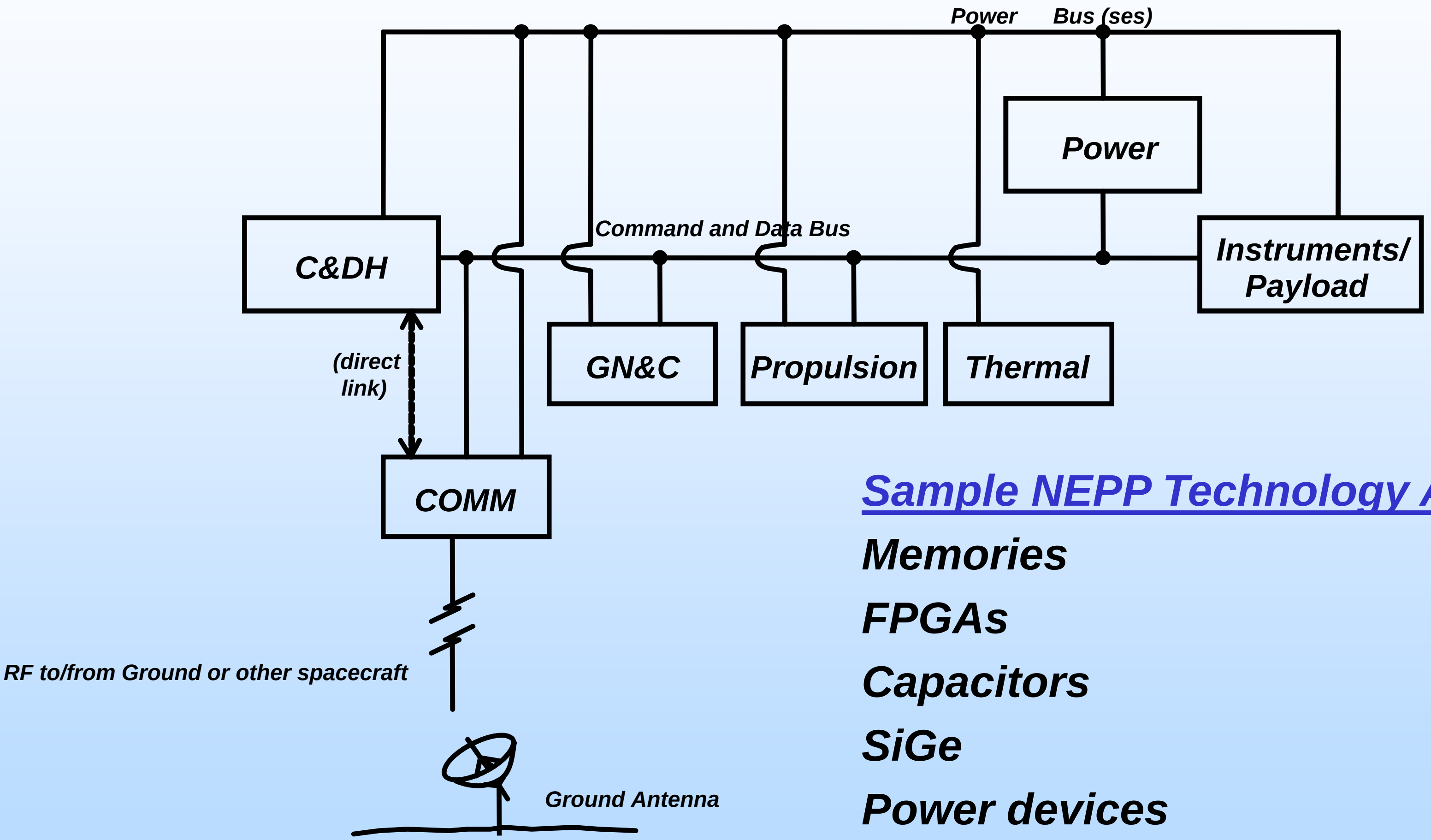
- New electronics technology
  - *Issues that are applicable to the next generation of space systems in conceptualization or preliminary design*
  - Examples
    - 45-90 nm CMOS
    - SiGe
    - State-of-the-art FPGAs
  - Collaboration with manufacturers and government programs for test, evaluation, and modeling
  - Development of new predictive performance tools

Typical Spacecraft Electrical Architecture



Typical Spacecraft Electrical Architecture

The 90/90 Goal



Sample NEPP Technology Areas

Memories

FPGAs

Capacitors

SiGe

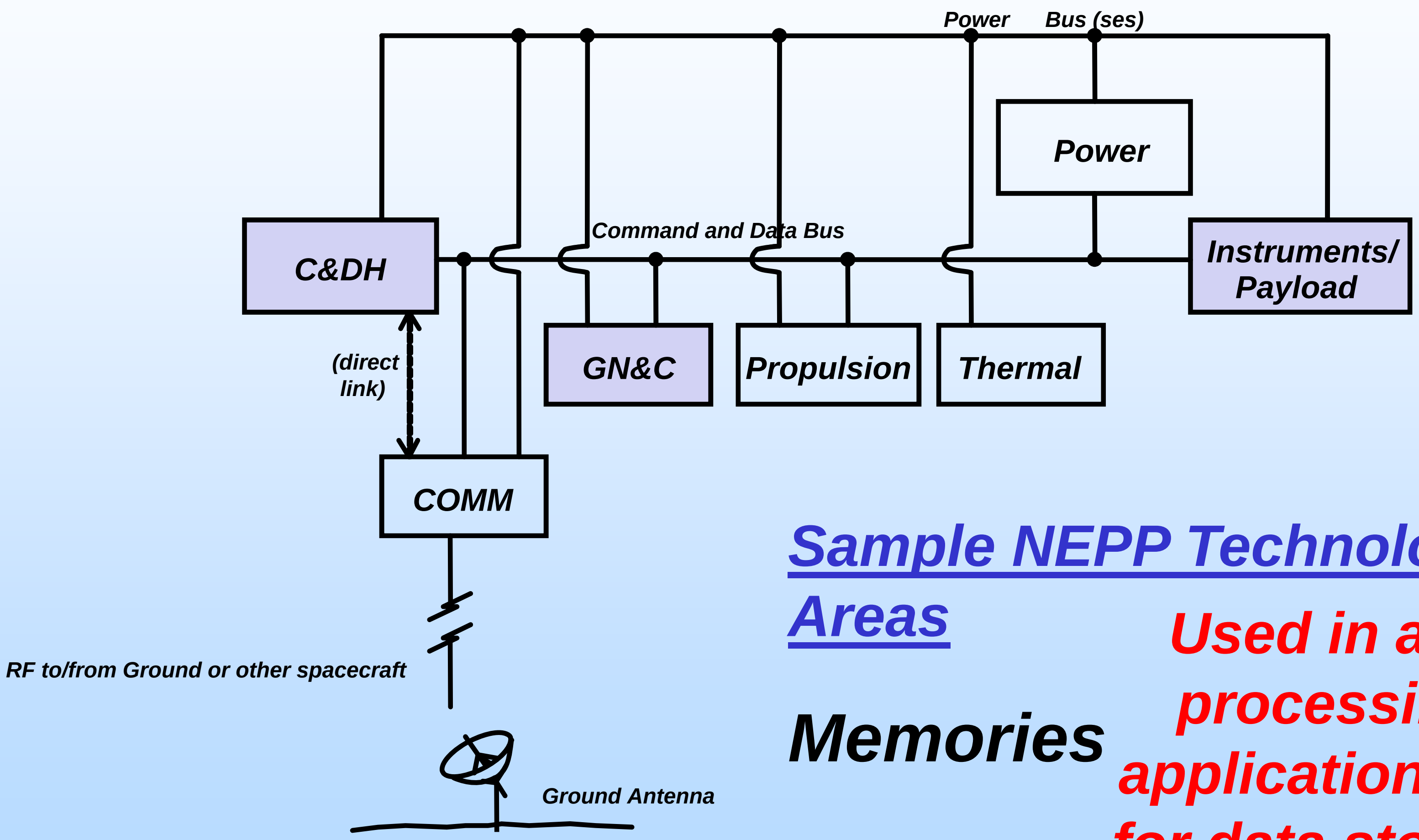
Power devices

90% of NEPP efforts should support

90% of NASA flight missions

Typical Spacecraft Electrical Architecture

The 90/90 Goal - Example



Sample NEPP Technology Areas

Memories

Used in any processing application and for data storage on a spacecraft.

NEPP Has a Wide Range of Efforts

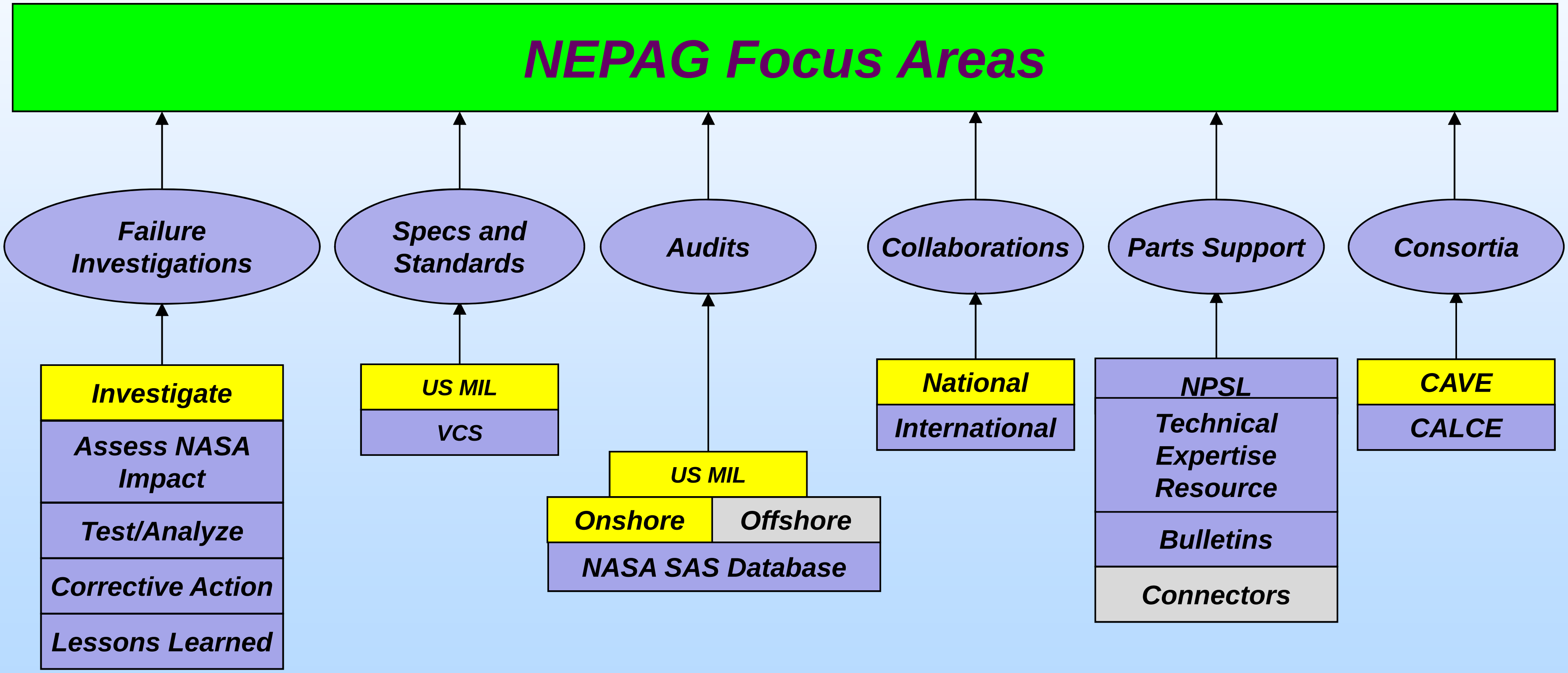
- **Tasks vary extensively in the technologies of interest**
  - **Building blocks like capacitors**
  - **Standard products like DC-DC Converters, linear bipolar devices, and A-to-D Converters**
  - **New commercial devices such as FPGAs and memories**
  - **Test structures on emerging commercial or radiation hardened technologies**
  - **Specialized electronics such as IR arrays and fiber optics**
  - **New assurance methods and investigations**
- **NEPP ETW provides forum to present recent results, as well as current and future plans**
- **Currently in FY11 planning cycle**
  - ***PRELIMINARY PLANS FOLLOW***

NASA Electronic Parts Assurance Group (NEPAG)

Core Areas are Bubbles; Boxes underneath are elements in each core

Legend

- 🟨 DoD and NASA Funded
- 🟪 NASA-only funded
- ⬜ Overguide



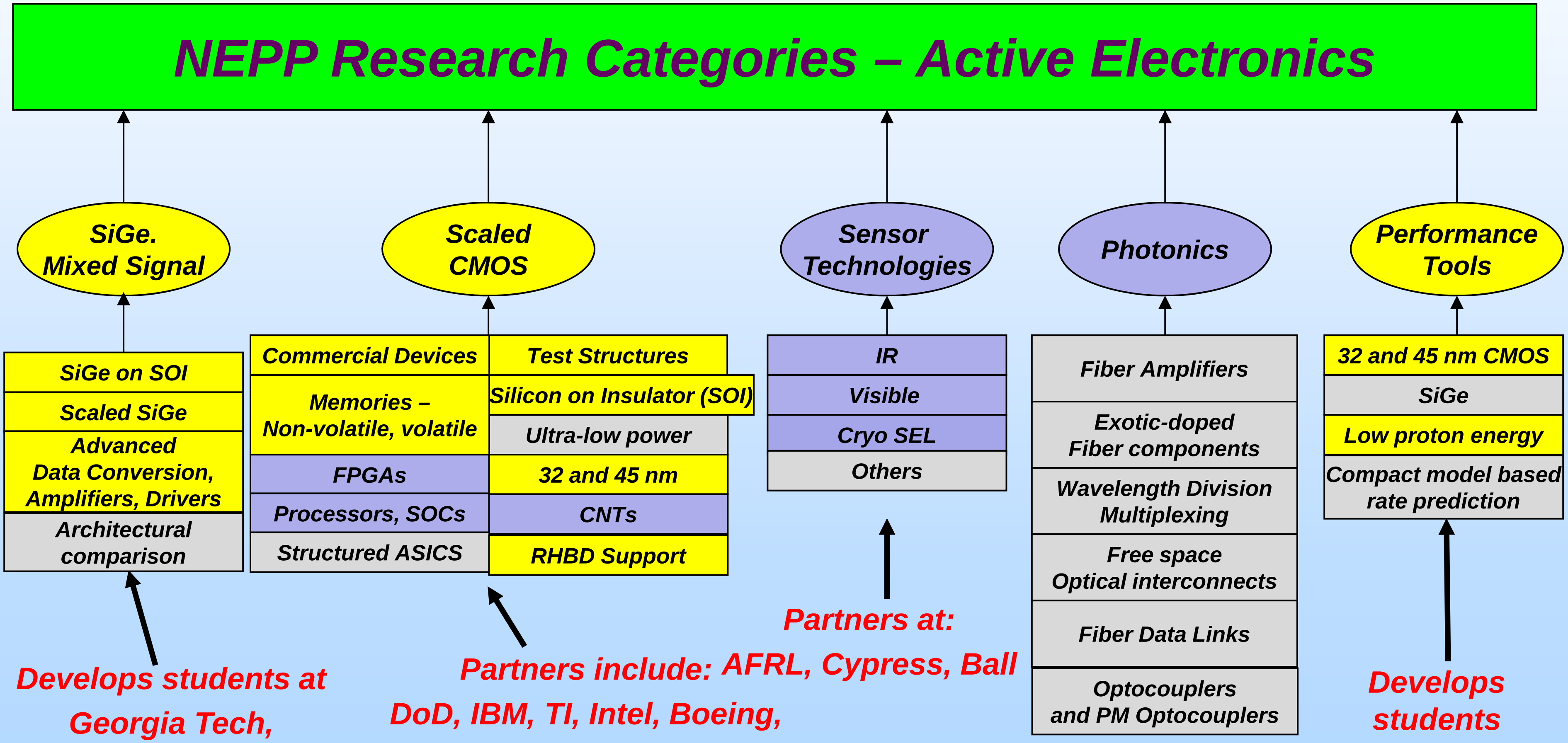
NEPAG Focus Areas

- *Failure Investigations*
  - 🟨 Investigate
  - 🟪 Assess NASA Impact
  - 🟪 Test/Analyze
  - 🟪 Corrective Action
  - 🟪 Lessons Learned
- *Specs and Standards*
  - 🟨 US MIL
  - 🟪 VCS
- *Audits*
  - 🟨 US MIL
  - 🟨 Onshore
  - ⬜ Offshore
  - 🟪 NASA SAS Database
- *Collaborations*
  - 🟨 National
  - 🟪 International
- *Parts Support*
  - 🟪 NPSL
  - 🟪 Technical Expertise Resource
  - 🟪 Bulletins
  - ⬜ Connectors
- *Consortia*
  - 🟨 CAVE
  - 🟪 CALCE

FY11 Radiation Plans for NEPP Core (1)

Core Areas are Bubbles;
Boxes underneath are variable tasks in each core

Legend
- DoD and NASA funded
- NASA-only funded
- Overguide



NEPP Research Categories – Active Electronics

SiGe. Mixed Signal
- SiGe on SOI
- Scaled SiGe
- Advanced Data Conversion, Amplifiers, Drivers
- Architectural comparison

Scaled CMOS
- Commercial Devices
- Memories – Non-volatile, volatile
- FPGAs
- Processors, SOCs
- Structured ASICS
- Test Structures
- Silicon on Insulator (SOI)
- Ultra-low power
- 32 and 45 nm
- CNTs
- RHBD Support

Sensor Technologies
- IR
- Visible
- Cryo SEL
- Others

Photonics
- Fiber Amplifiers
- Exotic-doped Fiber components
- Wavelength Division Multiplexing
- Free space Optical interconnects
- Fiber Data Links
- Optocouplers and PM Optocouplers

Performance Tools
- 32 and 45 nm CMOS
- SiGe
- Low proton energy
- Compact model based rate prediction

Develops students at Georgia Tech, Vanderbilt, Auburn

Partners include: DoD, IBM, TI, Intel, Boeing, Actel, Atmel, Xilinx, Altera, Cypress

Partners at: AFRL, Cypress, Ball

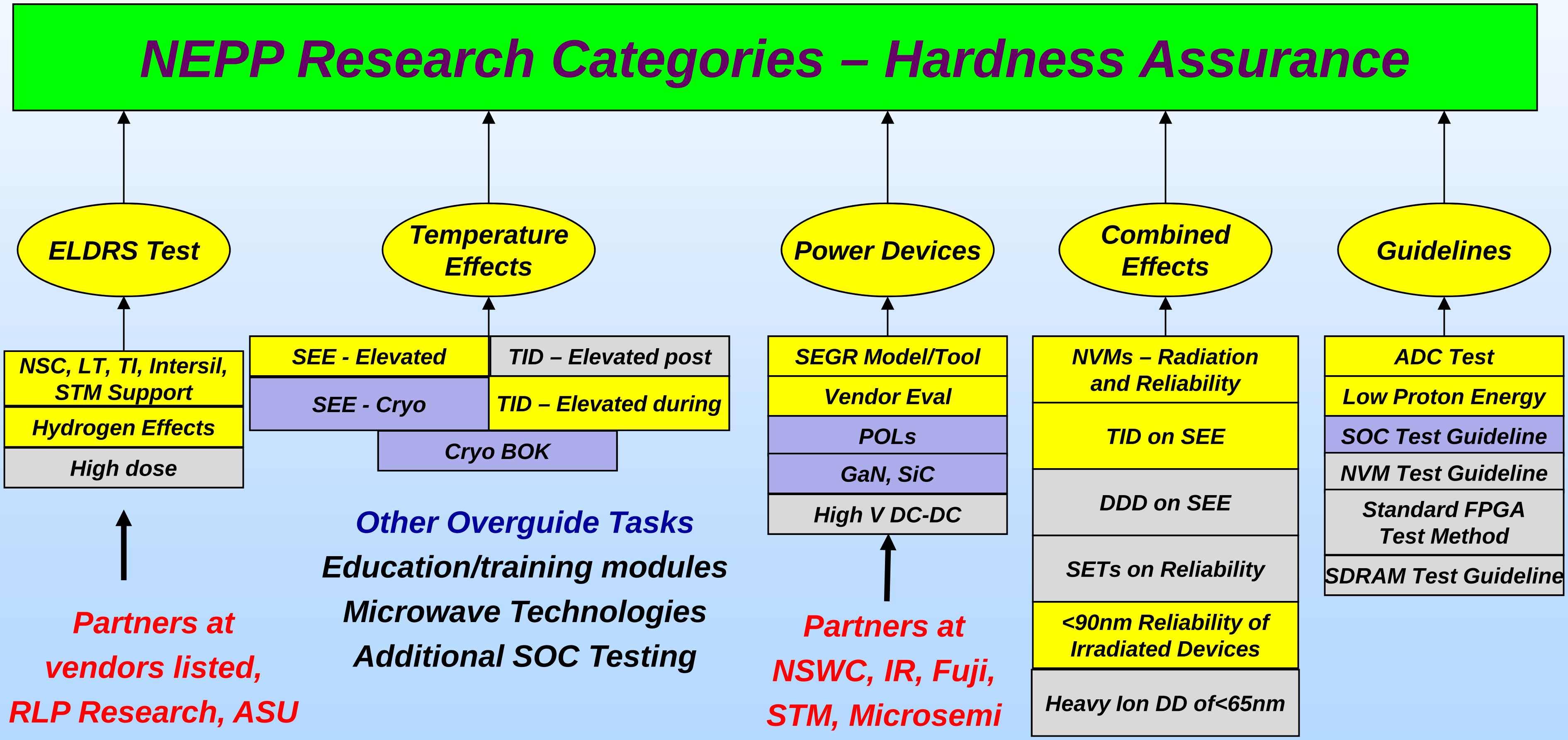
Develops students at Vanderbilt

FY11 Radiation Plans for NEPP Core (2)

Core Areas are Bubbles;
Boxes underneath are variable tasks in each core

Legend

- 🟨 DoD and NASA funded
- 🟪 NASA-only funded
- ⬜ Overguide



NEPP Research Categories – Hardness Assurance

ELDRS Test
- 🟨 NSC, LT, TI, Intersil, STM Support
- 🟨 Hydrogen Effects
- ⬜ High dose

Partners at vendors listed, RLP Research, ASU

Temperature Effects
- 🟨 SEE - Elevated
- ⬜ TID – Elevated post
- 🟪 SEE - Cryo
- 🟨 TID – Elevated during
- 🟪 Cryo BOK

Power Devices
- 🟨 SEGR Model/Tool
- 🟨 Vendor Eval
- 🟪 POLs
- 🟪 GaN, SiC
- ⬜ High V DC-DC

Partners at NSWC, IR, Fuji, STM, Microsemi

Combined Effects
- 🟨 NVMs – Radiation and Reliability
- 🟨 TID on SEE
- ⬜ DDD on SEE
- ⬜ SETs on Reliability
- 🟨 <90nm Reliability of Irradiated Devices
- ⬜ Heavy Ion DD of<65nm

Guidelines
- 🟨 ADC Test
- 🟨 Low Proton Energy
- 🟪 SOC Test Guideline
- ⬜ NVM Test Guideline
- ⬜ Standard FPGA Test Method
- ⬜ SDRAM Test Guideline

Other Overguide Tasks
Education/training modules
Microwave Technologies
Additional SOC Testing

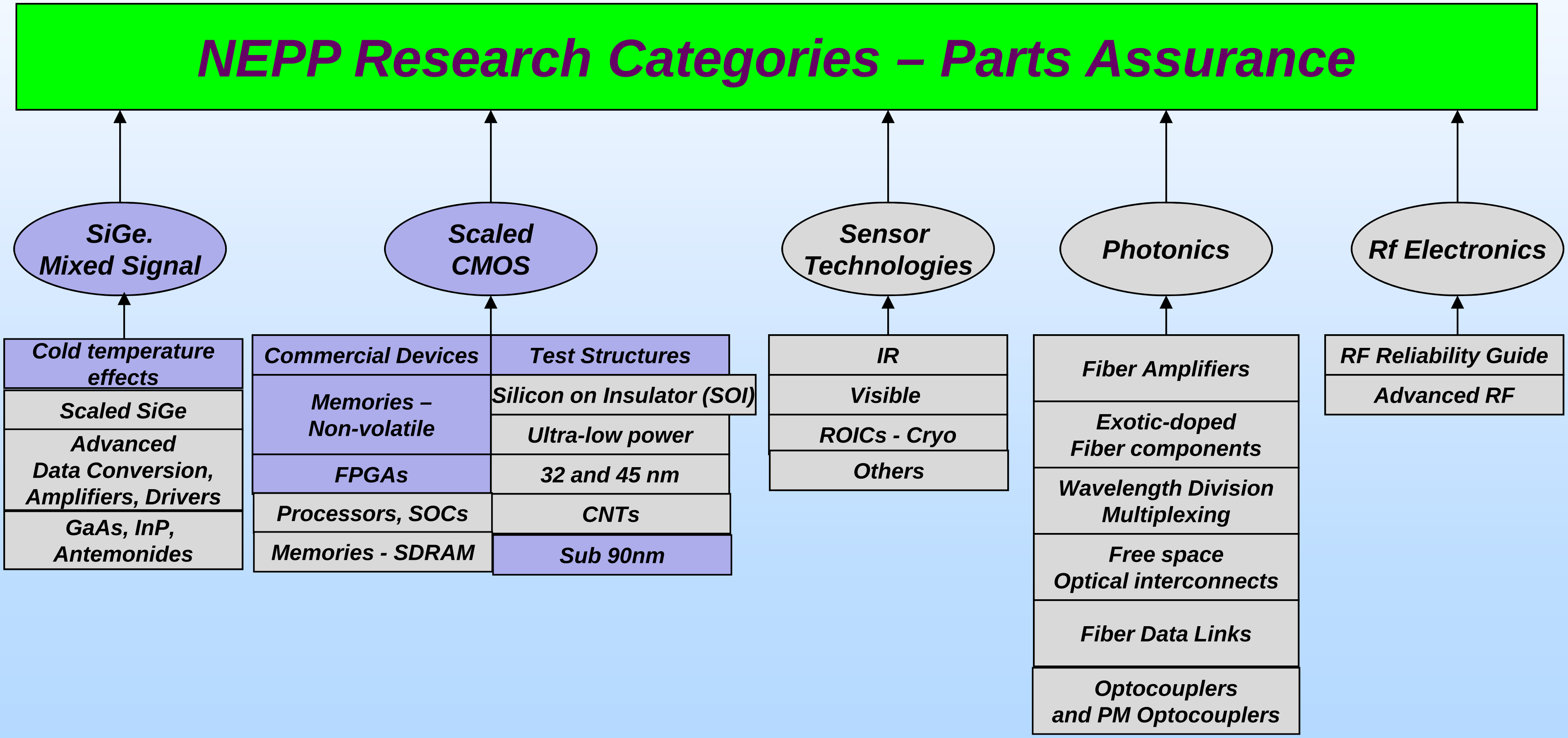
FY11 Parts Plans for NEPP Core (1)

Core Areas are Bubbles;
Boxes underneath are variable tasks in each core

Legend

NASA-only funded

Overguide



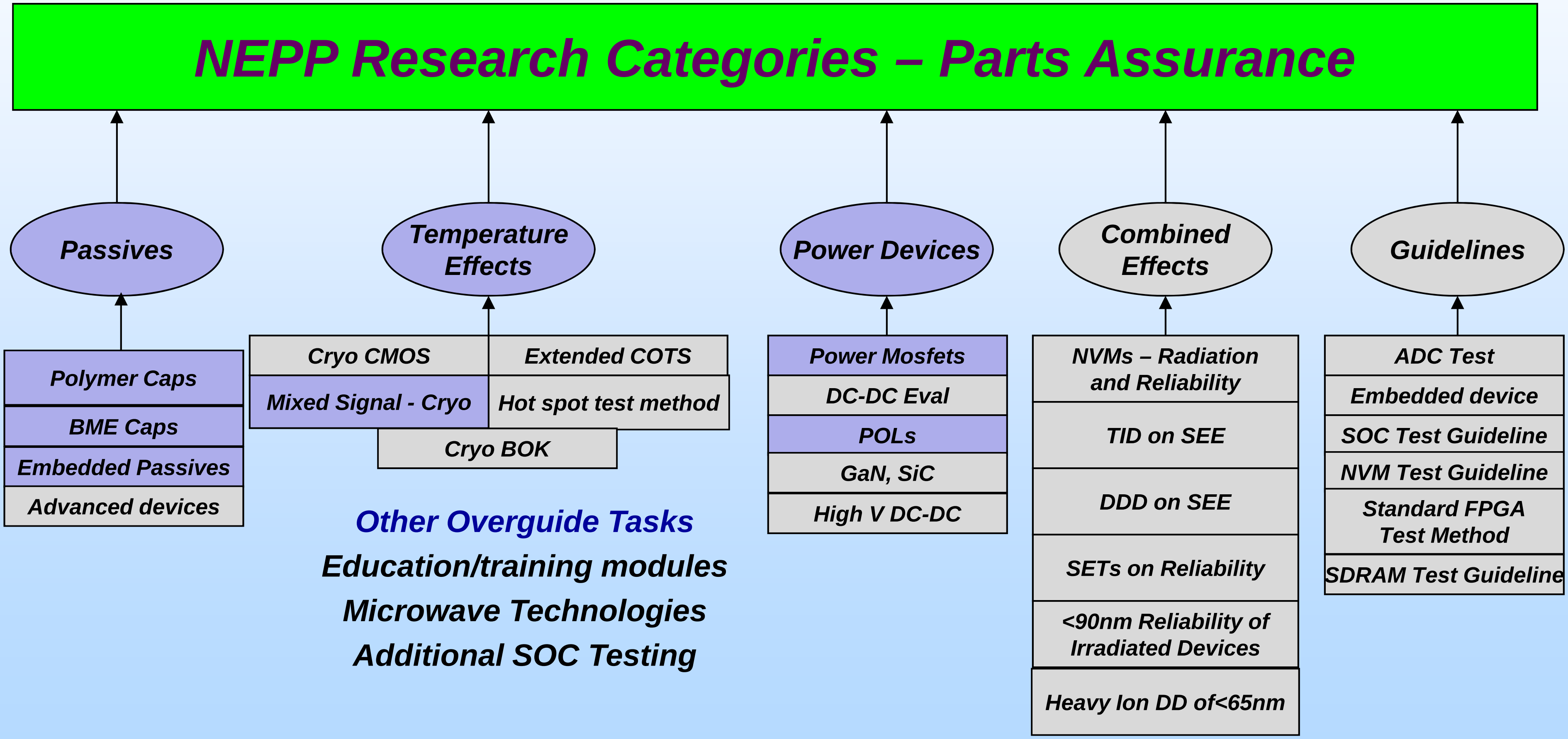
NEPP Research Categories – Parts Assurance

- **SiGe. Mixed Signal**
  - Cold temperature effects
  - Scaled SiGe
  - Advanced Data Conversion, Amplifiers, Drivers
  - GaAs, InP, Antemonides
- **Scaled CMOS**
  - Commercial Devices
  - Memories – Non-volatile
  - FPGAs
  - Processors, SOCs
  - Memories - SDRAM
  - Test Structures
  - Silicon on Insulator (SOI)
  - Ultra-low power
  - 32 and 45 nm
  - CNTs
  - Sub 90nm
- **Sensor Technologies**
  - IR
  - Visible
  - ROICs - Cryo
  - Others
- **Photonics**
  - Fiber Amplifiers
  - Exotic-doped Fiber components
  - Wavelength Division Multiplexing
  - Free space Optical interconnects
  - Fiber Data Links
  - Optocouplers and PM Optocouplers
- **Rf Electronics**
  - RF Reliability Guide
  - Advanced RF

FY11 Parts Plans for NEPP Core (2)

Core Areas are Bubbles;
Boxes underneath are variable tasks in each core

Legend
- NASA-only funded
- Overguide



NEPP Research Categories – Parts Assurance

Passives
- Polymer Caps
- BME Caps
- Embedded Passives
- Advanced devices

Temperature Effects
- Cryo CMOS
- Extended COTS
- Mixed Signal - Cryo
- Hot spot test method
- Cryo BOK

Power Devices
- Power Mosfets
- DC-DC Eval
- POLs
- GaN, SiC
- High V DC-DC

Combined Effects
- NVMs – Radiation and Reliability
- TID on SEE
- DDD on SEE
- SETs on Reliability
- <90nm Reliability of Irradiated Devices
- Heavy Ion DD of<65nm

Guidelines
- ADC Test
- Embedded device
- SOC Test Guideline
- NVM Test Guideline
- Standard FPGA Test Method
- SDRAM Test Guideline

Other Overguide Tasks

Education/training modules

Microwave Technologies

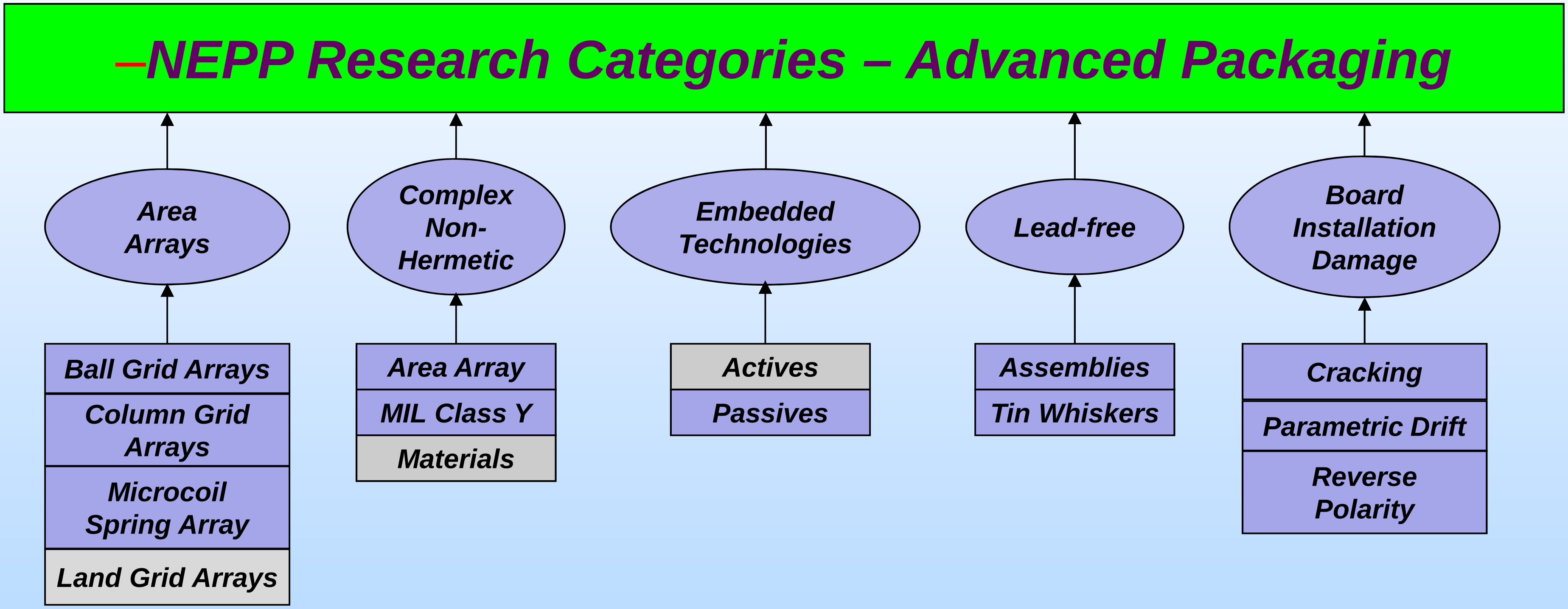
Additional SOC Testing

Core Element - Packaging

Core Areas are Bubbles;
Boxes underneath are variable tasks in each core

Legend

NASA-only funded
Overvguide



–NEPP Research Categories – Advanced Packaging

- Area Arrays
  - Ball Grid Arrays
  - Column Grid Arrays
  - Microcoil Spring Array
  - Land Grid Arrays
- Complex Non-Hermetic
  - Area Array
  - MIL Class Y
  - Materials
- Embedded Technologies
  - Actives
  - Passives
- Lead-free
  - Assemblies
  - Tin Whiskers
- Board Installation Damage
  - Cracking
  - Parametric Drift
  - Reverse Polarity

Samples of NEPP Impact to the Community (1 of 2)

NASA Flight Projects and some of the related areas that NEPP has provided a knowledge-base that has allowed anomaly/problem resolution

- MAP
  - Single Event Transients (SETs) – anomaly resolution led to NASA alert
- TERRA
  - Optocouplers, Solid State Recorders (SSR), High Gain Antenna anomaly
- AURA
  - Oscillators
- AQUA
  - Interpoint DC-DC converters
- TRMM, XTE
  - SSRs, FODBs
- TOPEX/Poseidon
  - Optocouplers
- SeaStar
  - SSRs
- Launch Vehicles
  - Optocouplers
- Suborbital
  - Parts screening
- Hubble Space Telescope
  - Optocouplers, Capacitors, SSRs, Fiber Optic Data Bus (FODB)
- Hubble Robotic Servicing
  - Processors
- JWST
  - Detector technologies
- Cassini
  - Interpoint DC-DC converters, optocouplers, processors
- AXAF/Chandra
  - Optics
- SWIFT
  - ACTEL FPGAs
- MER
  - ELDRS, Processors, Memories, Packaging
- ISS
  - Fiber optics, wire/cable
- Shuttle
  - ACTEL FPGAs, capacitors

Samples of NEPP Impact to the Community (2 of 2)

NEPP has supported DoD and other government anomaly/problem issues, technology developments, as well as joint knowledge-base development that have import to the NASA community

In addition, NEPP has worked with industry to develop improved products for spaceflight

- Government partners
  - DoD
    - USD(AT&L)
    - Defense Threat Reduction Agency (DTRA)
    - Air Force Research Laboratory (AFRL)
    - Air Force Space and Missile Command (AFSMC)
    - Missile Defense Agency (MDA)
    - Defense Advanced Research Projects Agency (DARPA)
    - NAVSEA
    - NAVAIR
    - Naval Research Laboratory
    - US Army Strategic and Missile Defense Command (USASMDC)
    - OGA
  - DOE
    - Sandia National Laboratories
    - Lawrence Livermore National Laboratories
    - Brookhaven National Laboratories
  - NSF
    - National Superconducting Cyclotron Laboratory
  - ESA
  - JAXA
  - CNES
  - Qinetiq (UK)

- Industry partners
  - Actel
  - Lambda/International Rectifier
  - Interpoint
  - Vishay
  - Presidio
  - BAE Systems
  - Honeywell
  - Aeroflex
  - Intersil
  - Xilinx
  - IBM
  - Freescale (formerly Motorola)
  - Cardinal
  - LSI Logic
  - Ball Aerospace
  - Micro RDC, many others

QUESTIONS?