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High Performance and Reliability Microelectronics Packaging

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IMAPS Advanced Technology Workshop on
High Reliability Microelectronics for Military Applications
May 17 - 19, 2011
Baltimore, MD USA

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Military Electronics Have Longer Lifetimes And Operate In More Severe Conditions

High Reliability Military Electronics

Higher Performance & Reliability

- Performance requirements for high reliability military exceed commercial

Longer Lifetimes

- Functional lifetimes of 20-30+ years.
  - Long Term Dormant Storage

More Severe Operating Environments

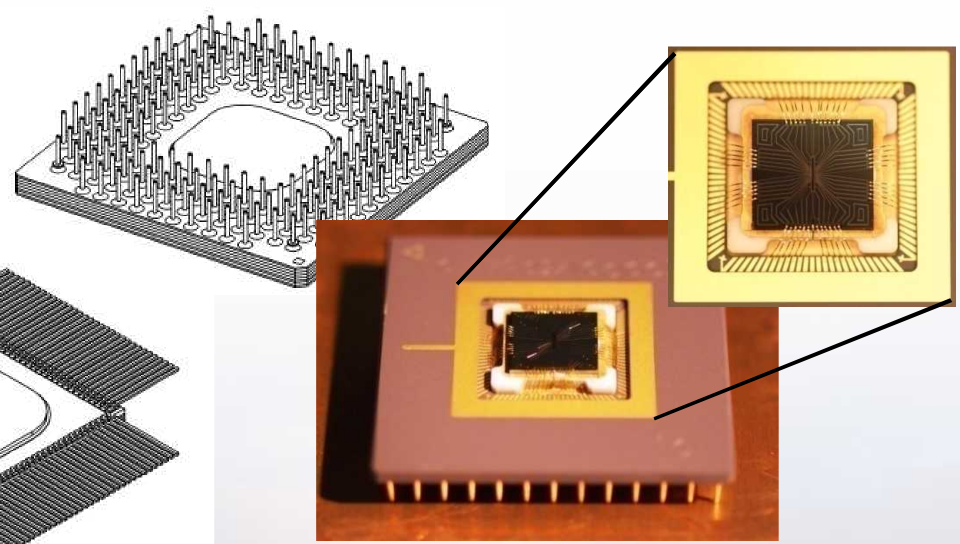
- Severe thermal & mechanical shock/vibration, temperature cycling, and humid & corrosive environments
- Harsh, application specific environments
  - **Space Applications** operated under high acceleration (g forces), vacuum, severe temperature changes and in radiation environments
  - ***Avionics*** undergo extreme changes in temperature, humidity, and atmospheric pressure (altitude) in a very short time periods

Hermetic Ceramic Packaging Has Traditionally Been Used For High Reliability

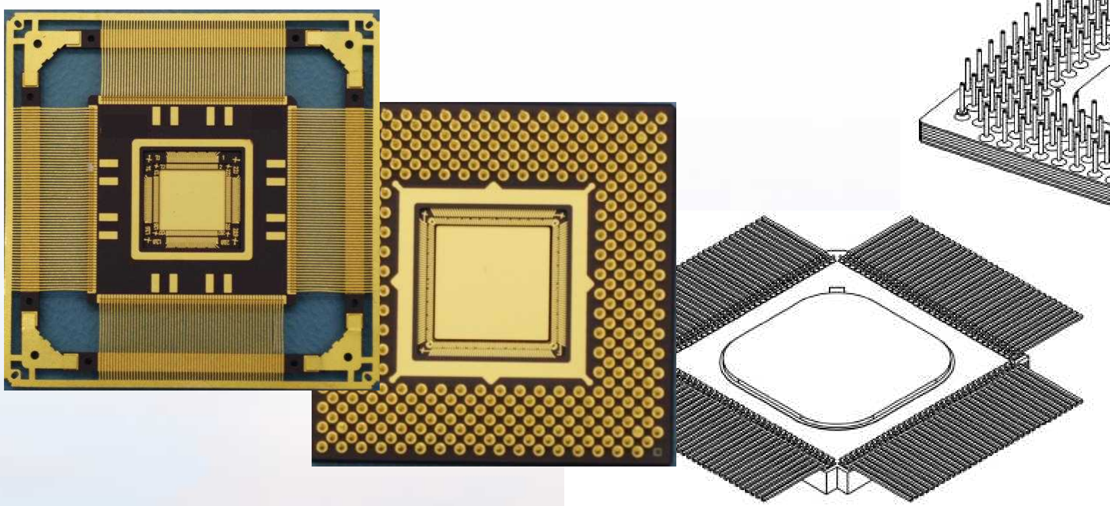
High Reliability Applications

- Military
- Space
- Medical
- Extreme Environments

Ceramic Pin Grid Array, PGA



Ceramic Quad Flat Pack, CQFP



Ceramics – thermal stability, low coefficient of thermal expansion, low gas diffusivity
Ceramic-To-Metal Seals - used in adverse temperature, shock, & vibration conditions
Alumina-Based Ceramics - excellent electrical & thermal properties

Tarr, http://www.ami.ac.uk/courses/topics/0261_herm/index.html

DoD Uses A Defense/Military Standard To Achieve Standardized Objectives

Acronym	Type	Definition
MIL-HDBK	**Defense Handbook**	**A guidance document** containing standard procedural, technical, engineering, or design information about the material, processes, practices, and methods covered by the DSP. MIL-STD-962 covers the content and format for defense handbooks.
MIL-SPEC	**Defense Specification**	**The essential technical requirements** for purchased material that is military unique or substantially modified commercial items. MIL-STD-961 covers the content and format for defense specifications.
MIL-STD	**Defense Standard**	**Establishes uniform engineering and technical requirements** for military-unique or substantially modified commercial processes, procedures, practices, and methods. There are five types of defense standards: interface standards, design criteria standards, manufacturing process standards, standard practices, and test method standards. MIL-STD-962 covers the content and format for defense standards.
MIL-PRF	**Performance Specification**	R**equirements in terms of the required results** with criteria for verifying compliance, without stating the methods. Defines functional requirements, the operating environment, and interface and interchangeability characteristics.
MIL-DTL	**Detail Specification**	**Design requirements** - materials to be used, how a requirement is to be achieved, or how an item is to be fabricated. Can contain both performance and detail requirements.

http://en.wikipedia.org/wiki/Defense_Standard

Leak Testing Is Used To Check For Small and Major Leaks Due To Damage Or Defects

Fine Leak Testing – The He Tracer Gas method

1) Vacuum cycle removes trapped gases/moisture
2) Package soaked in He under pressure
3) He leakage rate is precisely measured under vacuum
   hermeticity = a given leak rate: e.g., < 10 E-8 cc/sec

Fine leak seal testing to specifications

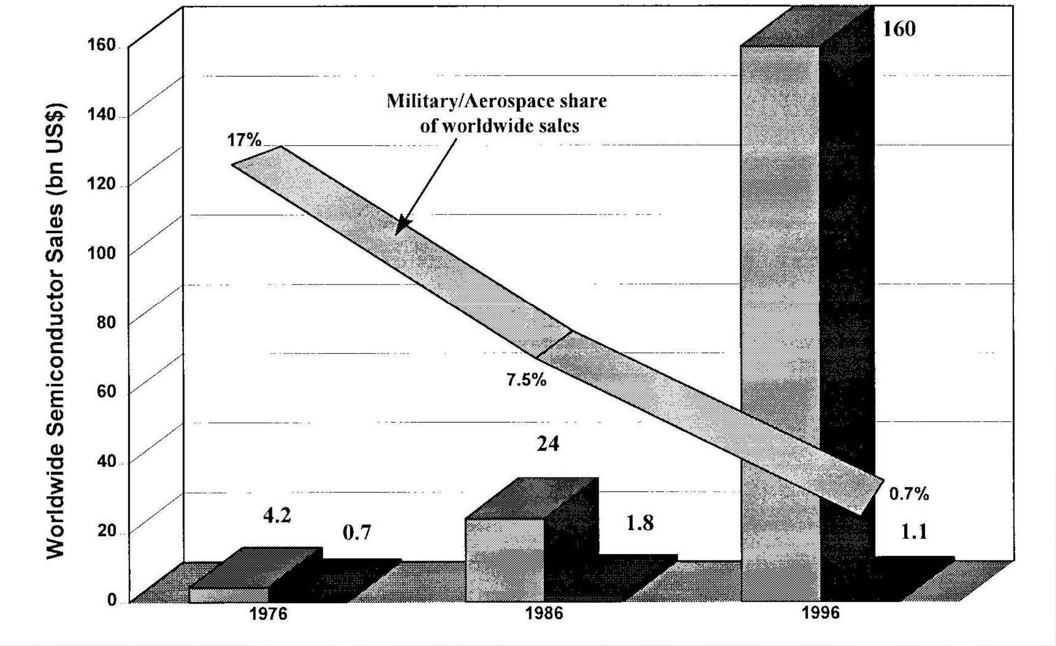
- Mil-Std 883 method 1014 conditions A1 and C1
- Mil-Std 750 method 1071 conditions H1 and C
- Mil-Std 202 Method 112 conditions C, D, A and E.

Gross Leak Testing – The Fluorocarbon Leak Test

1) Vacuum cycle removes trapped gases/moisture
2) Package is soaked in a fluorocarbon liquid under pressure
3) Package is visually monitored while immersed in liquid

The Hermetic Ceramic Packaging And Military Microelectronics Markets Are Shrinking

- **Ceramics are only $9 billion of the $2 trillion electronics market**
  - Ceramic Packaging is Small and Shrinking
    - High Reliability (Military, Space, Medical) Applications
- **The military market has decreased from ~20% to <1%**



- D.N. Donahoe & G.M. Poliskie "Ceramics In Modern Electronics", Adv. Microelectronics, 37(2), 6-8 (2010)
- L.G. Vettraino & S.H. Rsibud, "Current Trends in Military Microelectronic Component Packaging," IEEE Trans. Components & Packaging Tech. **22** [2] 270-81 (1999)

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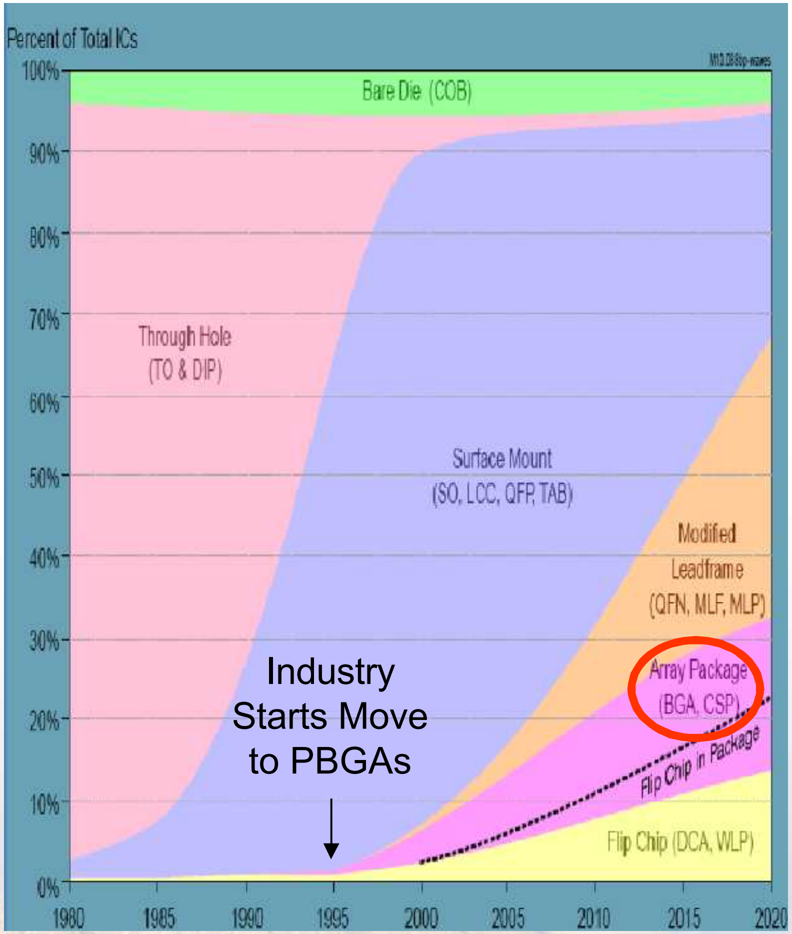
The Microelectronics Industry Is Moving To Plastic Packaging & Area Arrays

- **Performance Drivers for PBGAs**
  - Higher I/Os Area Arrays (e.g., vs.QFP)
  - Miniaturization - Smaller Form Factor (footprint & thickness)
- **Economic Drivers for Plastic Packaging**
  - Faster (~10x), Less Expensive Design/Development (5-10x) vs. Ceramic
  - Faster Delivery (5-10x) Of Less Expensive Packages (10 – 20X)
- **1994 Perry Memo Changed DoD Policies**
  - Use commercial parts/practices, while maintaining superior reliability
  - Use components made using best commercial practices for affordable access to leading-edge technology



High Reliability Microelectronics Development & Manufacturing Requires Systems-Level Design

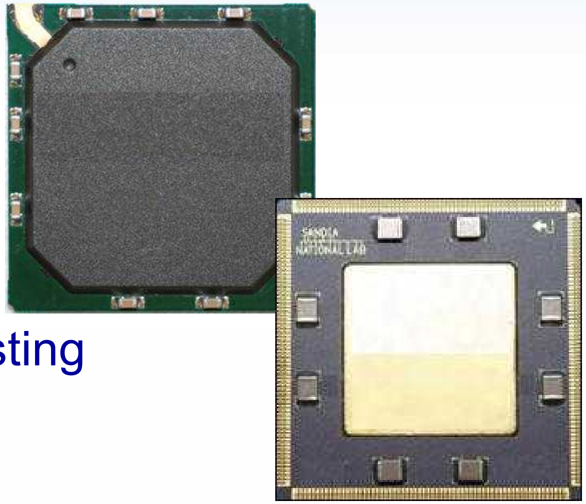
- **Systems-level design, from components through first level assembly/packaging to board level assembly is critical for high reliability**
  - Total management of materials, processes, design, and reliability
    - Packaging needs to be considered early in the design cycle
  - Consideration must be given to the end use and storage conditions
- **Materials, interfaces, and processes determine the integrity of the package**
  - Develop a fundamental understanding of the materials, interfaces, and mechanics issues in packaging
  - Apply fundamental understanding to model designs, processing, & reliability
- **Materials compatibility and stability are critical for performance & reliability**

G. Kelly, J. Alderman, C. Lyden and J. Barrett, "Microsystem packaging: lessons from conventional low cost IC packaging," J. Micromech. Microeng. ***7*** *(1997) 99–103.*

Sandia Designs, Develops, & Delivers High-Reliability Microelectronics

Hi-Reliability Ceramic & Plastic Packaging

- Custom, semi-custom & COTS packages & assembly
  - Per mil standards & performance/reliability specs.
- COTS Testing, Qualification, & Insertion



Assembly

- Die placement/attach – 1-2 µm
- Wire/ribbon bonding - 65 µm pitch
- Hermetic sealing/Encapsulation
- Balling
- Dam & Fill

Process Testing

- Wire pull
- Die shear
- Leak testing

High-Reliability Design

- Thermo-mechanical modeling
- Experimentally-validated modeling

Performance Testing

- Burn In & Electrical Testing

Reliability Testing & Modeling

- Accelerated aging
  - Temperature cycling, HAST
- Long-term dormant storage
- Destructive physical analysis (DPA)
- Lifetime predictions
- Solder fatigue modeling

Hermetic Ceramic Packaging Has A Proven Record Of Performance & Reliability

High Reliability Ceramic Hermetic Packaging

Strengths

- Proven performance & reliability
- Established designs and materials/compatibility
- Established, high-yield manufacturing
- Standard assembly testing and qualification testing

Challenges

- Shrinking supply chain
- Limited selection of open-tool packaging
  - Performance compromises
- Low-volume, batch processing
  - Source inspection required for quality and yield

Potential Improvements

- Six sigma continuous manufacturing/improvement practices
- Systems-level design/development & design for reliability

Hermetic, High-Rel Assembly & Testing Are Required For MIL-STD-883 & MIL-PRF-38535

Assembly Testing

- **Die Shear Strength**
- **Bond Strength**
- **Constant Acceleration (Centrifuge)**
- **Particle Impact Noise Detection (PIND)**
- **External Visual**
- **Seal**
  - Fine Leak
  - Gross Leak
- **Temperature Cycling**
- **Wire Bond Pull Strength**

MIL-STD 883 Qual. Testing

- **Environmental Tests**
  - Temperature Cycling
  - Thermal Shock
  - Seal, Fine & Gross Leak Test
- **Mechanical Tests**
  - Constant Acceleration
  - Mechanical Shock
  - Destructive Wire Bond Pull
  - Die Shear Strength
  - PIND
- **Group B Tests – Class S**
  - Temperature Cycle
  - Constant Acceleration
  - Fine & Gross Leak

COTS Electronics Insertion Is Being Enabled Through Testing & Predictive Modeling

Commercial Off The Shelf (COTS) Electronics Components

Strengths

- Advanced technology, low cost, commercially available components
  - Compatible materials and controlled assembly
- Joint COTS electronic qualification/insertion efforts
  - Established test program
    - Highly accelerated testing & long term dormant storage
  - Experimentally-validated, predictive lifetime modeling

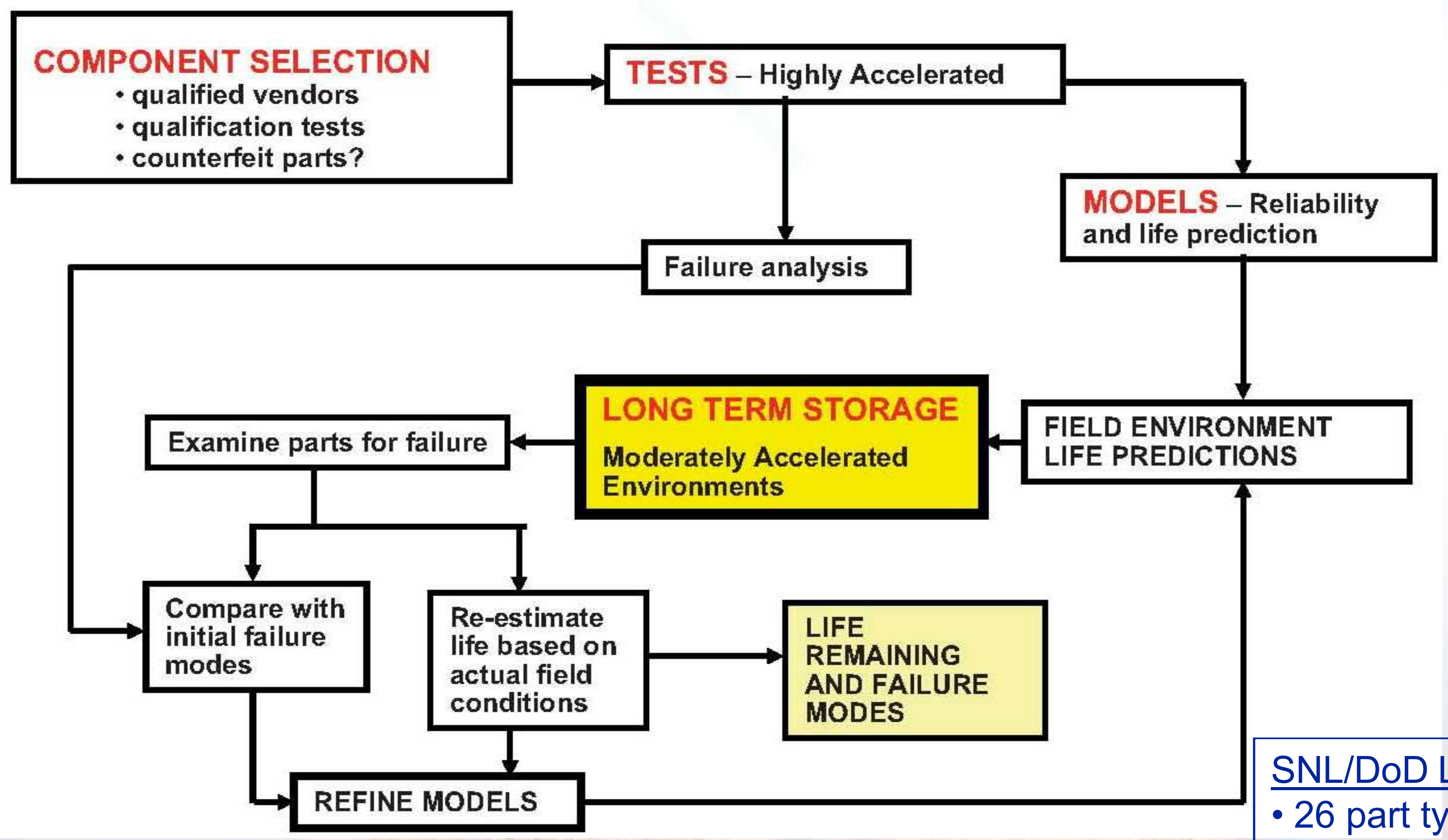
Challenges

- Testing & qualification for high reliability applications
  - Use-based specifications/requirements
    - Representative testing
- Managing the supply chain

Potential Improvements

- Moderately accelerated testing
- Qualifying vendors and classes of components

Methodology Employed To Qualify COTS Electronics For High Reliability Applications



SNL/DoD LTDS
- 26 part types
- 26,000 parts
- 5 test sites

J. Lopez, L. Rohwer, Lauren, R. Wavrik, J. Aragon, J. White, and J. Marchiondo Jr., "Long term dormant storage experiment of COTS components under field conditions," 13th International Components for Military and Space Electronics (CMSE) Conference, February 9-12, 2009, San Diego, CA.

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Additional Work Is Required To Test & Qualify Advanced Plastic Packaging Technology

High-Reliability Plastic Packaging

Strengths

- Advanced, less expensive, higher I/O commercial technology (e.g. PBGA)
- Faster development & turn times (e.g., for ASIC testing & development)
- Builds on COTS electronic qualification/insertion efforts
  - Established testing methods & lifetime models - highly accelerated testing

Challenges

- Testing & qualification for high reliability applications
  - Use-based specifications & representative testing
  - Solder joint inspection
- Materials compatibility
  - The majority of the problems originate from complex material interactions
- Process understanding and control

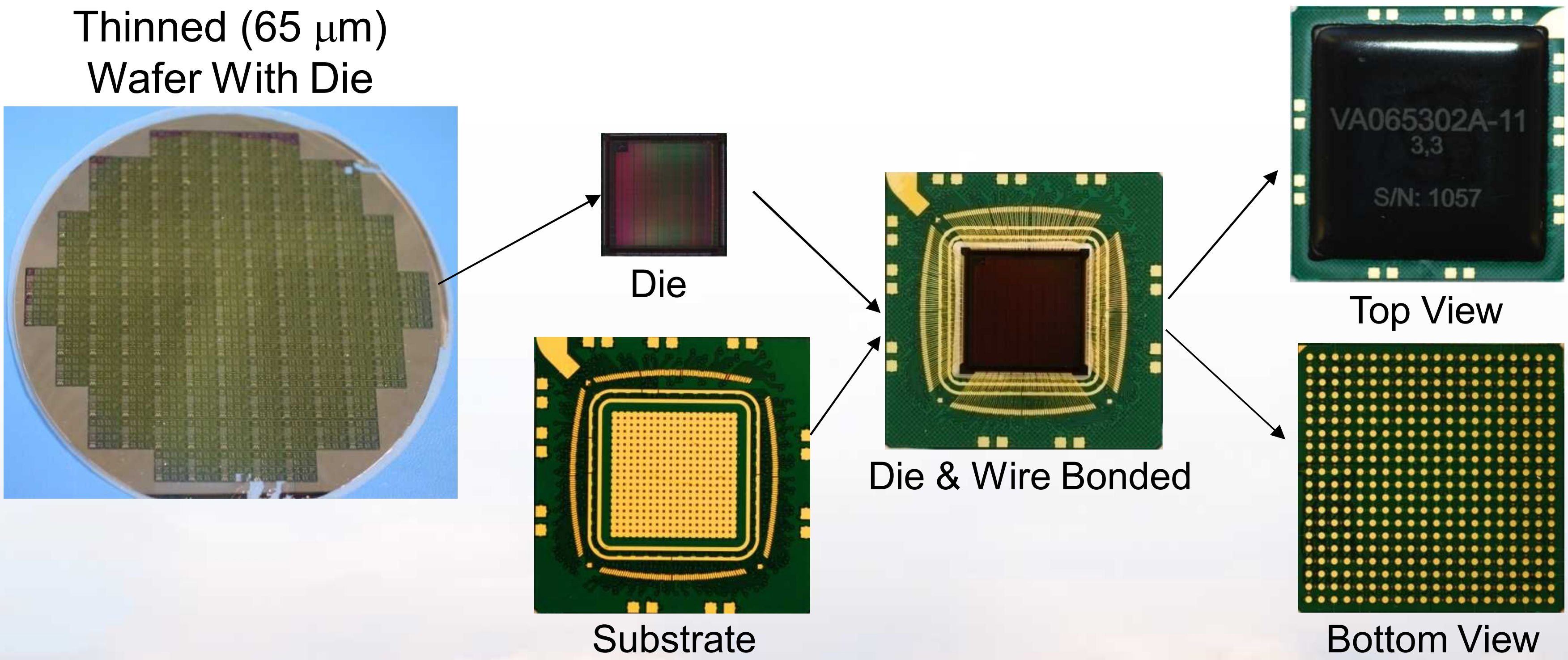
Potential Improvements

- Experimentally-validated, modeling enabled design/optimization
- Systems-level design/development & design for reliability

Plastic Packaging/Assembly & Testing Are Enabling ASIC Development

Microsystems Assembly/Packaging Process Flow

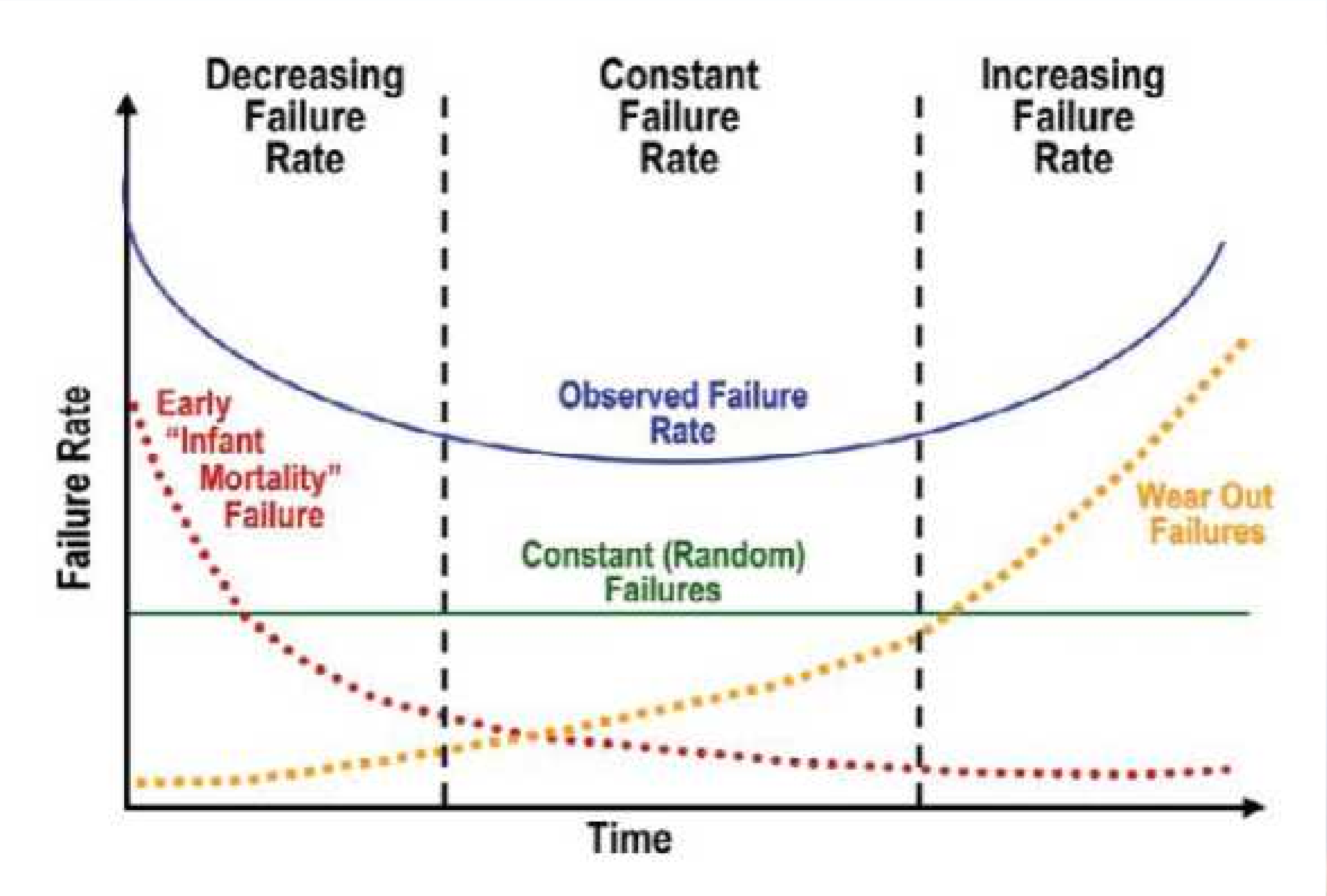
Wafer Thinning → Dicing → Die Placement & Attach → Wire bond → Encapsulate



"Packaging needs to be considered very early in the design cycle, and consideration must be given to the end use environmental conditions in which the microsystem will be placed"

G. Kelly, J. Alderman, C. Lyden and J. Barrett, "Microsystem packaging: lessons from conventional low cost IC packaging," J. Micromech. Microeng. ***7*** *(1997) 99–103.*

High Reliability Is Achieved By Weeding-Out Bad Parts, And Understanding/Controlling Wear Out



"Bathtub Curve", Wikimedia Foundation, Inc.: http://www.en.wikipedia.org/wiki/Bathtub_curve

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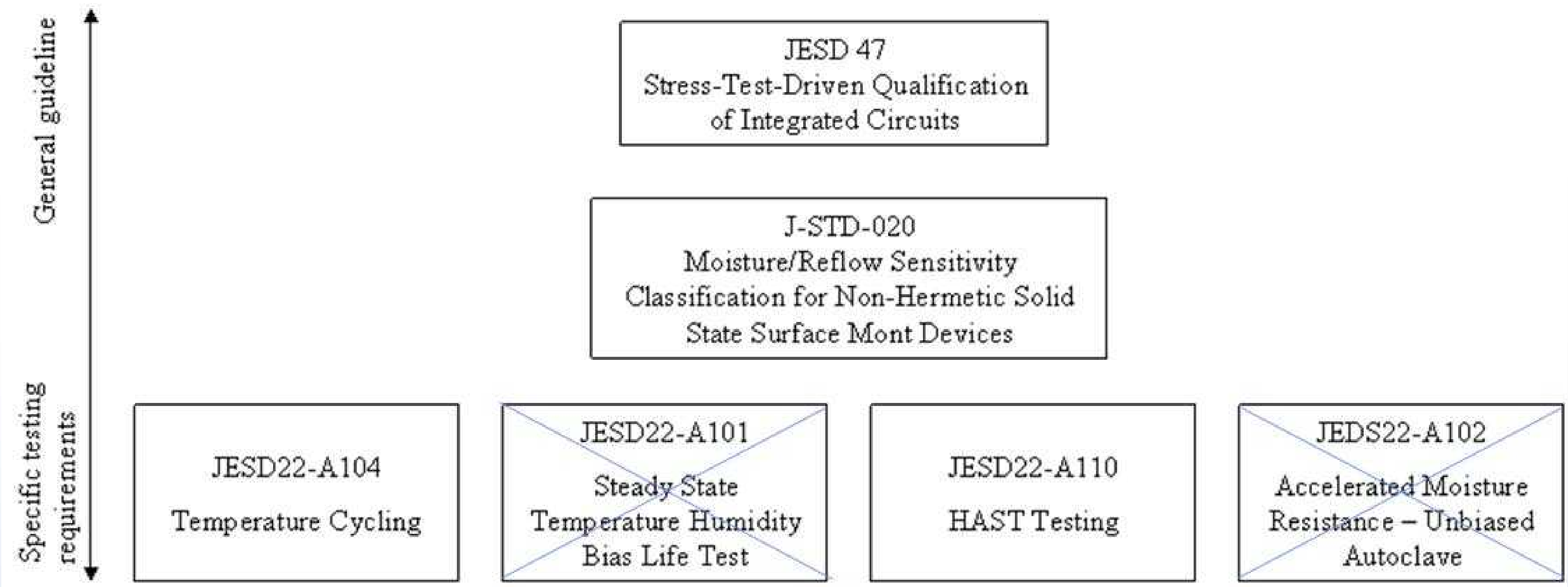
The JEDEC Standard Structure Is Being Used To Test/Qualify Plastic Packaging For Hi Rel

JESD 47 Provides The Overarching Guidelines



Temp. cycling & moisture are the environmental factors of greatest concern for reliability.

Parts are tested using *MIL-STD-883, Method 101 0* and *JESD-22, Method A104*

Note: This qualification standard is not specifically aimed at extreme use conditions

JEDEC Standards Can/Should Be Modified To Apply To The Specific Use Conditions

Standard	Source	Moisture Sensitivity Test	Temp Cycling	Unbiased HAST	Comments
JEDEC	Internet	Moisture Sensitivity Level, level 3IPC/JEDEC J-STD-020	-55 to +125 C, 700 cycles	130 C/85%R.H., 96 Hours	Industry Standard
SNL Qualification		Moisture Sensitivity Level, level 3IPC/JEDEC J-STD-020	-55 to +125 C, 1000 cycles	130 C/85%R.H., 350 Hours	
Amkor	Internet	Moisture Sensitivity Level, level 3IPC/JEDEC J-STD-020	-55 to +125 C, 1000 cycles	130 C/85%R.H., 96 Hours	Monitoring Key Indices
CISCO	Personal Contact	MEETS JEDEC Standards			
NASA	Personal Contact	Currently does not use PBGAs. Plan to use PBGA in Constellation program was cancelled.			

The JEDEC Standard Must Be Adapted To The Service Life Of The High-Reliability Application

Arrhenius-Peck model

$$A_f = \left(\frac{RH_{service}}{RH_{HAST}}\right)^{-3} \exp\left[\left(\frac{Ea}{k} * \left(\frac{1}{T_{Service}} - \frac{1}{T_{HAST}}\right)\right)\right]$$

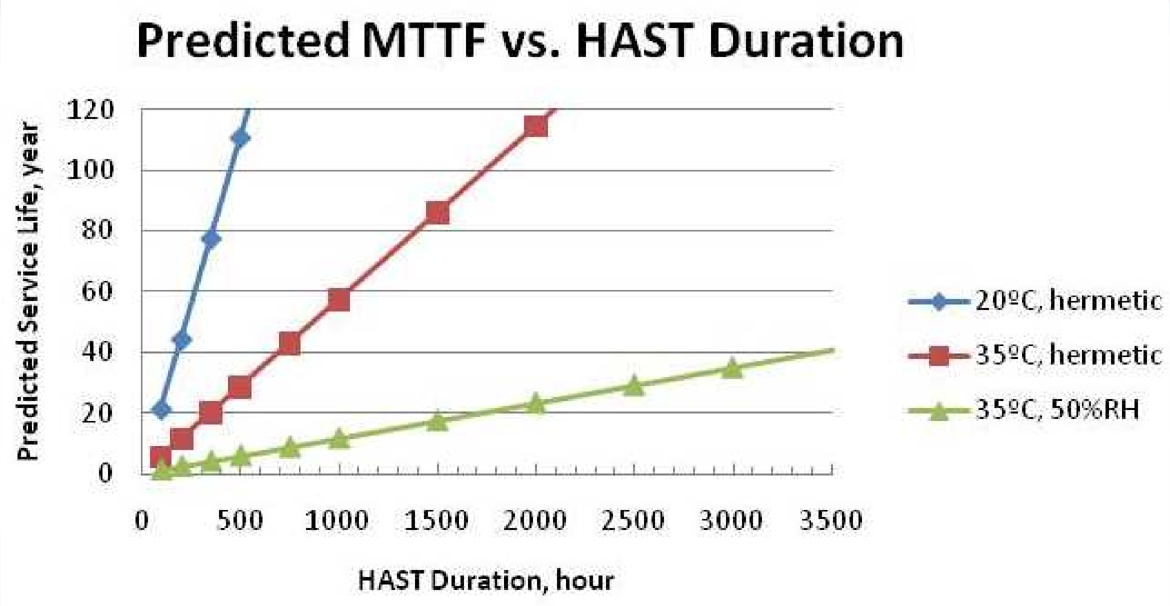
- Activation energy, Ea, is determined experimentally, set to an industrial accepted standard, or conservatively set to 0.7 eV.

Service Life Prediction

$$t_{service} = A_f * t_{HAST}$$

S.M Tam, "Demonstrated Reliability of Plastic-Encapsulated Microcircuits For Missile Applications, IEEE TRANS. ON RELIABILITY, ***44****, [1], 1995*

Time To Failure Decreases With Decreasing Ea, & Increasing Temperature & Humidity



More HAST testing hours are required to qualify a part:

- for higher temperature or humidity operation
- that has a lower Ea failure mechanism

Pass HAST hours	20C, Hermetic	35C, Hermetic	35C, 50%RH
96.00	21.20	5.49	1.12
168.00	37.10	9.62	1.96
350.00	77.30	20.03	4.08
500.00	110.42	28.62	5.83
750.00	165.64	42.93	8.74
1000.00	220.85	57.24	11.65

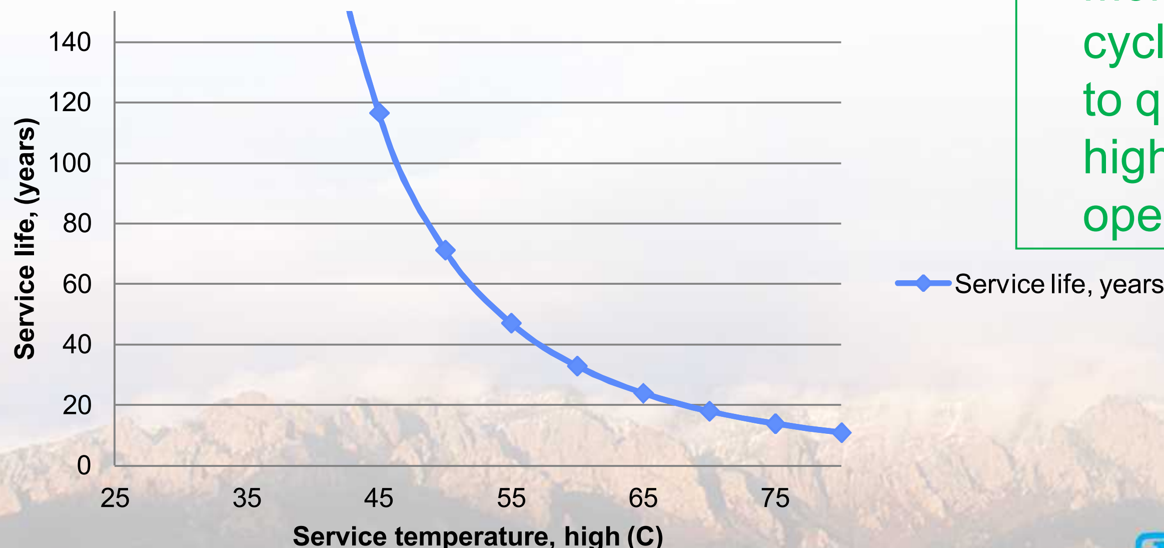
The Predicted Service Life Decreases With Increasing Service Temperature

Coffin-Manson model

$$AF = \left(\frac{T_{test,high} - T_{test,low}}{T_{service,high} - T_{service,low}}\right)^{1.9} * \left(\frac{f_{service}}{f_{test}}\right)^{1/3} * \exp\left[1414 * \left(\frac{1}{T_{service,high}} - \frac{1}{T_{test,high}}\right)\right]$$

- $T_{test,\ high}$ = 125°C, $T_{test,\ low}$ = -55°C, f_{test} = 51.96 cycles/day
- $T_{service}$, low = 25°C, $f_{service}$ = 1cycle/day

Service Life Predictions Based on Temperature Cycling



More temperature cycles are required to qualify a part for higher temperature operation

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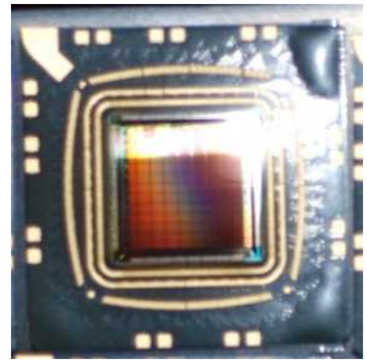
Materials & Processing Issues Are Identified Using Microscopy, Ultrasound, X-Ray, & DPA

Plastic Packaging Issues

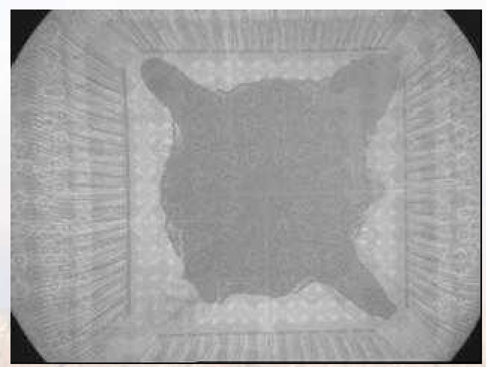
- Materials
  - Delamination
  - Substrate warping
- Process quality
  - Die attach: epoxy coverage
  - Wire bonding: weak bonds
  - Molding: flashing, wire sweep
- Electrical/Reliability
  - High Leakage Current

Optical Microscopy

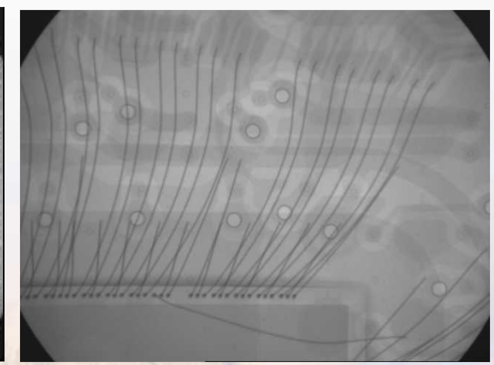



Corner Delamination

X-Ray

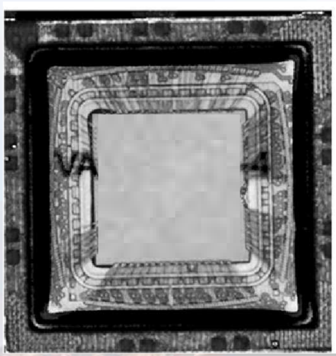
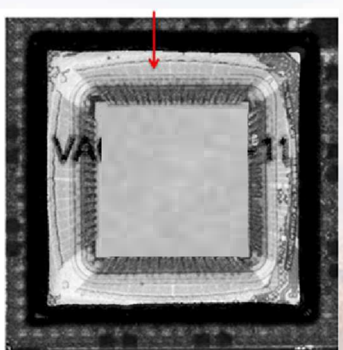


Epoxy Coverage



Wire Sweep

Ultrasound Microscopy - CSAM

Substrate Delamination

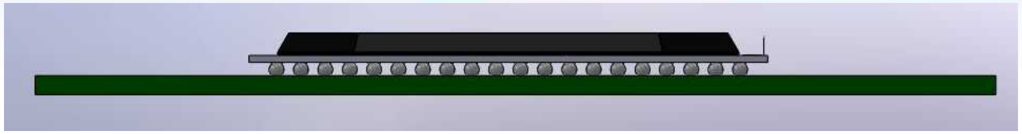
JEDEC Moisture Sensitivity Level (MSL) Classifications Affect Board Level Assembly

			Soak Requirements			
	Floor Life		Standard		Accelerated	
Level	Time	Cond degC/%RH	Time (hrs)	Cond degC/%RH	Time (hrs)	Cond degC/ %RH
1	unlimited	<=30/85%	168+5/-0	85/85	n/a	n/a
2	1 year	<=30/60%	168+5/-0	85/60	n/a	n/a
2a	4 weeks	<=30/60%	696+5/-0	30/60	120+1/-0	60/60
3	168 hours	<=30/60%	192+5/-0	30/60	40+1/-0	60/60
4	72 hours	<=30/60%	96+2/-0	30/60	20+0.5/-0	60/60
5	48 hours	<=30/60%	72+2/-0	30/60	15+0.5/-0	60/60
5a	24 hours	<=30/60%	48+2/-0	30/60	10+0.5/-0	60/60
6	TOL	<=30/60%	TOL	30/60	n/a	60/60

Trapped moisture vaporizes to produce tremendous internal package stress
Popcorn cracking = Package cracking due moisture-induced stress.

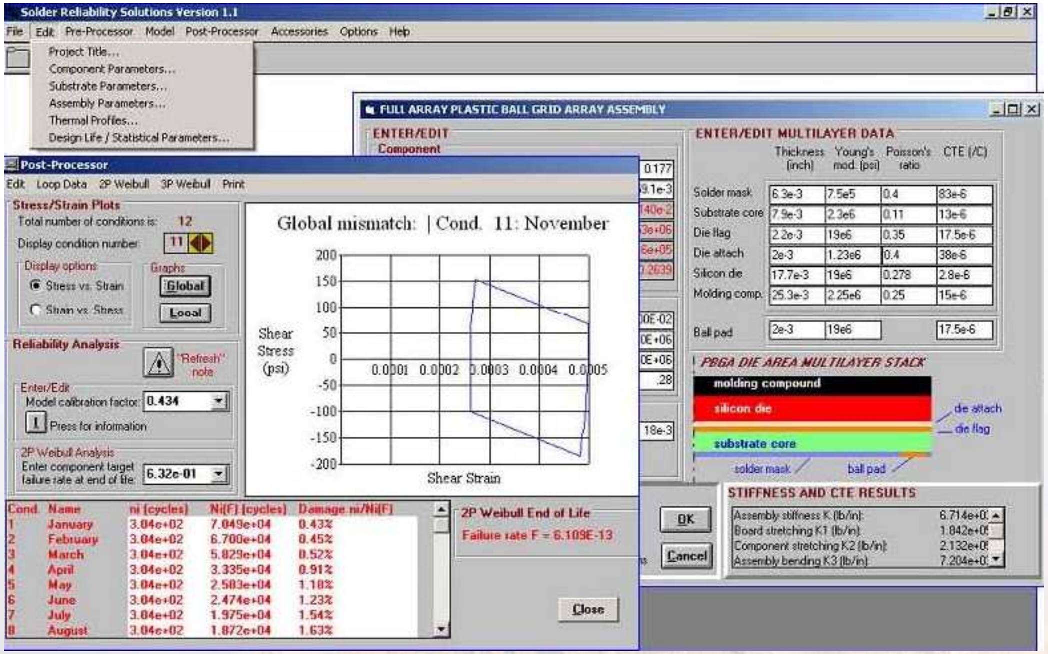
http://www.siliconfareast.com/msl.htm

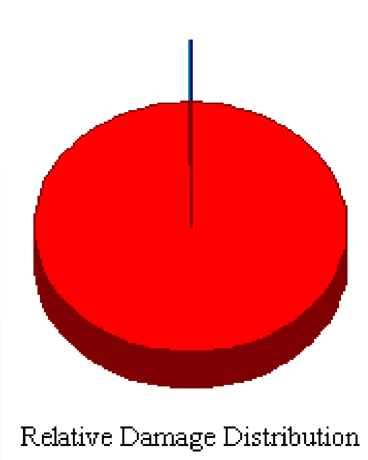
Solder Fatigue Modeling Can Be Completed To Assess Board Level Reliability



Solder Fatigue Modeling - 400 ball BT BGA on FR4, 18ºC temp. range

- 100 year designed solder fatigue life1, 37 year failure free time
- Lifetime cumulative fatigue damage <3%

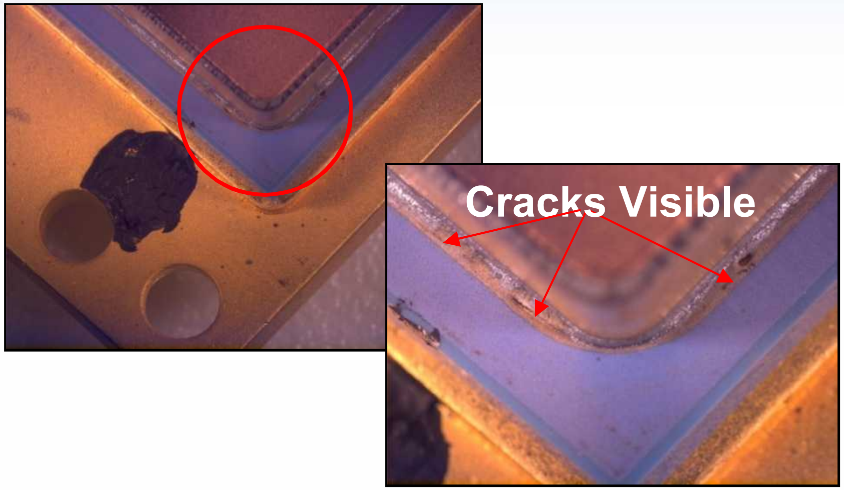


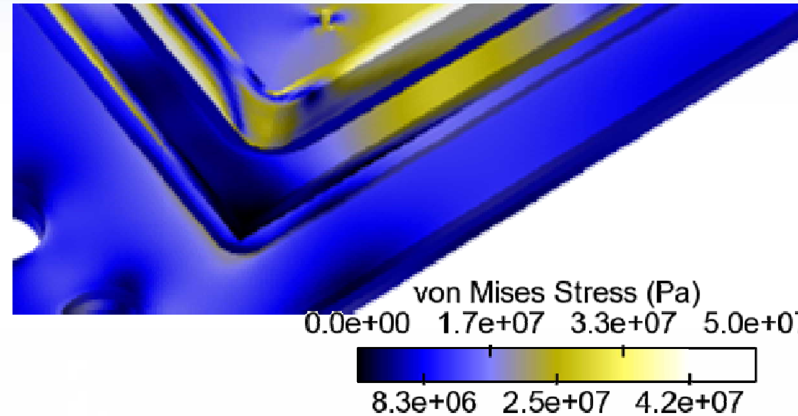


•J.-P, Clech, Solder Reliability Solutions: a PC-Based Design-for-Reliabiliy Tool, Surface Mount International Conference. Proc. P136-151. Republished in Sold. Surf. Mt. Technol., Vol 9, 1997, 45-54

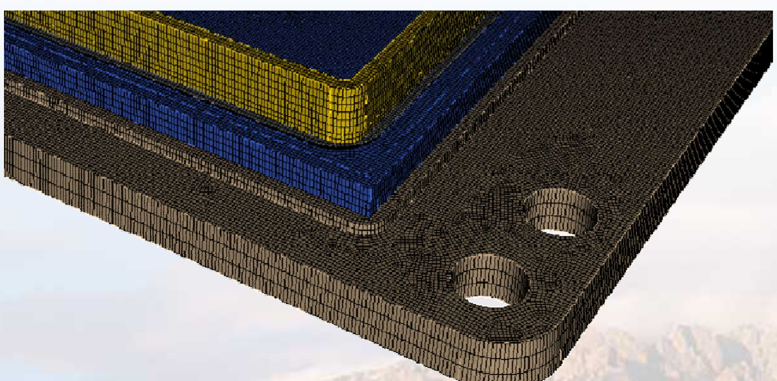
• http://www.siliconfareast.com/solder-joint-reliability.htm

Thermomechanical Modeling Provides Design Guidance To Minimize Stress & Improve Reliability

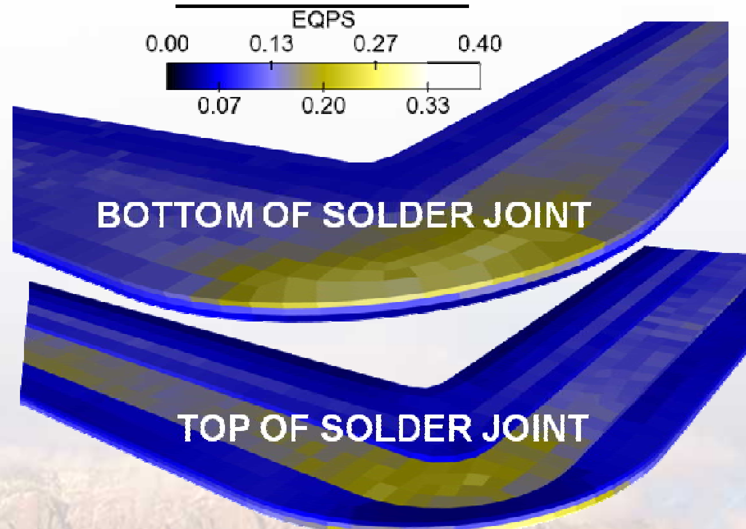




760k 8-node hexahedral element thermo-mechanical model/simulation



Plastic St rain



N. Young, J. Massad, and K. Ewsuk, "An Assembly-Based Structural Model for LTCC Package Design and Reliability," Proc. Ceram. Interconnect and Ceram. Microsystems Tech. Conf. (CICMT) 2011, IMAPS, Washington DC, 2011

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Designing For Reliability Is Enabled By Coupling Stress/Strain & Lifetime Modeling

Assembly/Testing Steps	Seal Frame Solder EQPS
Assembly	0.35
Electrical Tests	0.43
Single Thermal Cycle	0.52

Coffin-Manson Failure Criterion

$$\text{No. Cycles to Failure} = \left(\frac{2.28}{\sqrt{3}\Delta EQPS} \right)^{\frac{1}{0.51}}$$

H.D. Solomon, IEEE Trans., CHMT-9, 1986
W. Engelmaier, IEEE Trans., CHMT-6, 1983

Strain Increment

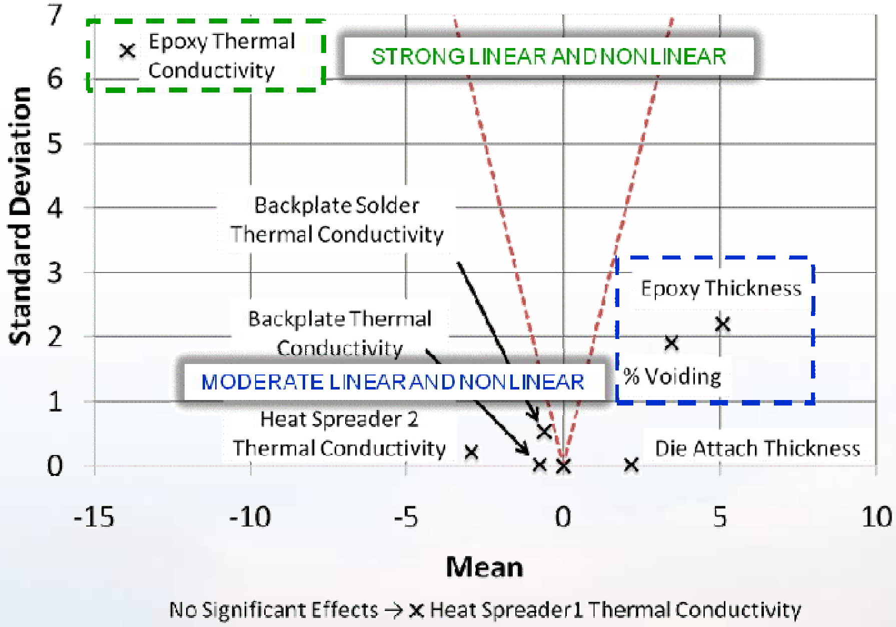
$\Delta EQPS$

equivalent plastic strain accumulated in one cycle (load + unload)

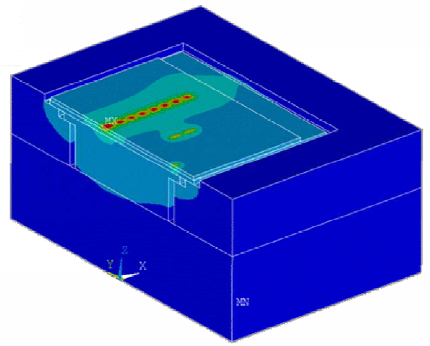
N. Young, J. Massad, and K. Ewsuk, "An Assembly-Based Structural Model for LTCC Package Design and Reliability," Proc. Ceram. Interconnect and Ceram. Microsystems Tech. Conf. (CICMT) 2011, IMAPS, Washington DC, 2011

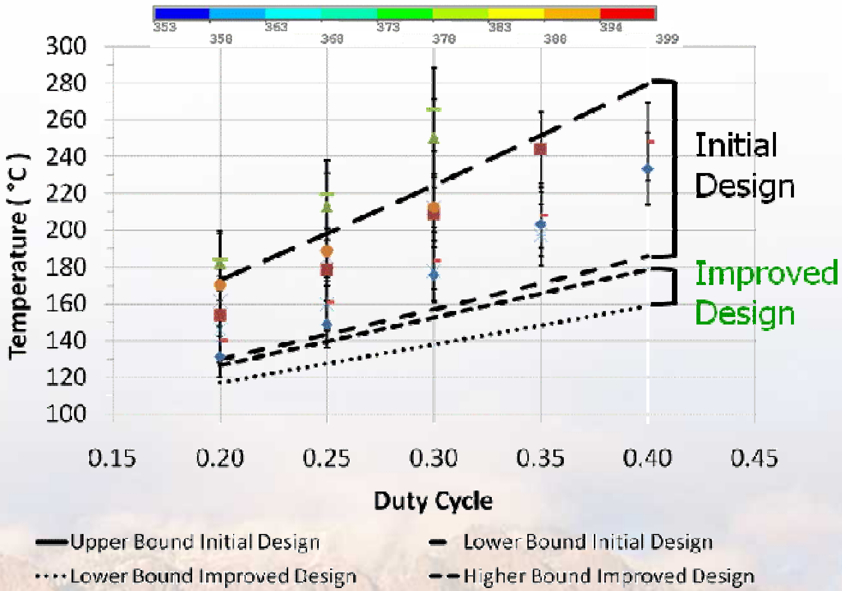
Sensitivity & Uncertainty Analysis, And Thermal Modeling To Optimize Package Design

Sensitivity Analyses Identify Critical Parameters



Thermal Modeling





N. Young, J. Johnson, and K. Ewsuk, "Microelectronics Package Design Using Experimentally-Validated Modeling and Simulation" Proc. 4th Intl. Symp. on Adv. Ceram. (ISAC4), Key Engineering Materials, 2011

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Summary: High Reliability Microelectronics Development Requires Experimentally-Validated, Modeling-Enabled, Systems-Level Design

- High Reliability Military Electronics Undergo More Extensive & Rigorous Testing Prior to Fielding, Have Longer Lifetimes, and Operate in More Severe Conditions
- Systems-Level Design is Critical to High Reliability Microelectronics Manufacturing
  - High Reliability is Achieved by Weeding-Out Bad Parts, and by Understanding/Controlling Wear-Out Through Modeling and Testing
- Testing & Predictive Modeling has Enabled COTS Electronics Insertion, and Provides a Path to Test & Qualify Advanced Plastic Packaging Technology
- The JEDEC Standard Structure, Adapted to Service Life Requirements, is Being Used to Test/Qualify Plastic Packaging for High Reliability Military Applications
- Design for Reliability is Enabled by Experimentally-Validated Thermo-Mechanical Modeling, Coupling Stress/Strain & Lifetime Modeling, and Solder Fatigue
  - Sensitivity & Uncertainty Analysis Enable Design Optimization