CALCE
Research on Risk Assessment, Mitigation, and Management for Pb-free Electronics

Michael Osterman
osterman@calce.umd.edu

calce

Electronic Products and Systems Center
University of Maryland
College Park, MD 20742
(301) 405-5323
http://www.calce.umd.edu

Formed 1987

ISO 9001 Certified, 1999

What is CALCE?

CALCE EPSC Mission:

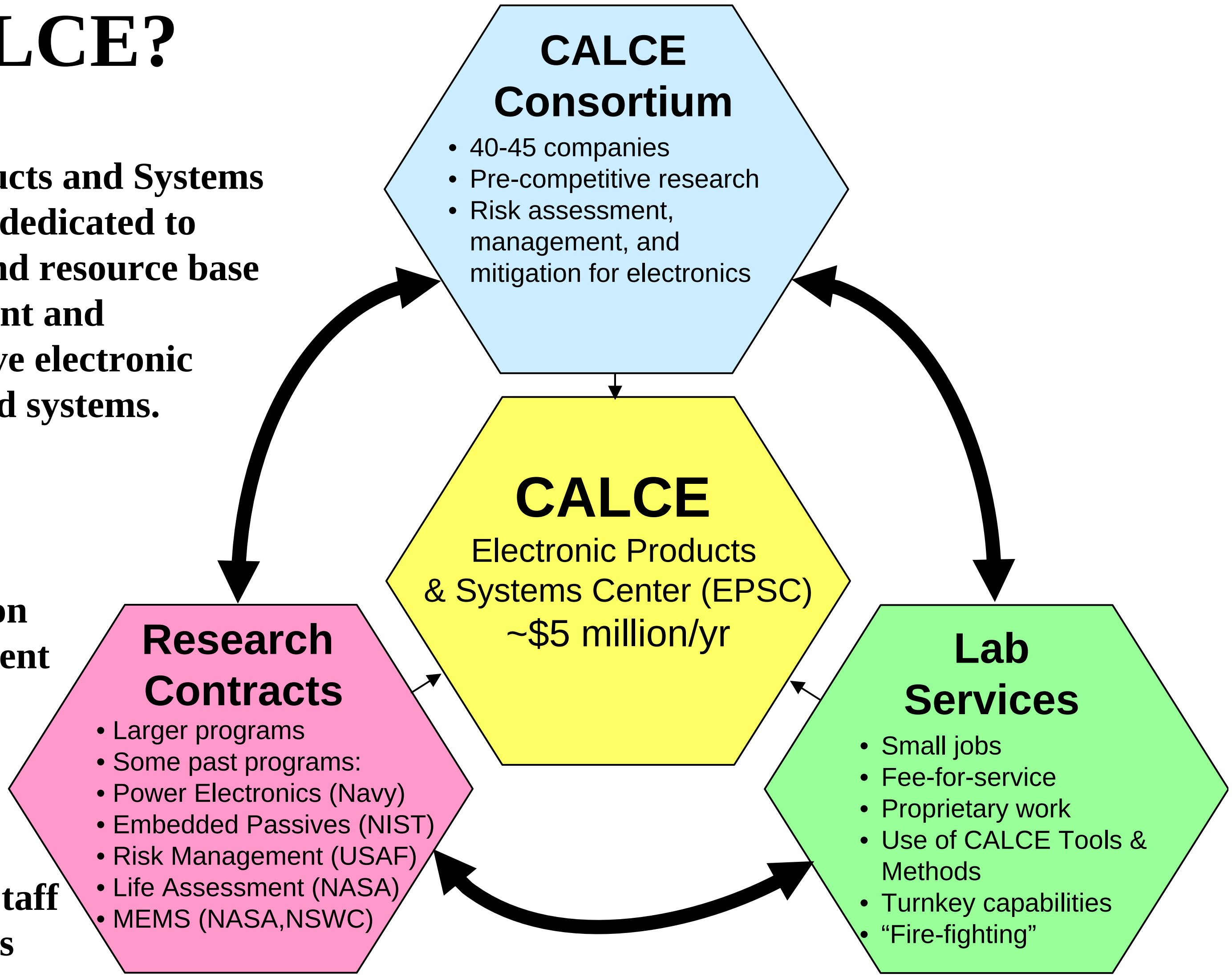
CALCE Electronic Products and Systems Center (founded 1987) is dedicated to providing a knowledge and resource base to support the development and sustainment of competitive electronic components, products and systems.

Areas of

- **Physics of Failure**
- **Design of Reliability**
- **Accelerated Qualification**
- **Supply-chain Management**
- **Prognostics**
- **Obsolescence**

CALCE EPSC Personnel:

~26 Faculty and Research Staff
EEs, MEs, MatSci, Physics
4 Software Developers
~19 M.S. students
~66 Ph.D. students



http://www.calce.umd.edu

Pb-Free Movement
- Overview of European Union Legislation -

WEEE (Waste of Electrical and Electronic Equipment)

- Requires manufacturers to reduce the disposal waste of electronic products by reuse, recycling and other forms of recovery
- Member states can set more severe requirements than those in the directive, based on Article 175 of the treaty.

RoHS (Restriction of Use of Hazardous Substances)

- Bans the use of Pb, Hg, Cd, Cr, Polybrominated biphenyls (PBBs), and Polybrominated diphenyl ethers (PBDEs) by July 1, 2006
- This 'Single Market' directive will be implemented by creating harmonized standards for the EU's international market. Namely, member states cannot pass more restrictive national laws.

Member states of EU were required to put national laws into place by August 13, 2004.

Current Pb-free Exemptions in RoHS

1. Defense related electronics
2. Lead in electronic ceramic parts
3. Lead in glass cathode ray tubes, electronics components, and fluorescence tubes
4. Lead in solders for servers, storage, and storage array systems (exemption granted until 2010)
5. Lead in solders for network infrastructure equipment for switching, signalling, transmission as well as network management for telecommunications
6. Lead in high melting temperature type solders (e.g., Sn-Pb solder alloys containing more than 85% Pb)
7. Other exemptions are being considered. For example,
   - Lead used in compliant-pin VHDM (Very High Density Medium) connector systems
   - Lead as a coating material for a thermal conduction module c-ring
   - Lead and cadmium in optical and filter glass

Some Newly Proposed Exemptions

- Lead in tin whisker resistant coatings for fine pitch applications
- Lead in connectors, flexible printed circuits, flexible flat cables

Electronics Markets

A large portion of the electronics industry is responding.

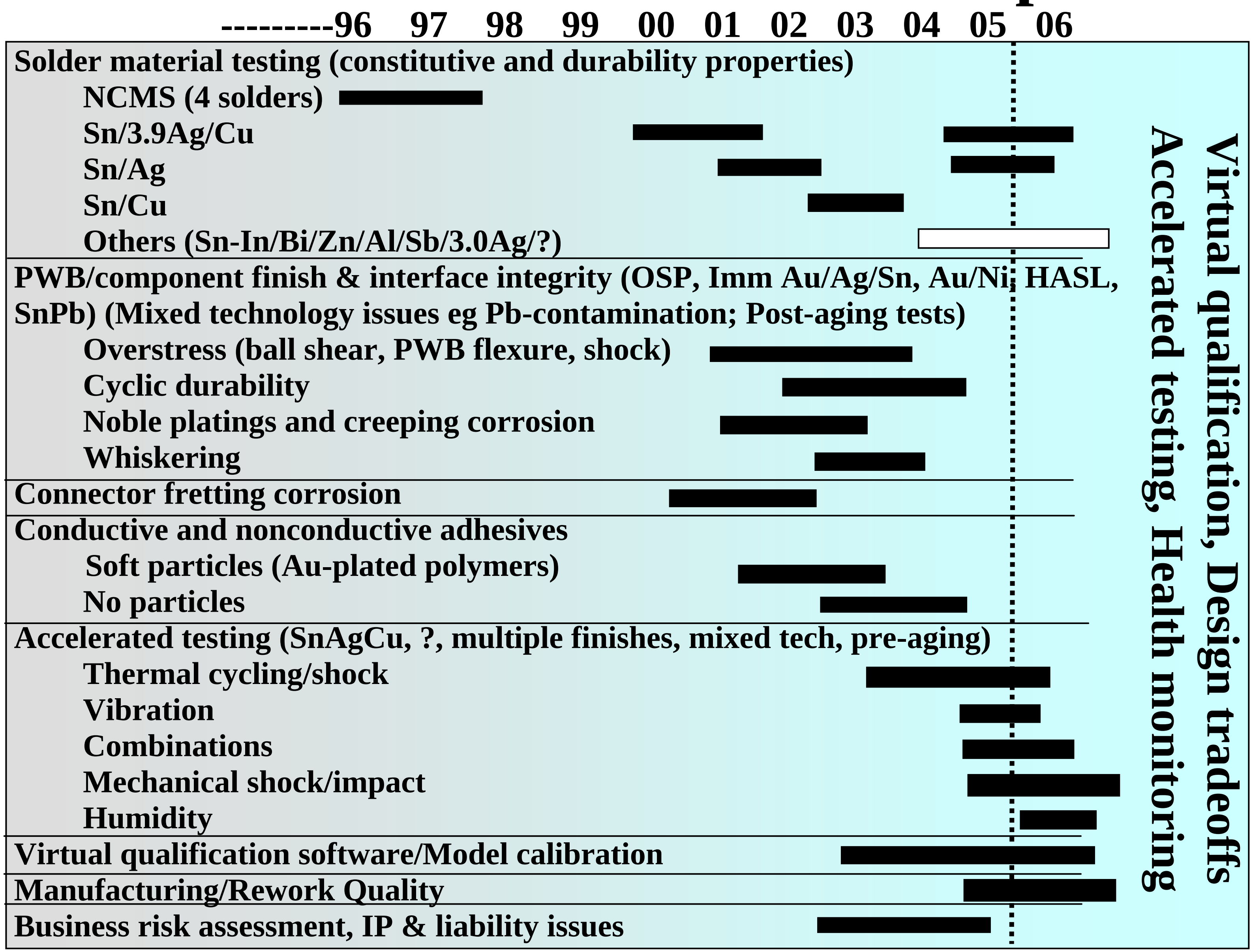
Electronic market sector	Market share 2004
Telecom	41 %
Computers	32 %
Consumer	15 %
Automotive	6 %
Industrial	5 %
Mil/Space	1%

While military electronic equipment is exempt, manufacturers of military systems will feel the impact of the Pb-free conversion process.

Challenges-General Pb-free Electronics

- No exact drop-in replacement for Pb-based materials/components.
- Solder alloy selection may vary based on application.
- Replacements likely to see wide adoption include
  - SnAgCu – Reflow
  - SnAgCu or SnCu or SnCuNi – Wave
  - SnAgCu or SnAg - Rework
- Changes in component finishes, die attach materials, solders joints
  - Higher processing temperatures (pop-corning, board warpage, delamination)
  - Compatibility with Pb-free processing (mixed technology)
  - Indirect failure mechanisms (tin whiskers, creep corrosion)
  - Solder joint reliability (durability, intermetallic growth)

CALCE Pb-free Roadmap

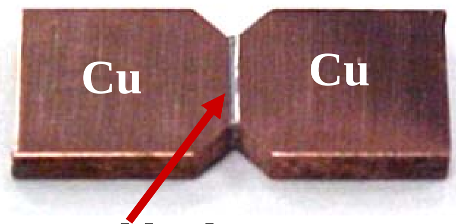


http://www.calce.umd.edu/lead-free/projects.htm

Mechanical Cyclic Fatigue Durability Properties of Pb-free Solder

Objective: Determine cyclic fatigue durability properties of lead-free solder

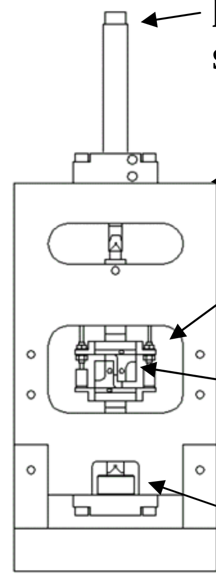
Miniature shear specimen

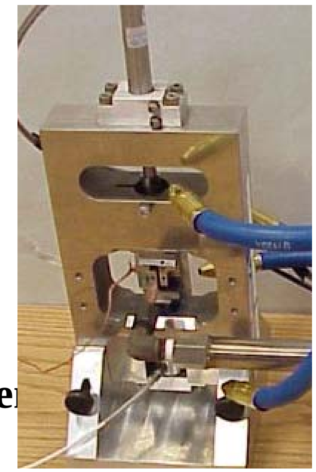


solder layer
(3mm x 1mm x 180 μm)

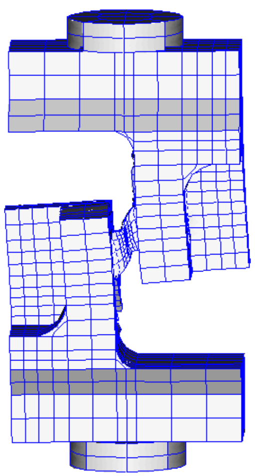
Test Setup

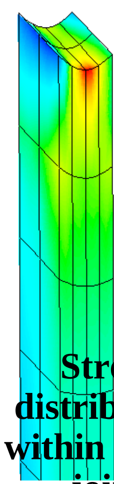
High-precision, custom testing frame provides control necessary for testing of miniature-scale specimens





Model of Test setup

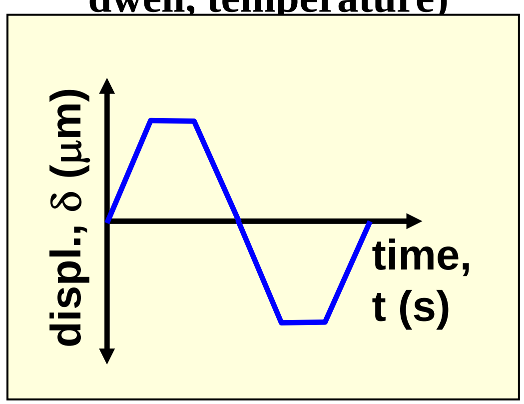




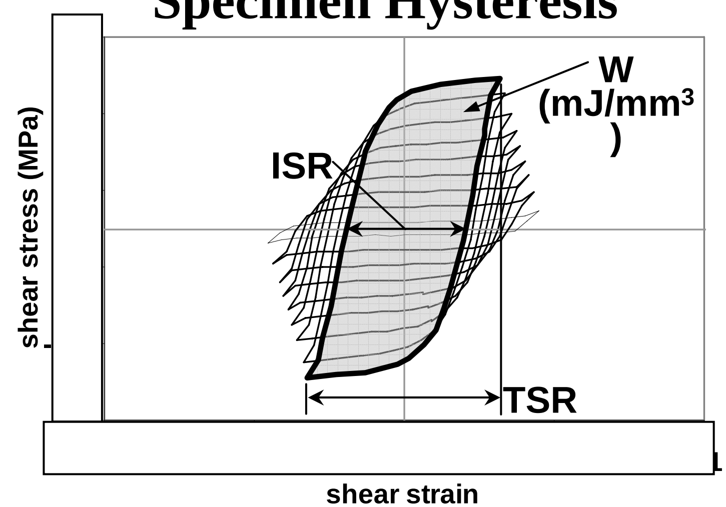
Stress distribution within solder joint

Cyclic durability Tests

= *f*(amplitude, ramp rate, dwell, temperature)

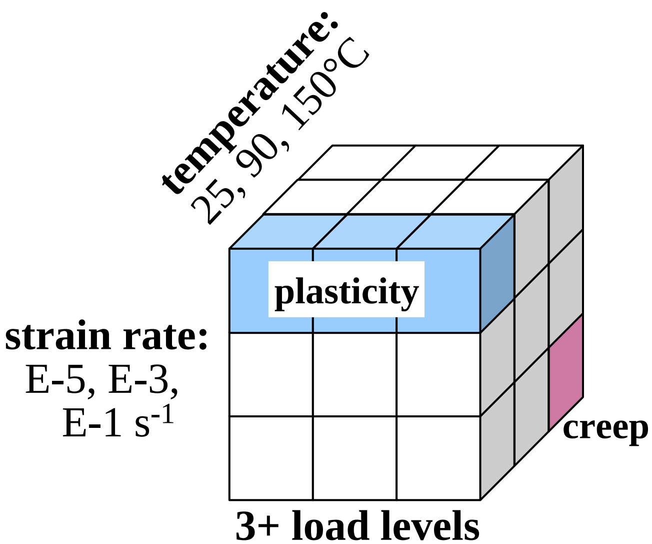


Specimen Hysteresis

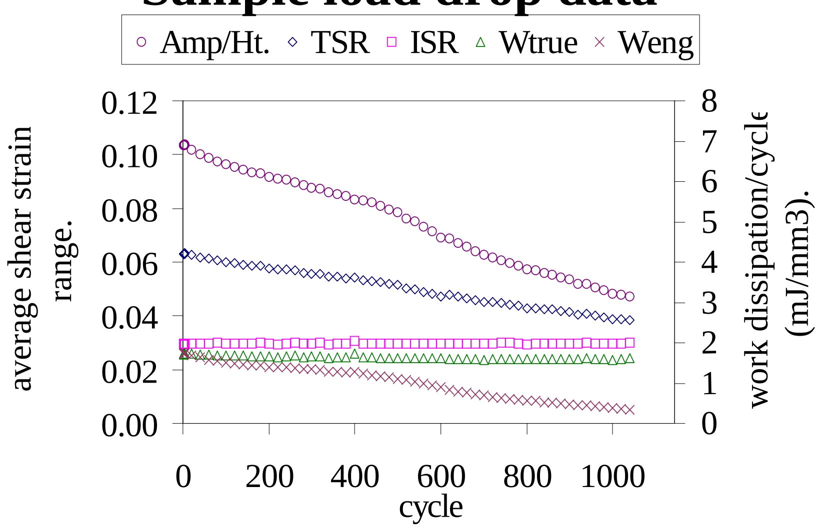


Durability Results Summary

TMM Test Matrix



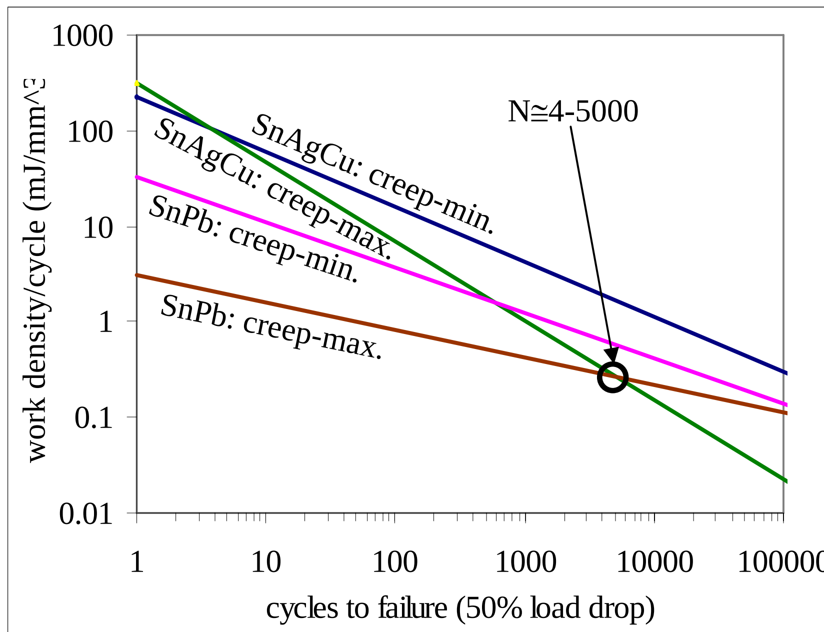
Sample load drop data



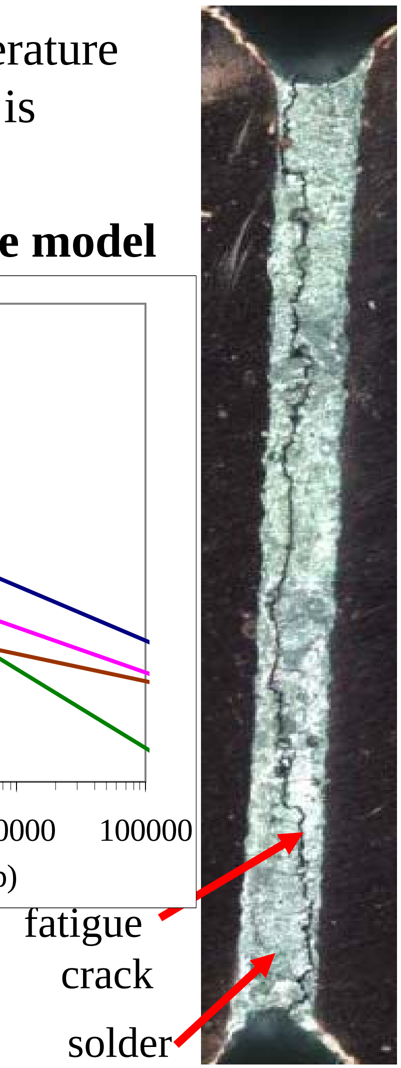
Fatigue test results for Sn3.9Ag0.6Cu

- Low data scatter
- Good agreement with published literature
- Cyclic durability of Sn3.9Ag0.6Cu is favorable to that of Sn63Pb37

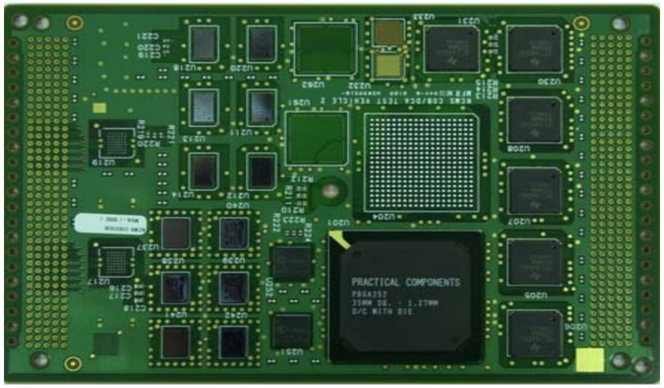
Energy-based fatigue damage model

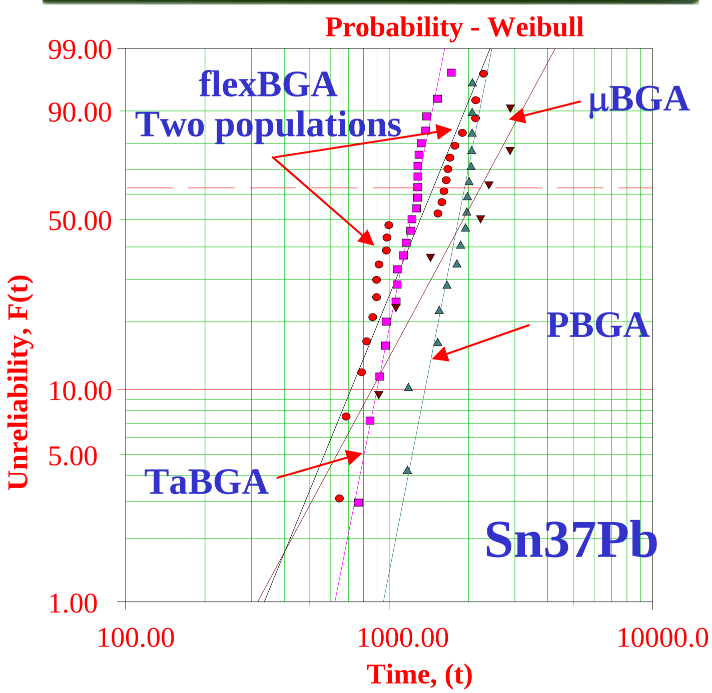


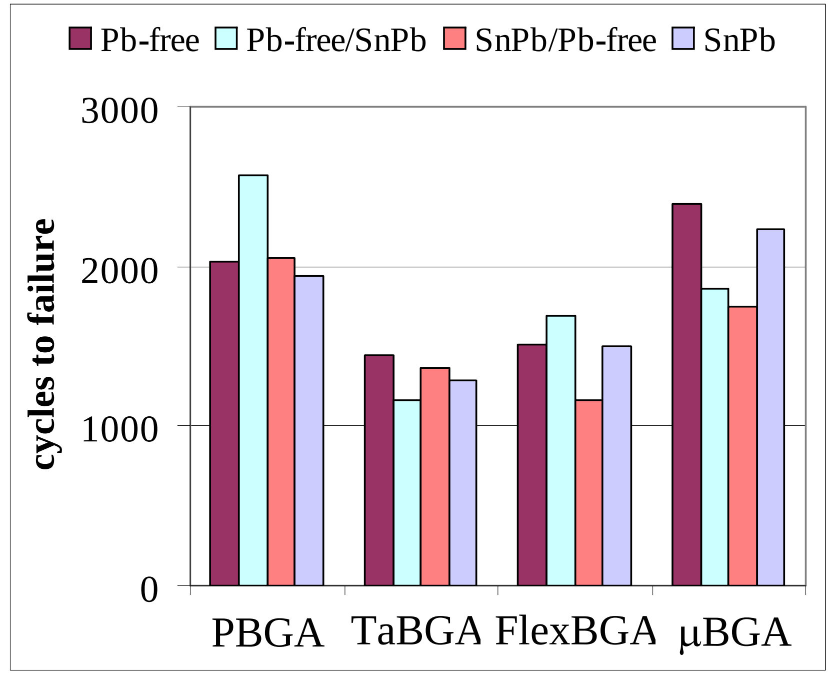
- Active failure mechanisms are verified post-test using optical and electron microscopy



Accelerated Thermal Cycling







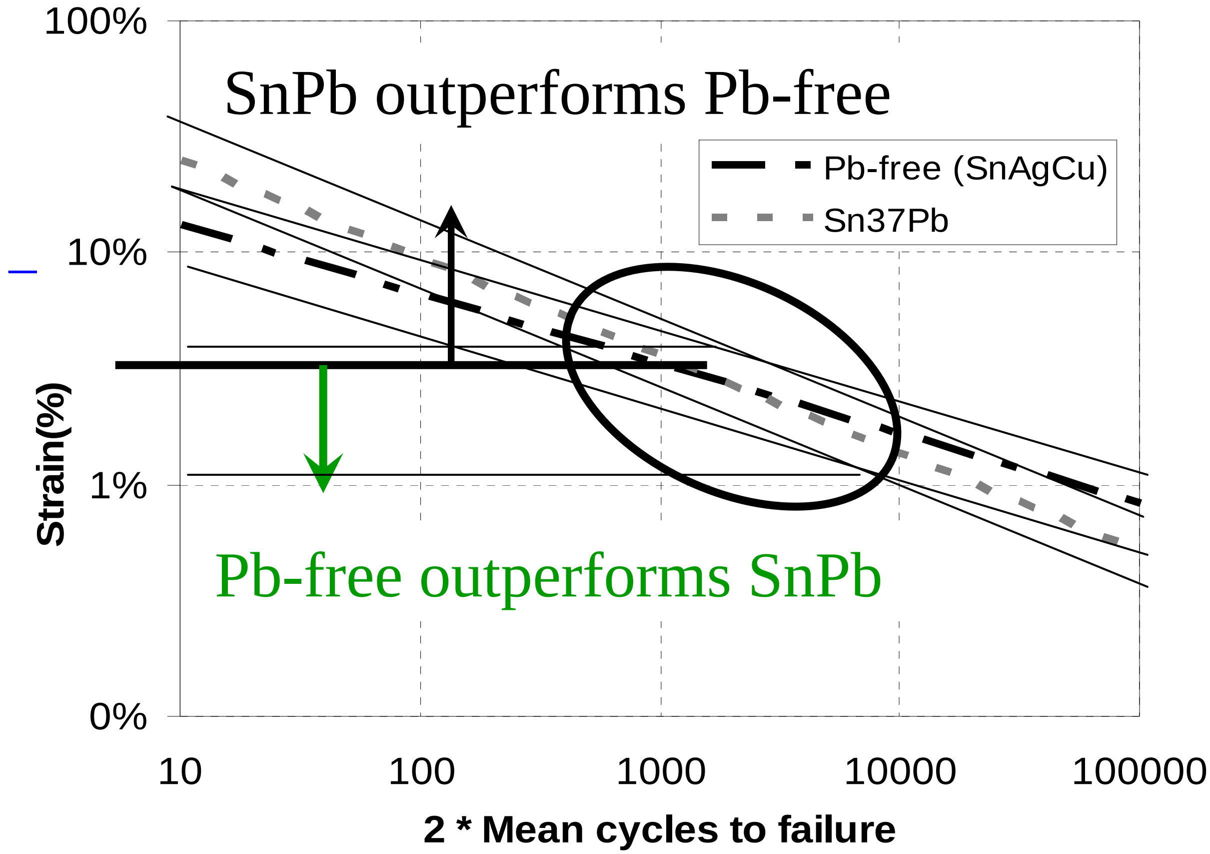
The effect of Pb contamination in mixed technologies

Some observations from tests

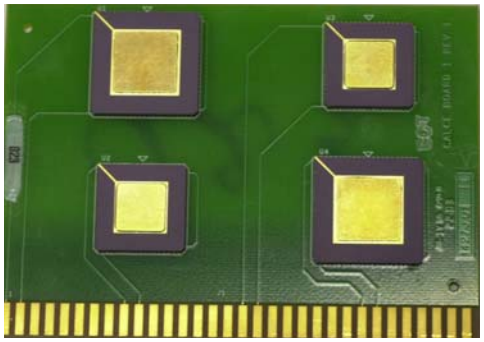
- Some early failures which appeared to be anomalies occurred in mixed systems.
- FlexPBGA144 has two distinct populations (for inner & outer nets)

Durability of Solder under a Temperature Cycle

Experimental data collected under C03-04 allowed CALCE to develop a preliminary rapid assessment model for Sn4.0-3.8Ag0.7Cu solder, released in the calcePWA software. Data consists mostly of standard test conditions (i.e. -40 to 125^{o}C, -55 to 125^{o}C, and 0 to 100^{o}C) with little variation in dwell or mean temperature.



Temperature Effect Study



Test Vehicle

- 68-pin LCCC: 24mm × 24mm, Ceramic
- 84-pin LCCC: 30mm × 30mm, Ceramic
- Board: 130 x 93 x 2.5 mm, FR4

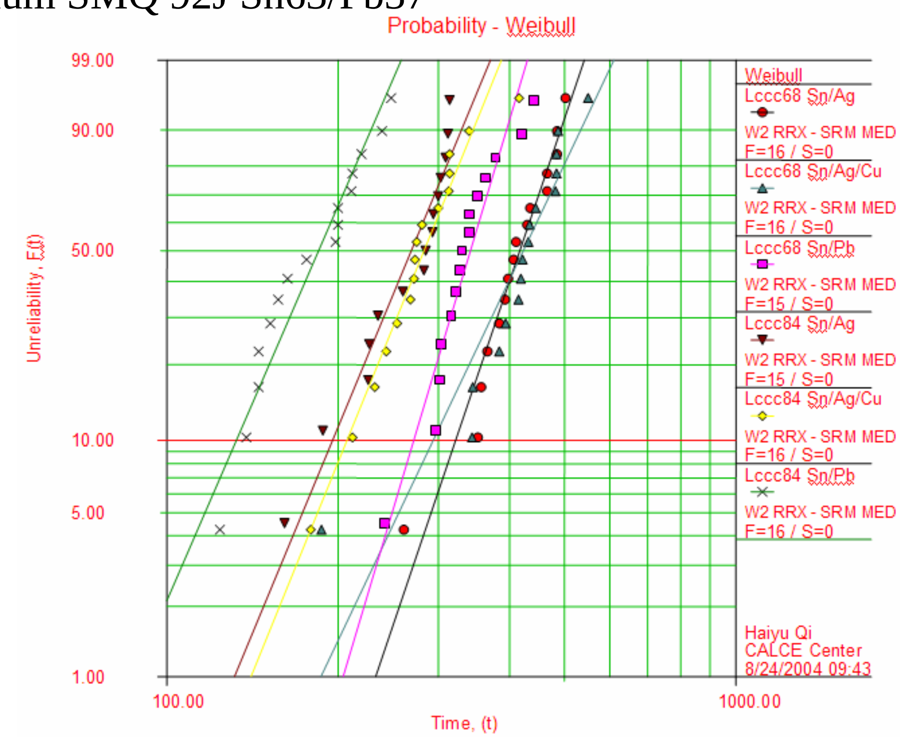
Solders Under Test

- Indium SMQ 230 Sn95.43/Ag3.87/Cu0.7
- Indium SMQ 230 Sn96.5/Ag3.5
- Indium SMQ 92J Sn63/Pb37

Test Matrix

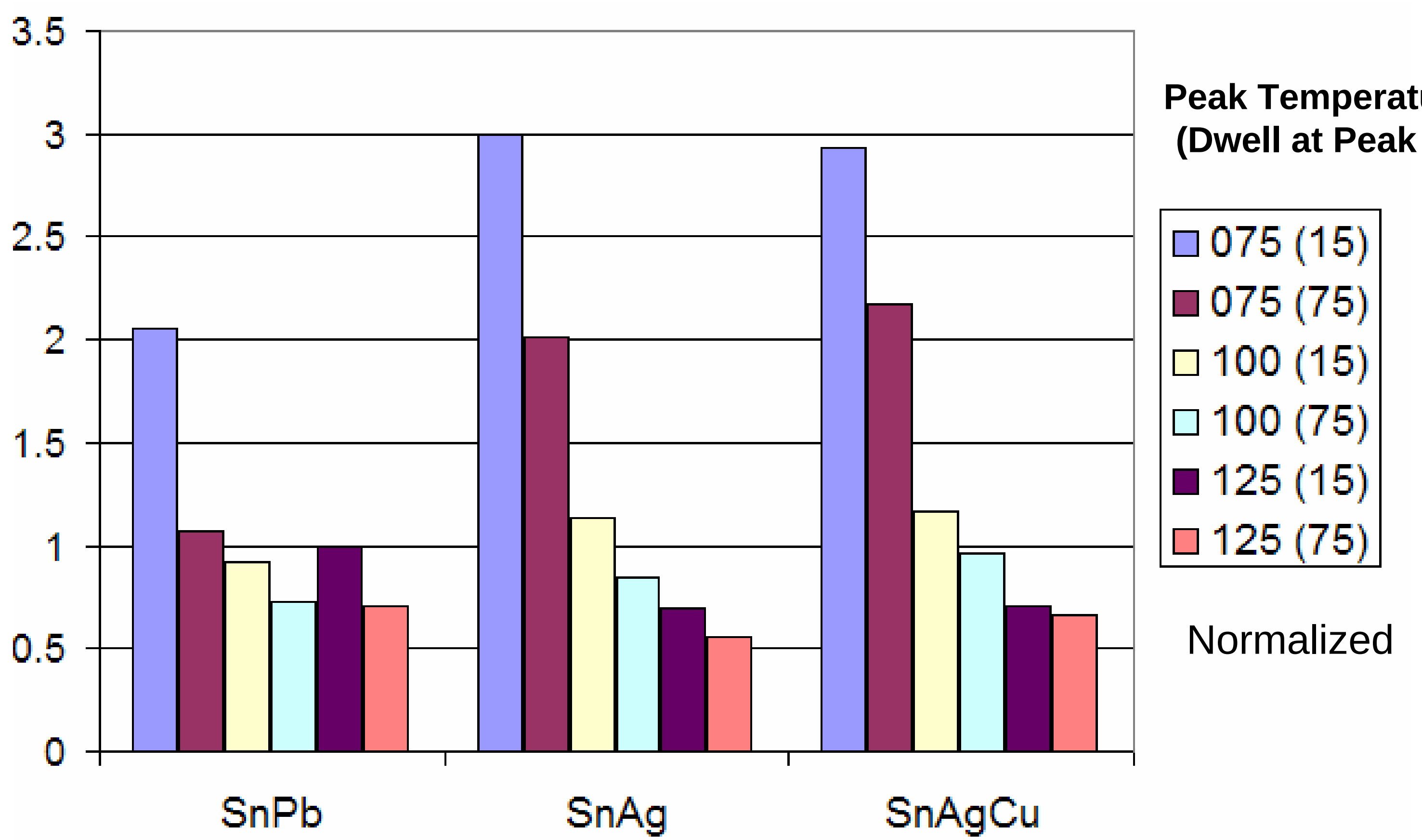
Test	Min Temp (˚C)	Max Range (˚C)	Dwell Time (min)	Status
1	0	100	15	Completed
2	25	125	15	Completed
3	-25	75	15	Completed
4	0	100	75*	Completed
5	25	125	75*	Completed
6	-25	75	75*	Completed
7	15	85	15	Pending
8	15	85	75*	Pending

* Extended dwell at max temp only. Dwell at min temp fixed at 15 minutes



Test Results for T_{mean} = 50ºC, ΔT=100ºC

Comparison of Time to Failure (68 IO Package)



For the Pb-free solders, increasing the average cyclic temperature showed a decrease in time to failure. As can be seen in the above chart, the behavior of the SnPb solder at the 100 and 125°C peak temperature shows non-monotonically decreasing behavior.

Rapid Failure Assessment Software for Pb-free

$$N_f = \frac{1}{2}\left(\frac{\Delta\gamma}{2\varepsilon_f}\right)^{\frac{1}{c}}$$

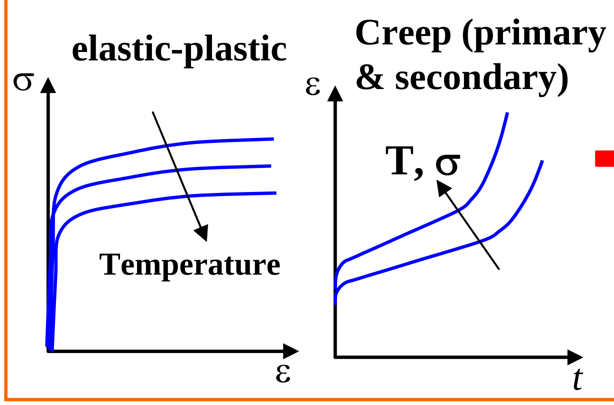
- N_f : mean number of cycles to failure
- $\Delta\gamma_p$: inelastic strain range
- ε_f, c : material constants

- Qualitative graph represents CalcePWA model predictions for SnPb and SnAgCu solders.
- Crossing point likely to shift due to temperature cycle parameters (i.e. mean temperature, temperature range, dwell time, and ramp rate)

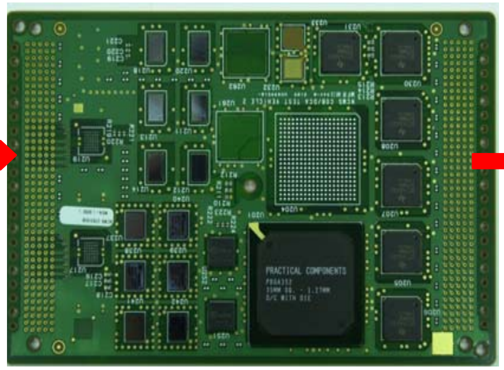
On-going efforts in rapid assessment of printed wiring assemblies has resulted in a preliminary model for assessing failure of Pb-free (SnAgCu) solder package to board interconnects.

Energy-Partitioning Damage Model:
Approach for Thermal Cycling

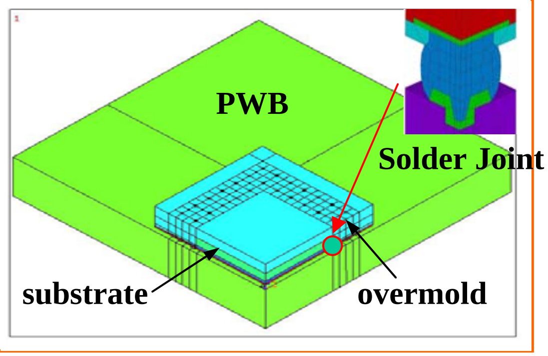
1 **Constitutive Properties of Solders**



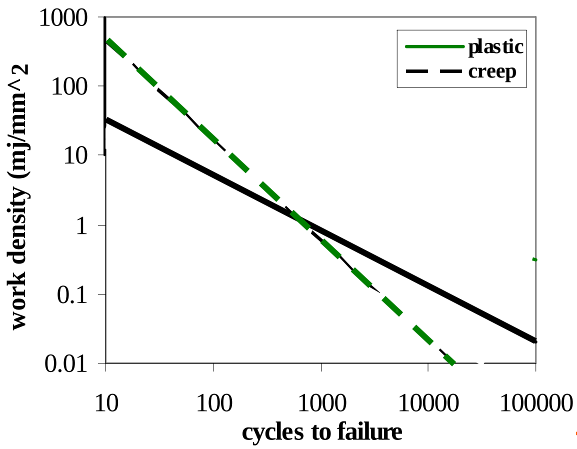
Test Vehicle



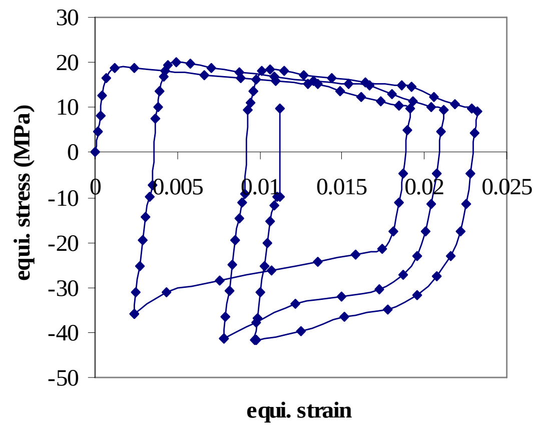
2 **Package Architecture**



4 **E-P Model**



3 **Stress-Strain Hysteresis**



plastic work density
creep work density

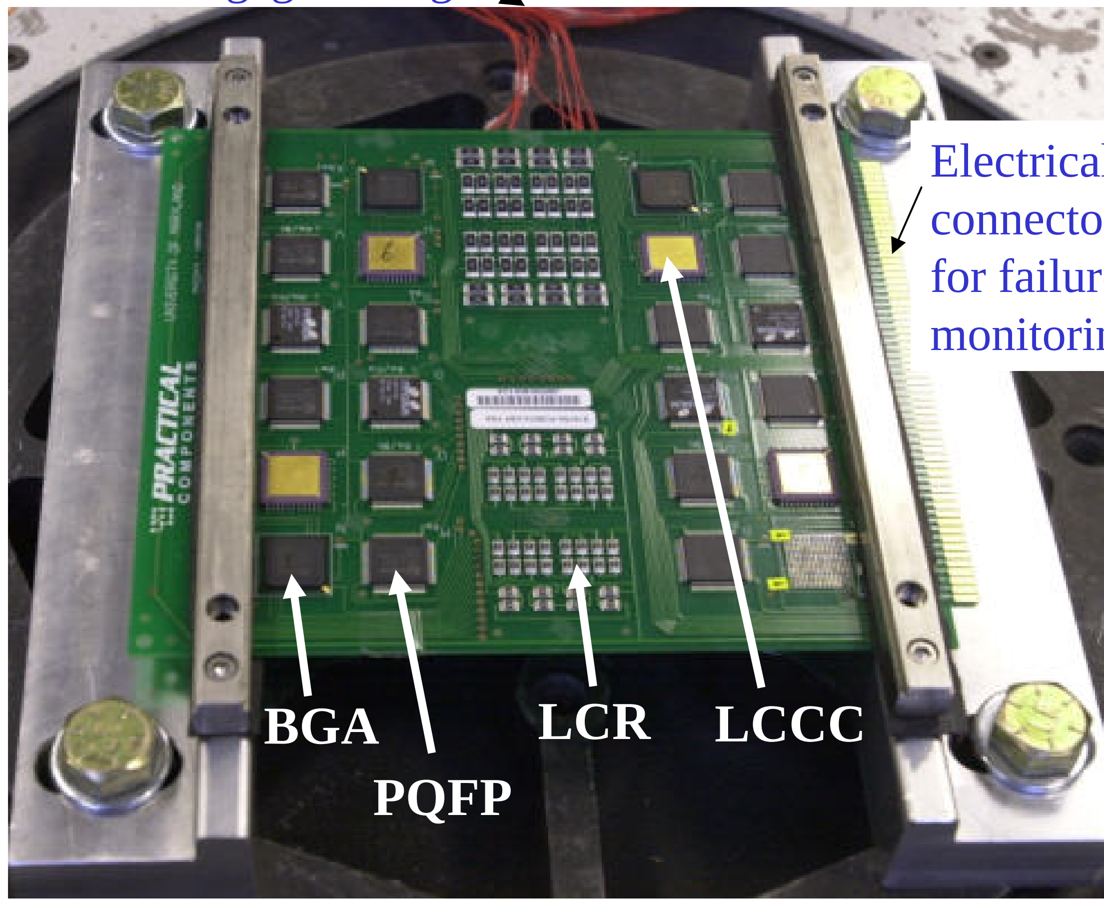
plastic damage N_{fp}
creep damage N_{fc}

5 **Total cycles to failure:** $\frac{1}{N_{ft}} = \frac{1}{N_{fp}} + \frac{1}{N_{fc}}$

Vibration Testing of Pb-free Assemblies

Pre-treatment	High temp storage 150ºC / 100 hours	
	SnPb HASL	SAC OSP
Overstress test (G_f)	3	3
Stress level 1 ($0.8G_f$)	3	3
Stress level 2 ($0.6G_f$)	3	3

Vibration Test Matrix



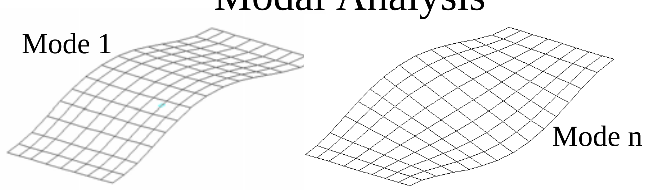
Vibration Test Configuration

All components are daisy-chained and monitored real-time for failure

Time Domain Vibration Durability Assessment

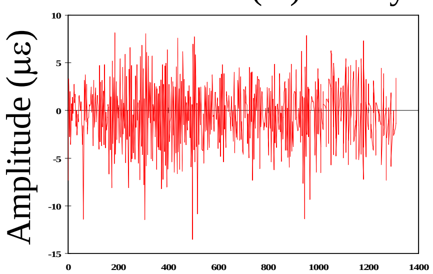
1a Global PWB Vibration Characterization

Modal Analysis

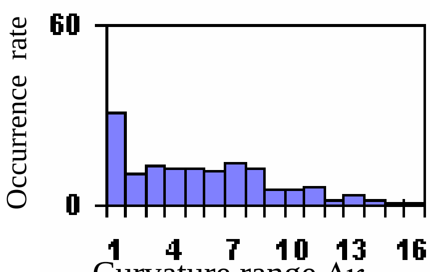


1b Vibration Response

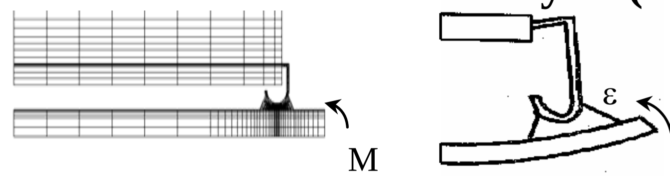
PWB curvature (κ) history

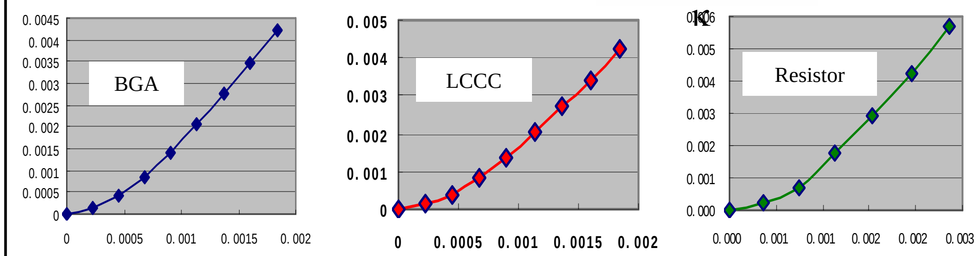


1c PWB curvature Range Distribution function (RDF) from cycle counting



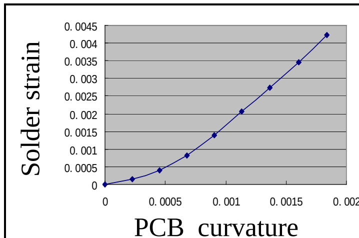
2 Local Interconnect Stress Analysis (C04-02)

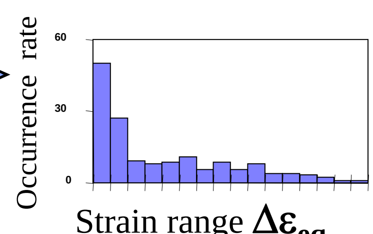




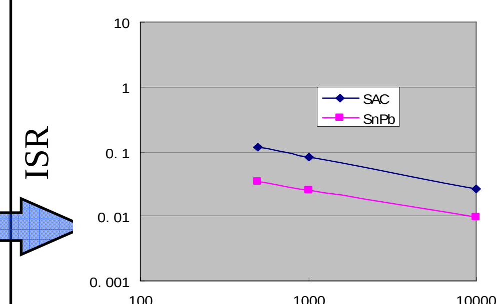
Solder strain as a fn of PWB curvature

3 Solder strain RDF





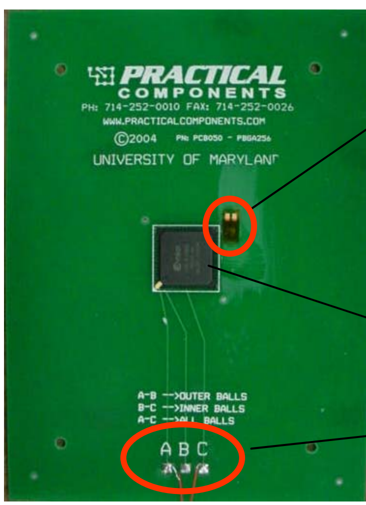
4 Vibration Durability Estimate based on Fatigue Damage



Impact Testing of Pb-free Assemblies

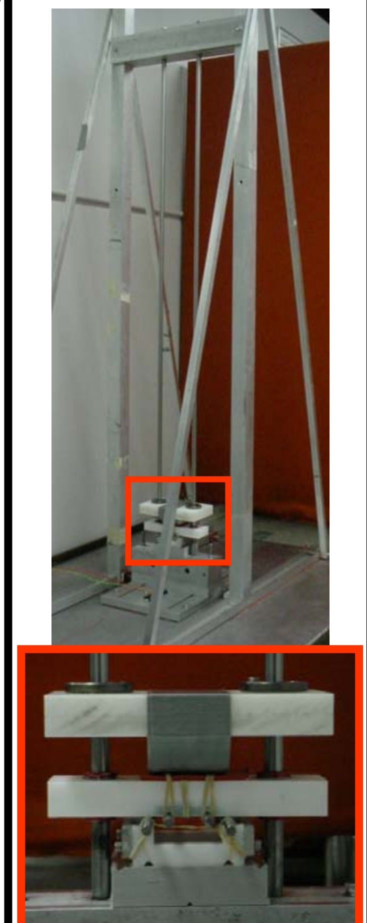
Specimen Design

- Plastic Ball Grid Array (PBGA) component
- 256 balls, 1mm pitch, full grid, daisy chained.
- Eutectic 63/37 Sn-Pb solder with OSP finish
- 5.5”X4”X0.062” FR4 printed wiring board



Test Setup

- Flexural loads
- Inertial loads



Instrumentation

- Strain gage on specimen
- Accelerometer on fixture
- Resistance monitoring system for failure detection
- 4 channel high speed data acquisition system
- LabView

Drops to Failure (N)

$$N = f(\varepsilon, \dot{\varepsilon}, a)$$

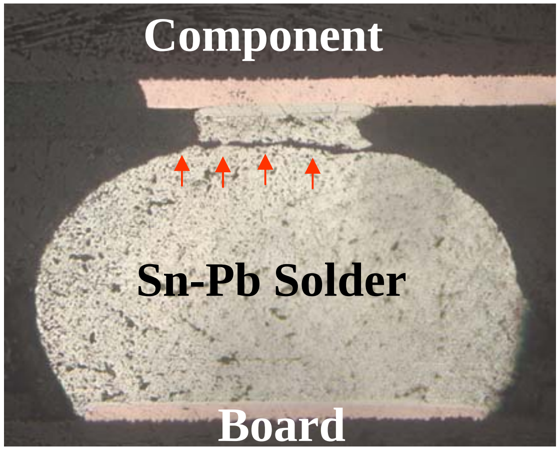
ε: PWA strain

$\dot{\varepsilon}$: PWA strain rate

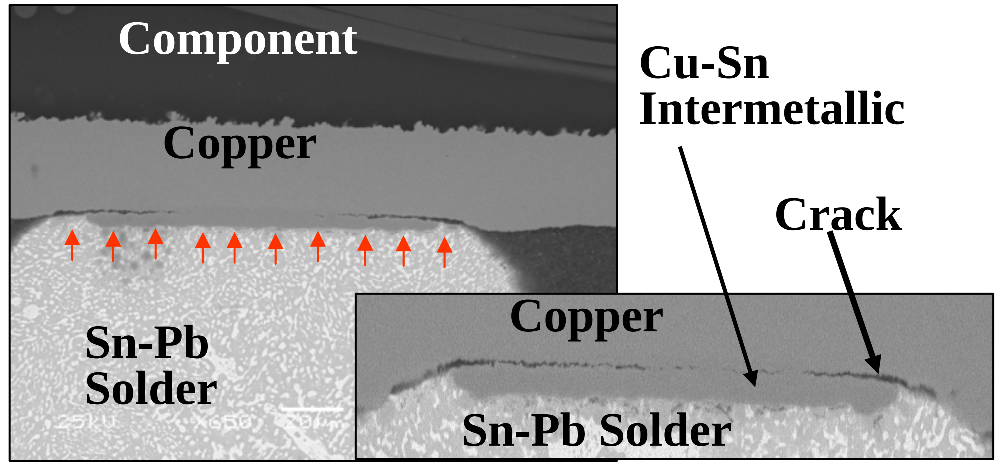
a: Component acceleration

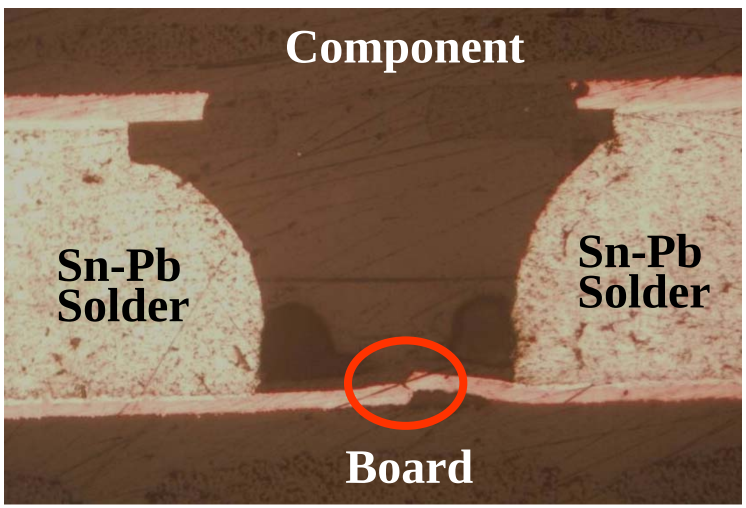
Failure Analysis: High Speed Flexure

Bulk solder failure

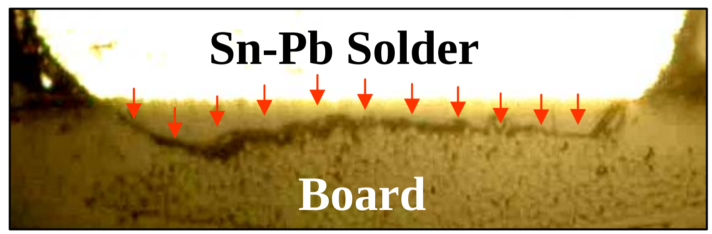


Intermetallic failure





Copper trace failure

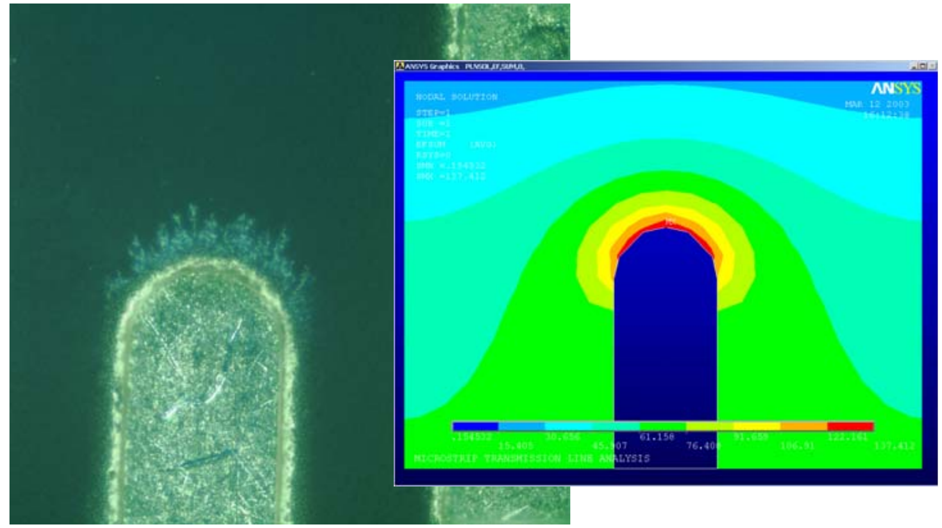


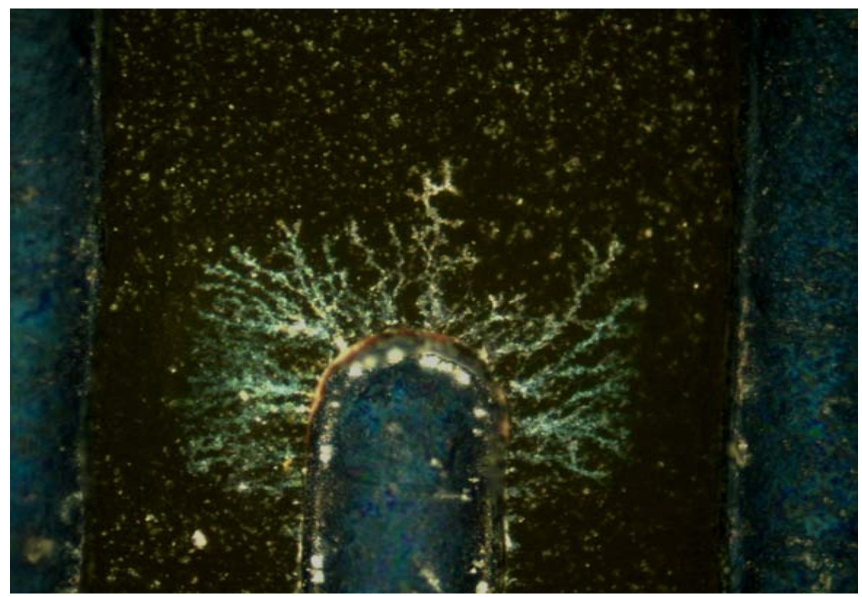
FR4 board failure

Failure site moves from bulk solder to intermetallic or copper trace as the PWA flexure rate increases.

Electrochemical Migration in the Age of Pb-Free

- What does Pb-Free mean to electrochemical migration (ECM)?
  - New plating materials
  - New interconnect materials
  - New flux chemistries
- ECM and alternative platings
  - ENIG and ImSn dependent upon plating quality
  - ImAg dependent upon electric field
- Sn-Based Alloys
  - Use environment likely to be acidic with the presence of oxygen and halides
  - Potential for order of magnitude increase in corrosion rate



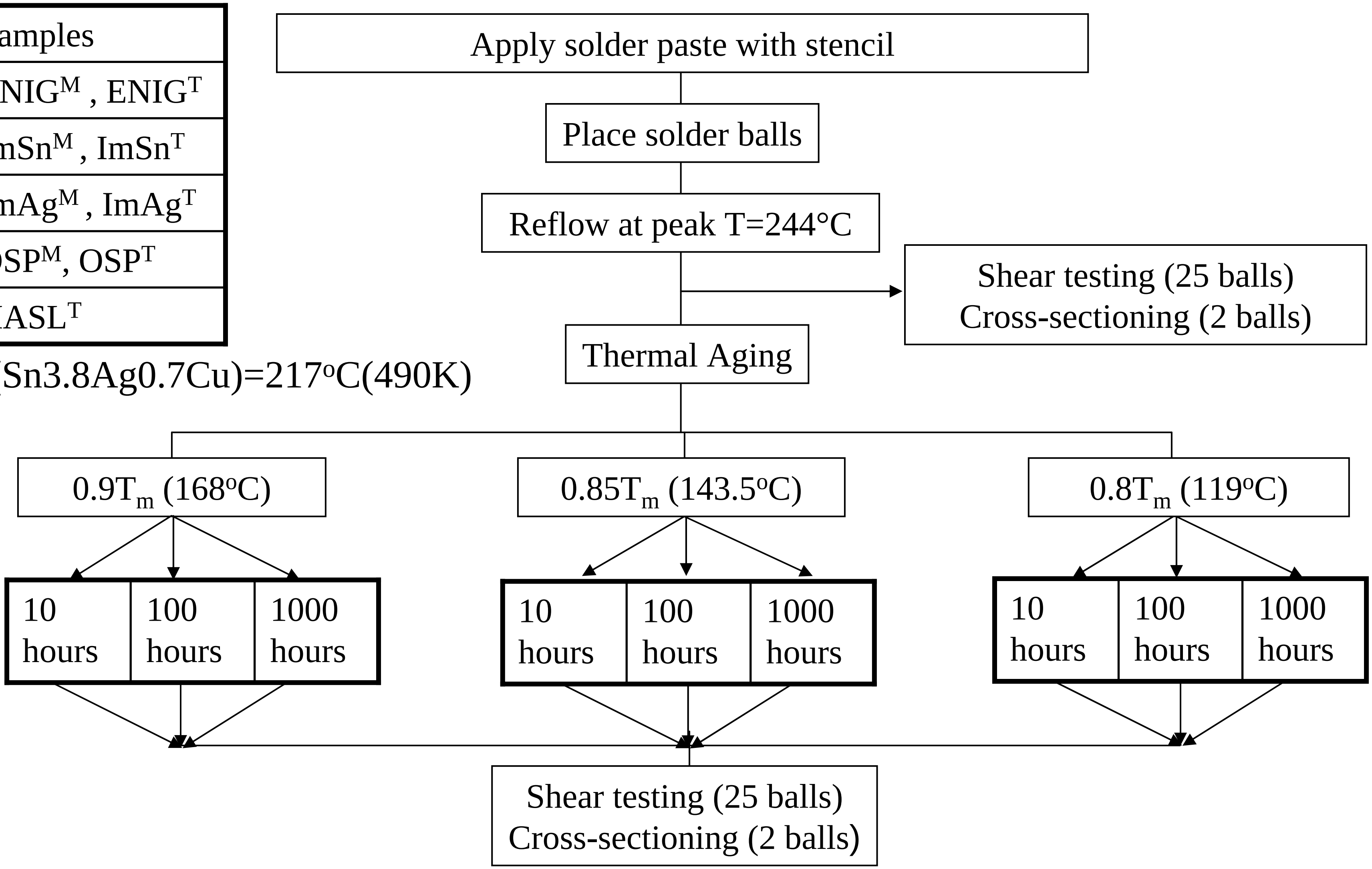


PWB Plating Study

Five different platings from two manufacturers were reflow soldered with Sn3.8Ag0.7Cu to determine the intermetallic formation and shear strength.

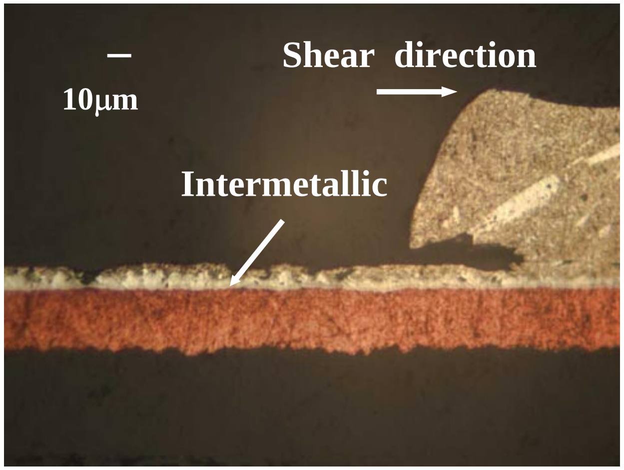
Samples
$ENIG^M$, $ENIG^T$
$ImSn^M$, $ImSn^T$
$ImAg^M$, $ImAg^T$
OSP^M, OSP^T
$HASL^T$

T_m(Sn3.8Ag0.7Cu)=217°C(490K)

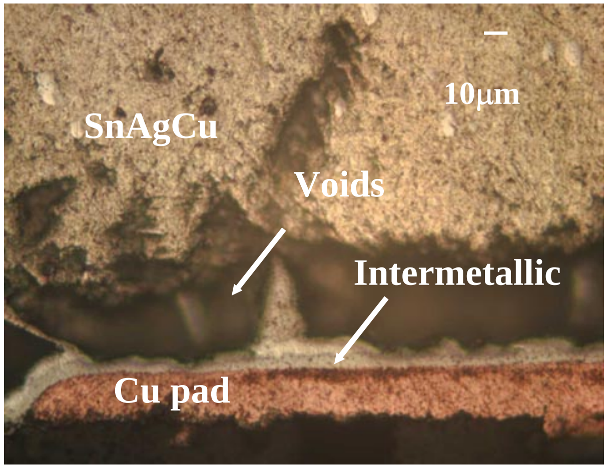


Sn-3.8Ag-0.7Cu and HASL^{T} Boards

A CALCE Study showed a weakened interface on HASL boards, which were soldered with Sn-3.8Ag-0.7Cu. After high temperature aging, the failure mode in shear testing shifted from the bulk solder to the interface (left) and over time, void bands were observed (right).



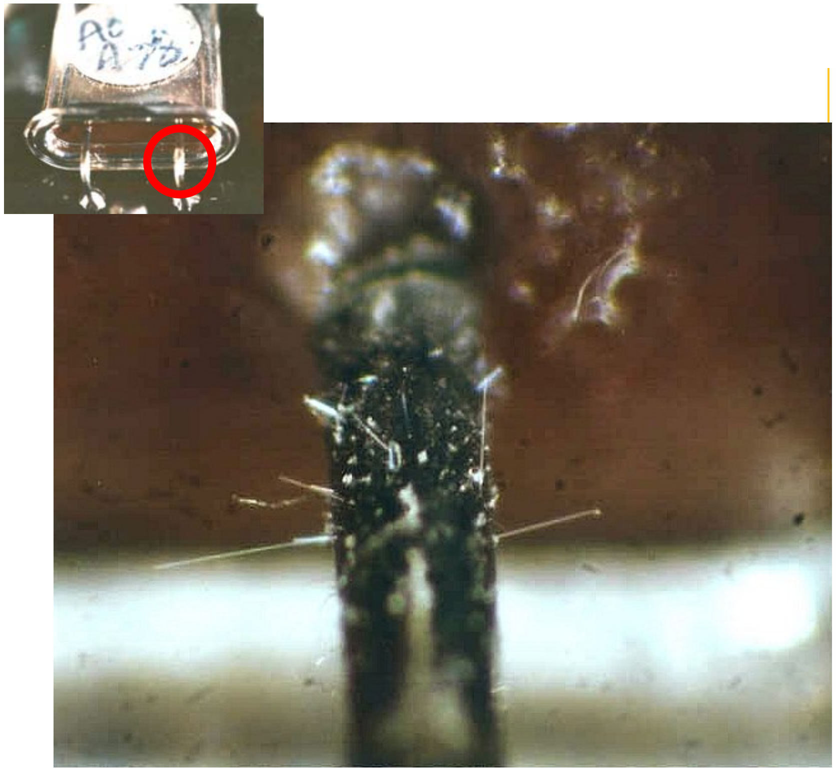
Shear testing failure at the interface between SnAgCu and intermetallic on HASL^{T} after aging 100 hours at $0.9T_m$ (168^{o}C)



Voids observed at the interface between SnAgCu and intermetallic after 1000 hours aging at $0.9T_m$

The most probable cause is tin depletion at the interface as tin from the HASL coating migrates toward the pad and forms intermetallics with copper, creating a weaker localized Pb rich region in the coating.

CALCE Tin Whisker Study



Tin Whisker Information

Tin Whisker Alert (Whitepaper) A candid discussion of the concern over failures in electronics related to "tin-whiskers" and its potential re-emergence due to the move lead-free solders.

Tin Whisker Risks (Whitepaper) A technical discussion of the "tin-whiskers" phenomenon, current knowledge and remaining questions.

Tin Whisker Experiences (Whitepaper) A collection of experiences where "tin-whiskers" have been observed.

Tin Whisker Mitigation Guide (Whitepaper) A guide for mitigating the risk of tin-whiskers as a failure source in electronic hardware.

In addition to conducting multiple research projects on lead free solder issues this past year, CALCE joined with a number of companies to author an alert regarding the use of pure tin as a surface finish.

This alert was followed closely by a mitigation guide authored by CALCE with inputs from companies participating in the Tin Whisker Alert Working Group.

http://www.calce.umd.edu/lead-free/tin-whiskers

CALCE Tin Whisker Team Studies (Roadmap)

2002

Tin Whisker Alert and Related Risks

CALCE Tin Whisker Team

C03-30

Tin Whisker Mitigation Guide

- Solder Dip
  - -No whisker was found at solder-dipped portion
  - -Sample size was too small
- Annealing and Reflow Tests
  - -Initiated experiments with bright and matte tin over brass, Cu, and alloy 42.
- Supplier survey
- Conformal Coating
  - -Initiated experiments to investigate the environmental conditions for tin whisker growth

TMTI Project -Solder Dipping-

C04-07

Bending, current, solder dipping, and current study

-Continue to monitor tin whisker growth on the specimens
-Focus on the specimens with Cu base

Monitoring finish selection of part suppliers; collecting, examining, and monitoring samples for whisker growth

Update of tin whisker mitigation guide

-Testing was conducted at Boeing/Raytheon

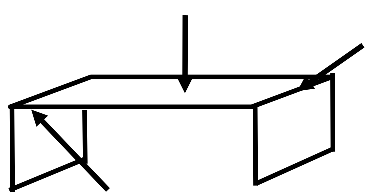
-Whisker could grow through some types of conformal coating

C05-O8

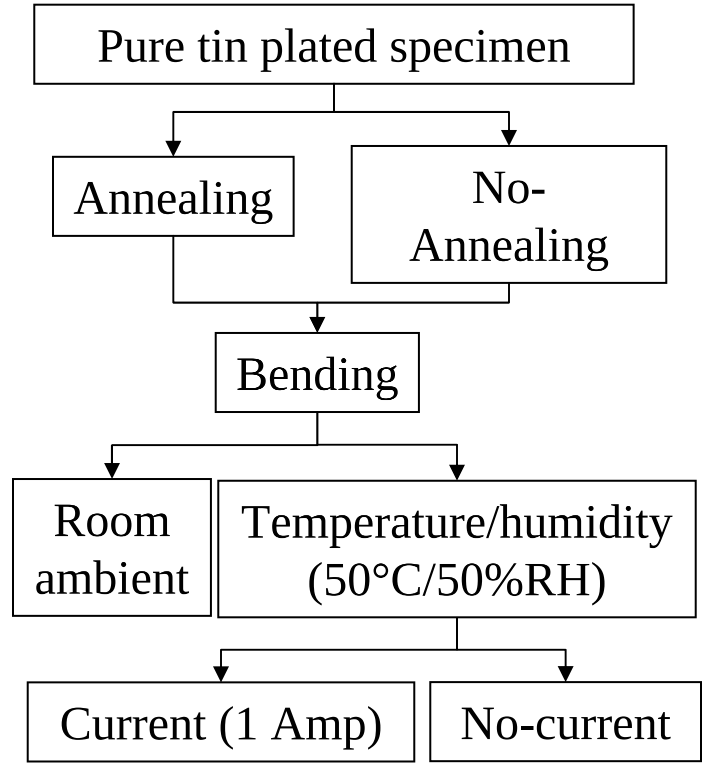
Tin whisker risk assessment methods and whisker growth studies

Bending and Current Study

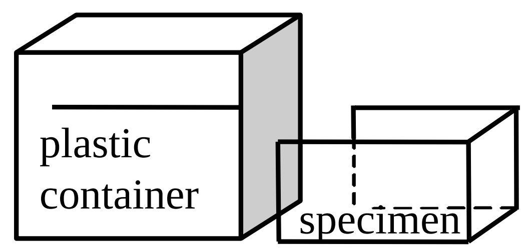
- Specimens
  - Size: 1.25”x0.5”x0.006”
  - Base material: Cu (Olin 194)
  - Plating: bright and matte tin (5μm thick)
- Pre-conditioning
  - Annealing at 150°C for one hour immediately after the plating (half of the specimens)
- Exposure
  - Temperature/humidity (50°C/50%RH)
    - Current (1 Amp) - half of the specimens
  - Room ambient
- Whisker observation
  - Specimens were periodically monitored (one week, 10 days, weekly afterwards).
  - Specimen were taken out of the chamber only during the surface observation.
  - Observation portions:



Test flow chart



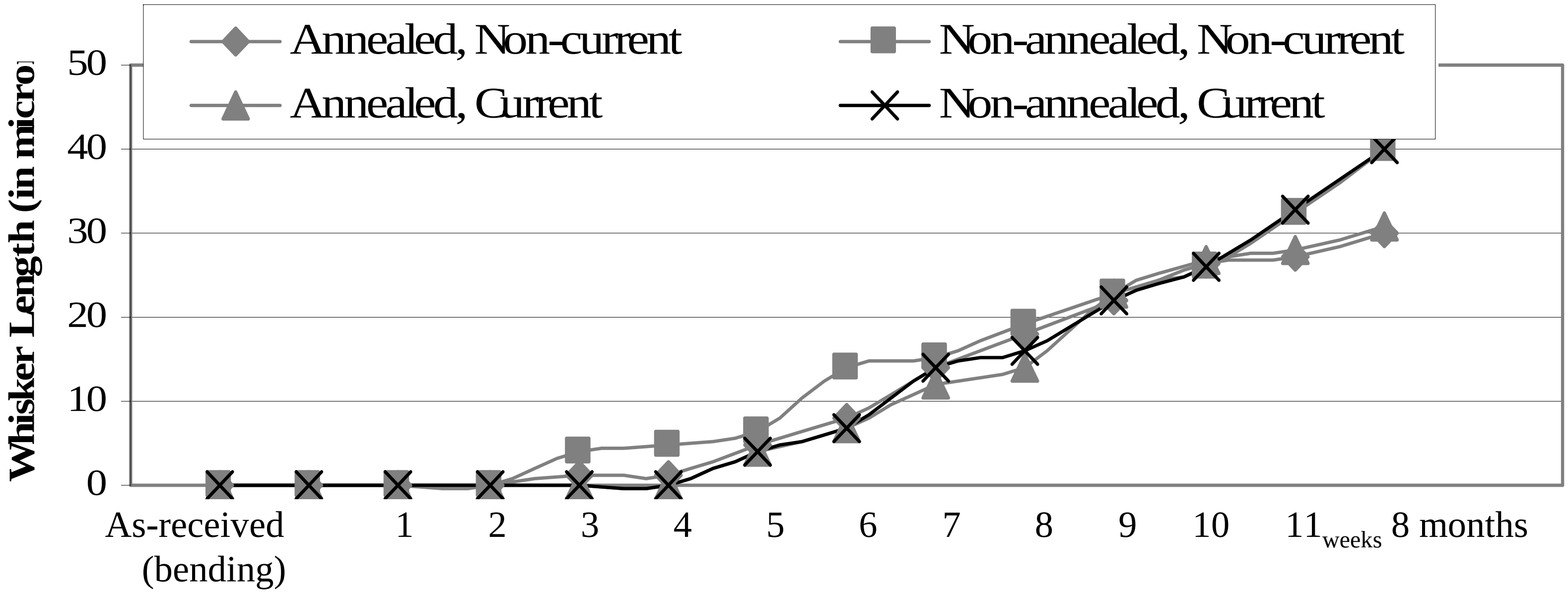
Bending method



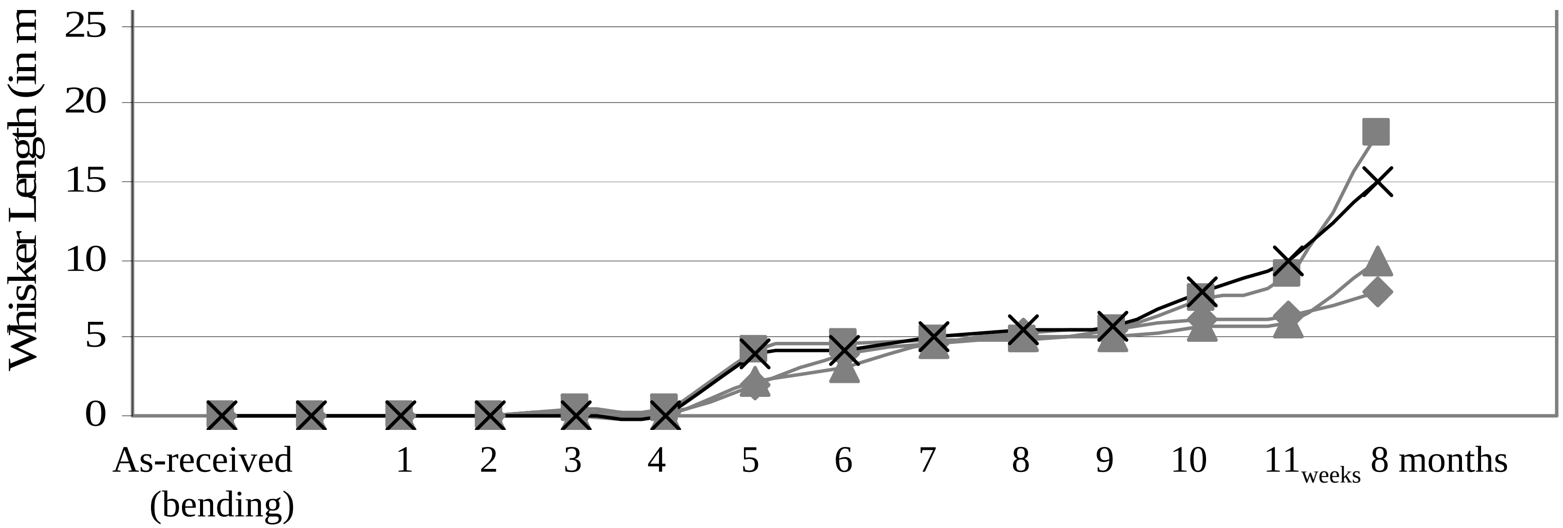
Maximum Whisker Length – Change with Time

- Inner Curve -

Bright tin



Matte tin



CALCE Pb-free Research 2005

C05-01 Effects of Manufacturing Variables on Quality and Durability of Lead Free Solder Joints (Continuation of C04-26)

C05-02 Accelerated Qualification of SAC Assembly: Combined Temperature Cycling & Vibration

C05-40 Durability of Pb-free Electronic Interconnects Under Impact Loading

C05-03 Reliability of SnAgCu Solder for High Temperature/High Power Assemblies

C05-04 Experiments to Validate calcePWA Vibration Model (Pb/Sn & Sn/Ag/Cu)

C05-05 Virtual Qualification of Pb-free Power Electronic Assemblies

C05-06 Effect of Temperature Cycle on the Durability Lead Free Interconnects (Sn-Ag-Cu and Sn-Ag) – Continued

C05-07 Durability of Reworked Pb-free and Mixed (Pb-free/SnPb) Solders Interconnects

C05-08 Tin Whisker Risk Metric and Mitigation Strategies for Electronic Assemblies

C05-09 Characterization of Moisture Absorption and Desorption FBGA Package in Storage and Lead-Free Reflow Soldering Conditions

C05-10 Robustness of Ceramic Capacitors Assembled with Pb-Free Solder

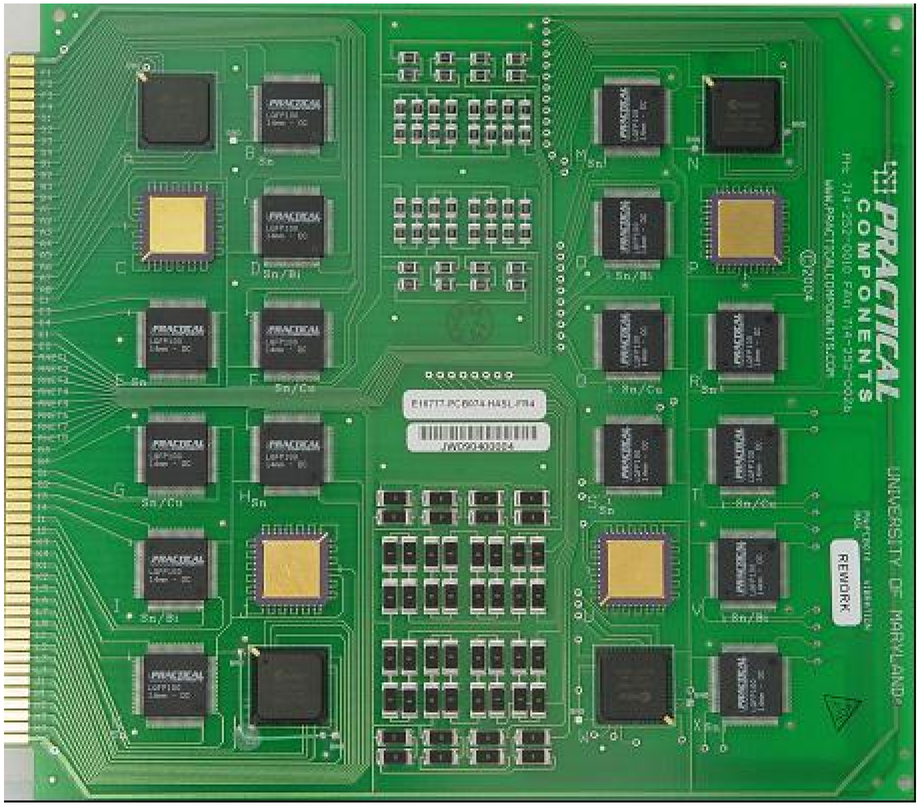
C05-11 Reliable Large-Area Pb-free Interconnects for Photovoltaic Cells Reliability and Failure Assessment

CALCE Pb-free Research Proposals 2006

P06-H4 Determination of Kinematic Hardening Coefficient of Pb-free Solder
P06-O5 Effect of Temperature Cycle on the Durability Pb-free Interconnects(Sn96.5Ag3.0Cu0.5 and Sn99.2Cu0.7Ni0.1)
P06-O7 Effect of Load Sequencing on Pb-free Solder Durability
P06-B3 Experiments to Validate calcePWA Vibration Damage Model (Pb/Sn & Sn/Ag/Cu) (continuation of C05-04)
P06-A1 Effect of Manufacturing Variability on Reliability of Pb-free Solder Joints (Continuation of C05-01)
P06-A5 Reliable Large-Area Pb-free Interconnects for Photovoltaic Cells (Continuation of C05-11)
P06-A8 Effect of Characteristic Relaxation Time on Accelerated Thermal Cycling Profiles for SAC Solders
P06-Z1 Electrochemical Migration on Lead-free Printed Circuit Boards with No-Clean Flux Technology
P06-M2 Investigation of High Temperature Green Solder Materials
P06-O4 Effect of Pb-free Reflow on Electrolytic and Box Capacitors
P06-G4 Characterization of Tin Pest Formation in Pb-free Solder Joints

Long-term Pb-free Reliability Study

- CALCE EPSC is conducting a comprehensive long-term lead-free reliability study supported by many companies.
- The goal of the study is to determine critical information related to the long-term (5-15 years) reliability of lead-free assemblies.
- This is a great opportunity for companies to benefit from these studies in a cost-effective way.
- Participation cost: $45K



CALCE Long-term Pb-free Reliability Study Experimental Matrix

Pre-treatment	Accelerated stressing	Solder and PCB pad finish				
		Sn-Pb	SAC	SAC	SAC	SAC
		HASL	Immersion Ag	Immersion Sn	ENIG	OSP
High temp. storage (150ºC/100 hours)	Vibration test	✓	✓	✓	✓	✓
High temp. storage (150ºC/350 hours)	Vibration test	✓	✓	✓	✓	✓
Low temp. storage (-55ºC/500 hours)	Vibration test	✓	✓	✓	✓	✓
Low temp. storage (-55ºC/1000 hours)	Vibration test	✓	✓	✓	✓	✓
None (Control)	Vibration test	✓	✓	✓	✓	✓
Not applicable	HAST (130ºC / 85%RH / 672 hours) + Bias (for corrosion test structure)	✓	✓	✓	✓	✓
None	Temp. cycling (-40ºC to 125ºC)	✓	✓	✓	✓	✓
None	Temp. cycling + vibration	✓	✓	✓	✓	✓

CALCE Lead Free Forum Web Site

- Current Issues
- Projects
- Services
- Training
- Articles
- Presentations
- Related Research Groups
- Contact Us

Lead Free and Green Electronics Forum

The CALCE Electronic Products and Systems Center's Lead Free Forum is dedicated to the collection, generation, organization, and dissemination of information related in the manufacture, assembly, and fielding of lead free and "green" electronic products and systems.

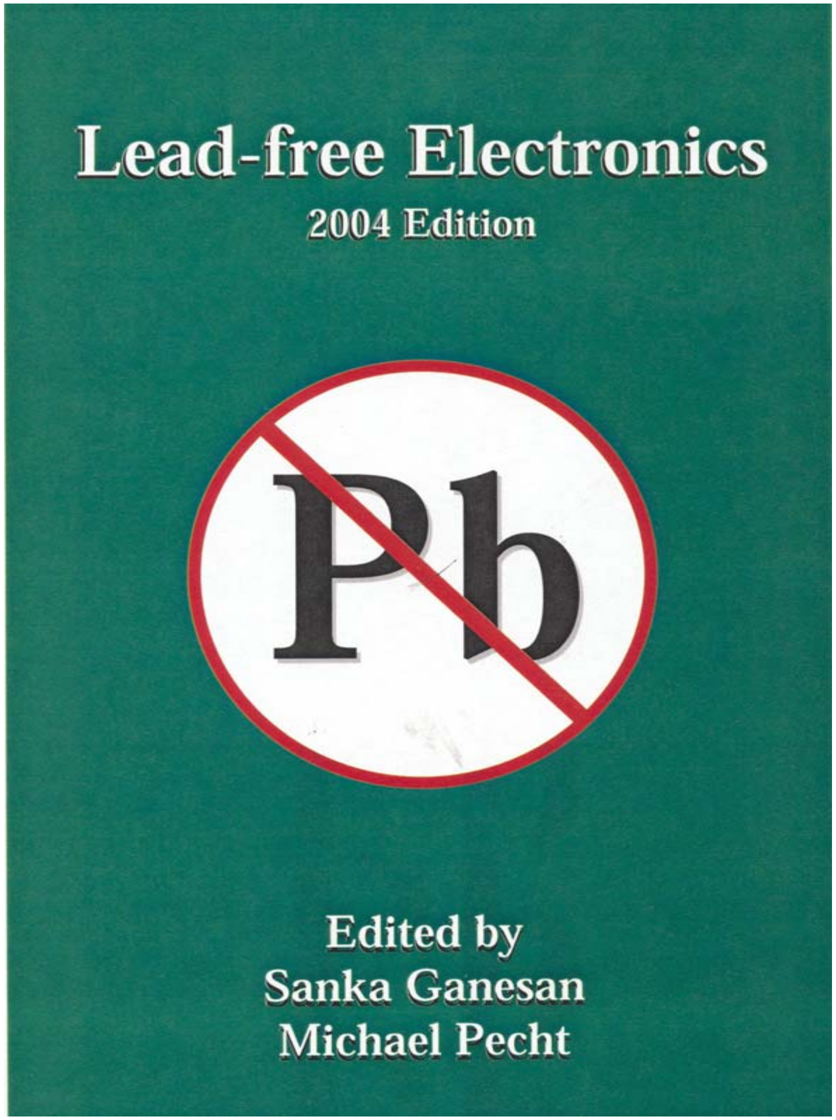
Current Issues and Events:

- CALCE Long-Term Reliability Study for Pb-free Assemblies CALCE has initiated a reliability study of Pb-free assemblies to examine issues related to PWB surface and component terminal finish and durability of package to board interconnects under temperature cycling, vibration, and combined temperature cycling and vibration conditions.
- Part Suppliers Survey (Updated 6/30/04) (CALCE Consortium Member's Only) MS Excel Spreadsheet) A survey of electronic part suppliers. The survey represents information collected though review of public postings from part suppliers, as well as direct contact with representatives of the part supplier. The information gathering is an on-going activity. Individuals are encouraged to check with their part suppliers to obtain the latest information.
- Lead-free Electronics - 2004 Edition A new reference book for Pb-free electronics is now available from CALCE EPSC Press. (CALCE Consortium Members)
- CALCE Pb-Free Patent Finder Software (Members' Only) A software tool for examining existing international patents for Pb-Free Solders. This software was developed in part under C03-01. (Updated Version 1.0.1 posted 2/17/04)
- Tin Whisker Studies Information related to the tin whisker as a potential source of failure in electronic hardware.

http://www.calce.umd.edu/lead-free/

Pb-Free Resources

http://www.calce.umd.edu/general/published/books/books.html



- Chapter 1 Lead-free Electronics: Overview
- Chapter 2 Lead-free Alloys: Overview
- Chapter 3 Constitutive Properties and Durability of Lead-free Solders
- Chapter 4 Interfacial Reactions and Performance of Lead-free Joints
- Chapter 5 Lead-free Manufacturing
- Chapter 6 Component-level Issues in Lead-free Electronics
- Chapter 7 Conductive Adhesives
- Chapter 8 Lead-free Separable Contacts and Connectors
- Chapter 9 Intellectual Property
- Chapter 10 Costs to Lead-free Migration
- Chapter 11 Lead-free Technologies in the Japanese Electronics Industry

CALCE Contact Information

- **Dr. Michael Pecht,** Center Director, Founder and Technical Advisor, Reliability & Supply Chain Policies
  301-405-5323, pecht@calce.umd.edu
- **Dr. Michael Osterman,** Consortium Operations Director, Software Development
  301-405-8023, osterman@eng.umd.edu
- **Dr. Abhijit Dasgupta,** Interconnect Reliability, Accelerated Testing
  301-405-5251, dasgupta@calce.umd.edu
- **Dr. Ji Wu,** Connecters & IC Sockets, Lead-Free Materials
  301-405-0765, jwu@calce.umd.edu
- **Dr. Bongtae Han,** Stress Measurement , Optical Measurement Techniques

  301-405-5255, bthan@calce.umd.edu
- **Dr. Patrick McCluskey,** Power Electronics, Component Reliability

  301-405-0279, mcclupa@calce.umd.edu
- **Dr. Diganta Das,** Parts Selection & Management
  301-405-5323, digudas@calce.umd.edu