Utilization of Advanced Microelectronics in Space Applications

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JPL

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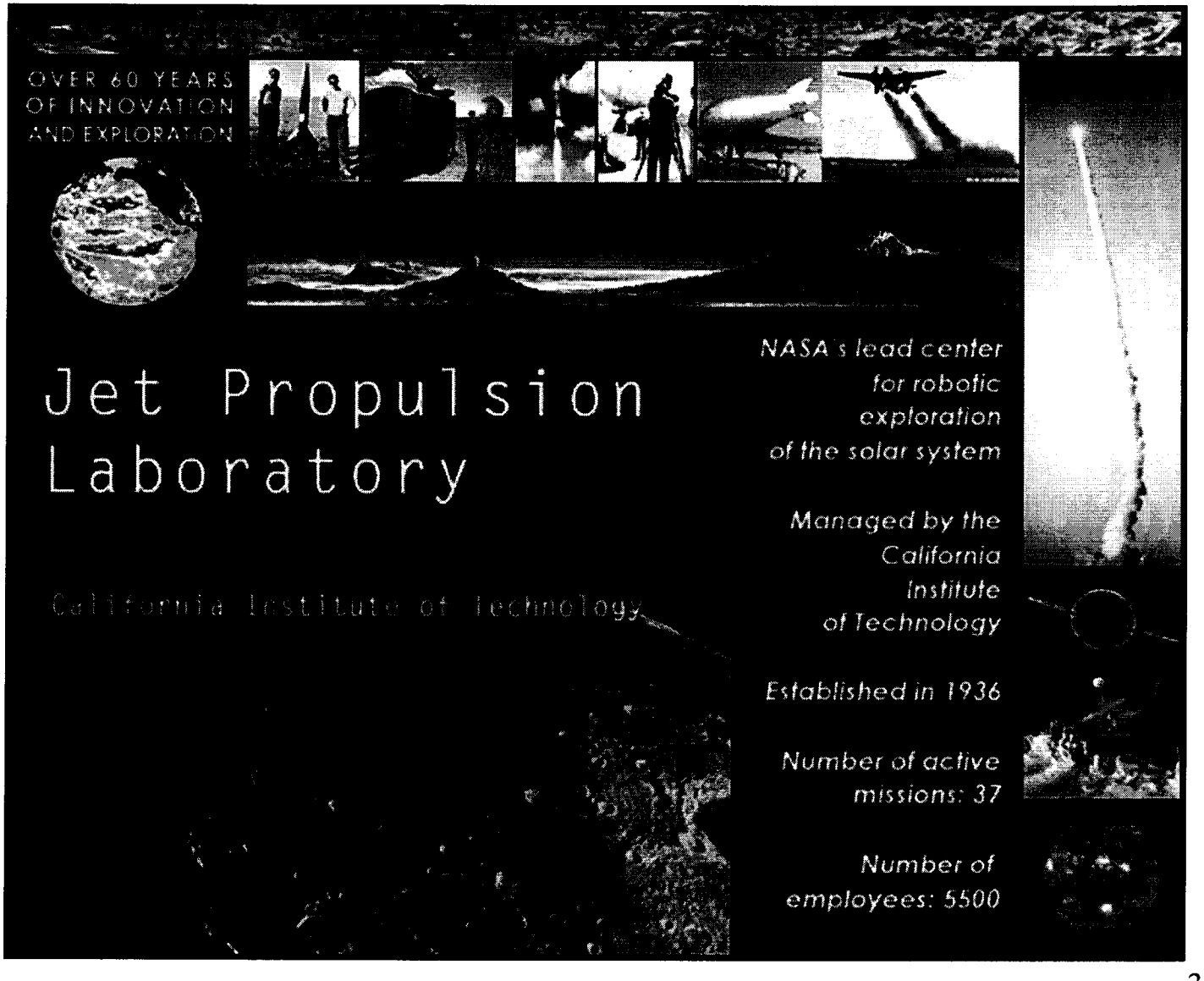
NASA

Outline

- About JPL
- Industry Trends & Challenges
- Environments and Reliability
- Trends at JPL
- Parts Evaluation Practices at JPL
- Considerations for Radiation Effects
- Conclusions

About JPL


OVER 60 YEARS
OF INNOVATION
AND EXPLORATION
Jet Propulsion Laboratory
California Institute of Technology
NASA's lead center for robotic exploration of the solar system
Managed by the California Institute of Technology
Established in 1936
Number of active missions: 37
Number of employees: 5500

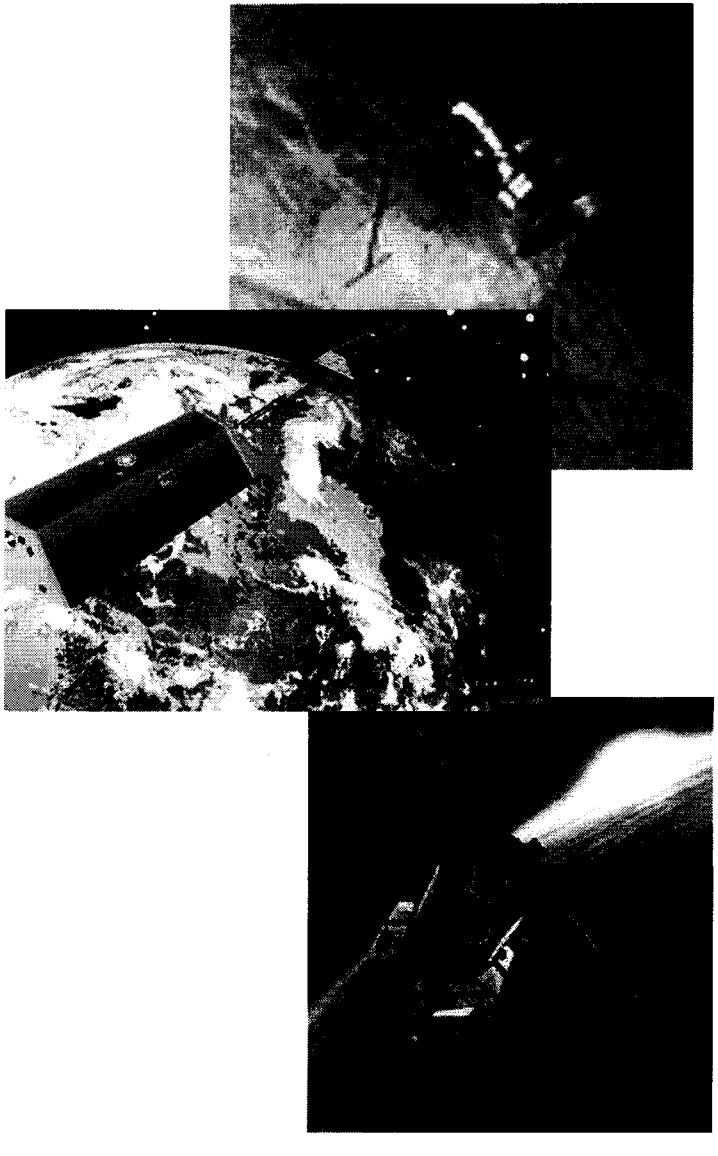
JPL Electronic Parts Engineering

JPL is the Lead NASA Center for Microelectronics Reliability and Radiation Effects

- 85 Researchers & Engineers
  - Reliability and Radiation Effects Testing, Analysis and Research
  - Selection, Evaluation, Test, and Characterization
  - Operate and Maintain the
    - Radiation Effects Laboratories
    - Reliability & Failure Analysis Laboratories
  - Failure Investigation and Analyses

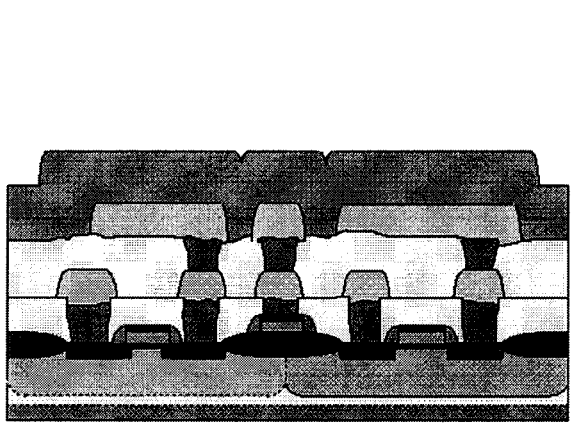
Introduction

- Utilization of advanced microelectronics and COTS in high reliability space systems presents substantial benefits.
  - Enhanced performance & functionality
  - Miniaturization
  - Lower power consumption
- It is critical that all aspects of reliability and relevant known failure modes and mechanisms be addressed prior to the insertion of the component in the application
- Question. How to determine the suitability of a specific COTS or advanced microelectronics product to space application?



Industry Trends

- Smaller Feature Size
  - Requires higher resolution analysis and sample prep equipment
  - Increased sensitivity to radiation effects
- More complex devices
  - Require improved and faster tester capability
- Fewer providers of Hi-Rel components
  - Necessitates increased use of COTS
  - Shift in emphasis from device specification to device analysis
- Accelerating technology development trend
  - Increased performance gap between State-of-the-Art and Hi-Rel suppliers
  - Faster introduction of new device technologies

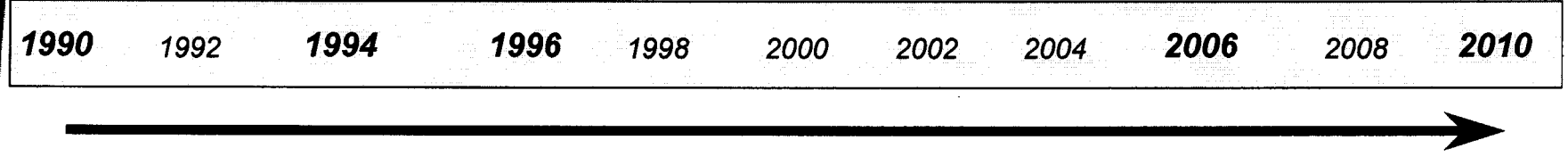


1.0µm
Yesterday

Today

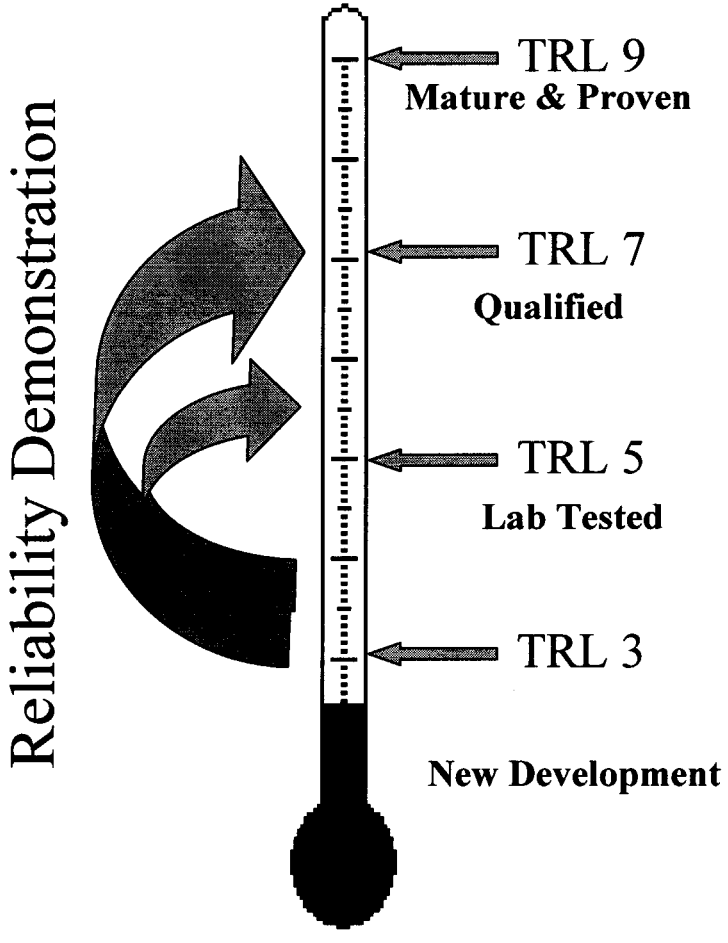
Pace of Technology Evolution

Stable Scaling	*Initial Change*	*Period of Rapid Change*	*Into the Unknown*
3 years per generation Yield & reliability improving	2 years per generation Yield & reliability flat ***Feature Size: 0.25μ***	Clusters of changes < 2 years per generation Technology Breakthroughs Generations that are not fully characterized Widening gap between manufacturing technology and reliability & F.A. tools ***Feature Size: 0.10μ***	Multiple problems with no known solutions



Challenges for Technology Insertion

- Technology Maturity
- Existing Mindset
  - Risk Avoidance vs. Risk Management
- Manufacturing & Produceability
  - Research Laboratory Environment
  - Limited Production
- Reliability Verification
  - New Failure Mechanisms
  - Statistical Meaning
- Environmental Challenges
  - Radiation
  - Thermal
  - Vibration



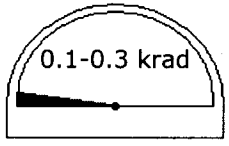
Technology Readiness Levels

Planetary Environments

Earth Orbiter

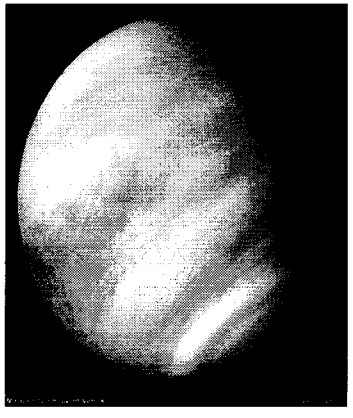
0 °C — 50 °C

TID



LEO: 1-3 yrs
(500-1500 cycles)

GEO: 10-15 yrs
(3500-5500 cycles)

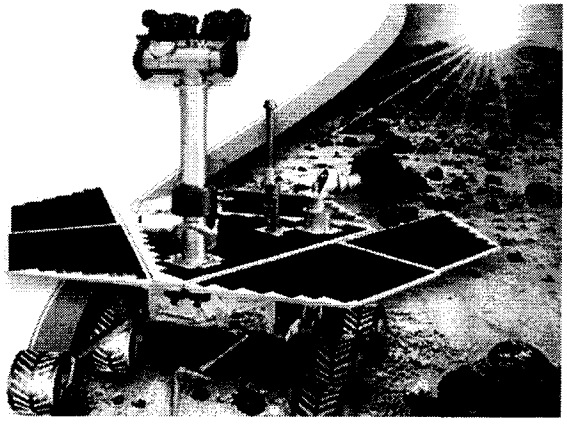


Venus

+470 °C

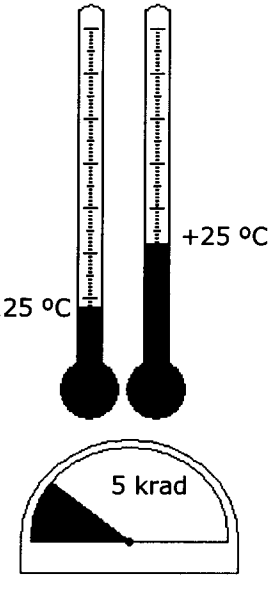
TID ~7 krad

Lifetime: ~1 hr
(on surface)



Mars Surface

−125 °C — +25 °C



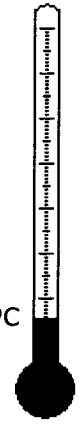
Lifetime: 90 days

Europa

TID ~7 Mrad

Lifetime: min/hrs
(on surface)

−145 °C



Reliability Prediction

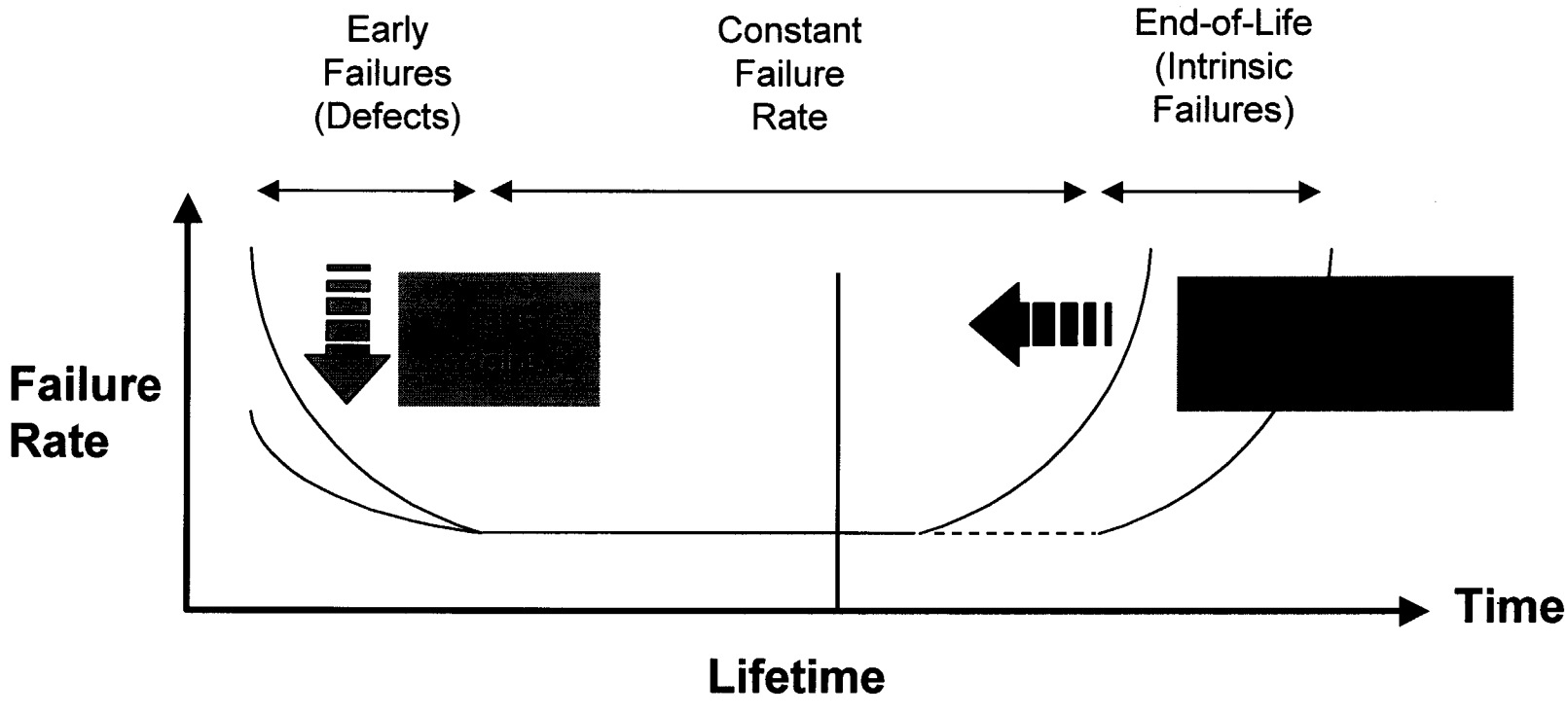
"The <u>Probability</u> that an item Will Perform a <u>Required Function</u> Under Stated Conditions for a Stated Period of <u>Time</u>"

- Probability: Described by Statistical Distribution with Average Parameter and Failure Rate
- Required Function: Defines Failure When Product No Longer Performs Function
- Time: Standard Unit of Measure (Seconds, Revolutions, etc.)

$$\mathbf{R = A \exp (-E_a/KT)}$$

- R = Rate of the Process
- A = Proportional Multiplier
- E_a = Activation Energy, a Constant
- K = Boltzman's Constant (8.6×10^{-5} eV/K)

Reliability Expectations

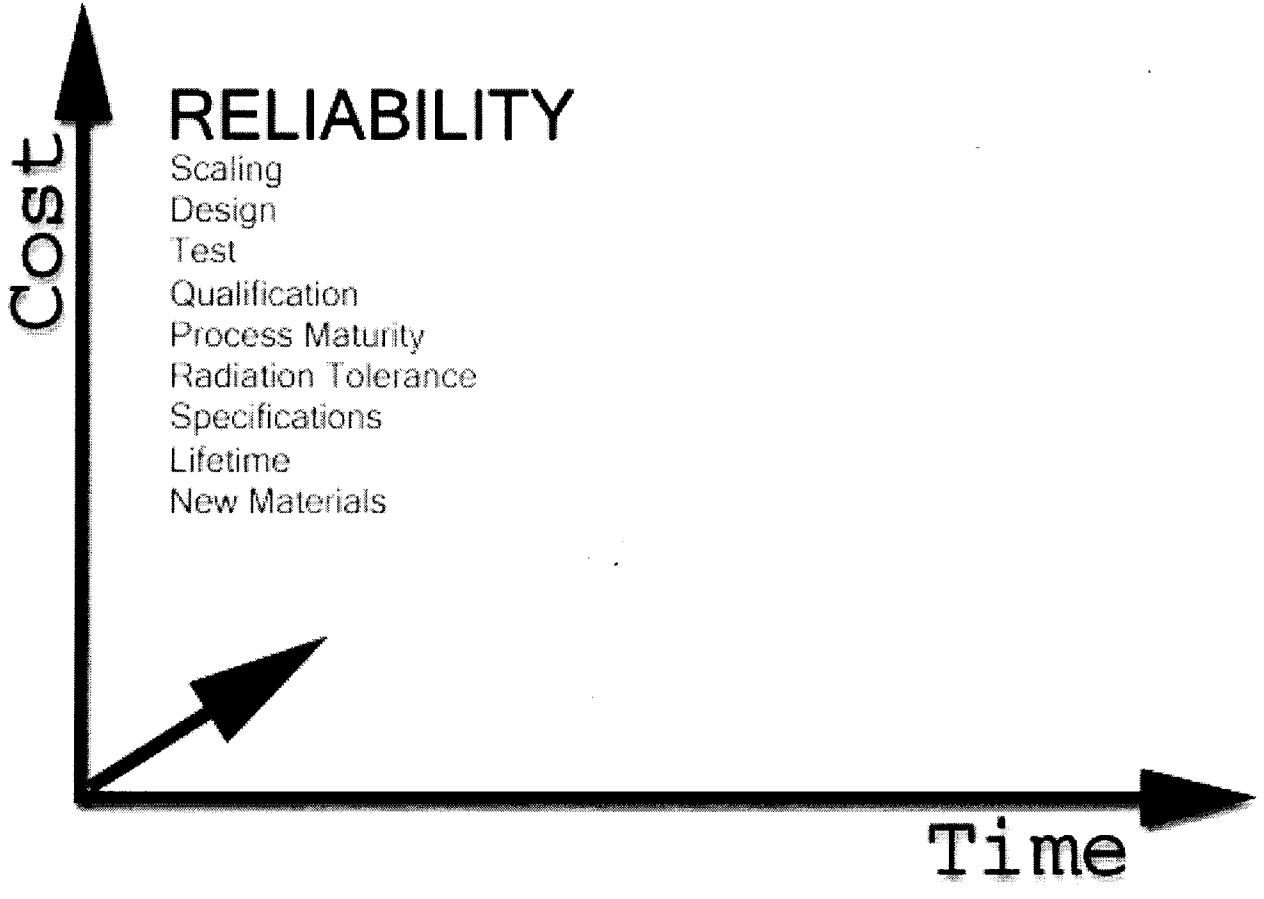


First introduction of new technologies typically suffers from higher early failure rates.

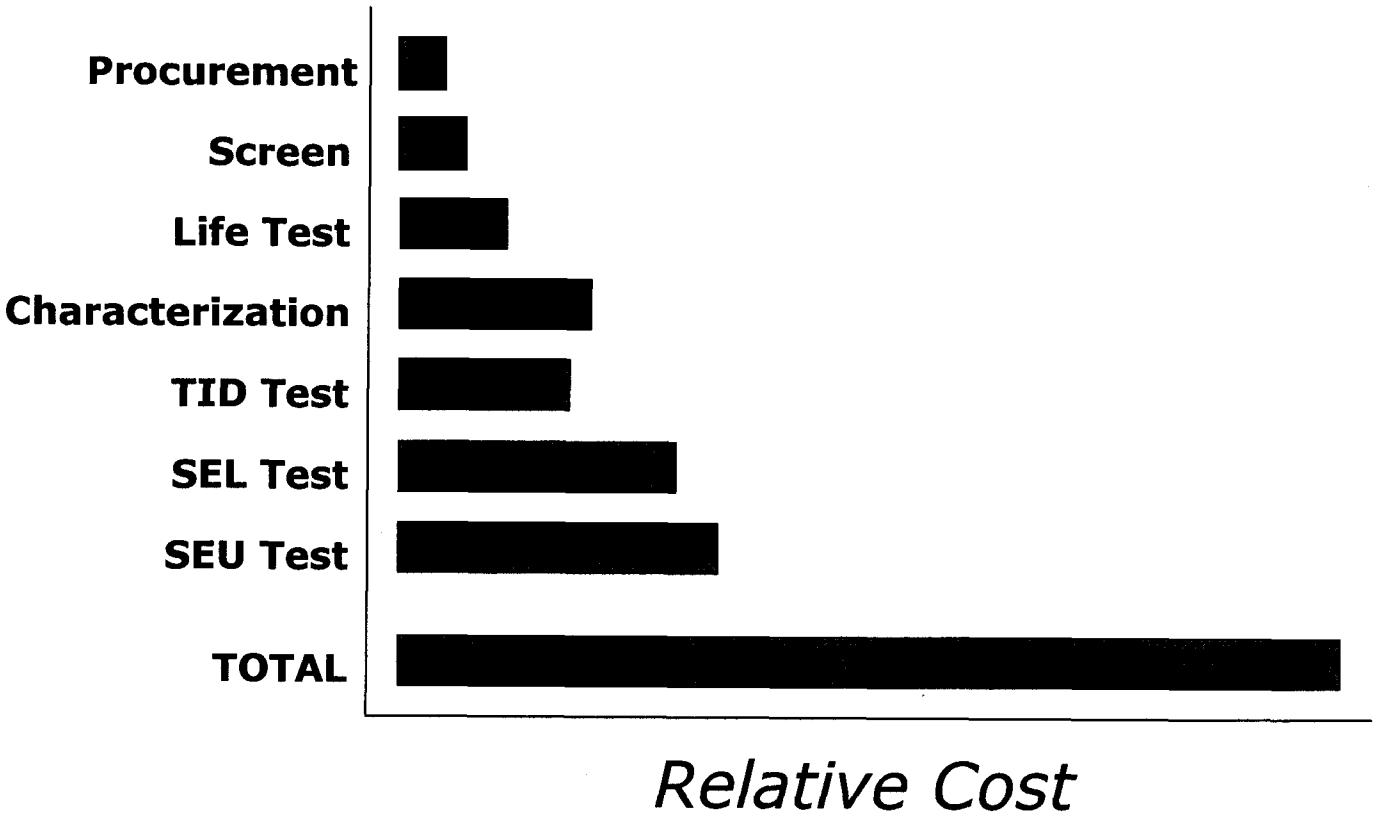
Process enhancements increase the dominance of intrinsic failure mechanisms

Reliability Impact

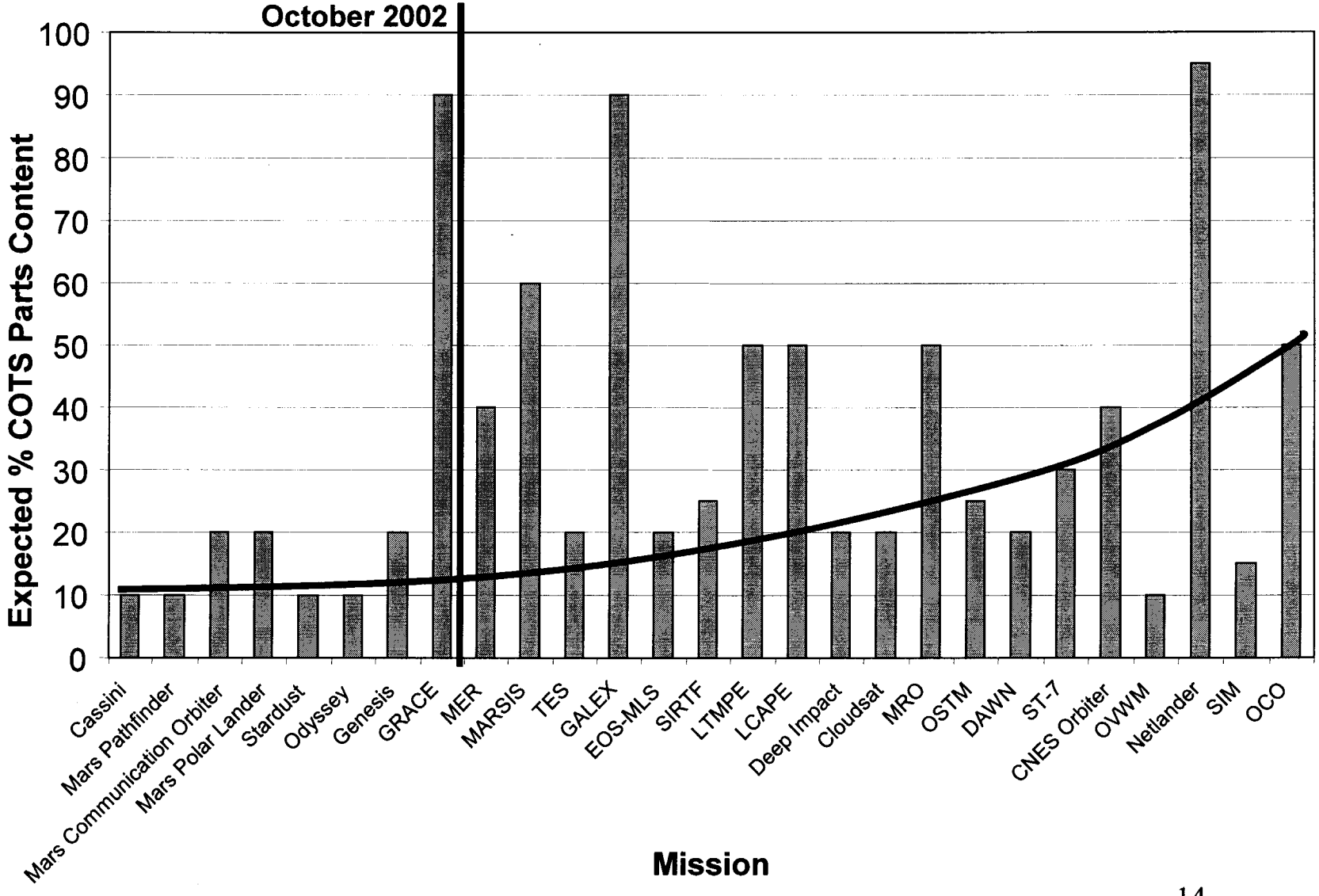
Reliability Dependencies and Impact to Cost



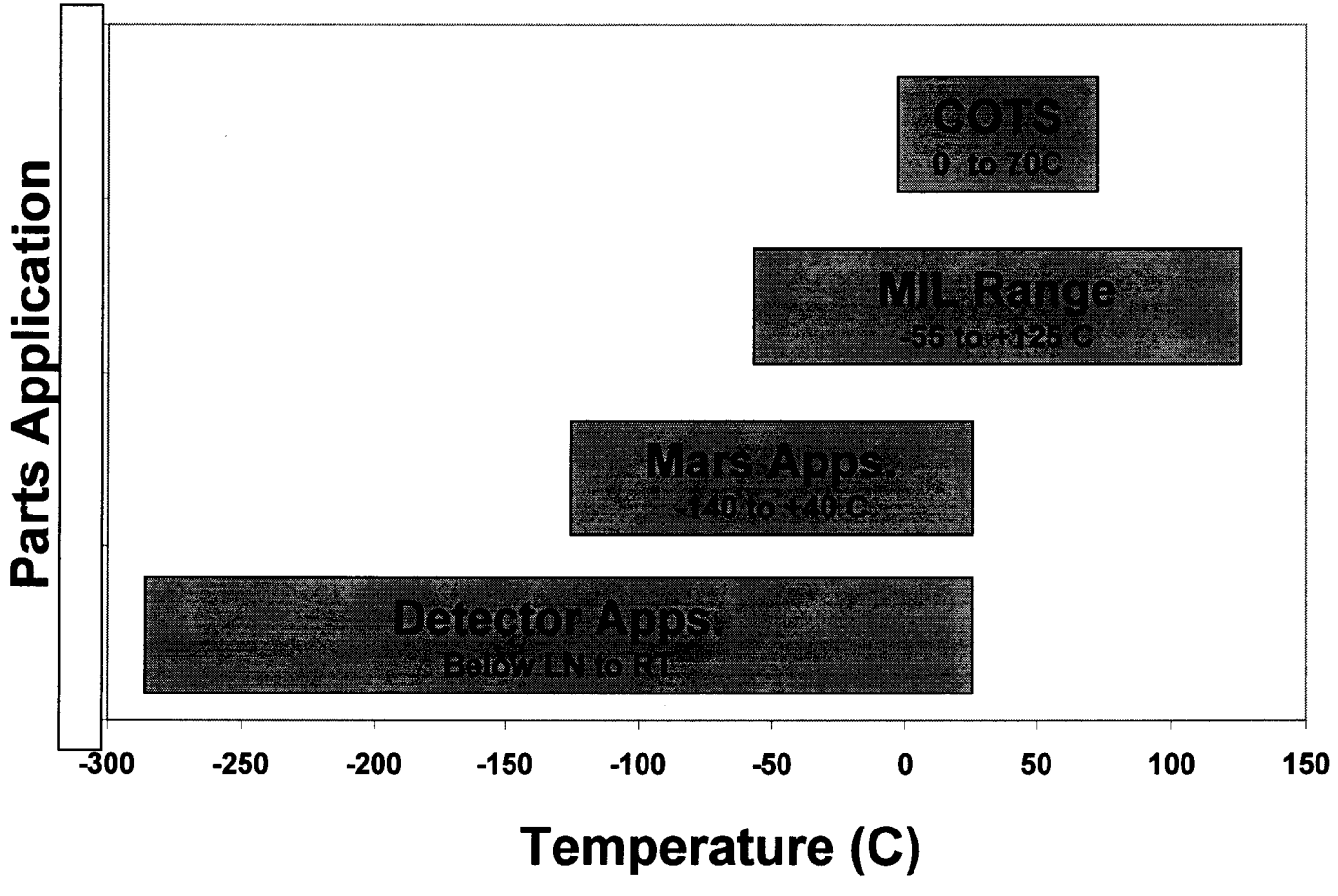
COTS Insertion Cost



COTS Utilization Trend at JPL

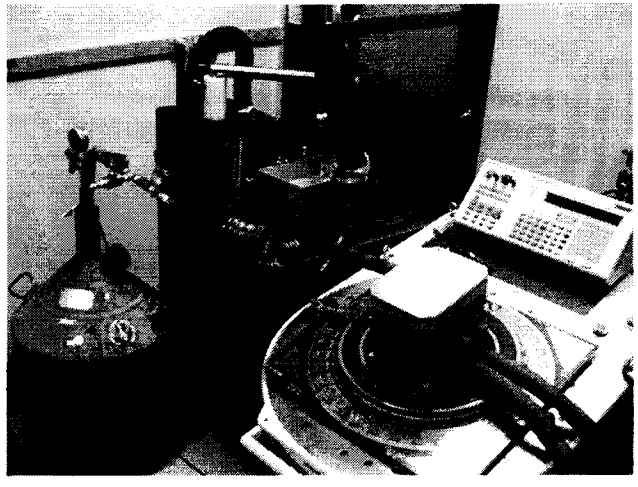


Parts Temperature Application Range

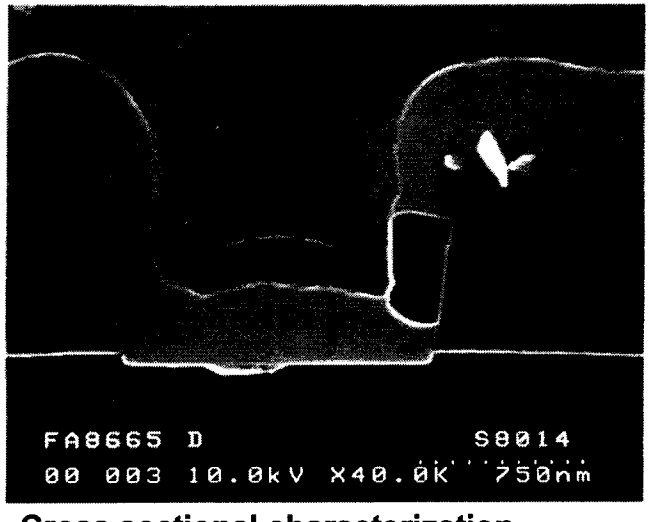


COTS Evaluation Practices at JPL

- Detailed investigation & analysis of specific COTS vendor processes and reliability practices
- Establish a working relationship with vendors at the engineering & management levels
- Develop suitable COTS product test and evaluation plans
- Perform characterization of COTS products under relevant environments
- Utilize established JPL COTS test and acceptance criteria



COTS characterization at intended application temperature

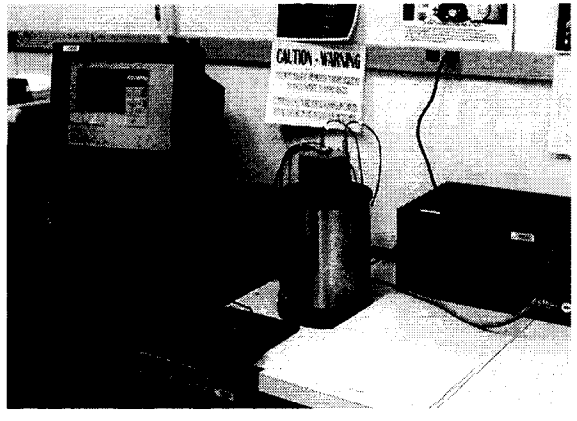


Cross sectional characterization showing void

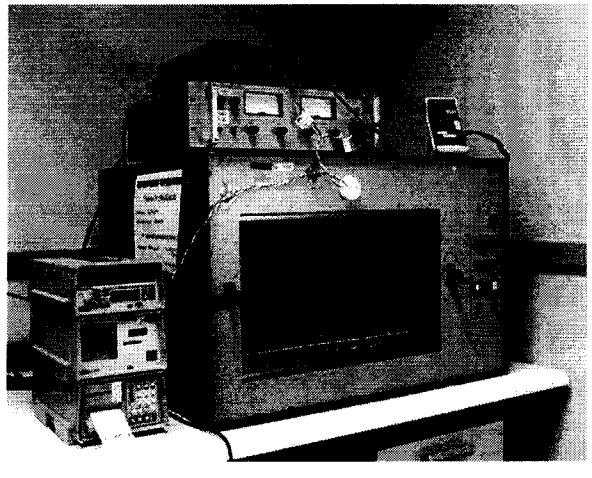
Special Environments

- **Special Tests and characterization may be necessary to determine suitability of the selected COTS components to the intended space application**

- **Three main environmental conditions must be considered:**
  - **Thermal Environment**
    - Operation at thermal condition beyond those experienced in normal operation on earth
  - **Mechanical shock environment**
    - Ability to withstand expected launch or acceleration environment
    - Utilize existing analytical and experimental techniques
  - **Radiation Environment**
    - Characterization of radiation tolerance under the intended application



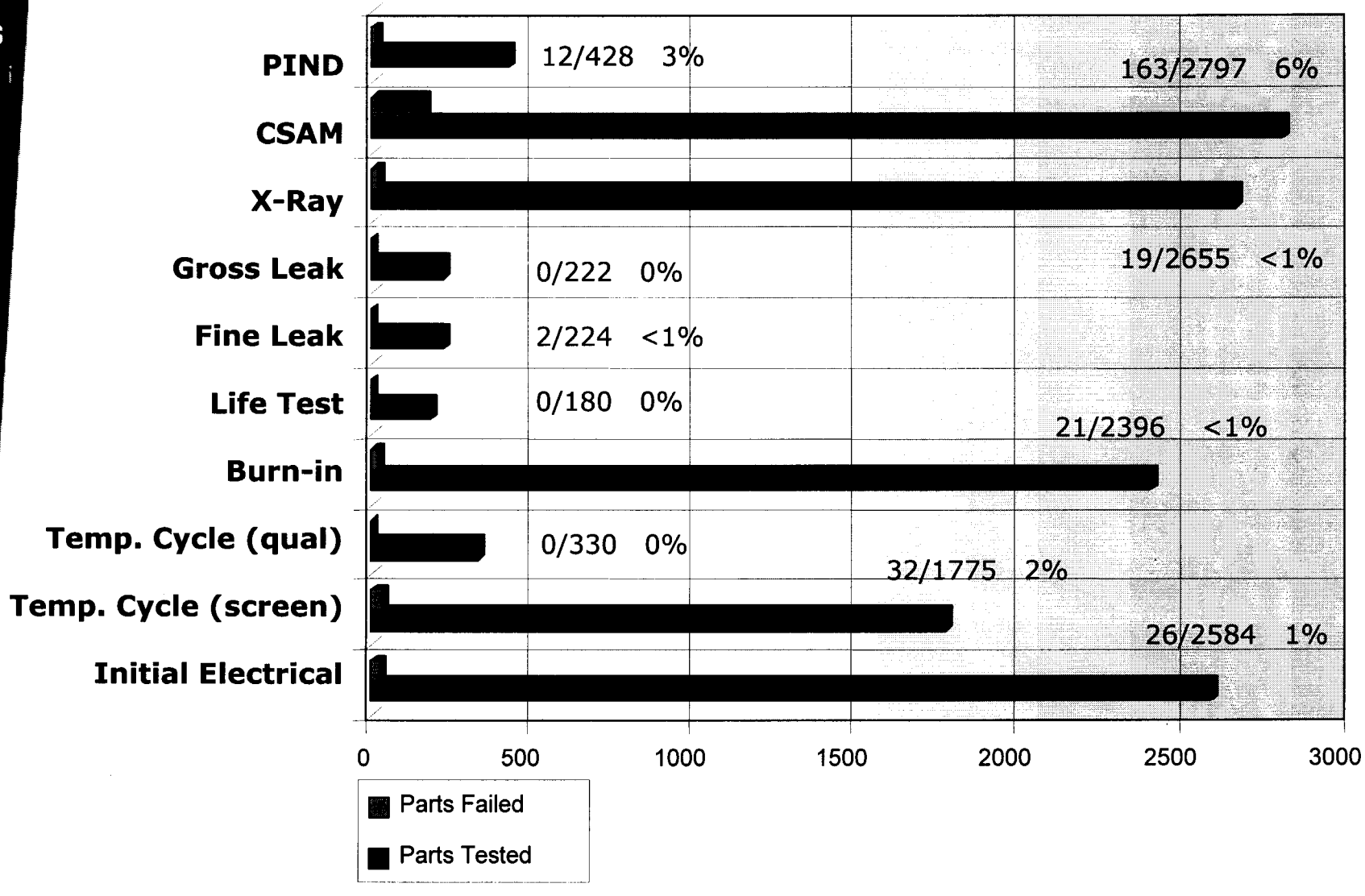
Vibration Test & Characterization



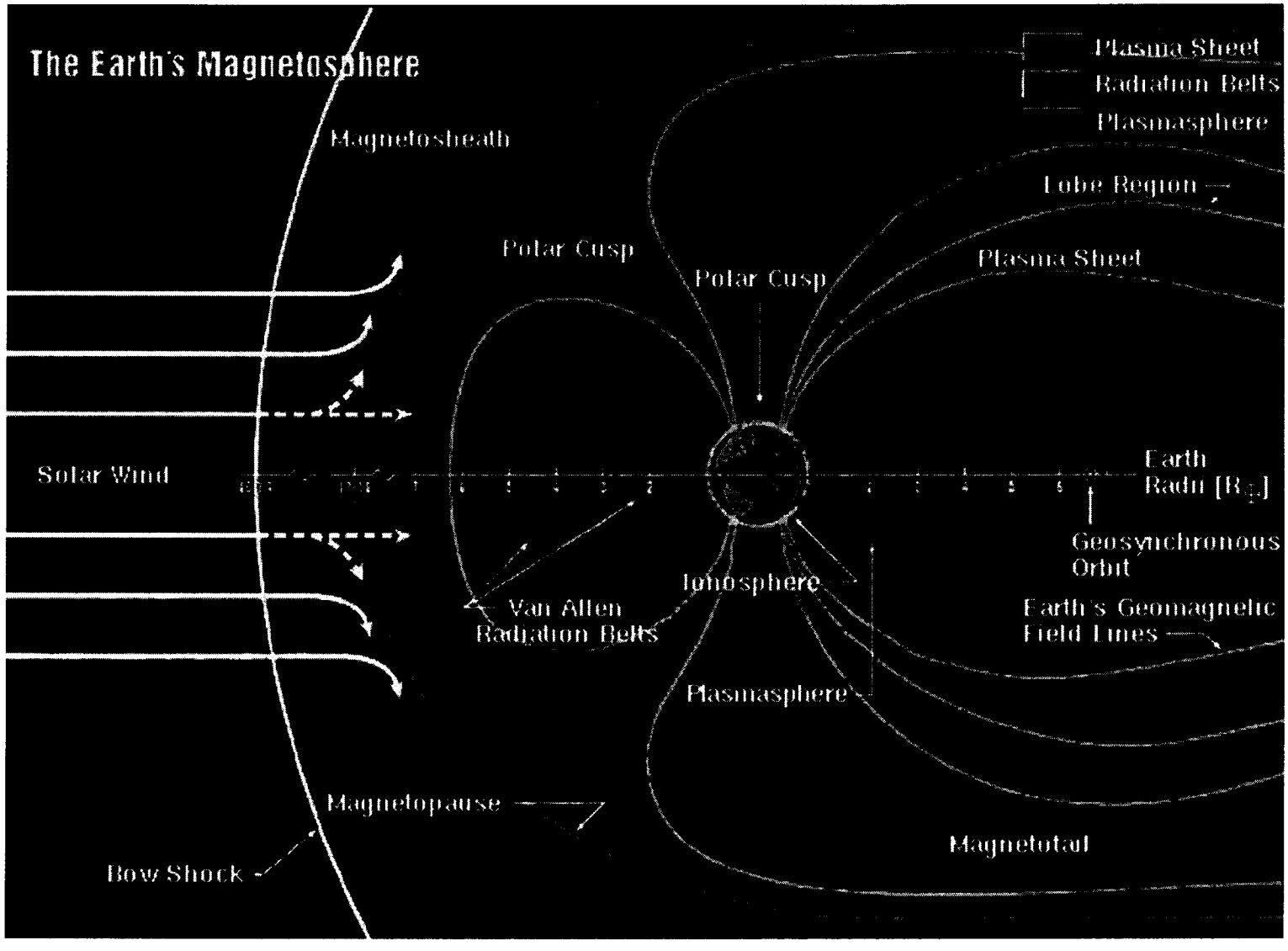
Thermal Characterization

Sammy Kayali
NASA/JPL

COTS Evaluation Results

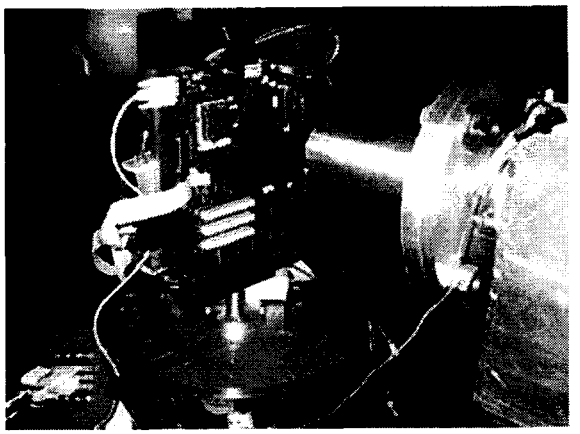


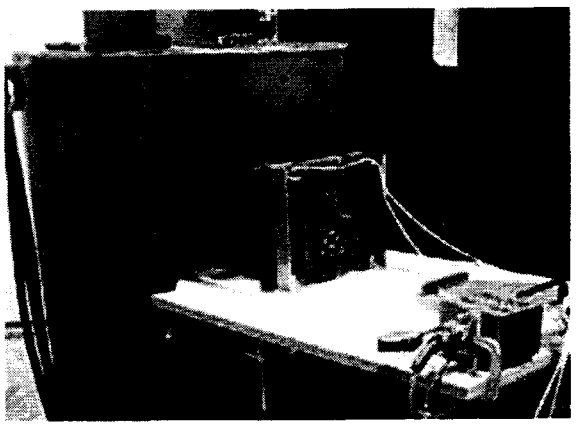
Radiation Considerations



Radiation Considerations

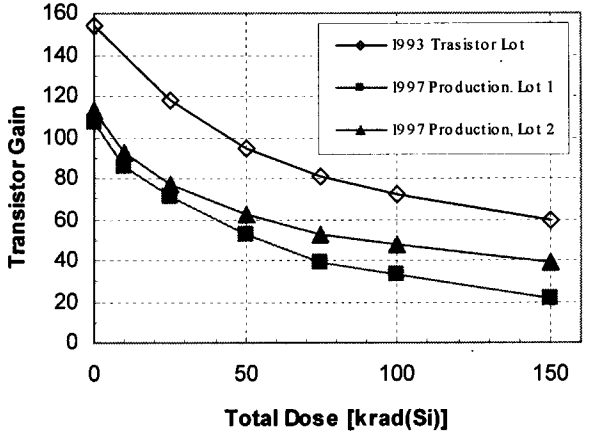
- **Radiation Effects are the most dominant discriminator in the selection and insertion of commercial or advanced microelectronics in high reliability space system**
- **Total Ionizing Dose Effects may be addressed with additional shielding or improved packaging techniques**
- **Single Event Effects can have a more detrimental impact on system reliability and survivability.**
  - **Single Event Latchup – Circuit Mitigation**
  - **Single Event Upset – System Management**
  - **Single Event gate Rupture – Design Precautions**



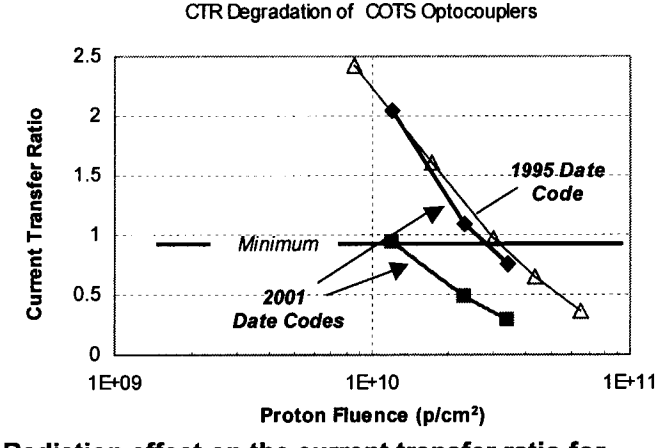


Radiation Characterization

- **COTS devices are not designed to withstand the radiation environment of space**
- **Small process changes may result in serious performance impact under a space radiation environment**
- **The lot variability of COTS devices necessitates characterization of every "lot" to assess suitability for the intended mission**
- **Standard practices at JPL require all parts to be evaluated for radiation effects, Total Ionizing Dose, Single Event Effects and Displacement Damage.**



Lot variations as evident in degradation of the transistor gain for JANTX2222A from 3 different lots.



Radiation effect on the current transfer ratio for 4N49-type optocoupler from 2 different date codes.

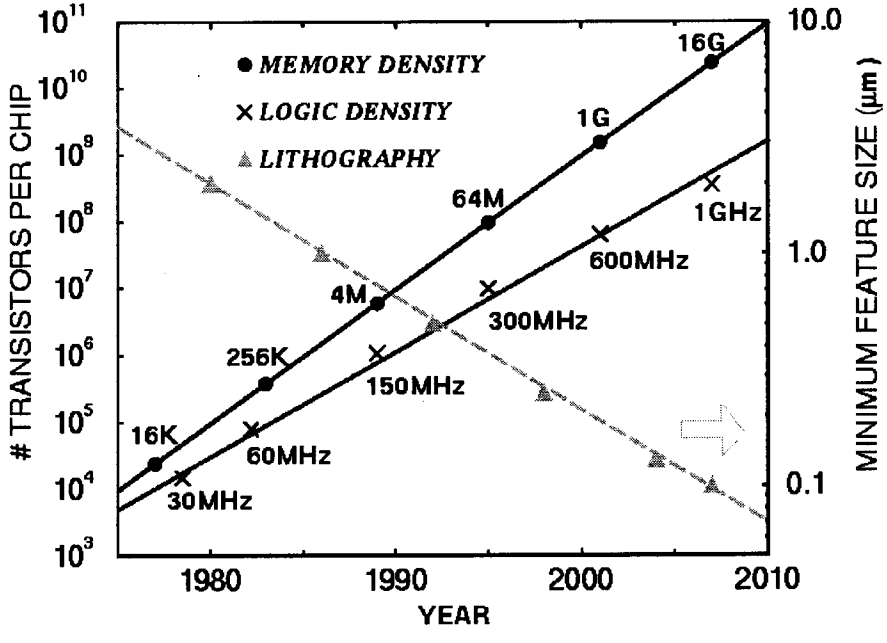
Conclusions

- **Utilization of COTS and advanced microelectronic technologies in space applications is essential to achieving future system performance goals**
- **There is a pronounced increase in the utilization of COTS components in high reliability space applications**
- **Characterization of the technology is critical to determining suitability to the intended application**
- **One of the most difficult obstacles for wider utilization of COTS components in space systems in the large variability in response to the effects of radiation**
- **The space application market is too small to attract the necessary investments to impact the desired improvements in reliability documentation.**

Back up Slides

Unprecedented Change

- Continued Shrinkage of Feature Size
- Higher Packing Density
- Improved Performance
- Faster Circuits
- Lower Power Dissipation
- Dramatic Reduction in Cost Per Function
- Current trends exceed Moors Law predictions



Issues in Silicon

<u>Ultra-Shallow Junctions</u>

Resistive contacts

Junction spiking

<u>*Gate Electrode*</u>

Band bending

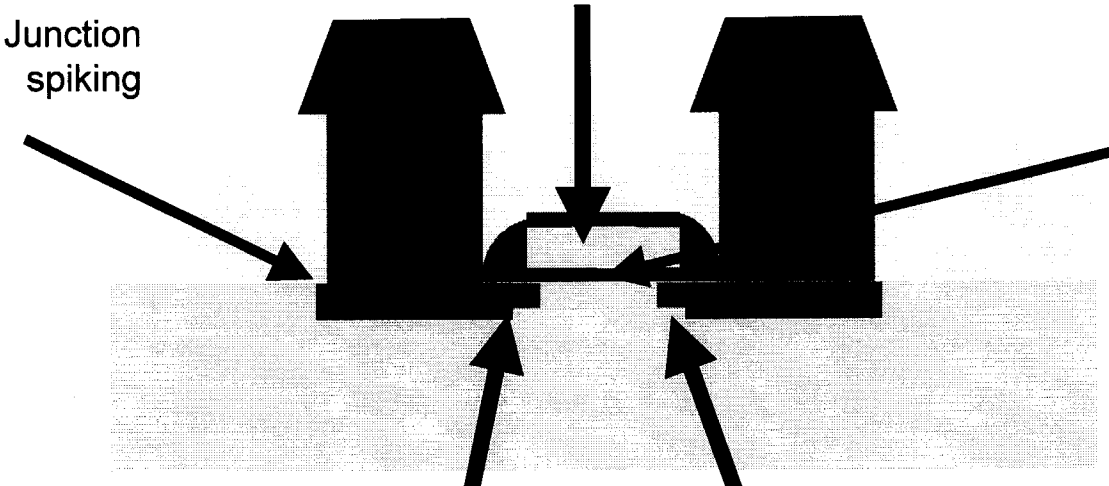
B penetration (p channel)

<u>Ultra-thin Gate Insulator</u>

Direct tunneling gate currents

Surface defects

Stress induced leakage currents



Sub-threshold leakage

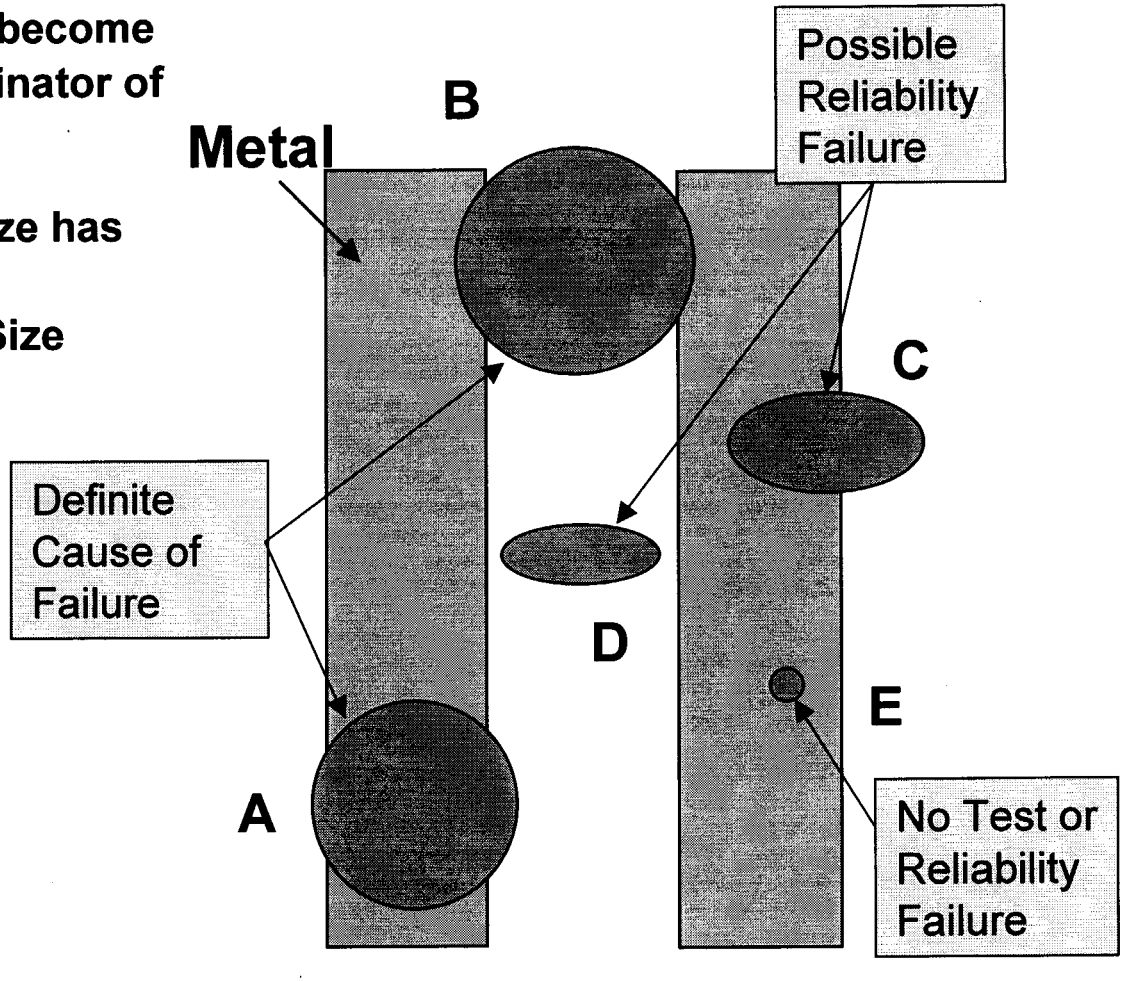
Punch through

Drain induced barrier lowering

V_{th} control

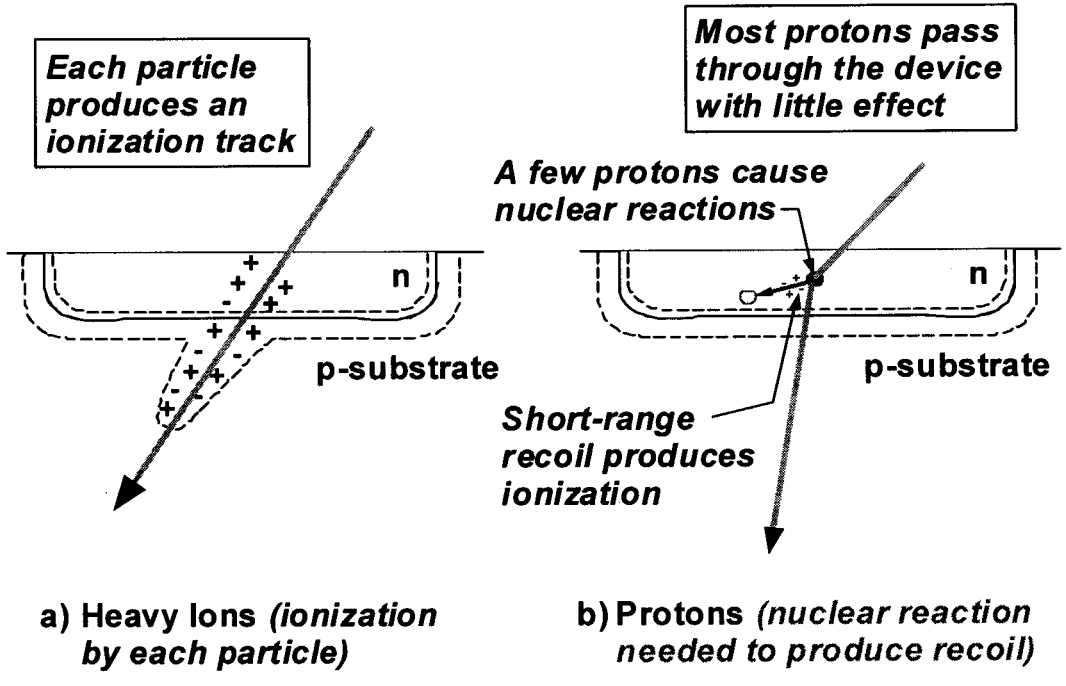
Surface Defects

- **Surface Defects have become a Very Critical Discriminator of Yield**
- **Detrimental Particle Size has Shrunk in response to Reduction of Feature Size**



Single Event Effects

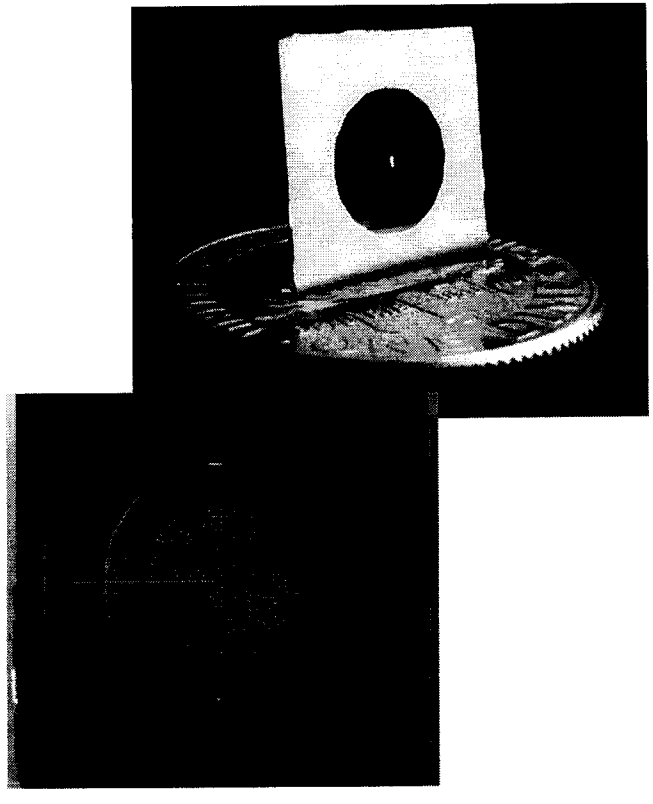
Direct and Indirect Processes for Single-Event Upset



Qualification

- The verification that a particular design, fabrication, workmanship and application are suitable and adequate to assure the operation and survivability under the required environmental and performance conditions.

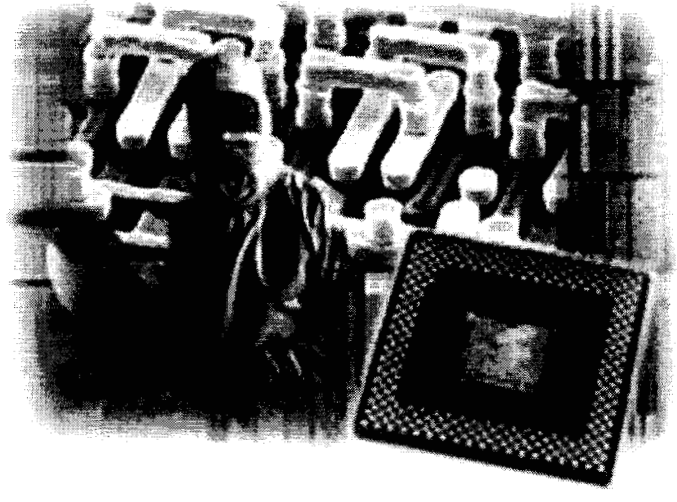
- Three main Elements
  - Process Qualification
  - Product Qualification
  - Product Acceptance



Process Qualification

Procedures and data demonstrating the control of the entire process of design and fabrication for a particular technology.

- Includes all aspects of the process:
  - Acceptance of starting materials
  - Documentation of procedures
  - Implementation of handling procedures
  - Establishment of Lifetime and failure data
  - Test Structures
  - Process Monitors
  - Technology Characterization Vehicles
  - Etc.



- In reality, production in a research & development environment will only cover a small segment of the described list.

- A practical option for the low volume high reliability user is to utilize test structures or samples to collect process variability data.

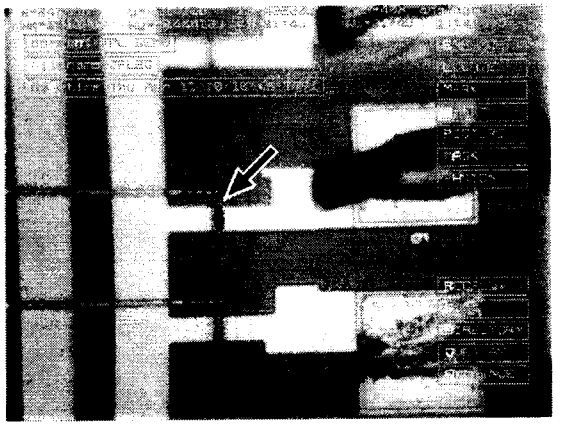
Product Qualification

Verification that a component will satisfy the design and application requirements under specific conditions

- **Design Verification**
  - Verification of model or simulation and layout prior to fabrication
  - Requires detailed knowledge of the design tools, device physics, layout tools, fabrication and test.

- **Product Characterization**
  - Determine an understanding of the limitations and characteristics of the design
  - Thermal Analysis and Test
  - ESD Sensitivity
  - Voltage Ramp
  - Temperature Ramp

- The challenge for the high reliability user is to design a set of tests suitable to the application at hand



Emission Microscopy

Thermal Characterization

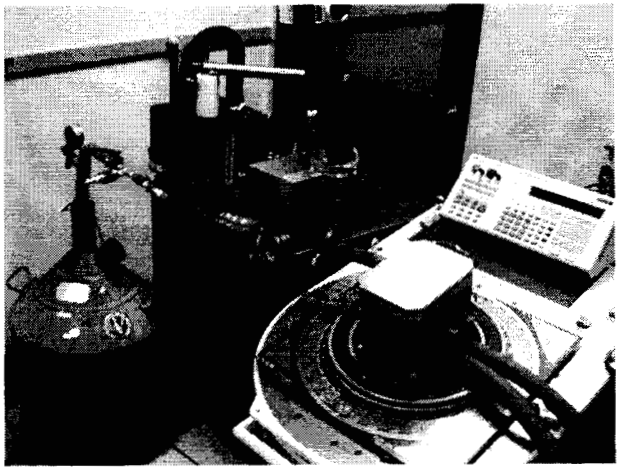
Product Acceptance

- For most advanced microelectronic devices fabricated in R& D environments, test and characterization of devices in their final packaged form is the only viable option to empirically assess the suitability of the product to the intended application.

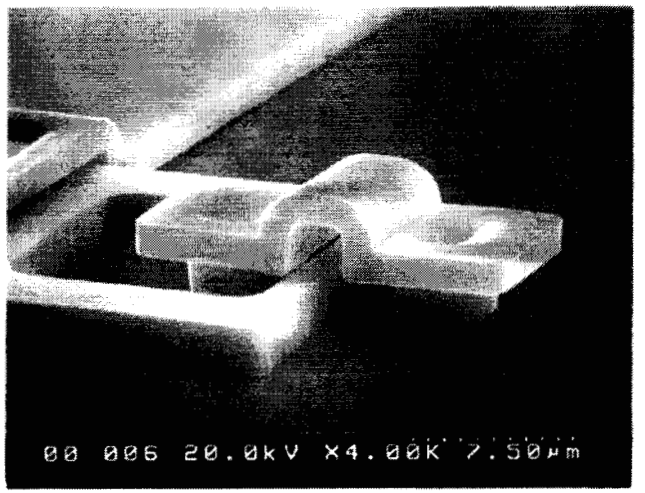
- Screening and qualification tests must be designed with the objective of detecting failure mechanisms affecting infant mortality and life under normal operating conditions
  - Construction analysis and destructive physical analysis are typically utilized to help the user in understanding the construction and workmanship of the product
  - The screening tests must be designed to detect both intrinsic and extrinsic failure mechanisms

- The challenge resides in the applied test conditions and interpretation of the resultant data.

- Utilization of standard MIL-STD type tests without consideration to material and design limitations may be detrimental



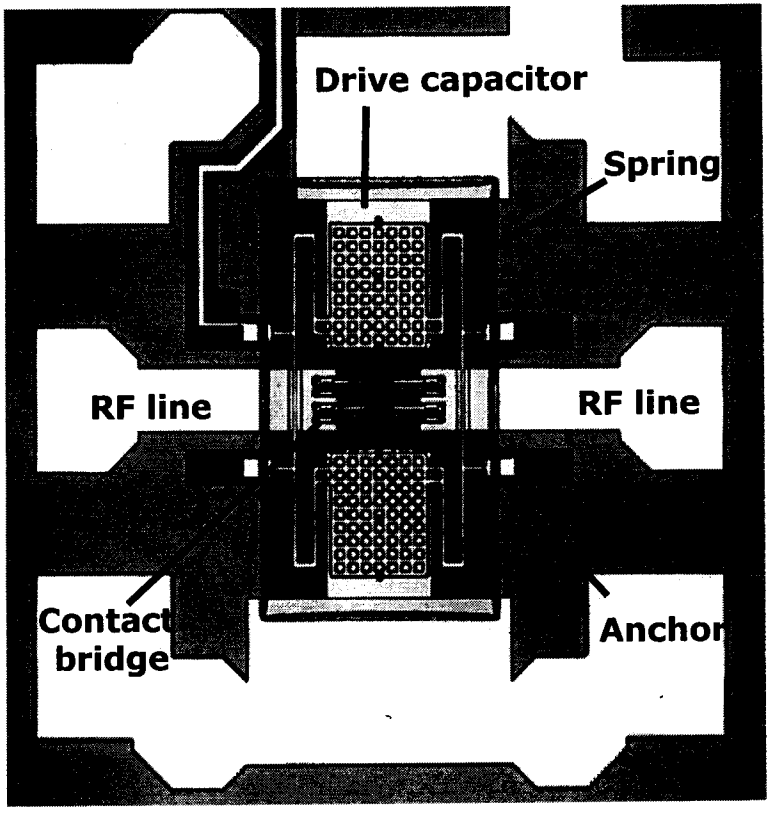
Characterization at intended application temperature



Hinge Test Structure

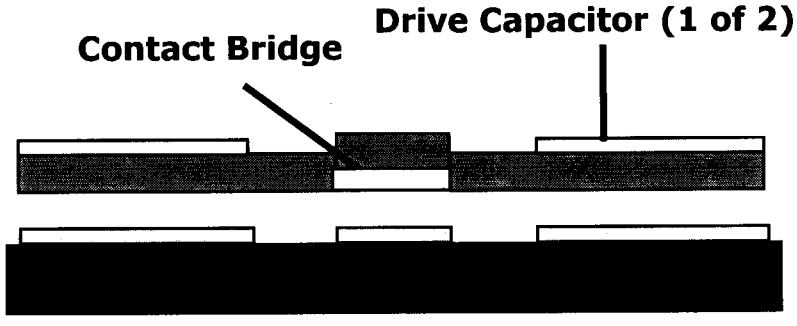
MEMS RF Switch
Characterization Example

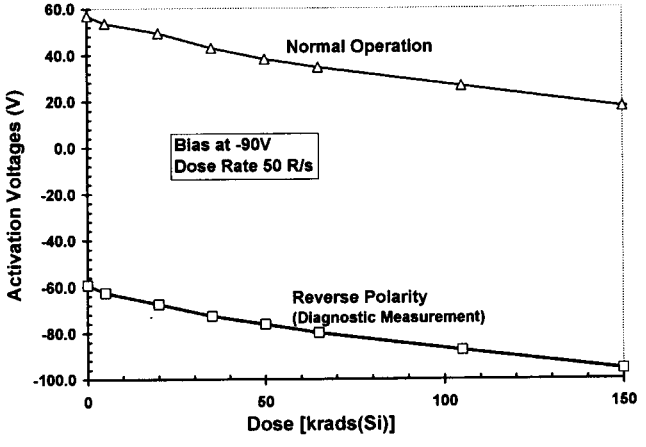
- Surface Micromachined GaAs Structure
- Fabricated by Rockwell Scientific Corporation
- Proprietary Dielectric Material
- Devices with 2 Different Actuator Configurations were examined
- Nominal operating voltage of 60 Volts with a resultant contact force of 50-100 uN



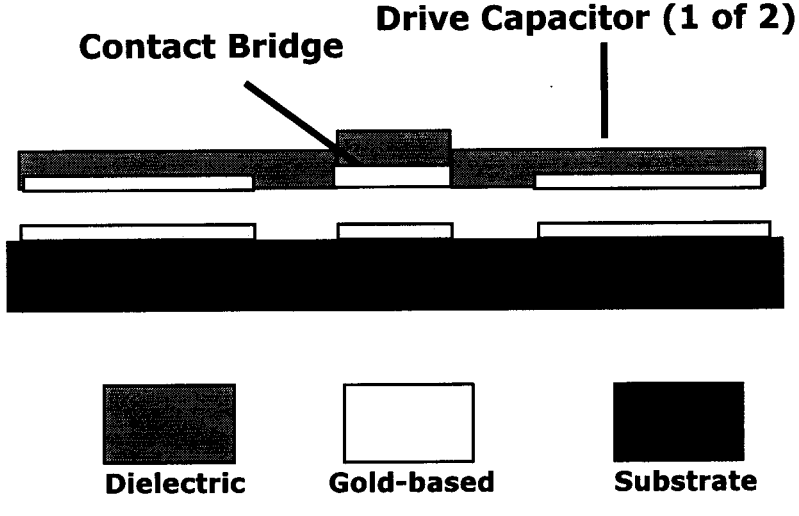
MEMS RF Switch
Radiation Test Results
Negative Bias

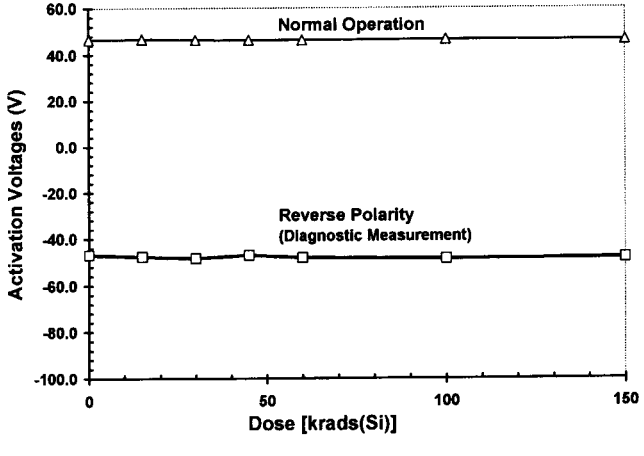
standard configuration





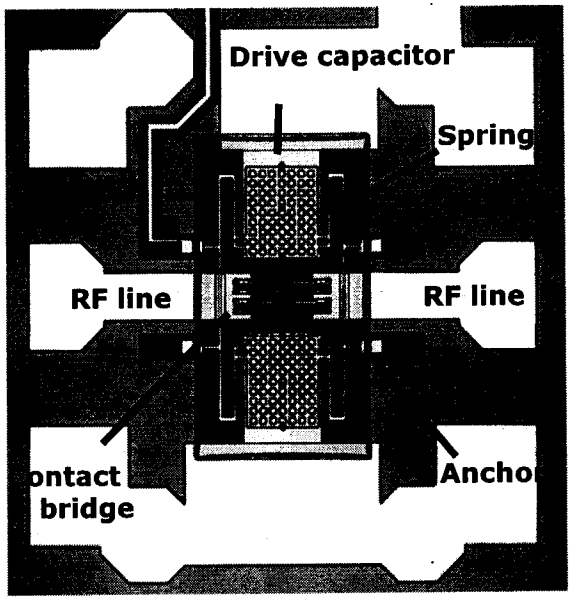
Alternate Configuration



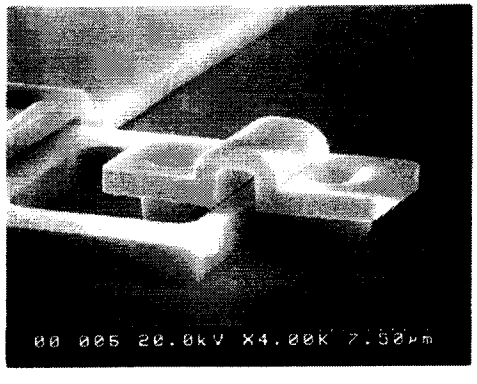


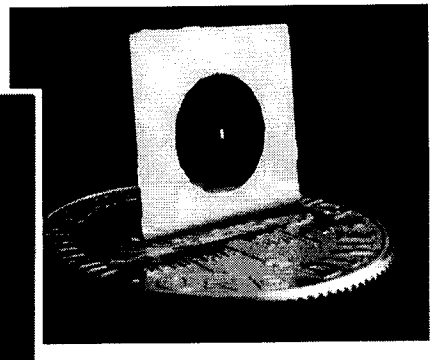
Advanced Technology Evaluation

- Examples
- Mixer Diodes for HP
- Bolometer Qualification
- MEMS RF Switch



MEMS RF Switch





COTS Evaluation

- Examples
- Memory for X2000
- MER Plastic Screens
- Other