NIST Research in Lead-Free Solders: Properties, Processing, Reliability

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National Institute of Standards and Technology
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UC SMART
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NEMI National Electronics Manufacturing Initiative, Inc.

NIST Projects in Solder Science

- Phase Transformations in Pb-Free Solder Systems

  http://www.metallurgy.nist.gov/phase/solder/solder.html
- Effect of Pb Contamination on Melting Behavior of Sn-Bi Alloys
- Failure Analysis for Reliability Trials in NEMI Pb-Free Task Force
- Fillet Lifting in Pb-Free Solder Alloys
- Properties Database for Pb-Free Solder Alloys

  http://www.boulder.nist.gov/div853/Solderability
- Test Methods - Sn-Pb and Pb-Free
- Sn Whisker Growth in Sn-based Surface Finishes
- Modeling of Solder Joint Geometries and Forces for SMT, Wafer-Level Underfill, and Photonics

NIST Metallurgy Division Home Page:
http://www.metallurgy.nist.gov/

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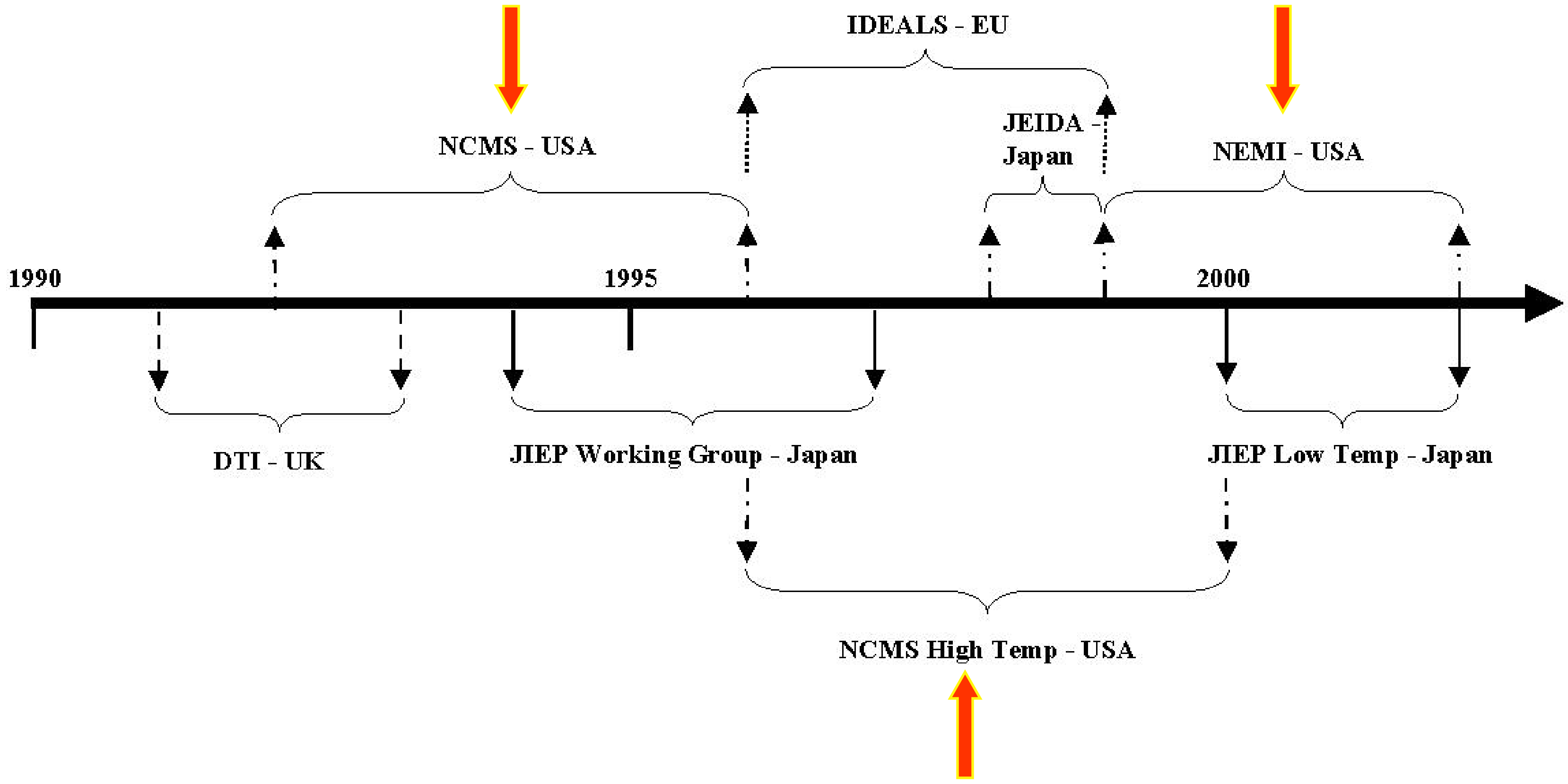
International R&D Industrial Projects in Lead Free Solder



NCMS Lead-Free Solder Project

? AT&T/ Lucent Technologies

? Ford Motor Company (Ford)

? General Motors (GM) —Hughes Aircraft

? General Motors—Delco Electronics

? Hamilton Standard, Division of United Technologies Corporation

? National Institute of Standards and Technology (NIST)

? Electronics Manufacturing Productivity Facility (EMPF)

? Rensselaer Polytechnic Institute (RPI)

? Rockwell International Corporation

? Sandia National Laboratories

? Texas Instruments Incorporated

NCMS

High Temperature Fatigue Resistant Solder Consortium

OEMs

- Delphi Delco Electronics Systems
- Ford Motor Company
- Rockwell International
- AlliedSignal

Component manufacturer

- Amkor

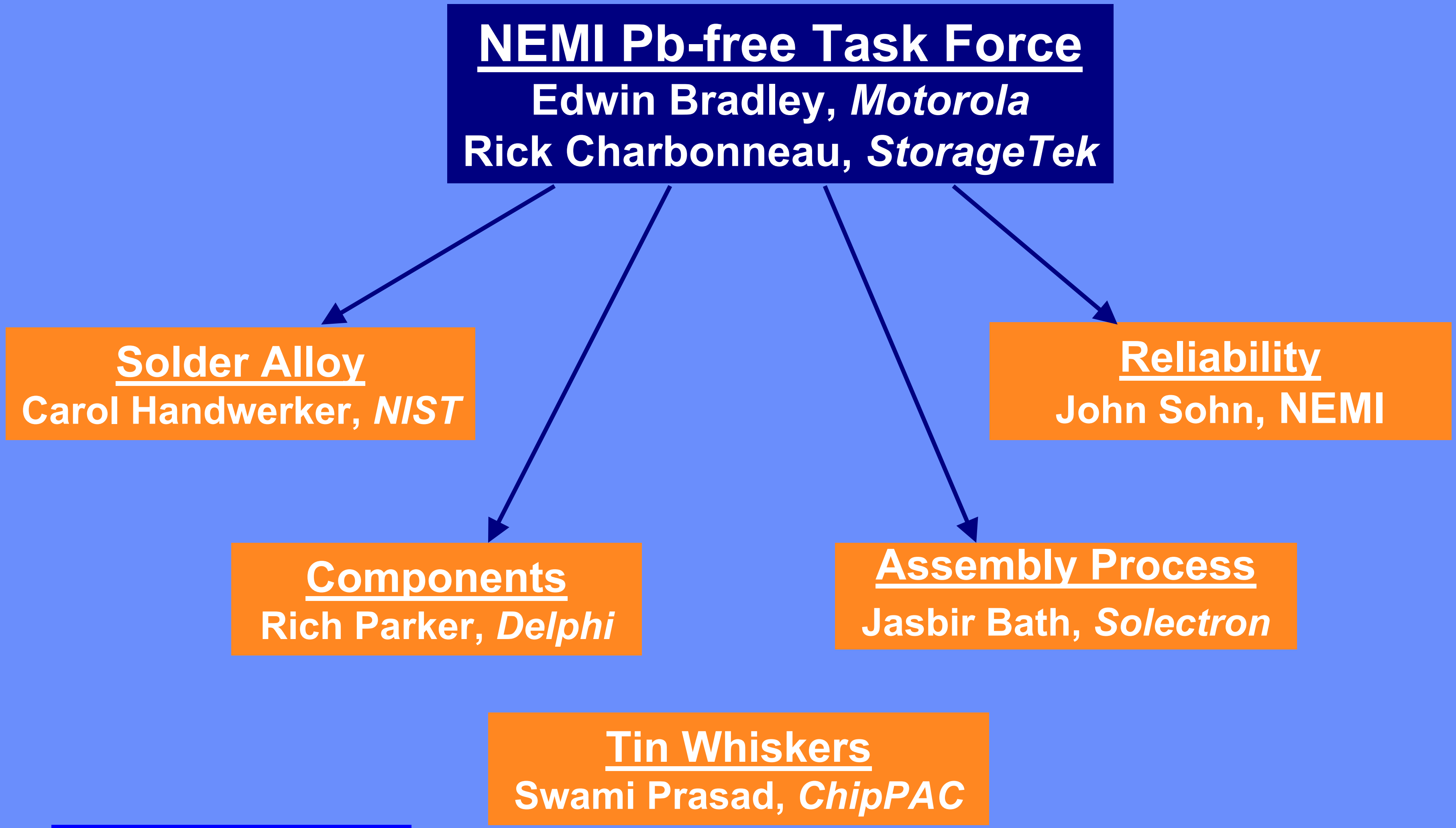
Solder suppliers

- Heraeus Cermalloy
- Indium Corporation
- Johnson Manufacturing

Federal Laboratories

- Ames Laboratory
- NIST

NEMI Task Group Structure



NEMI Pb-free Task Force
Edwin Bradley, *Motorola*
Rick Charbonneau, *StorageTek*

Solder Alloy
Carol Handwerker, *NIST*

Reliability
John Sohn, NEMI

Components
Rich Parker, *Delphi*

Assembly Process
Jasbir Bath, *Solectron*

Tin Whiskers
Swami Prasad, *ChipPAC*

NEMI Solder Alloy Team

Mission: Provide the Task Force with critical data and analyses needed for making decisions with respect to solder alloys, manufacturing, and assembly reliability.

- Provide assessment of candidate solder systems to choose industry “standard” lead-free alloys for reflow and wave soldering.
- Generate key data for decision making if not available in the literature.
- Develop “best practices” experimental procedures to measure the mechanical, thermal, electrical and wetting properties of lead-free solders.
- Develop public domain solder databases for properties and literature references for lead-free alloys.
- Promote modeling for reliability through generation of best possible data and modeling methods.

Results of NEMI-NIST Workshop

Modeling and Data Needs for Lead-Free Solders

✍ Held in conjunction with TMS meeting in New Orleans, LA on February 15, 2001

✍ Workshop report serving as roadmap for developing and analyzing data

http://www.nemi.org/PbFreePUBLIC/index.html

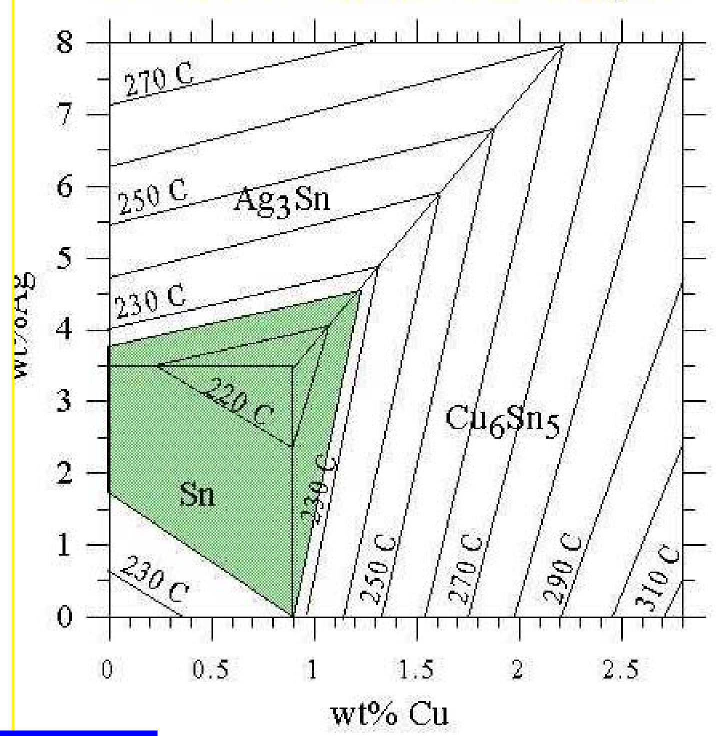
Prioritized Data needed for finite element modeling of thermal cycling test results

- Comprehensive test datasets: thermal cycling conditions, materials, component and board geometries, assembly information
- Mechanical and thermal property data as function of composition, temperature and test method with goal: robust data

Eutectic of Sn-Ag-Cu solder system

- Bill Boettinger, Kilwon Moon, Ursula Kattner, Carol Handwerker of NIST performed studies to determine the true Sn-Ag-Cu eutectic composition - data used by Task Force in choosing new “standard” alloys for reflow and wave soldering

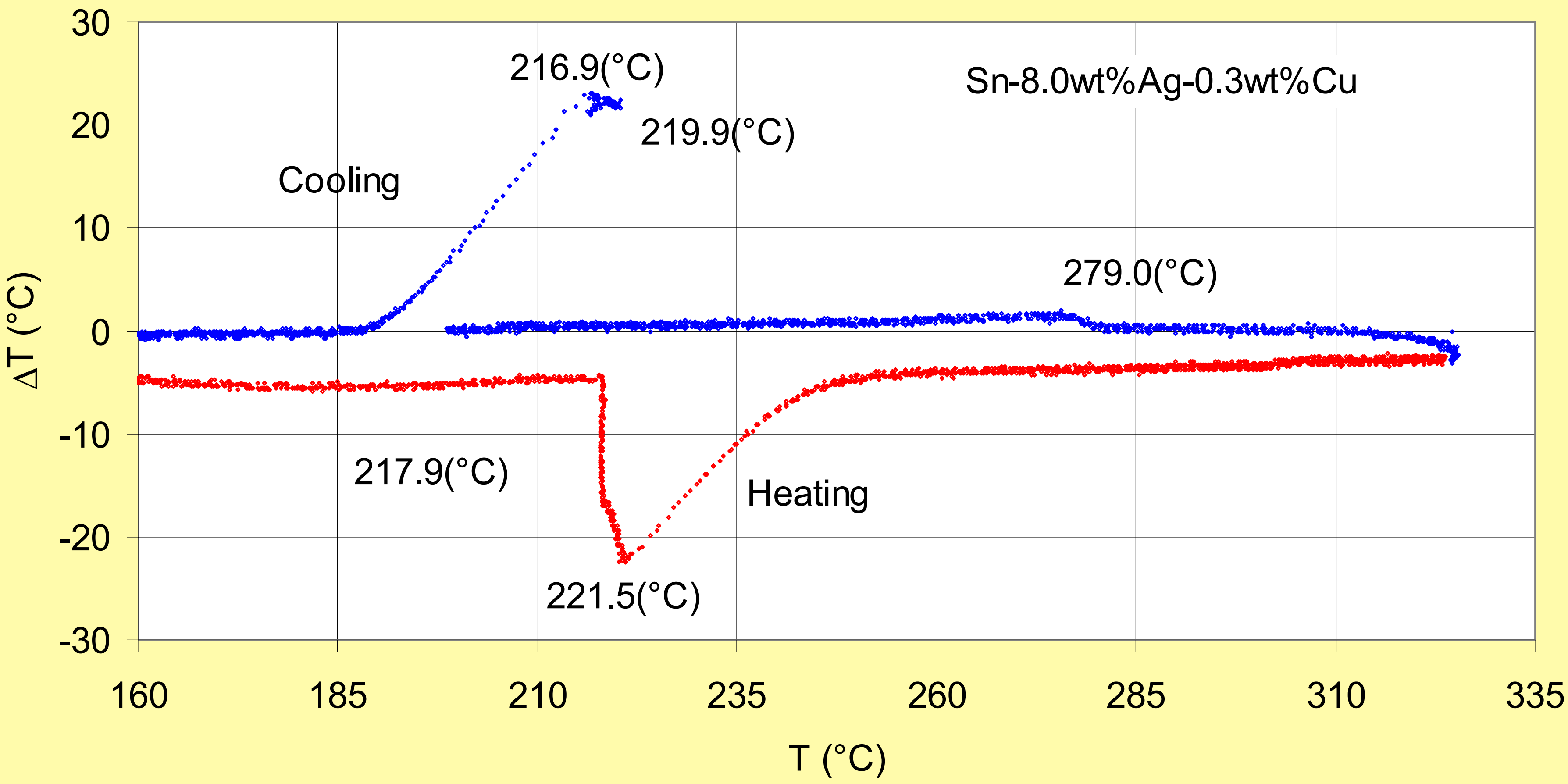
Ternary Liquidus Surface based on NIST analysis of data from NIST, Marquette, and Northwestern



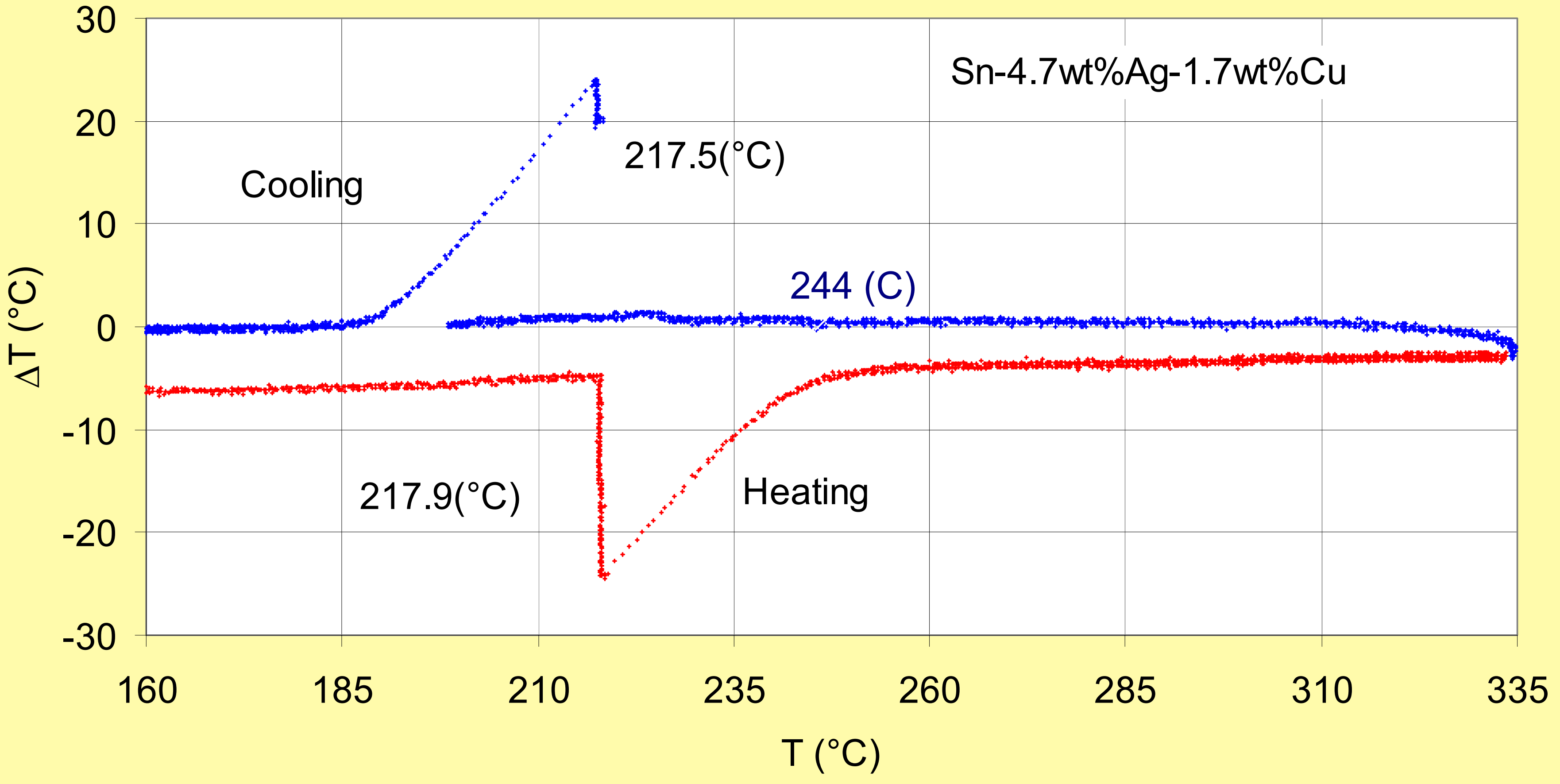
Ternary Eutectic Composition
Sn - 3.5 Ag - 0.9 Cu
at 217°C

Alloys in green shaded area have freezing range <10°C.

DTA Curve of Sn-Ag-Cu Alloy

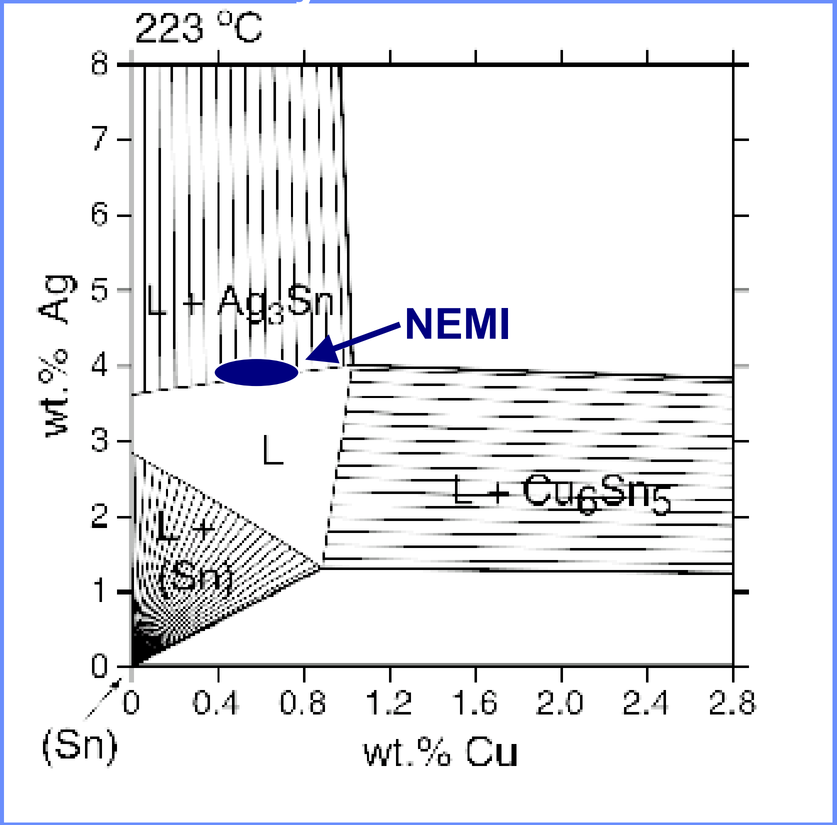


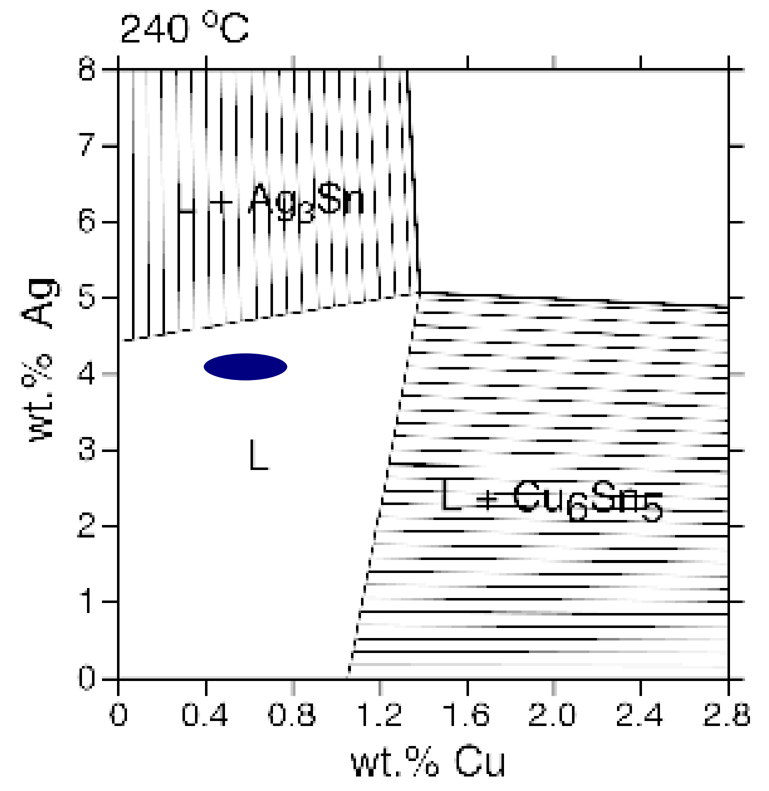
DTA Curve of Sn-Ag-Cu Alloy



Reflow Profile: Minimum Allowable Joint Temperature

For 223°C and 240°C composition ranges over which solder is 100% liquid - denoted by "L"





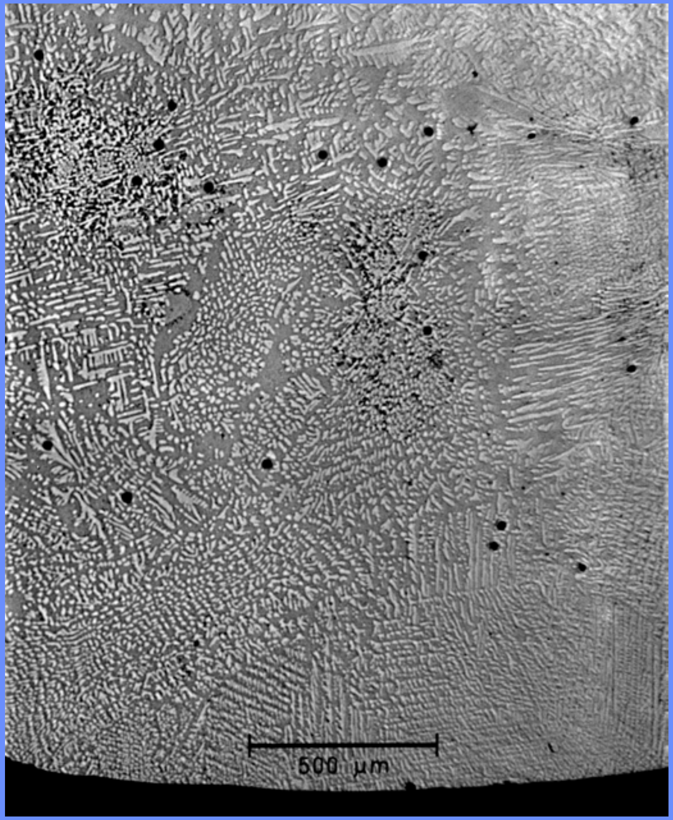
Helped to clarify solder melting temperatures from solder paste wetting dynamics and effect of air reflow

Microstructure of Bottom Region of Samples
12 hr @ 219 °C; Water Quenched

Sn-4.7wt%Ag-1.7wt%Cu

Large Cu_6Sn_5 Present

Sn-3.2wt%Ag-0.7 wt%Cu



No Large Cu_6Sn_5 Present

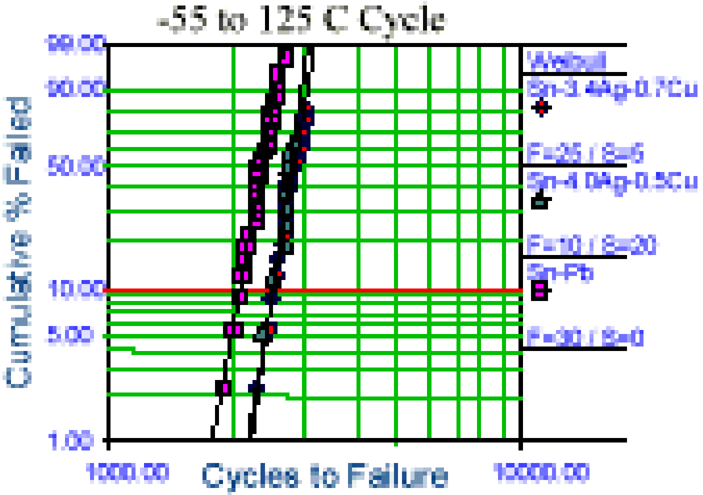
Comparison of Two Sn-Ag-Cu Alloys

Two Compositions

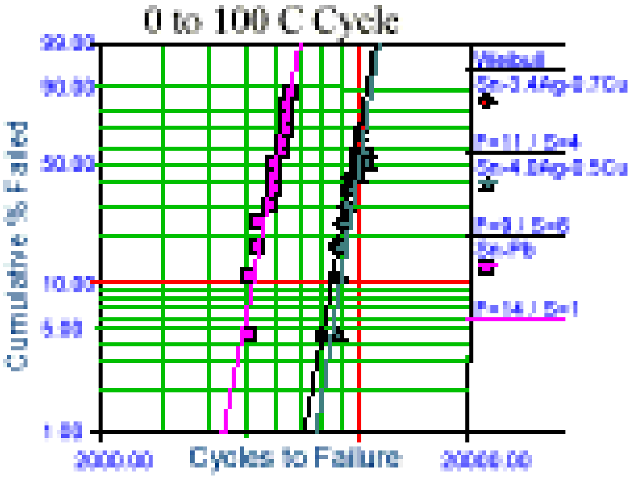
Sn - 4.0 Ag - 0.5 Cu

Sn - 3.4Ag - 0.7 Cu

- **Sn/Pb vs. Sn/Ag/Cu (*fle*XBGA Package)**



β1=16.07, η1=2886.19, ρ=0.98
β2=19.28, η2=2809.33, ρ=0.91
β3=15.16, η3=2409.32, ρ=0.99



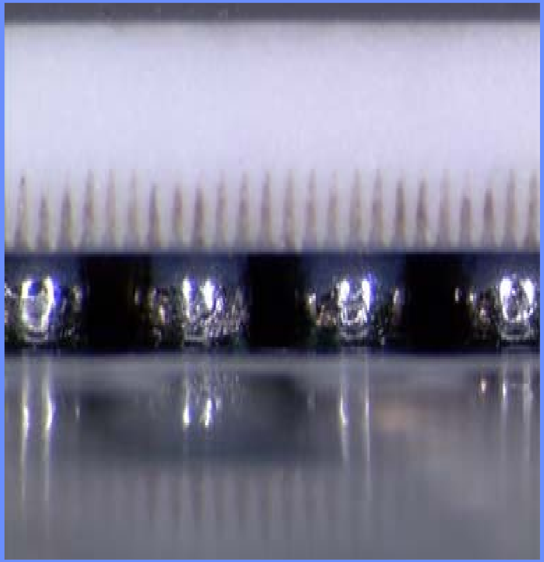
β1=13.95, η1=9983.61, ρ=0.99
β2=15.70, η2=10068.55, ρ=0.84
β3=12.95, η3=6194.94, ρ=0.97

- **No Difference in two Sn/Ag/Cu Compositions**
  - Sn/Ag/Cu Better than Sn/Pb
    - 25% for -55 to 125ºC Cycle
    - 80% for 0 to 100ºC Cycle

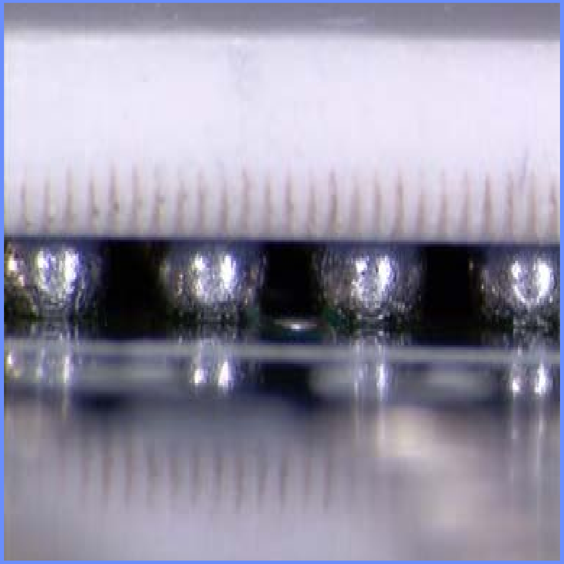
Amkor Technology

NCMS High Temperature Fatigue Resistant Solder Program

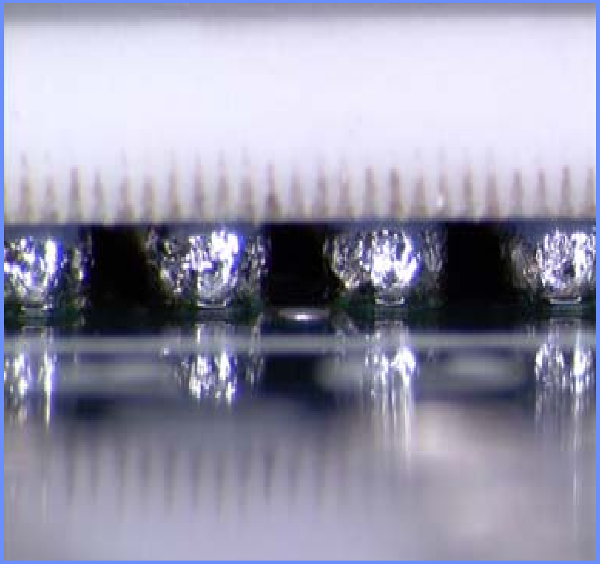
Universal Build Visual Inspection Results: CBGA



Tin-lead paste/
tin-lead CBGA
(Shiny joint)

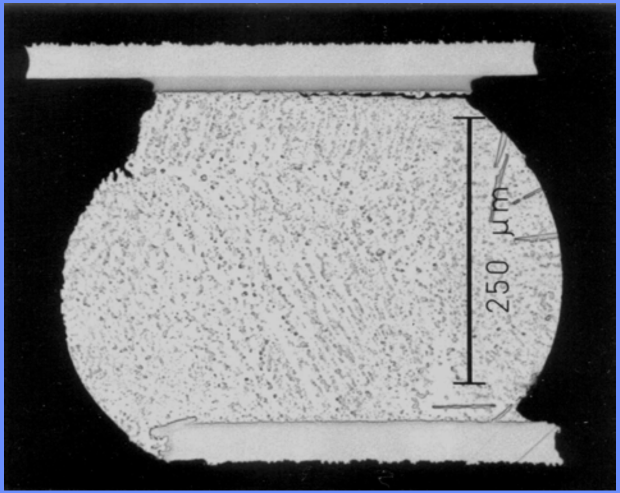


Lead-free paste/
Tin-lead CBGA
(Dull joint)



Lead-free paste/
lead-free CBGA
(Cratered solder joint)

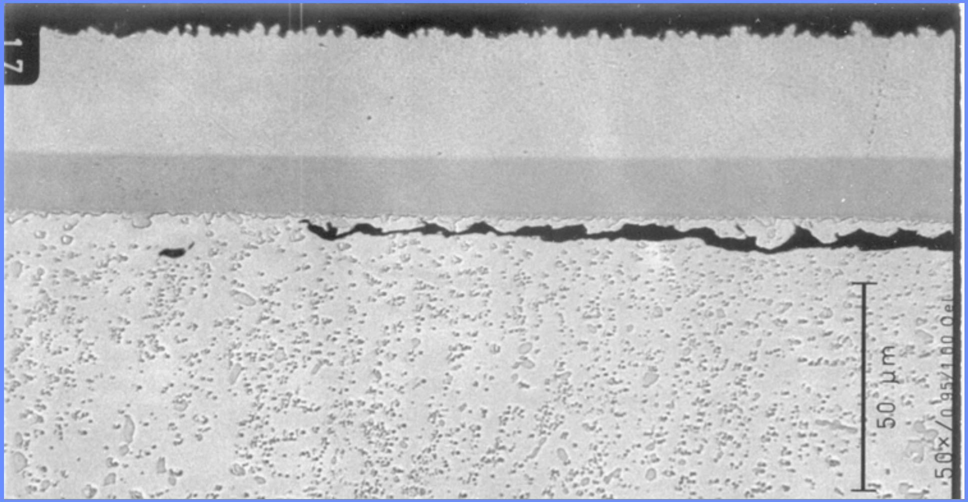
169CSP Failure Analysis: LF-LF, -40 °C to +125°C



No electrical failure up to 3425 cycles.

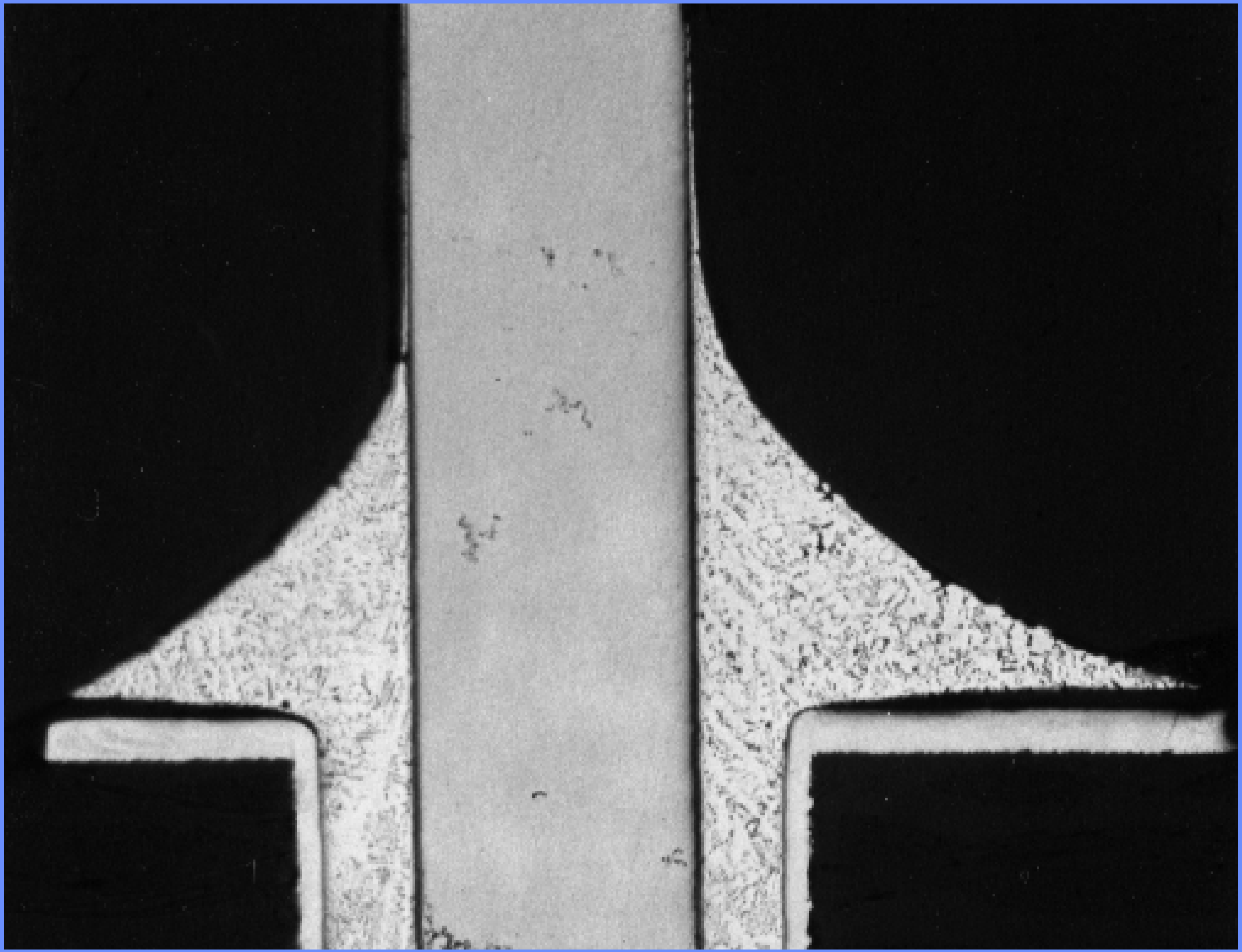
Worst joint in second row in from outer edge.

The contrast in the Sn phase indicates dendrite “single crystals” where all the dendrites are of the same orientation.

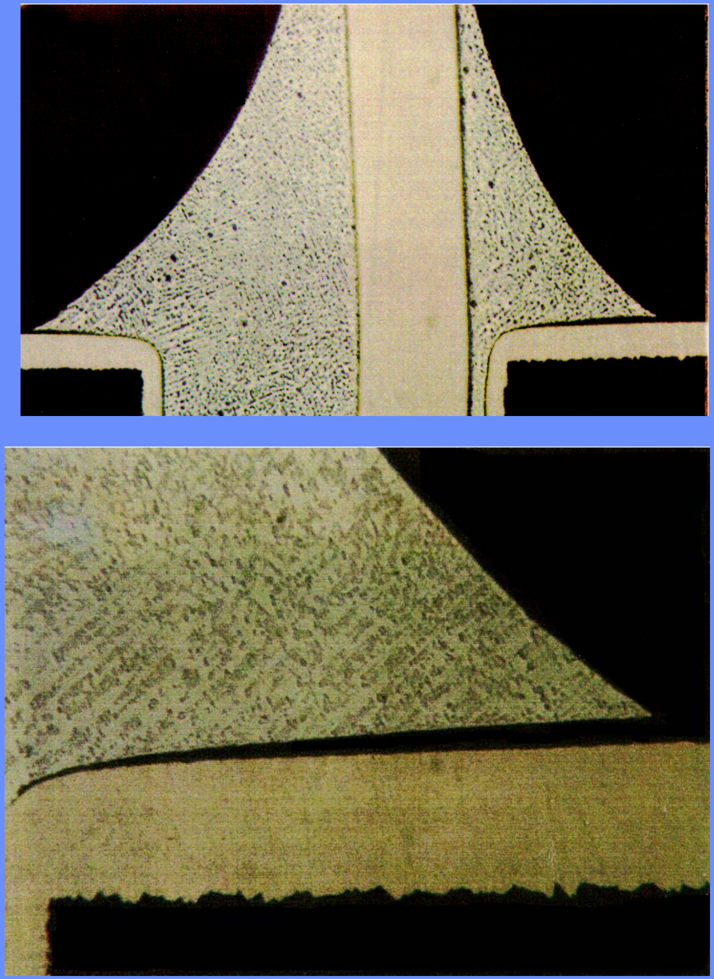


Fracture path appears to be affected by the presence of intermetallic particles at the interface on the component side. Fracture stays in the solder but the path appears to be deflected by nearby intermetallic particles. The roughness associated with this top interface parallels the roughness of the intermetallic layer.

Fillet Lifting in High-Tin Solders

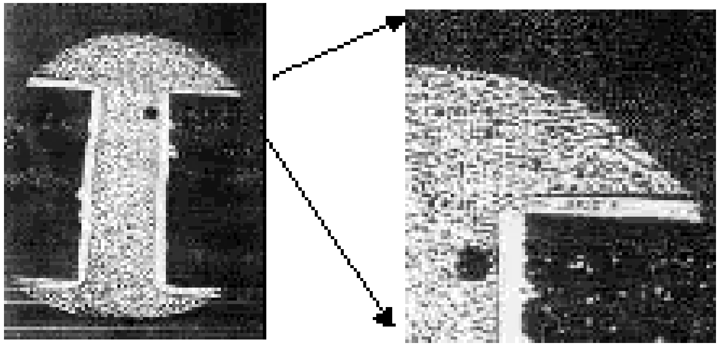


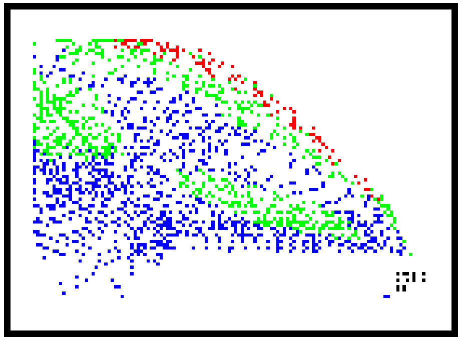
Morphololology of Fillet Lifting



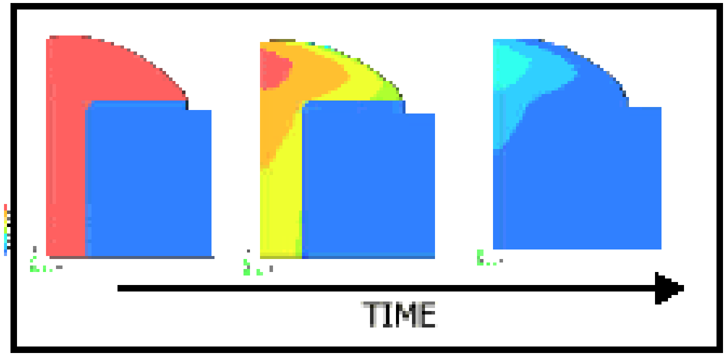
- Separation between intermetallic and solder
- Crack stops at knee on land side
- Sometimes cracking also between component lead and solder
- Not seen in surface mount joints on same board
- Seen in high-Sn alloys, including Sn-3.5Ag
- Not obseved in eutectic Sn-Pb and Sn-Bi

Fillet Lifting – Lead Free

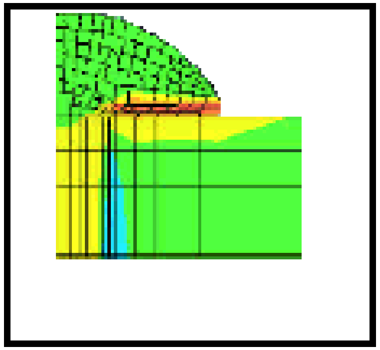




Marangoni Flow



Solidification



Stress

Chris Bailey - University of Greenwich and Bill Boettinger - NIST

Effect of Composition on Fillet Lifting

Alloy	Composition (wt%)						Measured Defect Rate	Calculated Defect Rate
	Sn	Ag	Bi	In	Cu	Sb		
A4	96.5	3.5					0.03	0.00
F02	96.2	2.5			0.5	0.8	0.09	0.16
F17	91.8	3.4	4.8				0.81	0.90
F43	91.5	2.5		5.0	1.0		0.18	0.18
F45	91.5	0.5		5.0	3.0		0.59	0.56
F46	95.0		5.0				0.84	0.85
F47	94.0		5.0	1.0			0.83	0.85
F48	92.0		5.0	3.0			0.93	0.85
F49	90.0		5.0	5.0			0.88	0.85
F50	95.0			5.0			0.04	0.00
F51	93.5	0.5		5.0	1.0		0.42	0.36
F52	92.5	1.5		5.0	1.0		0.28	0.27
F53	94.0		1.0	5.0			0.40	0.17
F54	92.0		3.0	5.0			0.58	0.51
F55	94.5	0.5		5.0			0.28	0.26
F56	93.5	1.5		5.0			0.13	0.17

Comparison between measured and calculated fillet lifting parameter as a function of composition

Linear function of composition fits well

Hot Tearing **is Root Cause of Fillet Lifting**

Critical factor: ΔT when solid between 90% and 100% solid

Effect of Pb Additions on Fillet Lifting

Sn-3.5Ag used as base alloy

A4 - Sn- 3.5Ag			F59 (A4 + 2.5Pb)			F60 (A4 + 5Pb)		
Board	Pad	Avg.	Board	Pad	Avg.	Board	Pad	Avg.
Thin	Small	0	Thin	Small	0.7	Thin	Small	0.4
	Large	0		Large	0.9		Large	0.2
Med.	Small	0	Med.	Small	1	Med.	Small	0.6
	Large	0.5		Large	1		Large	0.7
Thick	Small	0	Thick	Small	1	Thick	Small	1
	Large	0.5		Large	1		Large	0.8

Pasty range: ~ 0°C 46 °C 43 °C

Predicted that Fillet Lifting would be seen in production through hole joints with Pb-Free solders and Pb-Sn board and/or component surface finishes

Widespread observation of fillet lifting (Nortel, Panasonic, Nippon Superior, ...)

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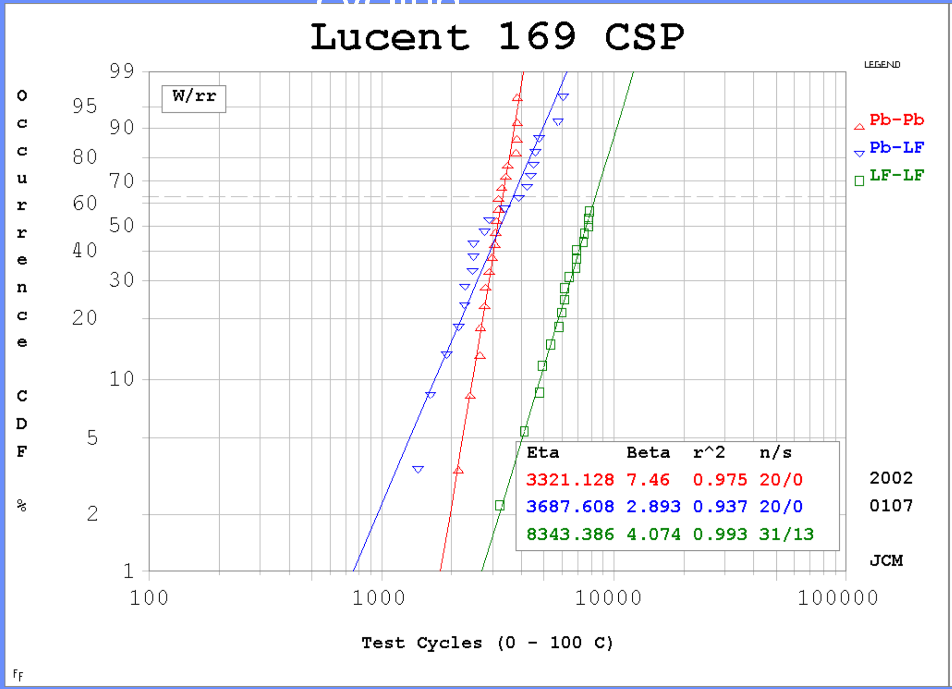
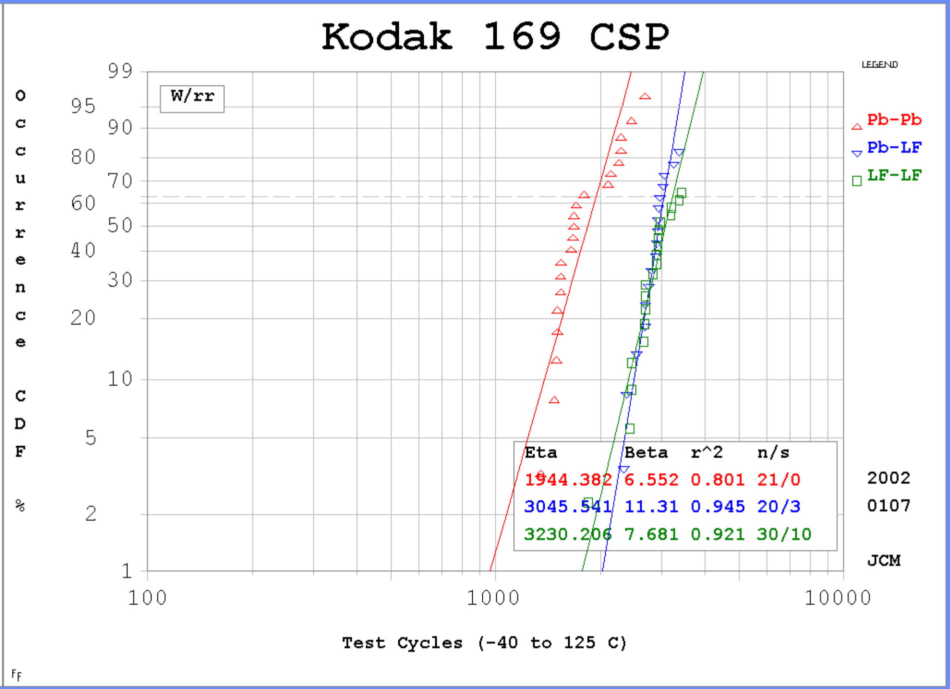
169CSP Weibull Analyses

0 to100?C cycling

-40 to +125?C cycling



Eta	Beta	r^2	n/s
3321.128	7.46	0.975	20/0
3687.608	2.893	0.937	20/0
8343.386	4.074	0.993	31/13



Eta	Beta	r^2	n/s
1944.382	6.552	0.801	21/0
3045.541	11.31	0.945	20/3
3230.206	7.681	0.921	30/10

Pb-Pb	Pb-LF	LF-LF
3321	3688	8343
7.5	2.9	4.1

Pb-Pb	Pb-LF	LF-LF
1944	3046	3230
6.6	11.3	7.7

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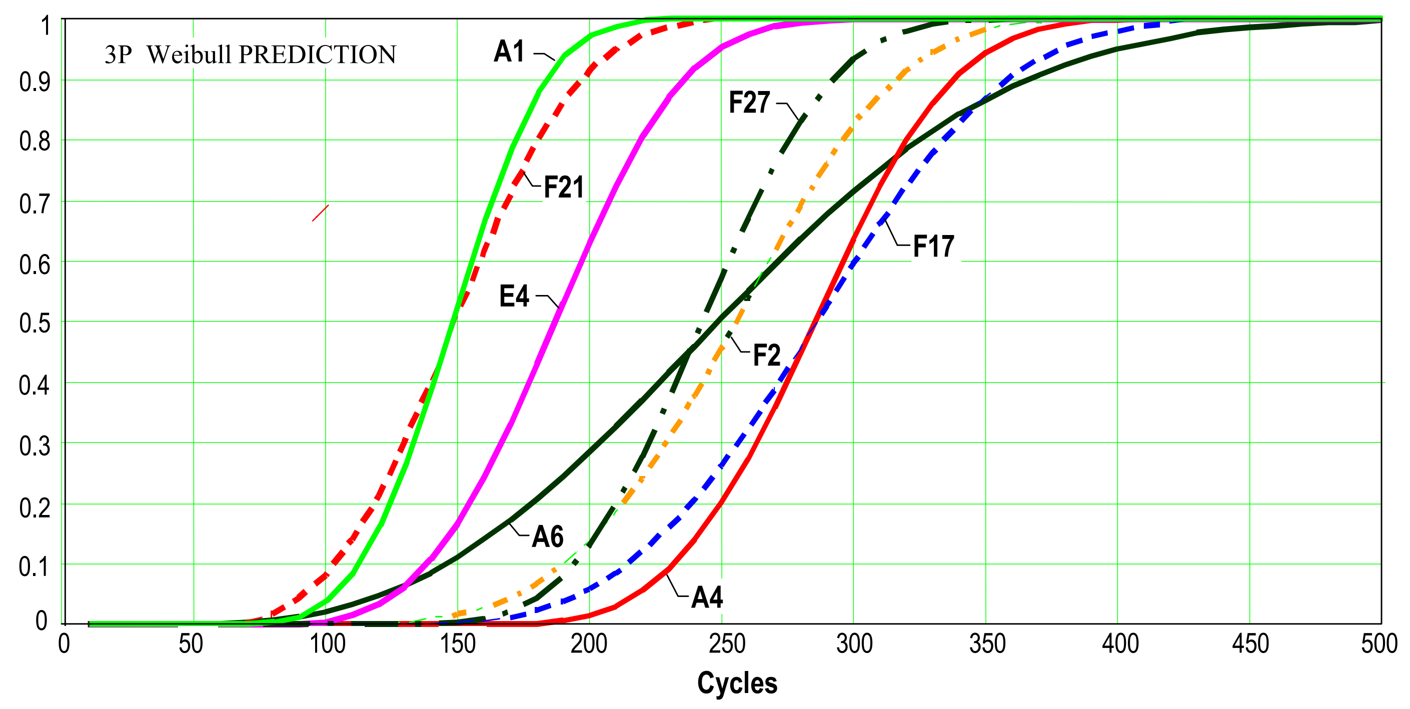
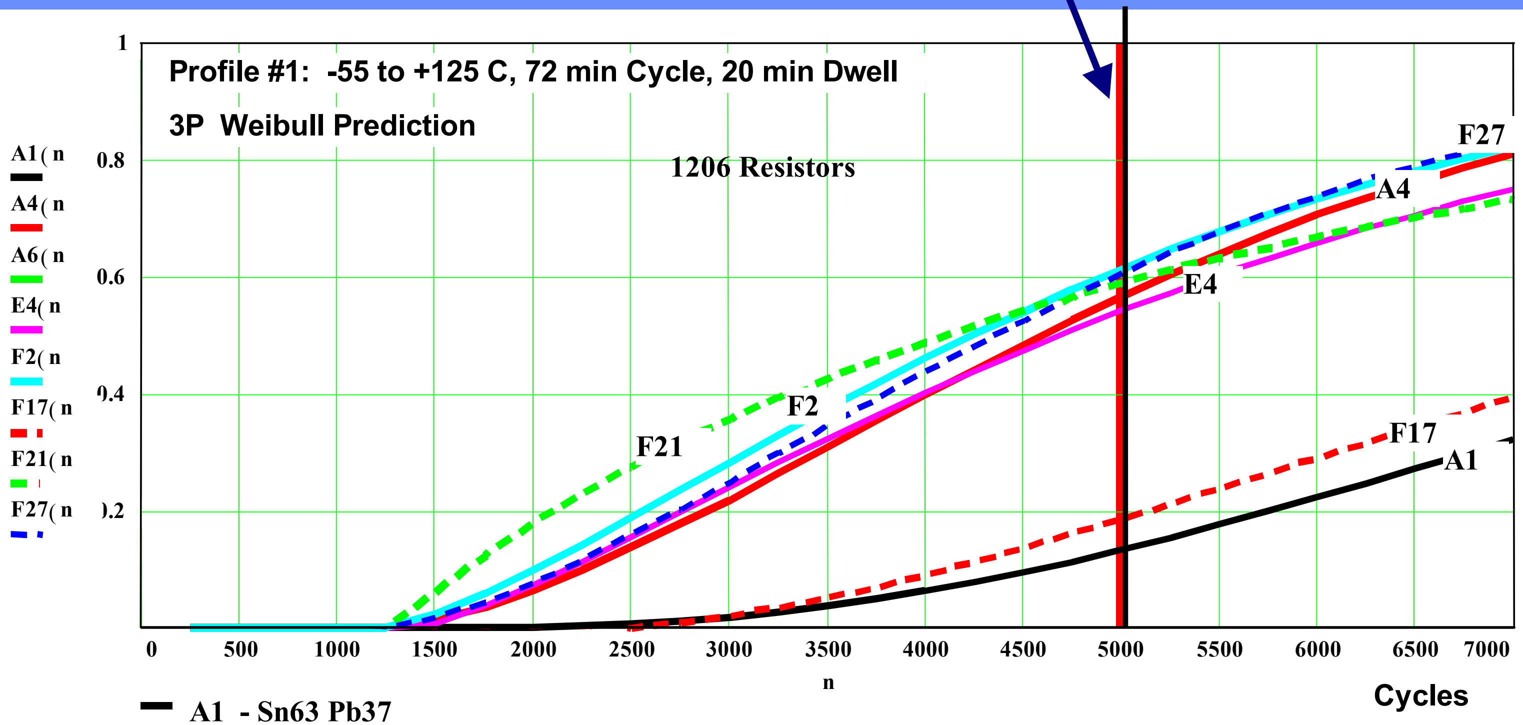
NCMS Lead-Free Project: Thermal Cycling Results for LCCCs

PROFILE #2: 0 to +100 C, 30 min Cycle, 5 min Dwell



NCMS Lead-Free Project: Thermal Cycling Results for 1206 Resistors

Test ended at 5000 cycles



- A1 - Sn63 Pb37
- A4 - Sn96.5 Ag3.5
- E4 - Sn95 Ag3 Bi2
- F2 - Sn96 Ag2.6 Cu 0.8 Sb 0.5
- F17 - Sn91.8 Ag3.4 Bi4.8
- F21 - Sn77.2 In20 Ag2.8
- F27 - Sn95 Ag3.5 Zn1 Cu.5

The curve for A6 is omitted because there is not enough failure data to compute reliable values for the Weibull parameters needed for life prediction.

NCMS Alloy Down-Selection Process

Pass/Fail Down Selection

Attributes	Acceptable Level
Toxicology	No Pb and Cd
Economics & Availability	Bi: <20 wt% In: <1.5 wt%
Composition	1 or 2 alloys from the same familty
Liquidus Temperature	<225°C
Pasty Range	<30°C
Tensile Properties Yield Strength Elongation	 > 2000 psi >> 10%

Decision Matrix Down Selection

			Scale		
Test	**Property**	**Weight**	**-10**	**0**	**5**
DSC	**Pasty Range (°C)**	**10**	**30**	**5**	**0**
Wetting	**F_{max} (μN)**	**2**	**300**	**500**	**700**
Balance	**t_0 (s)**	**2**	**0.6**	**0.3**	**0.1**
	$t_{2/3}$ (s)	**2**	**1**	**0.45**	**0.5**
TMF	**Thermomechanical Fatigue (% of Sn-37Pb)**	**10**	**75**	**100**	**150**
	Weighted Score				

79 Alloys

11 Alloys

8 Alloys

Results from Thermal Cycle Testing

Acceleration factors different for different alloys - different components

How can rational comparisons be made?