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

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Formed 1987

ISO 9001 Certified, 1999

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What is CALCE?

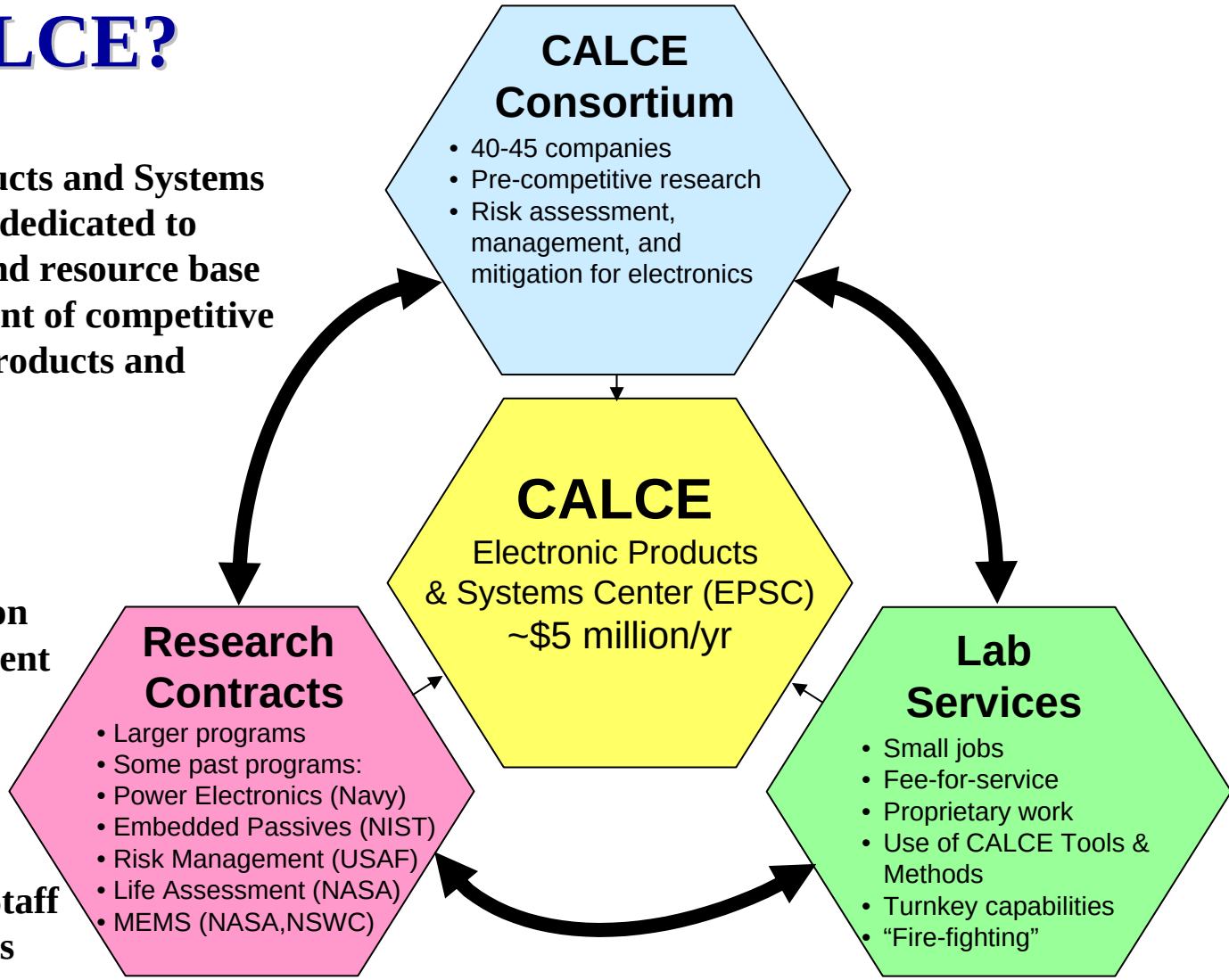
CALCE EPSC Mission:

CALCE Electronic Products and Systems Center (founded 1987) is dedicated to providing a knowledge and resource base to support the development 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



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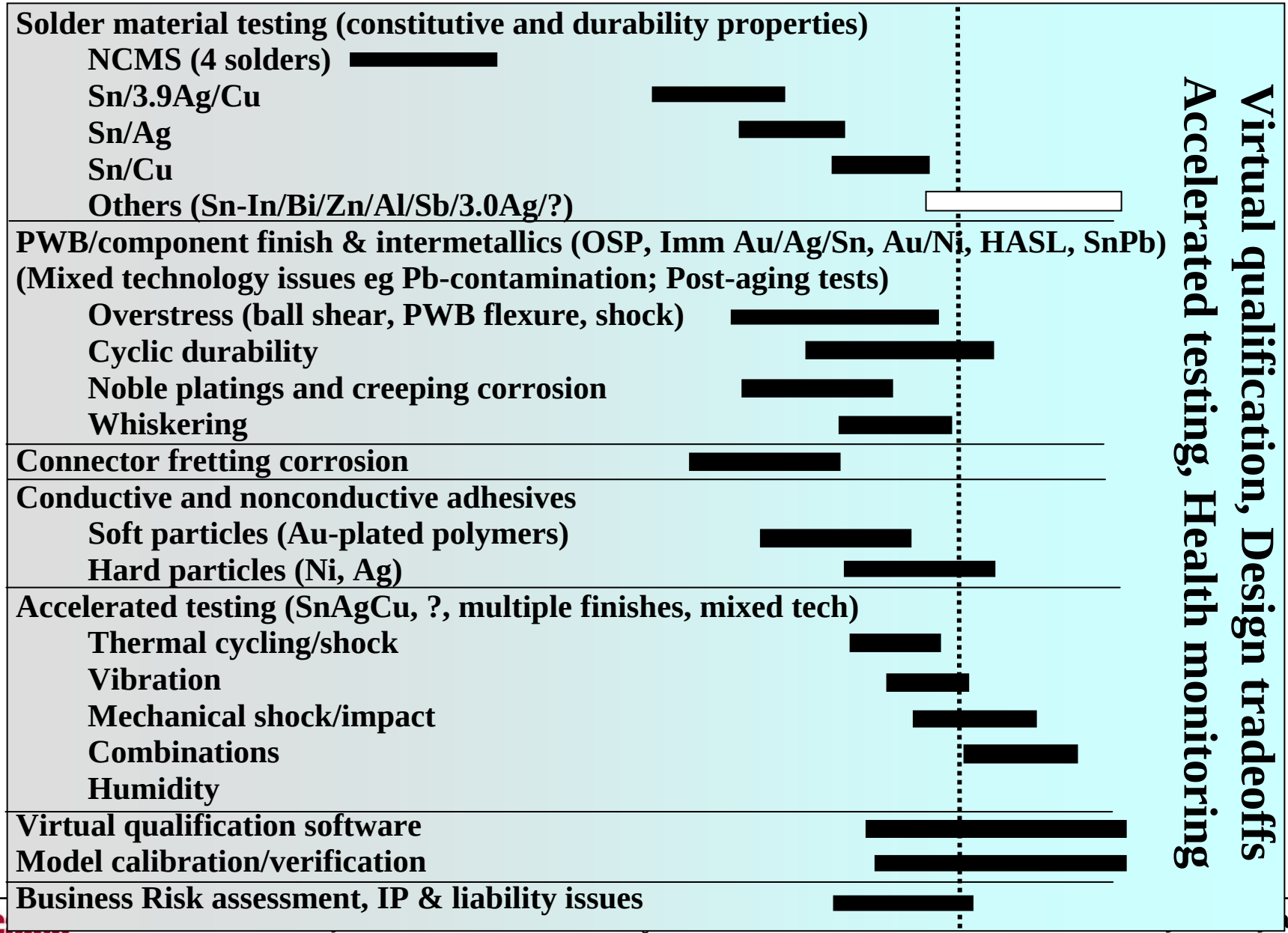
CALCE Pb-free Tasks: Draft Roadmap



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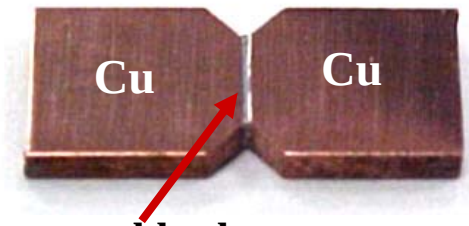
Mechanical Cyclic Fatigue Durability Properties of Pb-free Solder

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

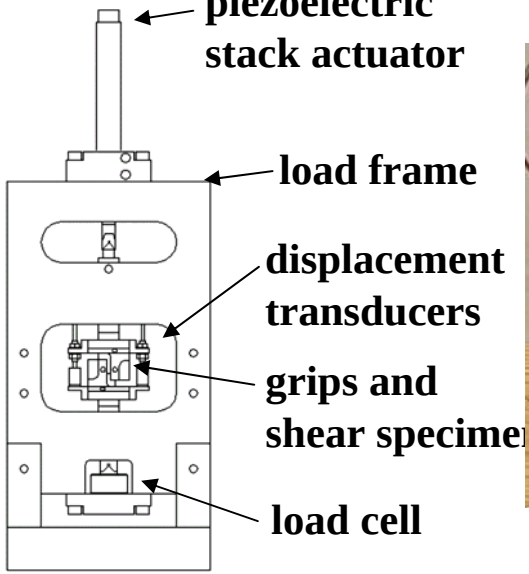
Miniature shear specimen

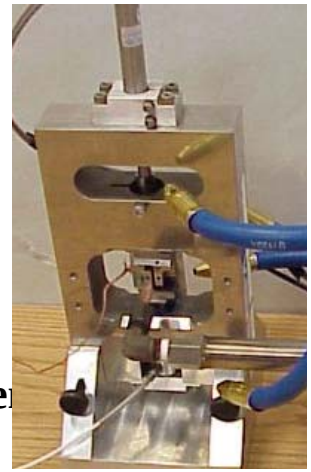


solder layer
(3mm x 1mm x 180 μm)

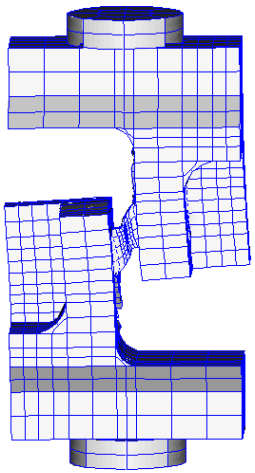
Test Setup

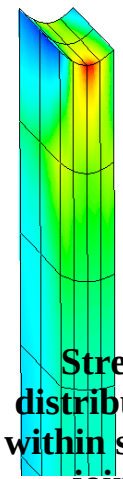
High-precision, custom testing frame provides control necessary for testing of miniature-scale specimens





Model of Test setup

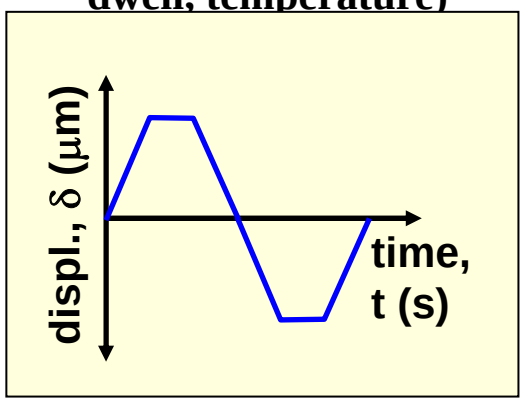




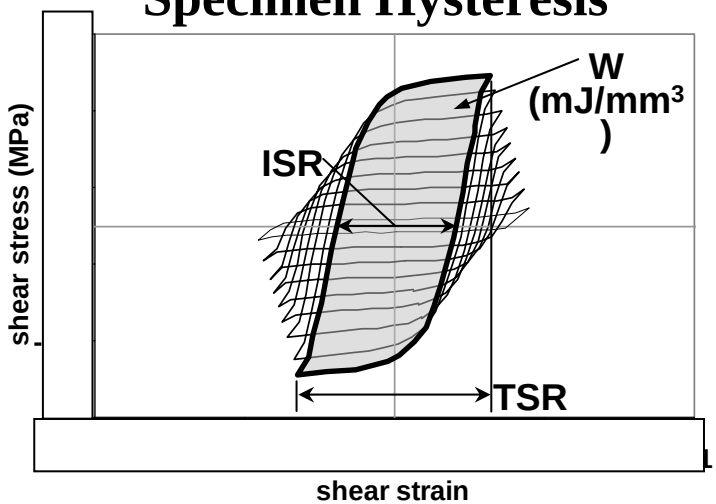
Stress distribution within solder joint

Cyclic durability Tests

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



Specimen Hysteresis



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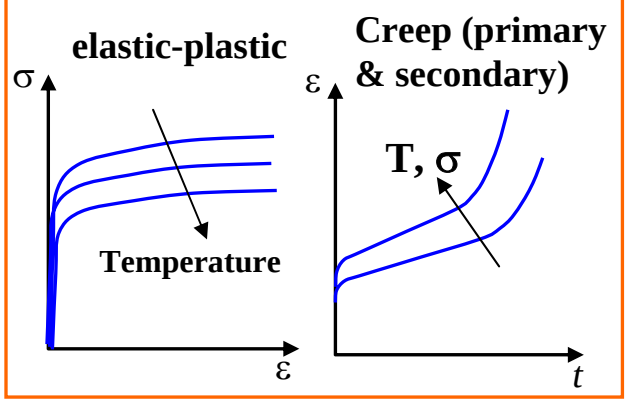
Energy-Partitioning Damage Model:
Approach for Mechanical Cycling

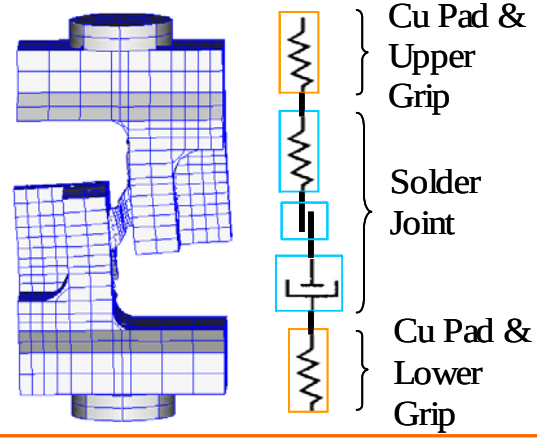
1

Constitutive Properties of Solders



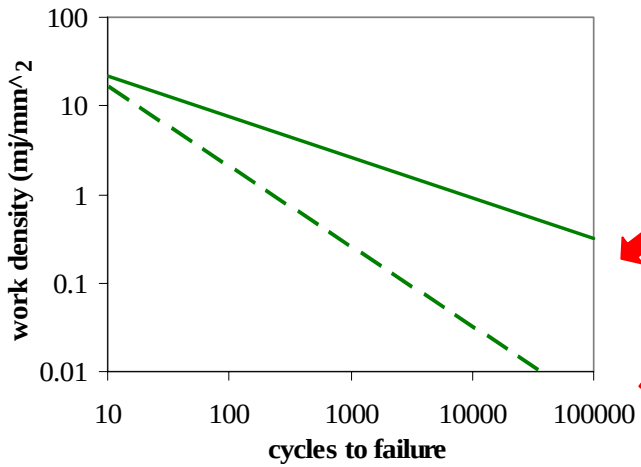
2

1-D Analytical Model and Geometry



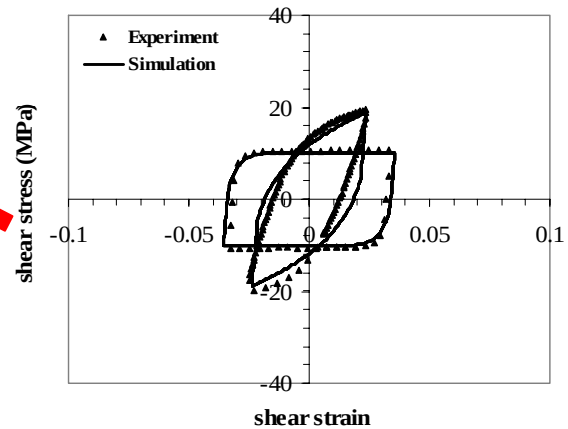
4

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:** $$\frac{1}{N_{ft}} = \frac{1}{N_{fp}} + \frac{1}{N_{fc}}$$

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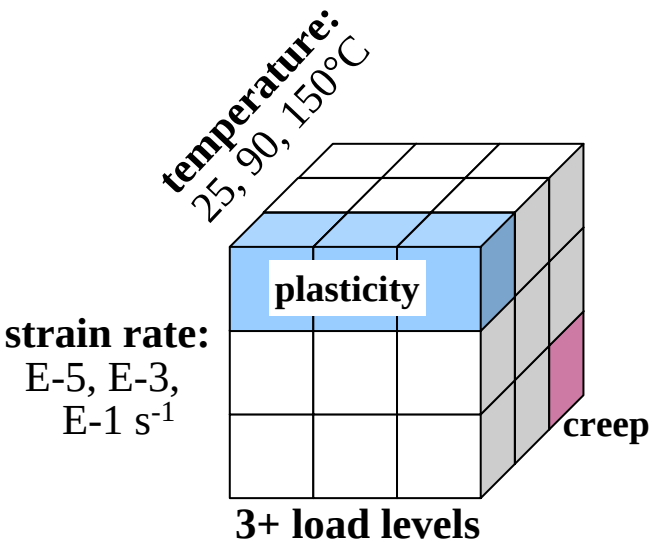
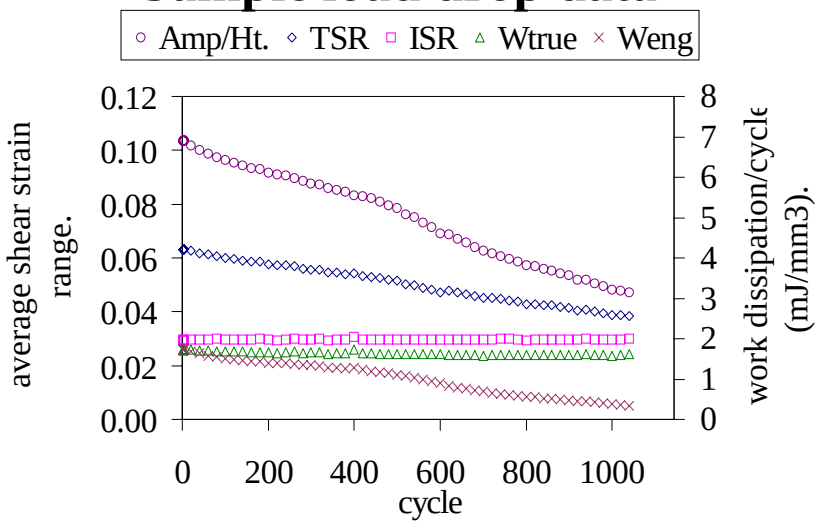
Durability Results Summary

TMM Test Matrix



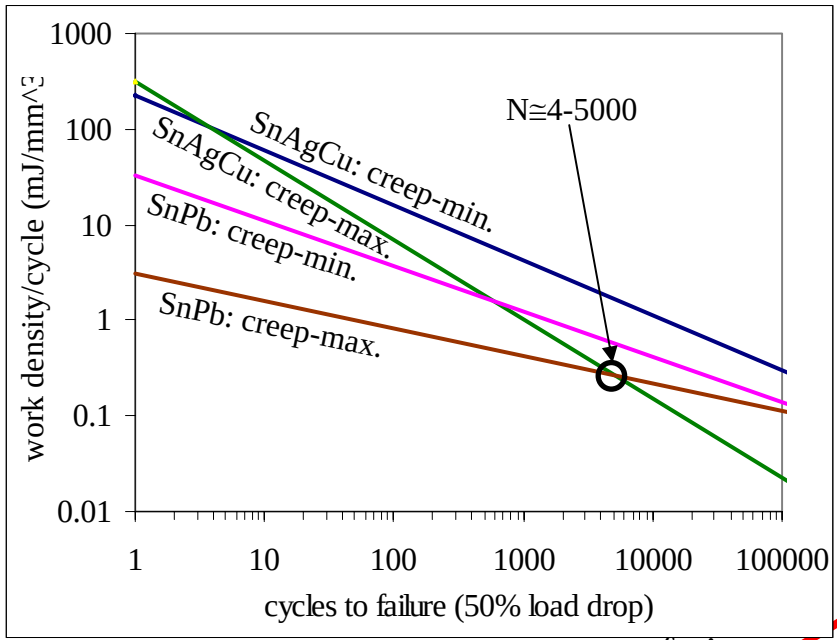
Sample load drop data



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

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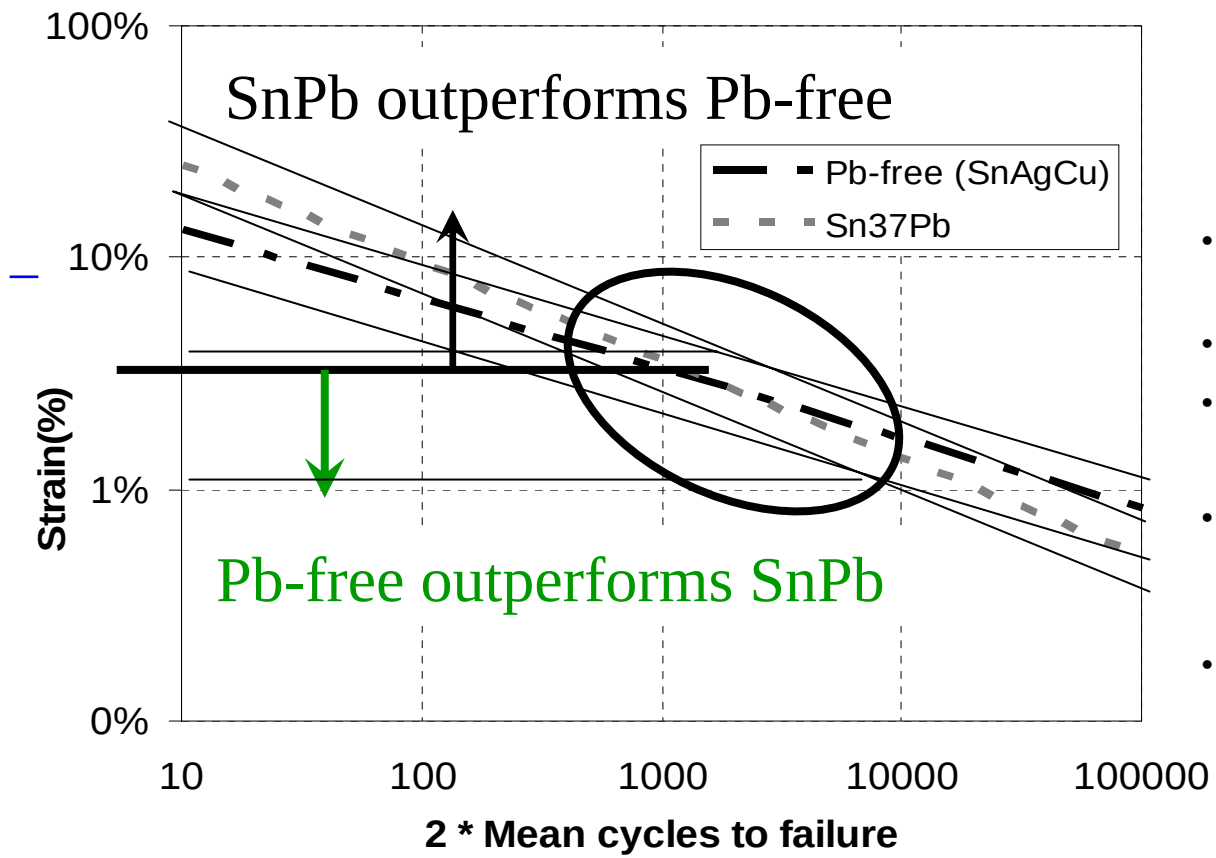
Durability of Solder under a Temperature Cycle

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°C, -55 to 125°C, and 0 to 100°C) with little variation in dwell or mean temperature.



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

- 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)

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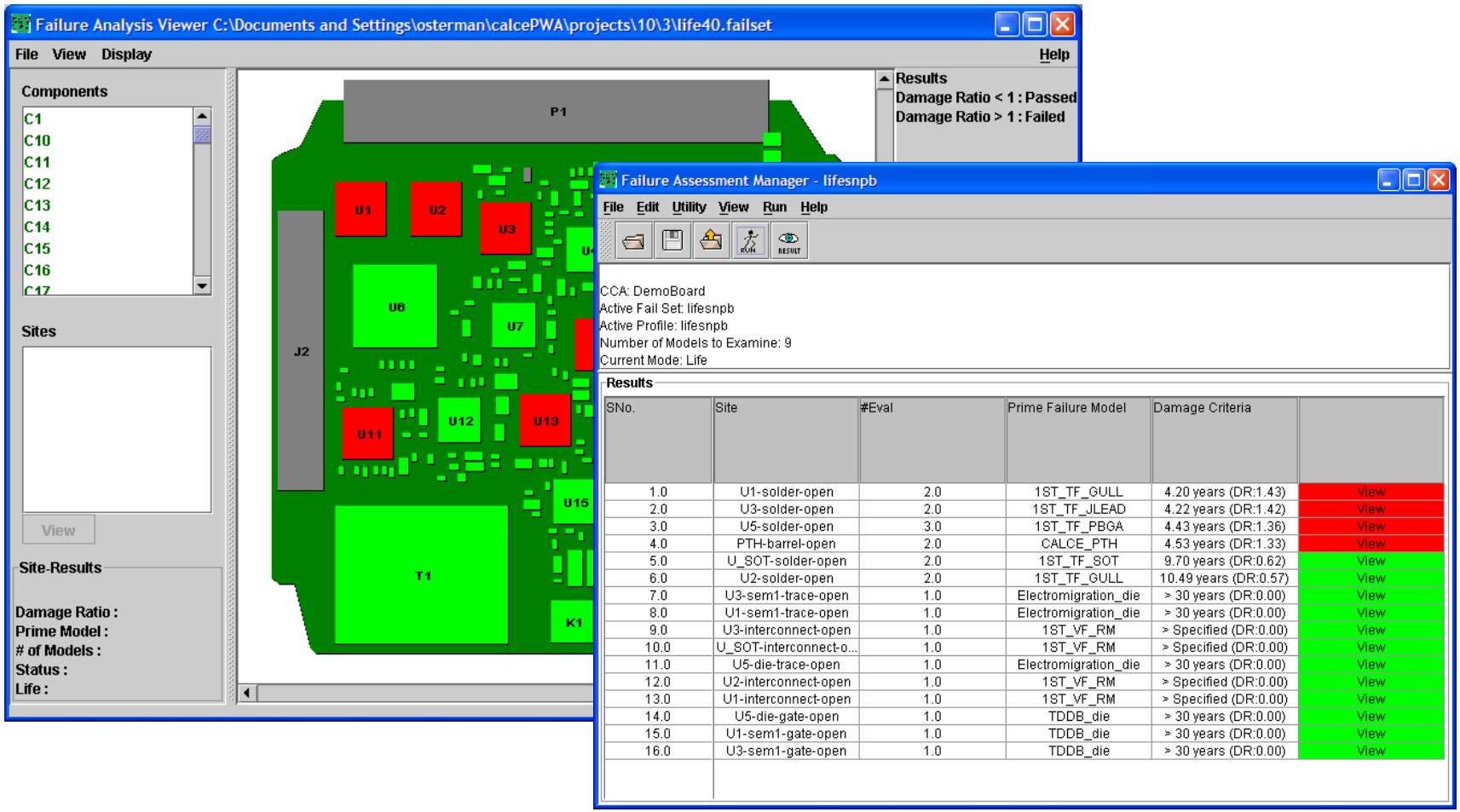
Rapid Failure Assessment Software for Pb-free



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. The model is implemented in calcePWA 4.0.

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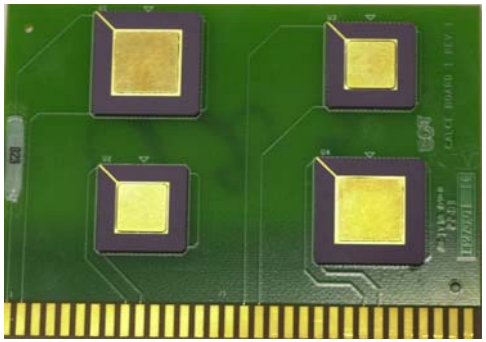
Temperature Effect Study



Test Vehicle

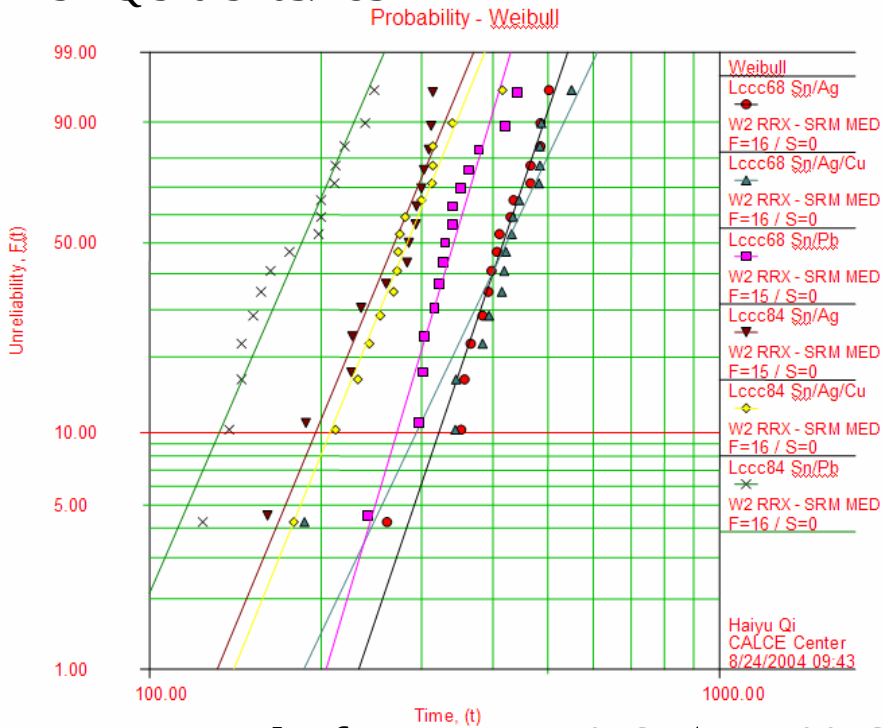
- 68-pin LCCC: 24mm × 24mm, Ceramic
- 84-pin LCCC: 30mm × 30mm, Ceramic
- Board: 130 x 93 x 2.5 mm, FR4

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	Mean Temp (˚C)	Temp. Range (˚C)	Dwell Time (min)	Status
1	50	100	15	Completed
2	25	100	15	Completed#
3	75	100	15	Completed
4	58	100	75*	In Test
5	83	100	75*	Pending
6	108	100	75*	Pending
7	TBD	TBD	TBD	Pending
8	TBD	TBD	TBD	Pending
9	TBD	TBD	TBD	Pending



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

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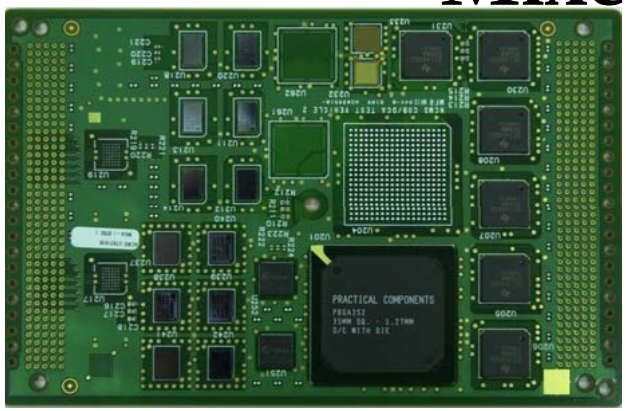
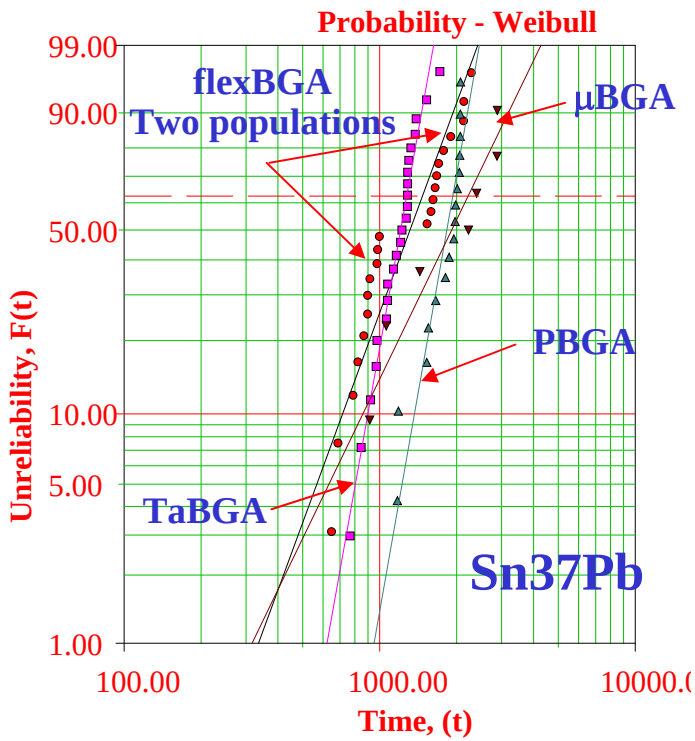
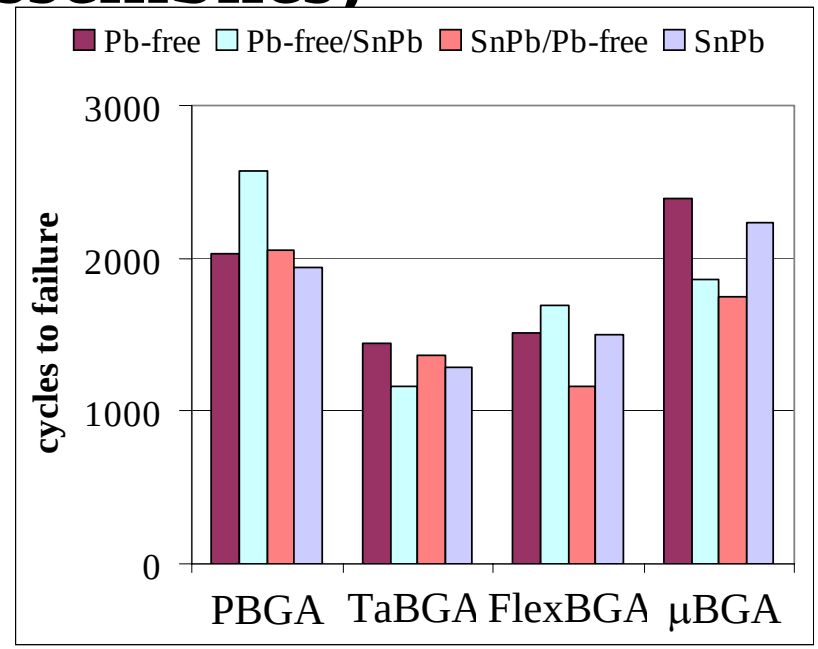
Accelerated Thermal Cycling (Pb-free and Mixed Assemblies)







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)

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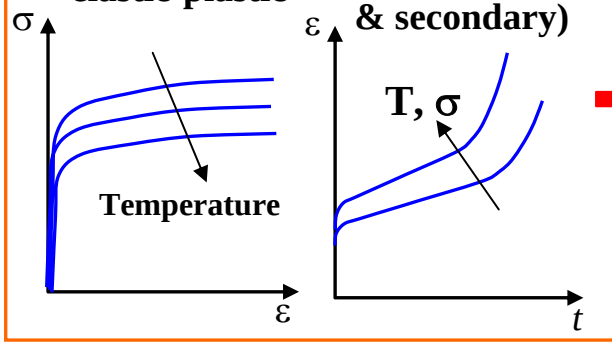
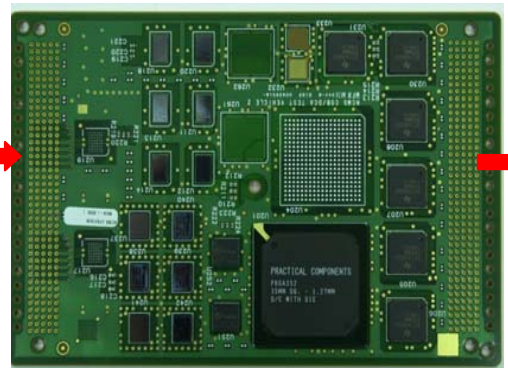
Energy-Partitioning Damage Model:
Approach for Thermal Cycling

1

Constitutive Properties of Solders

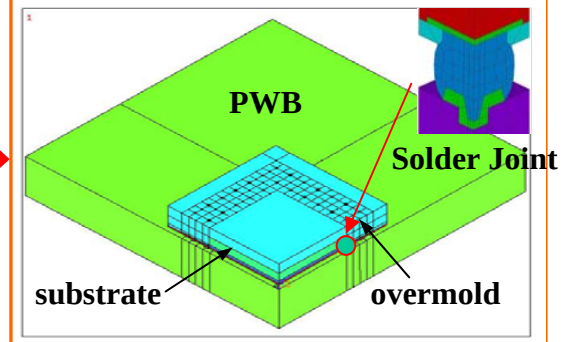


Test Vehicle



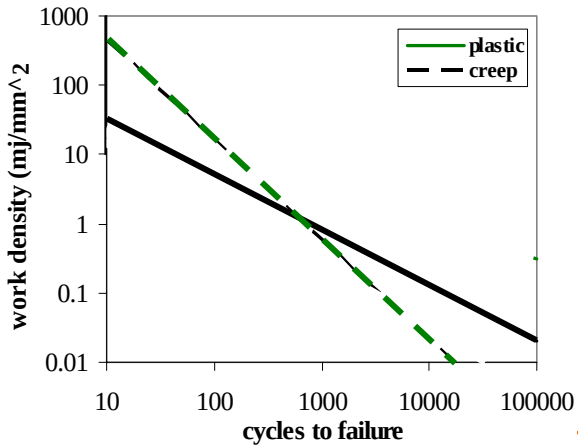
2

Package Architecture



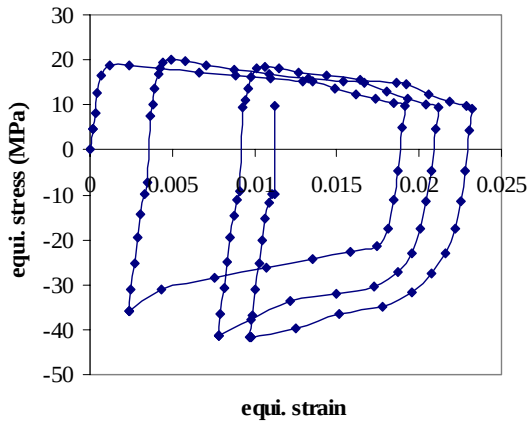
4

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:** $$\frac{1}{N_{ft}} = \frac{1}{N_{fp}} + \frac{1}{N_{fc}}$$

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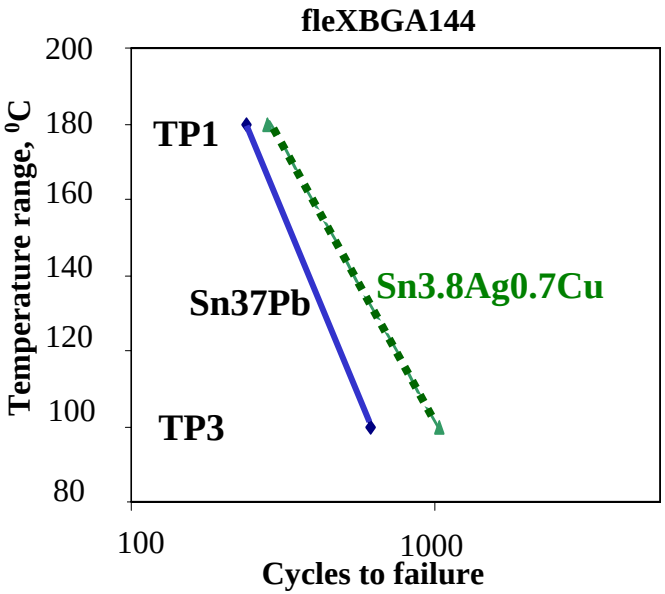
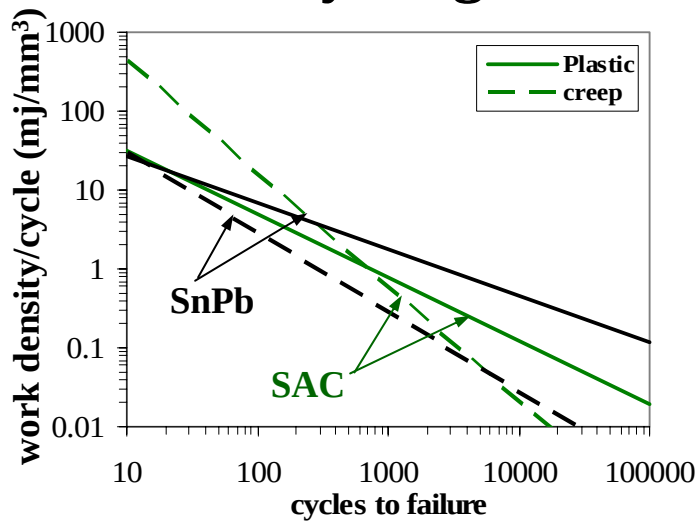
Energy-Partitioning Damage Model:

Thermal Cycling





$$W_p + W_c = W_{p0} N_{fp}^{\ c} + W_{c0} N_{fc}^{\ d}$$

$$1/N_f = 1/N_{fp} + 1/N_{fc}$$

Profile	Package	Temperature Range	Ramp Rate (°C/min.)	N_f (63%)		$\Delta W_{pl}/\Delta W_{cr}$	
				SnPb	SAC [2]	SnPb	SAC
TP1 [1]	fleXBGA2	0 to 100°C	10	6194	10368	0.01	0.75
TP2 [1]	fleXBGA2	-40 to 125°C	11	2328	2966	0.13	0.69
Our TP	fleXBGA1	-55 to 125°C	6/10	902	1300	0.15	0.75
Our TP	TABGA96	-55 to 125°C	6/10	1370	1453	0.11	0.67
TP3 [1]	fleXBGA2	-55 to 125°C	90	2409	2809	0.35	0.91

[1] Syed, A., 2001, "Durability and Au Embrittlement of Lead Free Solders for BGA Applications", 2001 International Symposium on Advanced Packaging Materials, pp. 143- 147

[2] Results of Sn4.0Ag0.5Cu are tabulated for the profiles used in the reference 1 above, while Sn3.8Ag0.7Cu was used for the other profile results for Nf and W.

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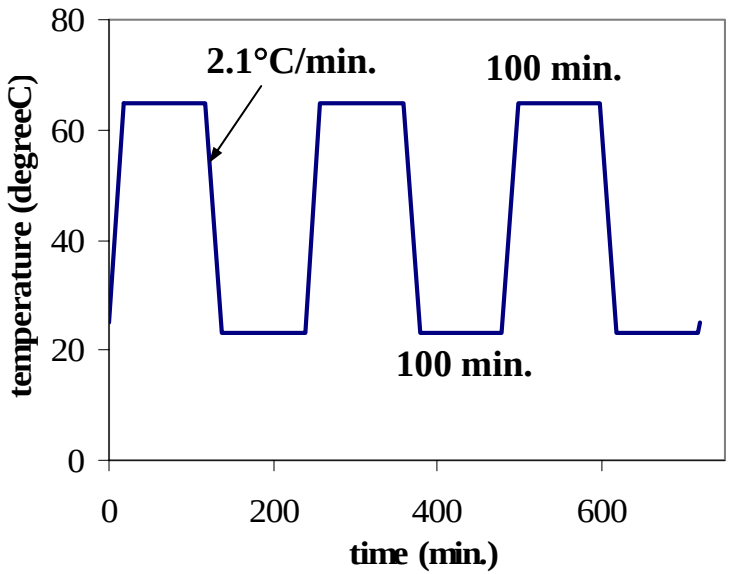
Life Cycle Durability Assessment - Thermal Cycling

FlexBGA 144

	Sn3.8Ag0.7Cu	Sn37Pb
Acceleration Factor	20	9
Characteristic Life	27621	7697
Cycles to 1 % Failure	16026 (21 years)	4466 (6 years)



Acceleration factor of the Sn3.8Ag0.7Cu solder is much larger than that of the Sn37Pb solder. This agrees with the results in the literature.

Under the field use environment, accumulated creep damage in the Sn3.8Ag0.7Cu solder joint is much less than that in the Sn37Pb solder joint (0.005 mJ/mm3 vs. 0.037 mJ/mm3) because of the better creep resistance of Pb-free solders.

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Long-term Pb-free Reliability Study

Initiated August 2004 Expected Completion Dec. 2005

	Pre-treatment	Accelerated stressing	Solder and PCB pad finish				
			Sn-Pb	SAC	SAC	SAC	SAC
			HASL	Imm Ag	Imm Sn	ENIG	OSP
Phase I	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 / 680 hours) + Bias)	✓	✓	✓	✓	✓
Phase II	None	Temp. cycling (-40ºC to 125ºC)	✓	✓	✓	✓	✓
	None	Temp. cycling + vibration	✓	✓	✓	✓	✓

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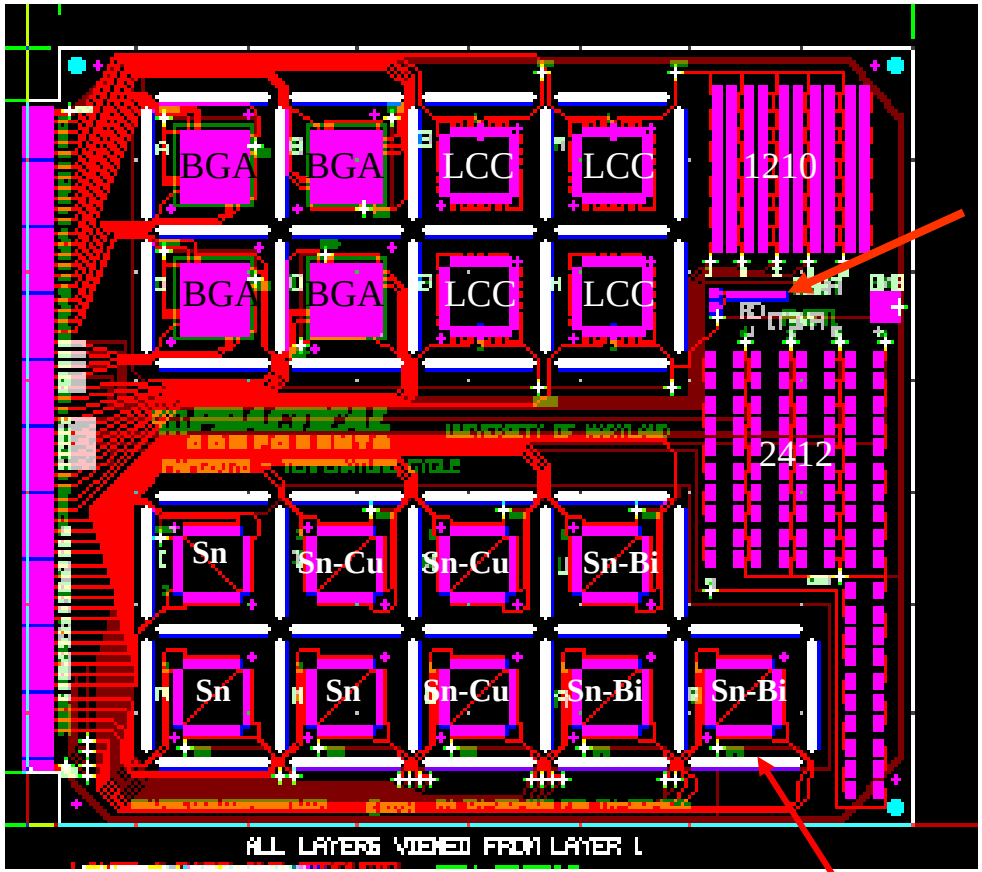
Long-term Pb-free Study
Test Vehicle : Temperature Cycling



Corrosion Test structure

Cut-out feature

- Daisy chained test vehicle with dummy (dummy silicon die) components.
- Size: 8” x 7”
- Thickness: 62 mils
- Material: FR4 (Tg=170-220C) and Polyimide (higher Tg).
- Cut-out features are incorporated to facilitate component removal after failure
- Corrosion test structure is incorporated to study electro-chemical migration

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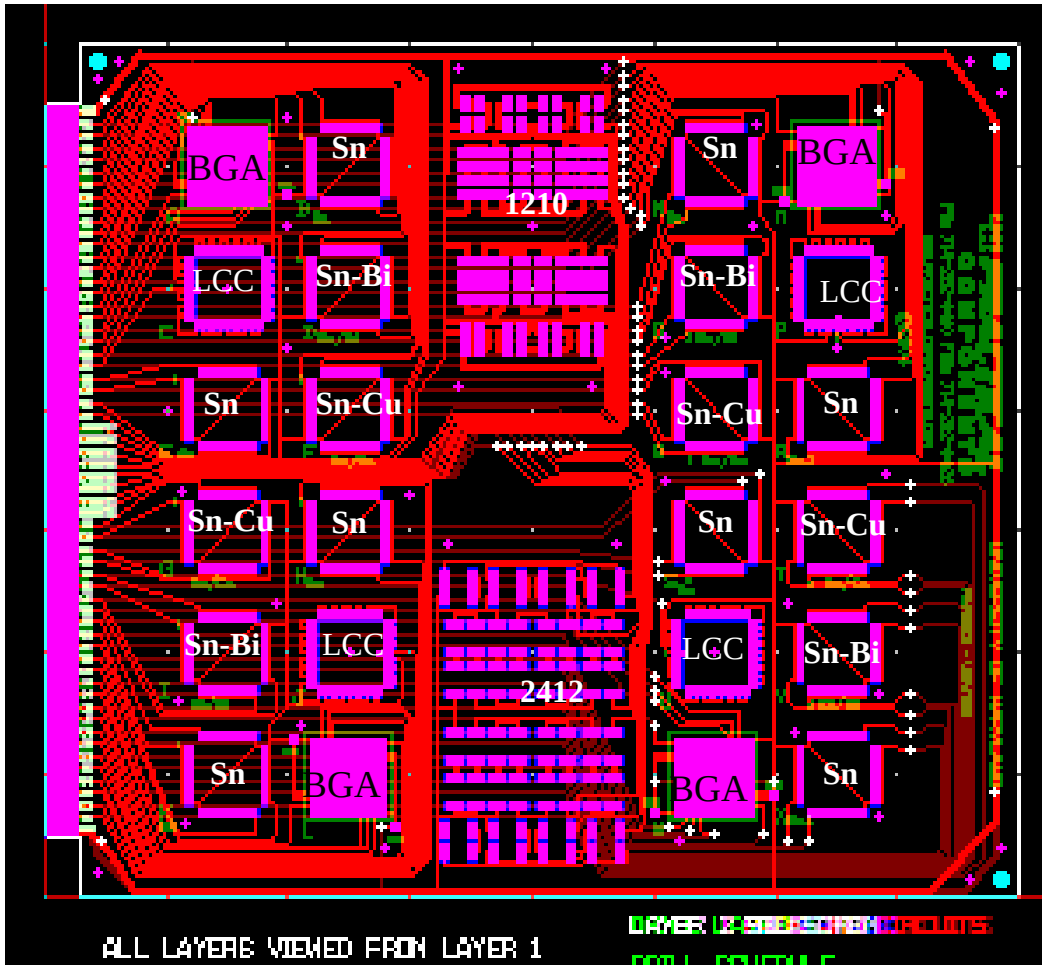
Long-term Pb-free Study
Vibration Tests: Test Vehicle



- Daisy chained test vehicle with dummy (dummy silicon die) components.
- Size: 8” x 7”
- Thickness: 62 mils
- Material: FR4 (Tg=170-220C) and Polyimide (higher Tg).
- Components are placed symmetrically to create near uniform stress distribution for each component

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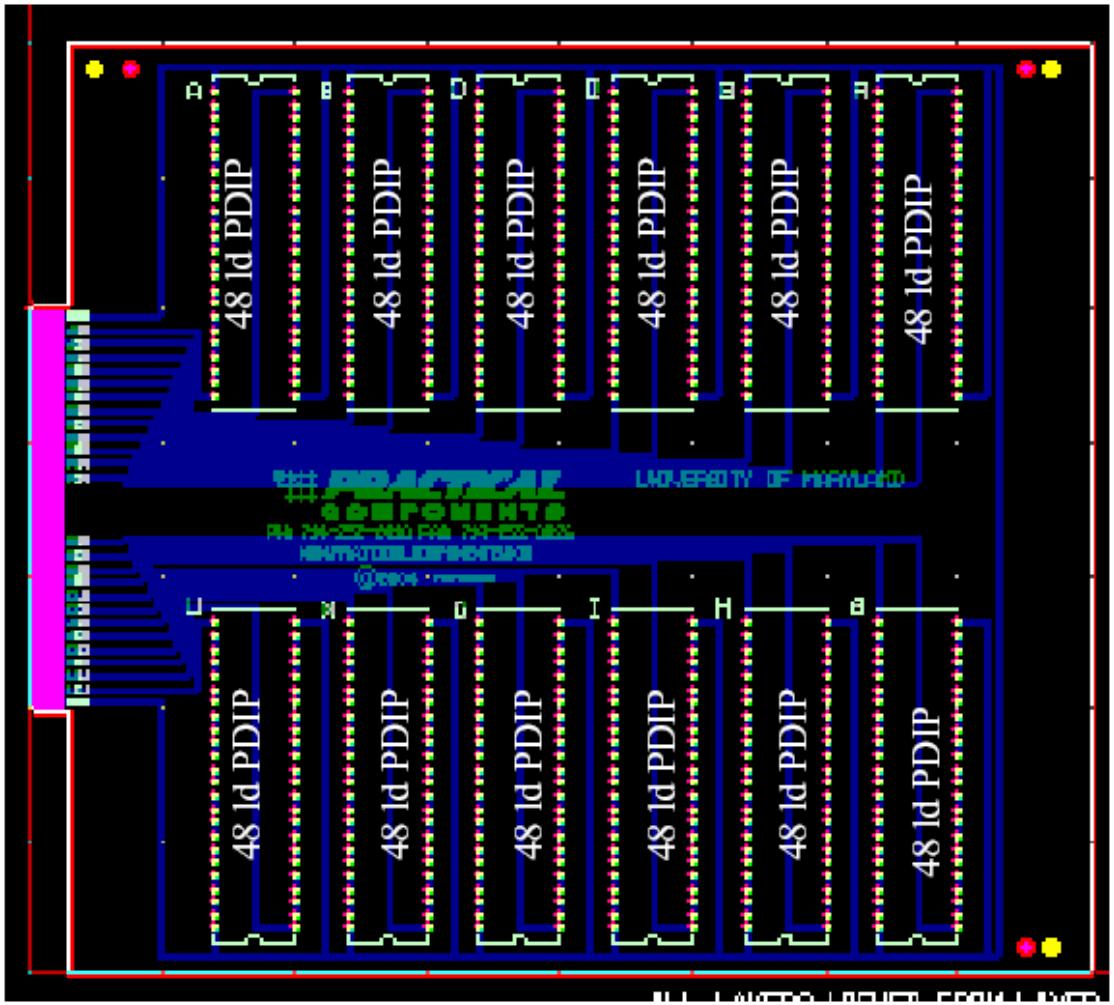
Long-term Pb-free Study

TH Design: Single Sided Through-hole (Wave Soldered)



Size: 8”x5”x0.062”
Material: CEM1

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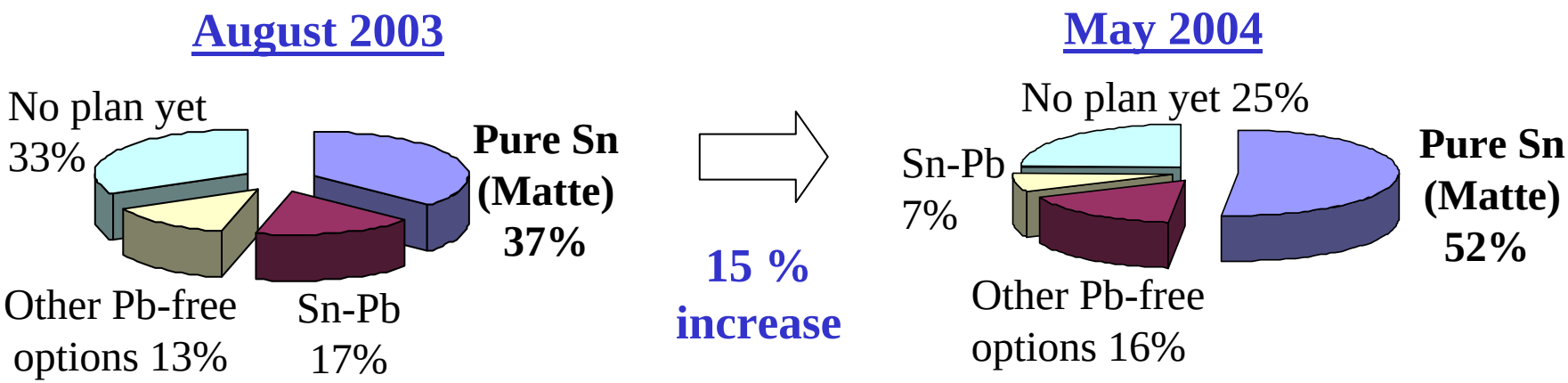
Component Suppliers' Plating Selection - Pb-free Transition -



Data is based on CALCE component supplier survey, available at: http://www.calce.umd.edu/lead-free/tin-whiskers/team/partsuppliers040519.xls

- Number of companies selecting pure tin (matte tin) as a Pb-free option has been increasing. Some companies have shifted from other Pb-free plating to pure tin.
- Advantages of pure tin plating includes
  - Wide availability
  - Closest characteristic to Sn-Pb properties
  - Least requirement for changes in the existing process
  - Cost effectiveness (pure tin is the cheapest among the tin-based finishes)

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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

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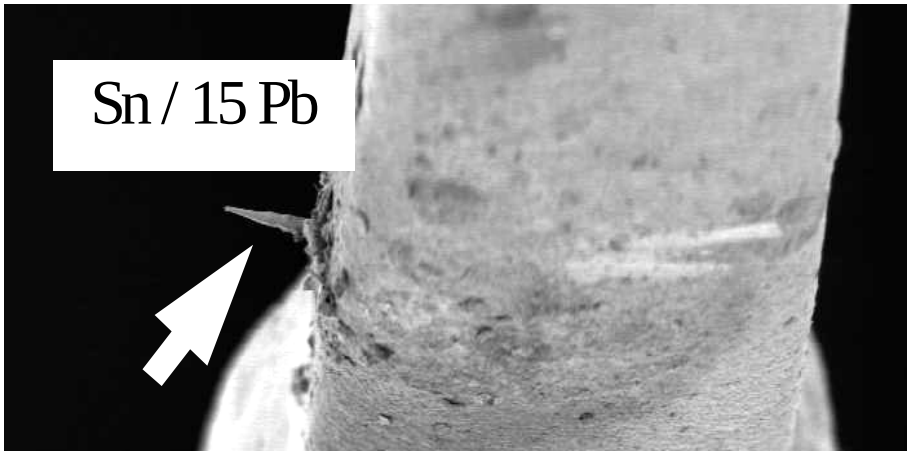
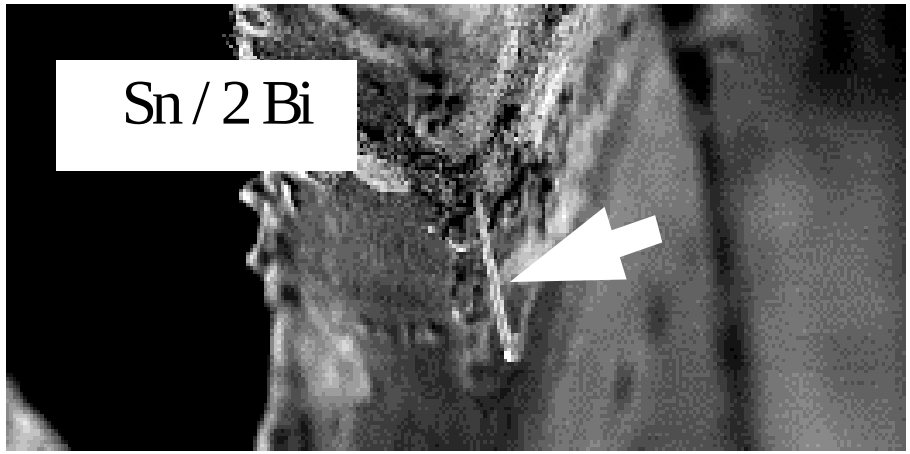
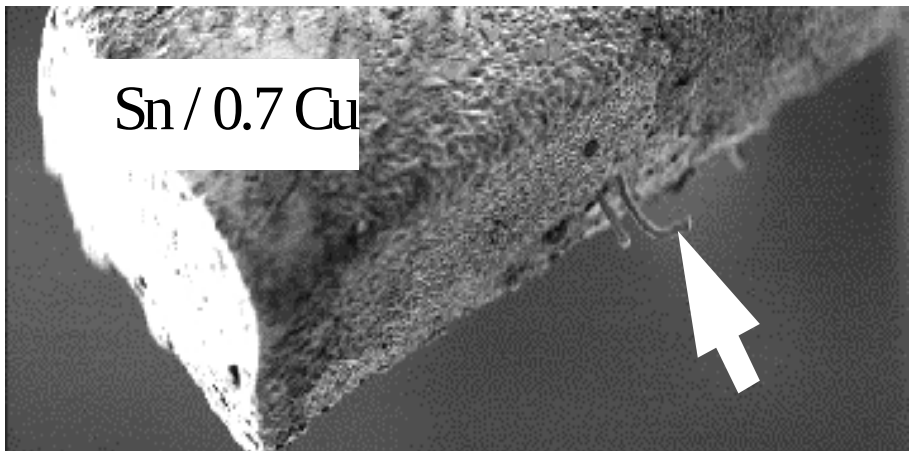
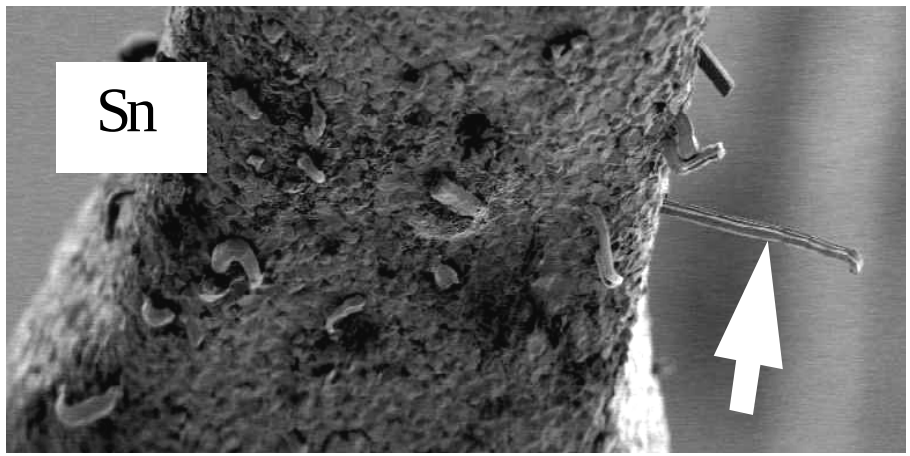
Whiskers Grown from Various Plating Types









[Courtesy of Motorola]

One reported observation based on 13-week period for the longest whiskers showed:
Sn-15Pb (40µm) < Sn-2Bi < Sn < Sn-Cu (170µm)

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CALCE Tin Whisker Team Studies (Roadmap)

2002

Tin Whisker Alert/Risks/Experiences

CALCE Whisker Team

2003

Tin Whisker Mitigation Guide

Solder Dip

-No whisker was found at solder-dipped portion
-Sample size was too small

Heat treatments

-Initiated experiments with bright and matte tin over brass, Cu, and alloy 42.

Conformal Coating

-Initiated experiments to investigate the environmental conditions for tin whisker growth

Supplier survey

2004

TMTI Project
-Solder Dipping-

Study on effect of bending, solder dipping, and current

-Initial results showed heat treatments may not be effective to mitigate the risks caused by tin whiskers
-Whiskers grow more on bright tin plated specimens than matte tin

-Testing was done at Boeing/Raytheon

-Whisker can grown through some types of conformal coating

Observation of pure-tin plated components

Examination of plating and grain size of pure-tin plated components

Update of tin whisker mitigation guide

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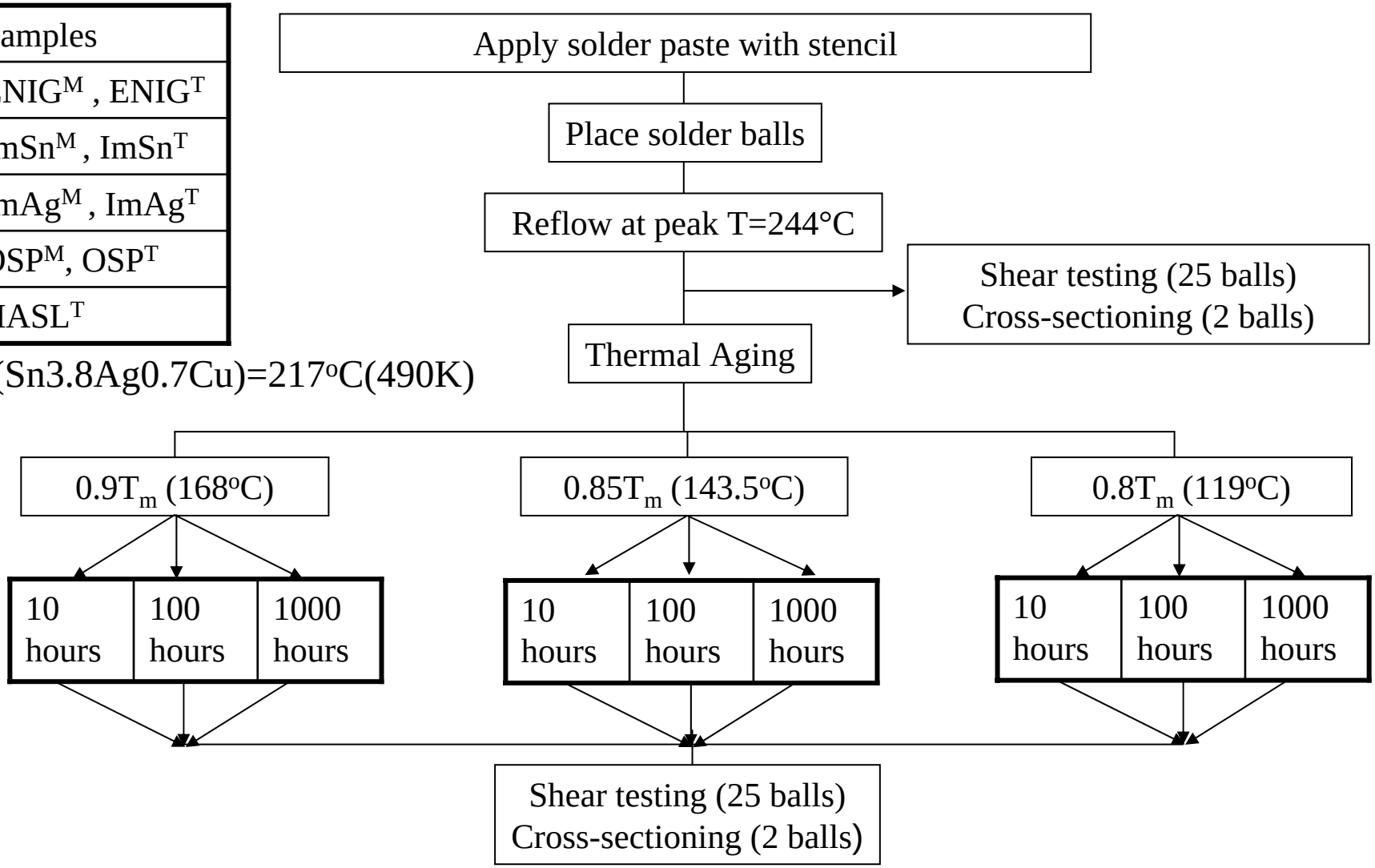
PWB Plating Study

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)



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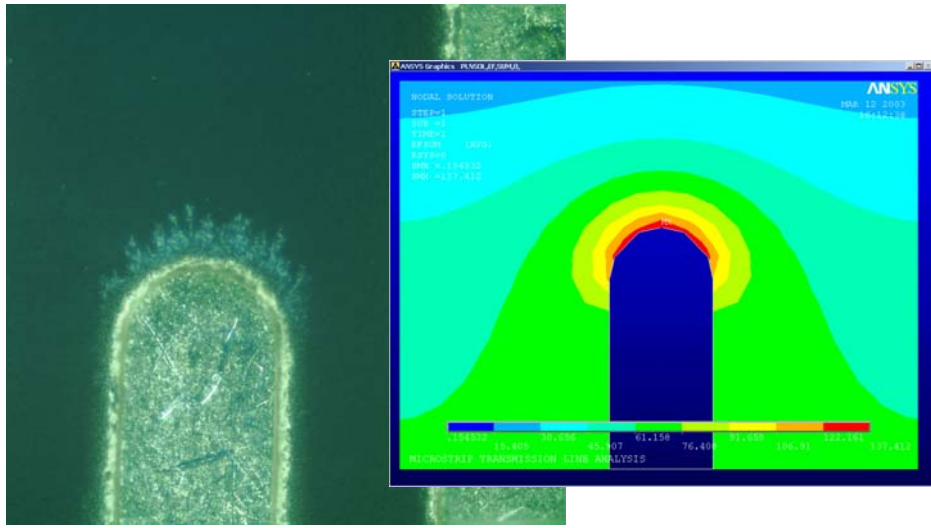
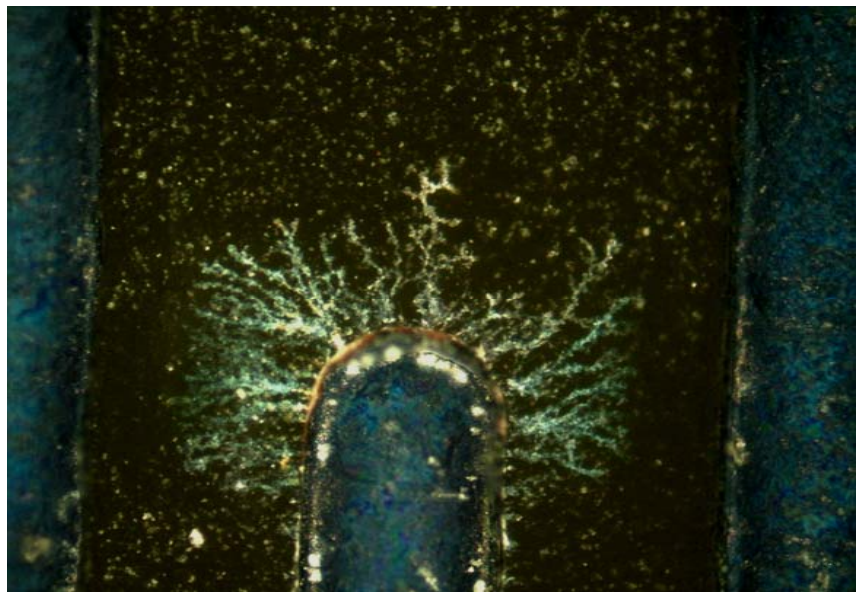
Electrochemical Migration in the Age of Pb-Free

- 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





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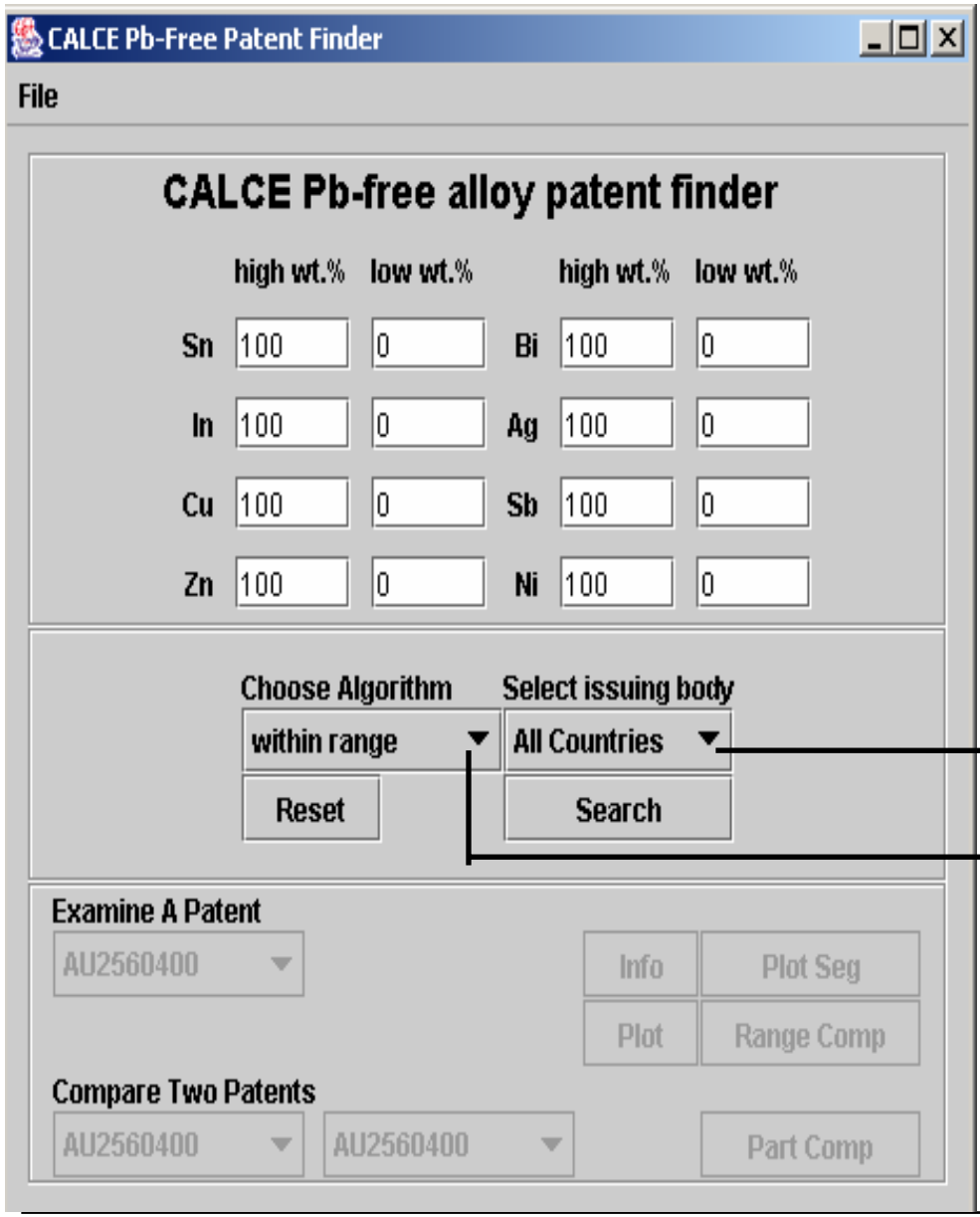
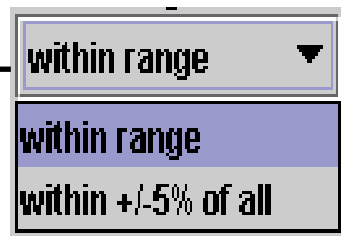
CALCE Pb-free Alloy Patent Finder



- Check if and where an alloy is patented
- Compare patented alloys



Choice of search methods

Restrict search by

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CALCE Consortium Pb-Free Research

2004
www.calce.umd.edu/members/projects/current.htm

C04-01 Logistics and Cost Analysis for Lead-Free Implementation
C04-02 Risk Assessment & Accelerated Qualification of Pb-free Electronics
C04-03 Durability Characterization of Pb-free Solders
C04-04 Effect of Temperature Cycle on the Durability Pb-Free Interconnects (Sn-Ag-Cu and Sn-Ag)
C04-05 Determination of Fatigue Constants of Lead-free Solder for calcePWA
C04-06 Intermetallic-Related Embrittlement of Lead-free Solder Die Attach
C04-07 Investigation of Tin Whiskers on Lead-free Plating (Pure Sn)
C04-08 Reliability of Pb-free Interconnect Solutions

2005
www.calce.umd.edu/members/projects/2005/project_development.htm

P05-A1 Durability Characterization of Sn-Zn Pb-free Solders
P05-A6 Influence of Processing Variabilities on the Durability of Pb-free Assemblies
P05-A2 Combined Thermal Cycling and Vibration of Pb-free Electronic Assemblies
P05-A5 Durability of Pb-free Electronic Interconnects Under Impact Loading
P05-B2 Experiments to Validate calcePWA Vibration Model (Pb/Sn & Sn/Ag/Cu)
P05-M4 Reliability of SnAgCu Solder for High Temperature/High Power Assemblies
P05-O3 Temperature Cycle Effects on Pb-Free Solder Durability (Continuation of C04-04)
P05-O6 Durability of Reworked Pb-free and Mixed (Pb-free/SnPb) Solders Interconnects
P05-O5 Tin Whisker Risk Metric and Mitigation Strategies for Electronic Assemblies
P5-M5 Effect of Ag Content on Intermetallic-Related Embrittlement and Shear Strength of Pb-free Solder
P5-H1 Robustness of SMT Electrolytic Capacitors under Pb-Free Reflow

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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/

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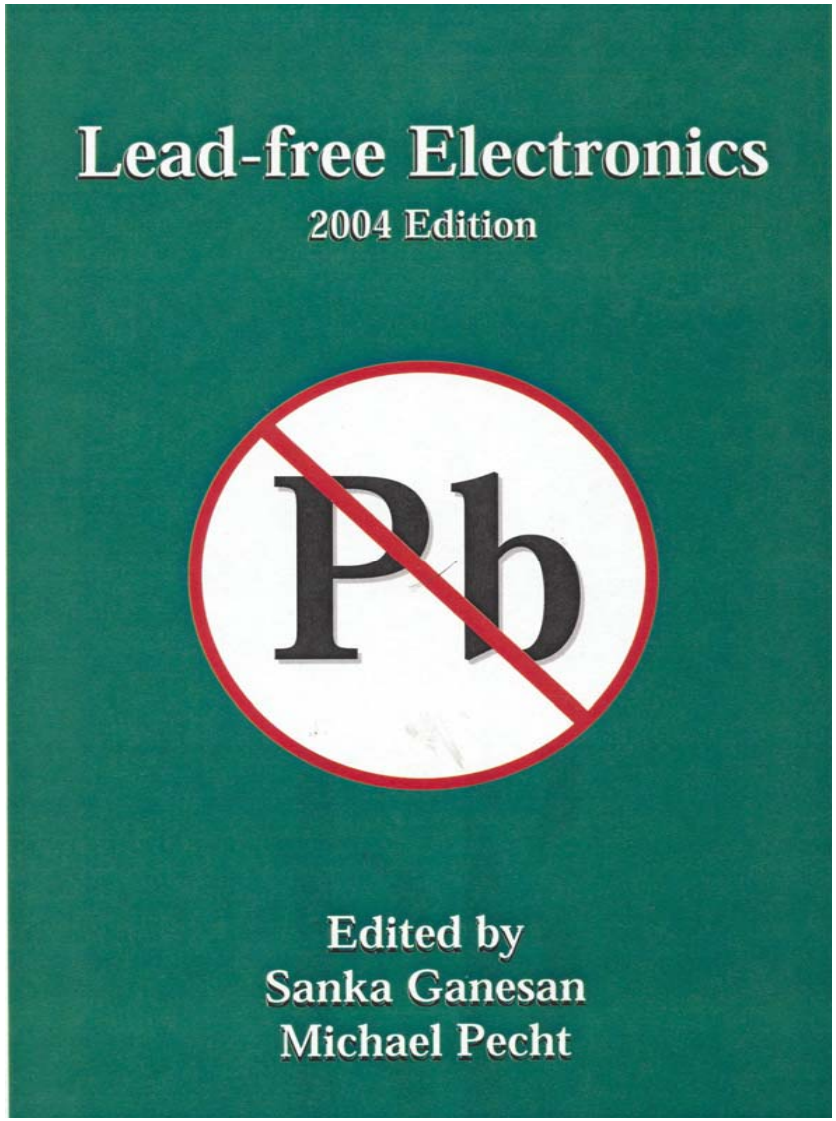
Pb-Free Resources

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

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