Correlation of Material properties to the Reliability performance of High Density BGA Package solder joints:

By

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For

IPC Reliability Summit

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Legal Information

Agenda

- ➢ Introduction
- LF Alloy Selection
- LF Material Properties
- LF Reliability Concerns and Test Results
- Reliability Data Analysis
- Summary
- Q&A

Scope / Objective

- Objective
  - To provide an overview of Pb-free (LF) material properties, LF challenges, LF and LF reliability results BGA components
- Scope
  - LF challenges and solder joint reliability (SJR) performance of LF alloys for 2nd level interconnect with main emphasize on SAC alloy system

Motivation for LF Transition

- **Government Regulations**
  - The European Union (EU) leads in environmental regulation, but China follows closely
    - California Bill AB 48 would follow UK adoption of RoHS
  - RoHS (EU Directive) restricts the use of the Lead substances in electronic products placed on the EU market after July 1, 2006 or later depending on market segment
- **Deployment Timelines**
  - Consumer electronics, July 2006
  - Sever and Telecom infrastructure exemption to be reviewed by EU in 2008

Position Statement

- Intel recognizes the magnitude and technical complexity involved with converting the world's board assembly industry from Pb/Sn to LF solders
- Intel has completed a major milestone in driving the LF technology across the industry by closely working with our customers and the supply chain to achieve a successful LF transition in worldwide electronics markets
- Intel has done extensive reliability testing on LF solder and processes for board assembly
- Intel believes its LF products and reference processes to be low risk

Agenda

- Introduction
- ➢ LF Alloy Selection and Material Properties
- LF Reliability Concerns and Test Results
- Reliability Data Analysis
- Summary
- Q&A

Synopsis

What we know about Pb-free solder joint…

- Solidification characteristics and microstructure
- Mechanical properties
- Impact of material properties on solder joint reliability
  - ❖ Improved fatigue performance vs. PbSn
    - **Longer fatigue life and better solder joint reliability**
  - ❖ Reduced shock performance vs. PbSn, **but passed board level shock & Vibe test conditions**
- Solder joint fatigue can be modulated by
  - ❖ Enabling configuration (e.g. w/ vs. w/o heat sink solution)
  - ❖ Board design (e.g. pad size & type)
  - ❖ Test methods (e.g. dwell time, temp range)

➢ **LF (SAC405) showed improved solder fatigue margin**

SAC Terminology

- **SAC stands for Sn-Ag-Cu solder**
- **Composition is sometimes written as SACxyz**
  - Where

    x.y = Silver (Ag) content in solder by weight

    0.z = Copper (Cu) content in solder by weight

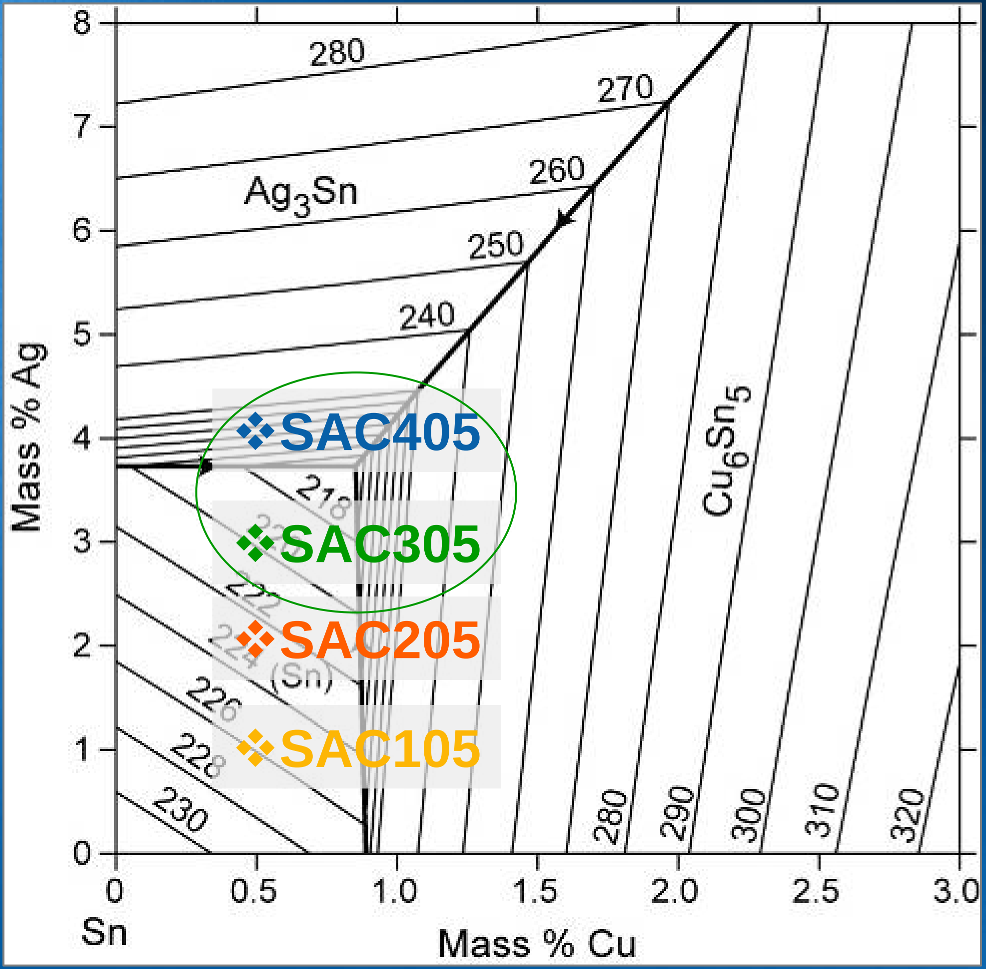
  100-x.y-0.z = Tin (Sn) Content

Examples:

- **SAC305 = 96.5%^ Sn / 3.0%^ Ag / 0.5%^ Cu (JIETA)**
- **SAC405 = 95.5%^ Sn / 4.0%^ Ag / 0.5^% Cu (Intel)**

^ Percentages by weight

Pb-free Solder (Sn-Ag-Cu) SAC alloy



Phase Diagram Source: K-W Moon et al, J. Electronic Materials, 29 (2000) 1122-1236

Pb-free SAC alloys range from 1% to 5 % Ag

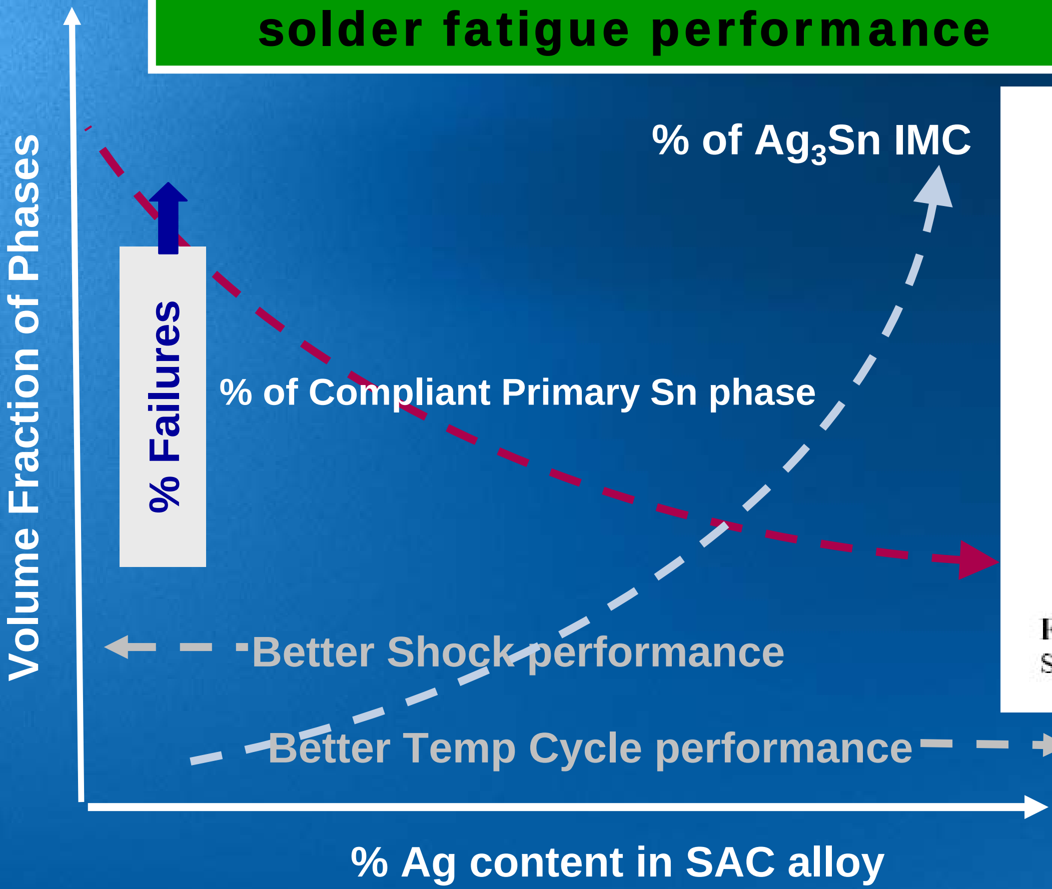
Different SAC alloys have different material properties and microstructure, so variations in performance are expected

SAC405 & SAC305 are similar enough they can be used together (i.e., SAC405 solder balls with SAC305 paste)

- **Best Practices: SAC305 - SAC405 for most applications SAC105 – Handheld Equipment**

The effect of Ag Content on LF Reliability

Increase in Ag content helps solder fatigue performance



Volume Fraction of Phases

% Failures

% of Ag_3Sn IMC

% of Compliant Primary Sn phase

Better Shock performance

Better Temp Cycle performance

% Ag content in SAC alloy

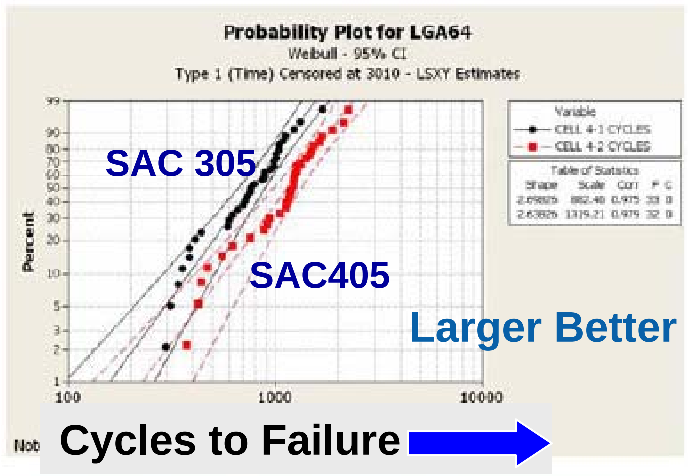


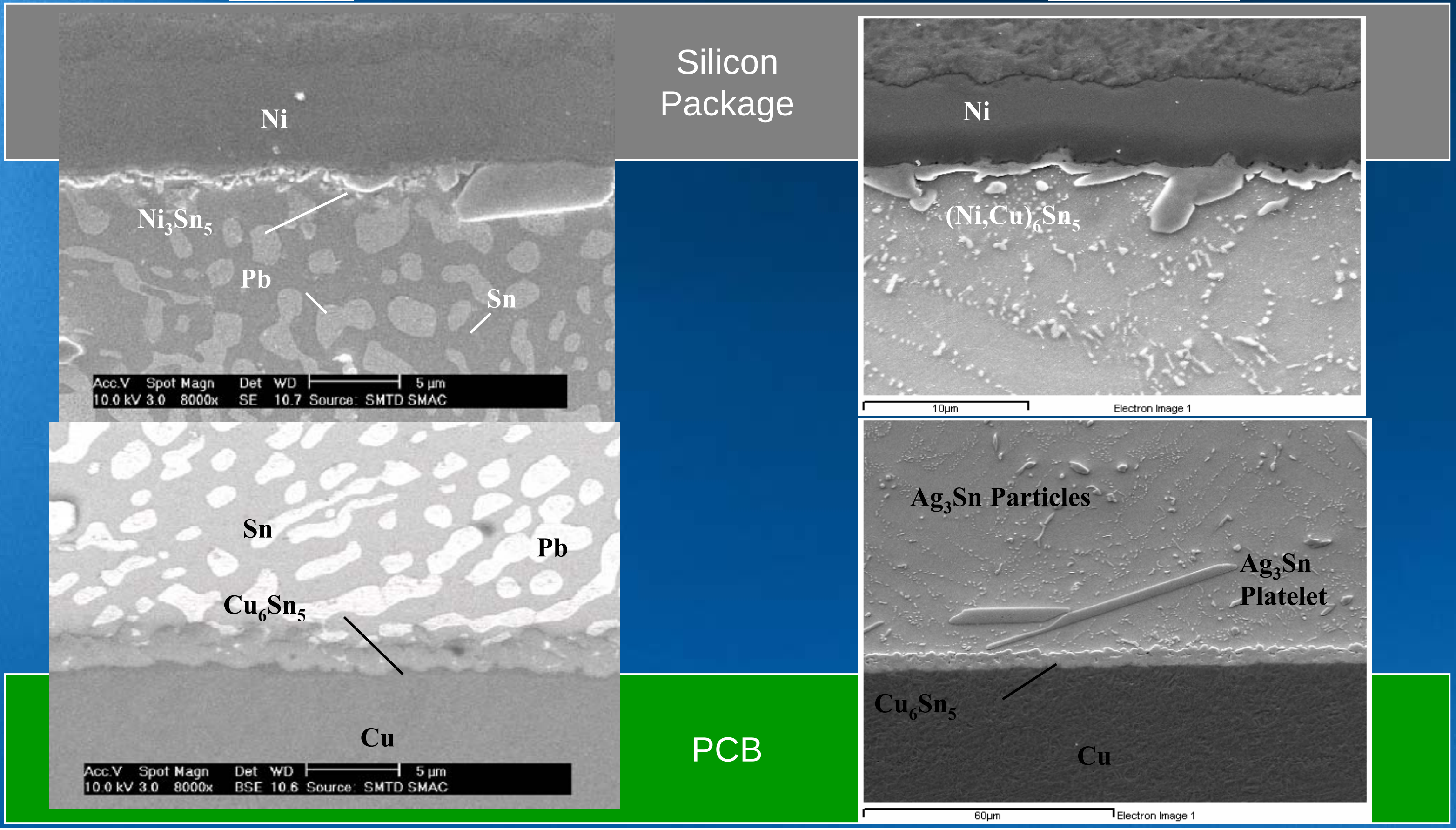
Figure 20. Weibull plots for pure SAC 305 (cell 4-1) and SAC 405 (cell4-2) LGA64, -55°C to 125°C

Literature Reference: P. Snugovsky et al : "Failure mechanism of SAC 305 and SAC405 in harsh environments and influence of board defects including black pad" SMTA 2007

- **SAC305-SAC405 alloy showed better long term reliability in temp cycle test (iNEMI Recommendation)**

Microstructure

PbSn **SAC405**



- Pb-free & PbSn interfacial intermetallics similar
- Bulk solder microstructure different
- Performance difference to stem from bulk properties

Typical Properties: PbSn vs. SnAgCu

Property	PbSn	SnAgCu	SAC Alloy
Melting Point	183 C	217 – 219 C	SAC405
Young's Modulus	35 GPa	53 GPa	SAC405
Tensile Strength (20C at $0.004s^{-1}$)	40 N/mm^2	48 N/mm^2	SAC387
Joint Shear Strength (20C at 0.1mm/min)	23 N/mm^2	27 N/mm^2	SAC387
Creep Strength (100C at 0.1mm/min)	1.0 N/mm^2	5.0 N/mm^2	SAC387

Compiled from multiple sources

- ➢ SAC405 is stiffer and stronger than PbSn
- ➢ Consequences of properties:
  - ✓ Improved fatigue performance
  - ✓ Reduced shock performance

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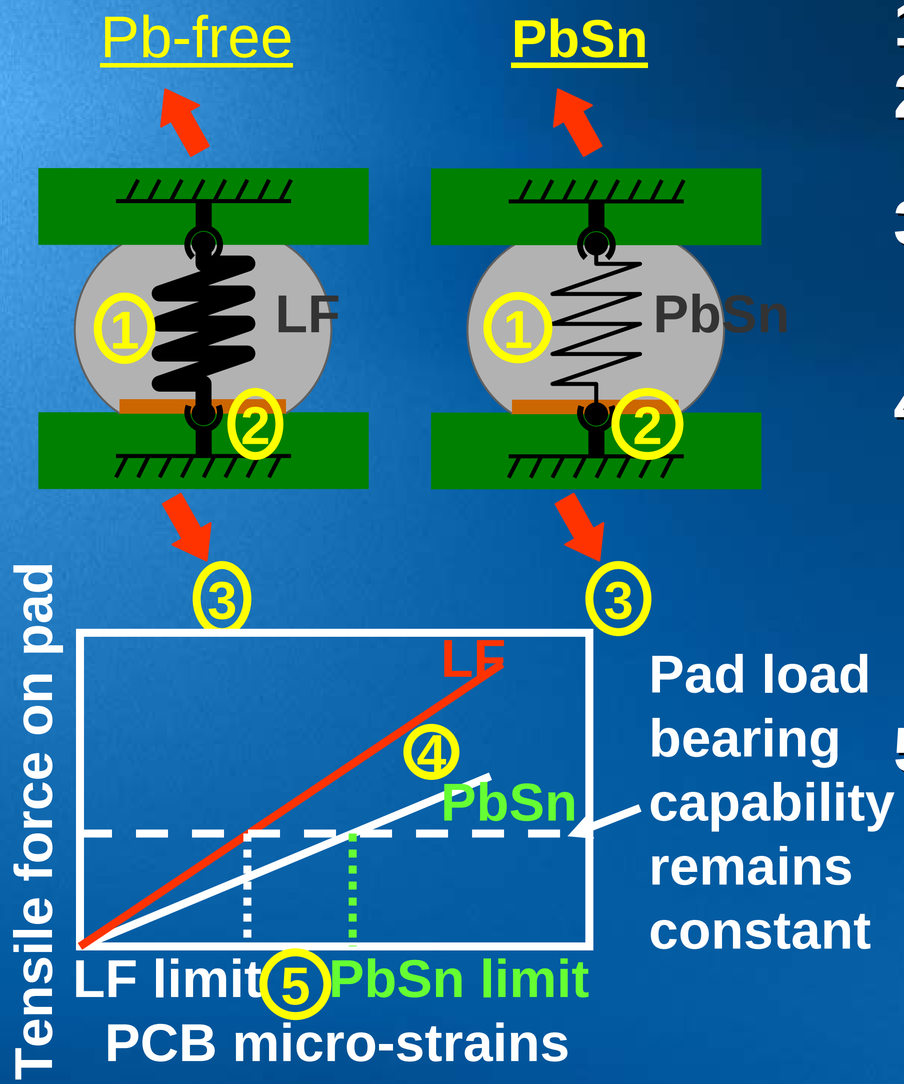
LF Reliability Concerns

LF Failures Concern	Stress Test	Comments
Solder fatigue	Temp Cycle	Electrical open/solder crack
Overstressing	Shock Test	Electrical open/solder crack
Overstressing	Vib Test	Electrical open/solder crack
PCB trace, via corrosion	Temp/Humid 85/85°C	Electrical open due to via, trace corrosion
IMC growth, Diffusion & Solder creep	Bake Test	Electrical open IMC growth, diffusion, & shorts due to solder creep

- **LF solder joint reliability requirement established based on expected failure mechanism**

Transient Bend: PbSn vs. Pb-free SJ

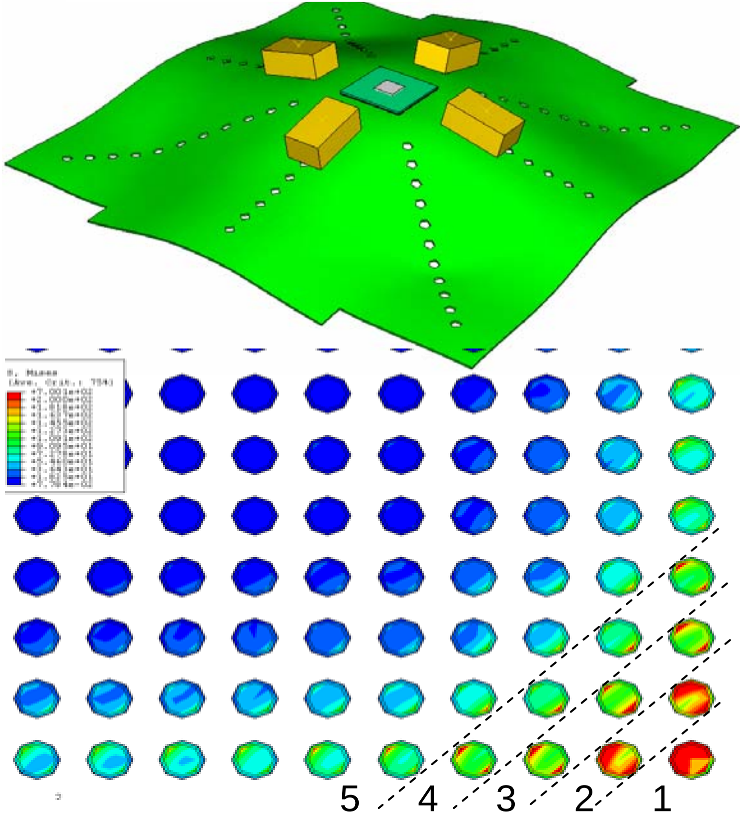


Pad load bearing capability remains constant

1. Lead free is stiffer than PbSn
2. Pad adhesion strength is equivalent for Pb-free and PbSn
3. Board bending pulls apart the opposite surfaces of the solder ball
4. Stiffer Pb-free ball generates higher forces on the pad. The softer PbSn ball deforms to accommodate bending, resulting in lower forces acting on the pad
5. Pb-free ball reaches the critical level of force required to pull the pad out at lower strain. This is a consequence of the ball material property, not the pad property

- **Pb-free stiffness reduces transient bend performance, but ICT fixtures redesigned to accommodate the need**

Shock Test Performance Comparison Between Sn/Pb vs. LF 2LI



FEA Model

Shock Level	Solder	Crack (%)Row				
		Non CTF		CTF		
		1	2	3	4	5
1	Sn/Pb	50	0	0	0	0
	LF	100	20	0	0	0
2	Sn/Pb	50	50	0	0	0
	LF	100	100	40	0	0
3	Sn/Pb	100	75	0	0	0
	LF	100	100	100	100	100

Design recommendation to include corner sacrificial (NCTF) balls for BGA packages

- ➢ **Stiffer LF solder joint → reduced shock tolerance**
- ➢ **However, passed intensive baseline S&V testing**

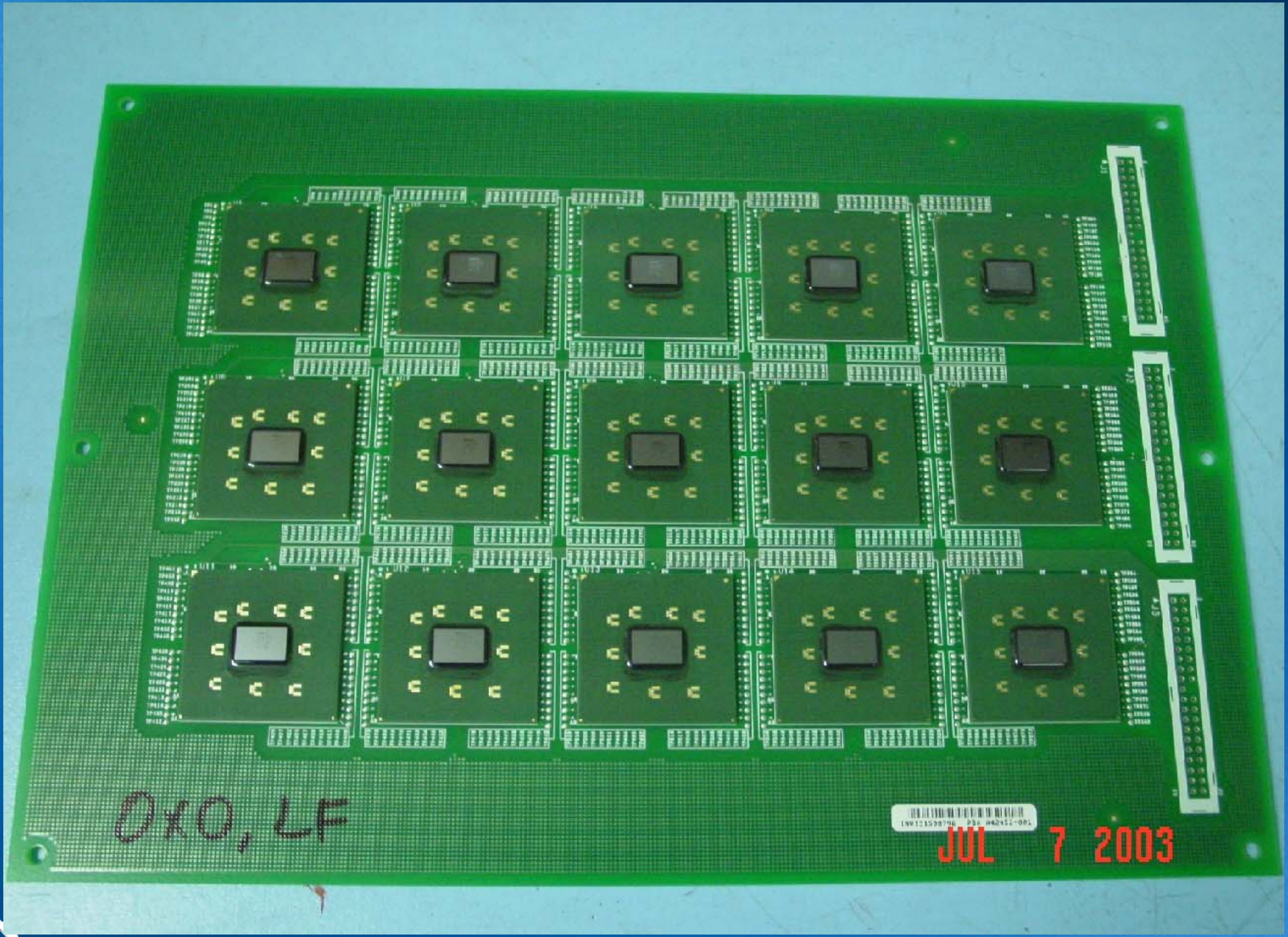
Factors Affecting Solder Fatigue

- Component to board CTE mismatch
- Component type: BGA vs. Socket
- Pad size (component and board)
- Pad size ratio
- Metallurgy (PbSn vs. SAC405)
- Component die size (Range : 8 mm to 12 mm)
- Body size (package size ranging from 14 to 42.5 mm sq)
- Body (package) thickness/stiffness
- Ball Array design
- PCB Board thickness/stiffness
- Joint shape
- Load on Solder joint
- Bend mode
- Surface finish compatibility

1 mm LF FCBGA Temp Cycle Test Vehicle Details

- **Test Vehicle (15 components per board)**
  - 1 mm FCBGA on 0.062 inch thick board (no load)
    - ❖ 1 mm pitch FCBGA packages with no heat sinks
      - Package Size : 37.5 mm Sq
      - Ball pattern: Full array and Depop
      - Die Size: 11.7 X 8.0 mm
    - ❖ Sample size for each leg: 45 units (3 boards)
    - ❖ PCB Pad parameters
      - Pad Type: Mixed (MD & SMD)
    - ❖ PCB parameter
      - Im/Ag surface finish, 18 mil PCB pad,& one PCB Supplier
    - ❖ Nominal reflow condition (SMT + wave)
    - ❖ Control Leg (Sn/Pb solder with HASL SF)
      - Sample size : 45 units (3 boards)

1 mm FCBGA Temp Cycle Test Vehicle



The Effect of Temp Cycle dwell Time on Temp Cycle Performance (-40 to +85 C)

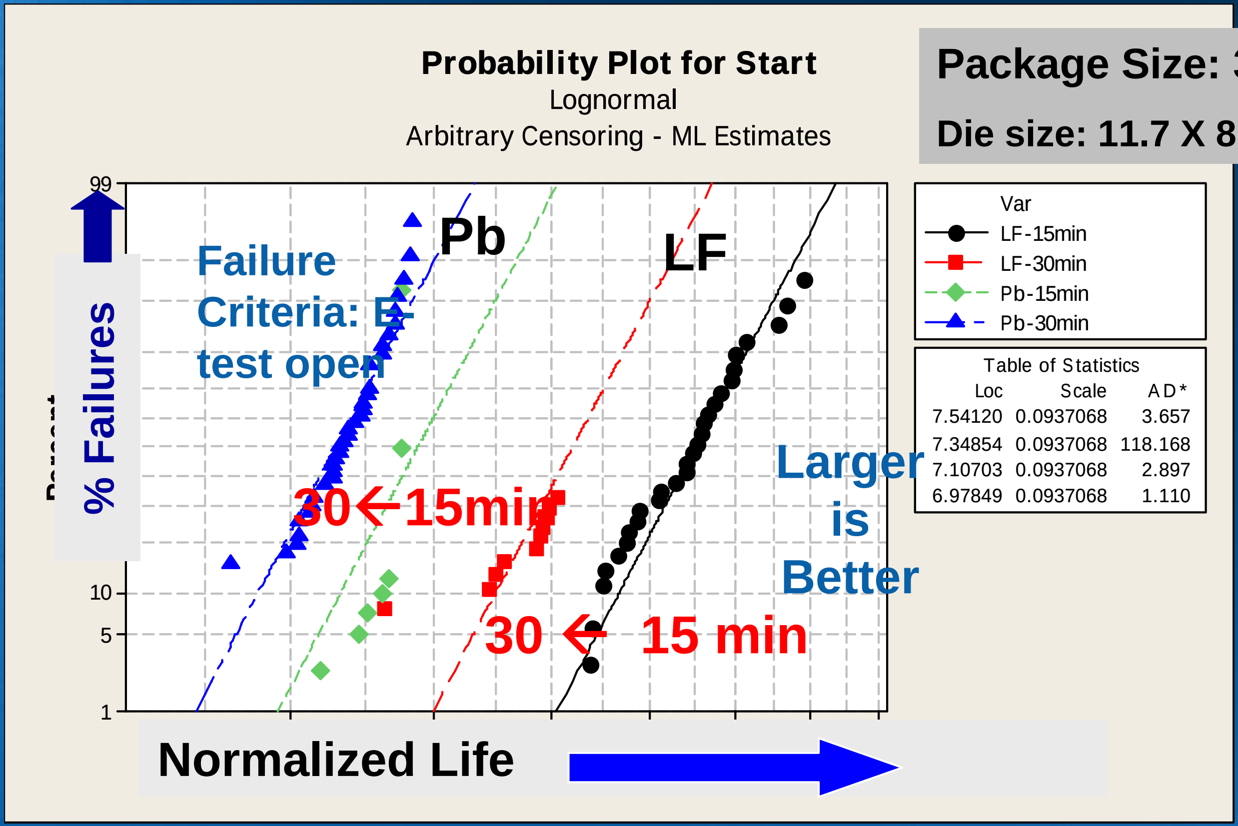


Table of Statistics

Loc	Scale	AD*
7.54120	0.0937068	3.657
7.34854	0.0937068	118.168
7.10703	0.0937068	2.897
6.97849	0.0937068	1.110

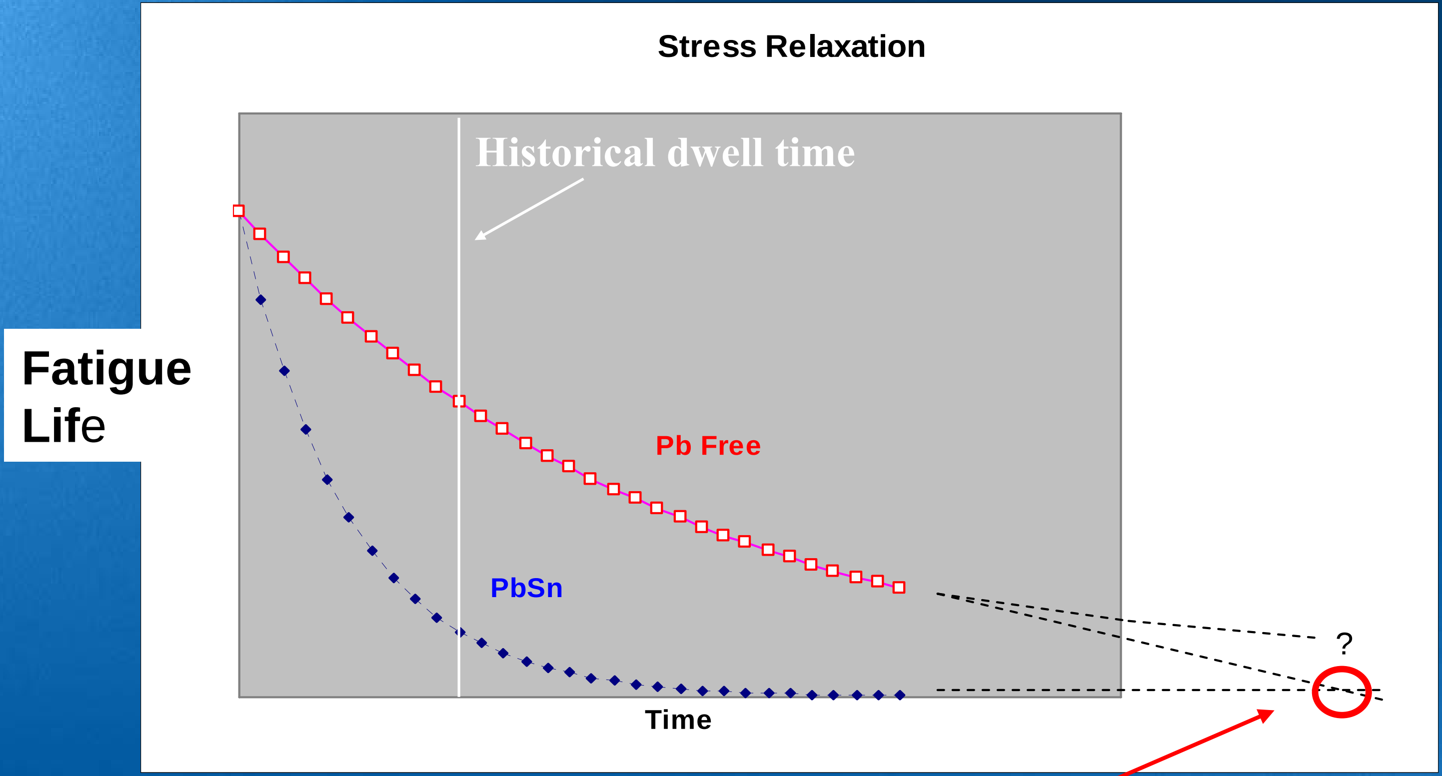
Package Size: 37.5 mm sq

Die size: 11.7 X 8 mm, 4 Layer

- **Increased dwell → reduced cycles to failure**
- **Pb-free better than PbSn for 15 and 30 min dwell**

Dwell Time Concerns

Does SAC405 show poor performance in extended dwell time (use condition) compared to Sn/Pb solder even though better performance seen in short time test?

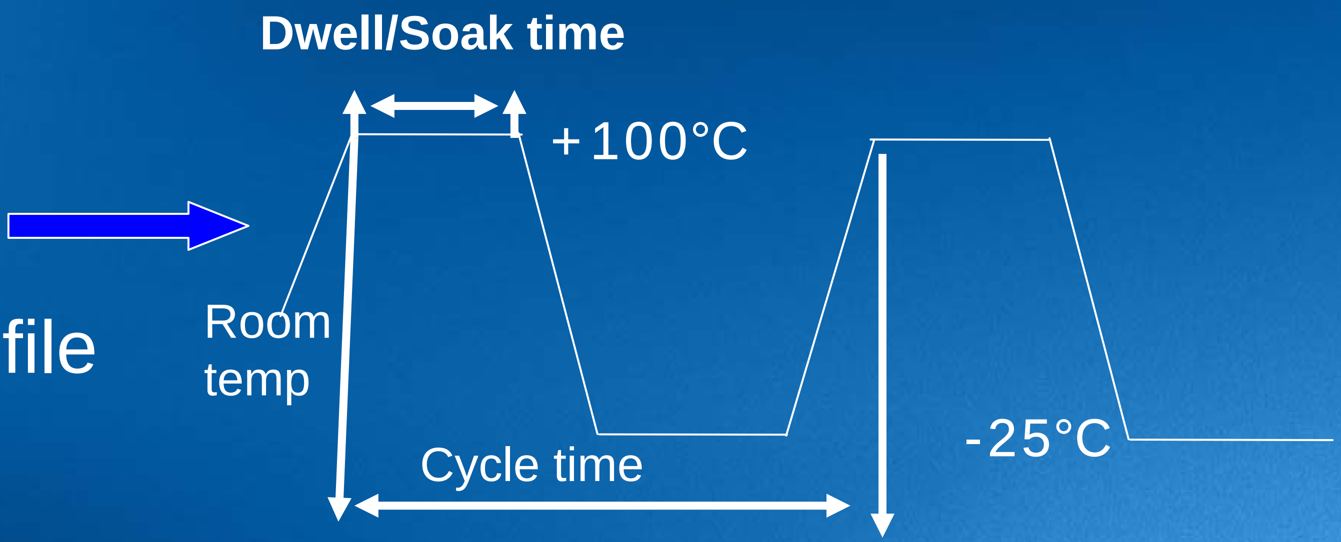


Does SAC405 cross-over Sn/Pb?

Impact of Temp Cycle Dwell Time

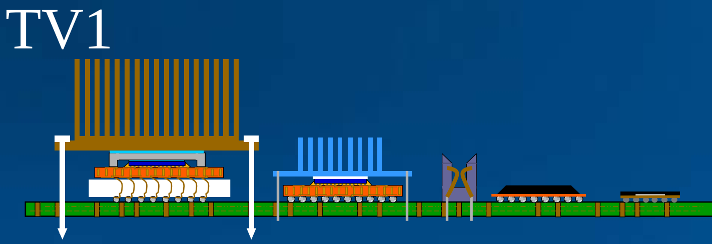
- There is a concern about dwell/ soak time performance for LF compared to Sn/Pb
- Does Sn/Pb reliability "cross-over" LF in extended dwell times
- Experimental plan was developed to address this

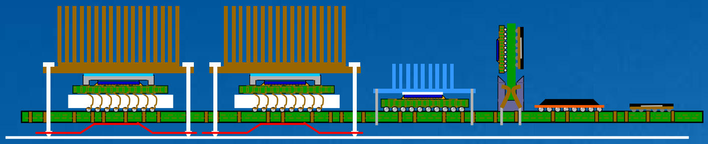
Typical temp cycle test profile



Dwell Time Impact Study

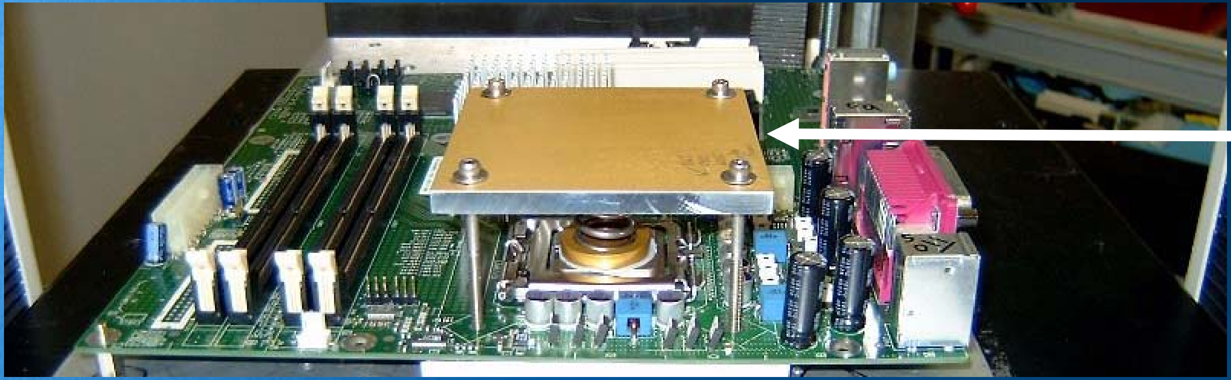
- **Purpose: To assess fatigue risk to LF products utilizing two different sockets and FCBGA packages**
- **Experimental Description**
  - Vehicles
    - ❖ Desktop Test Vehicle board (TV1)
      - Sn/Pb and LF
      - Fully enabled
    - ❖ Dual-proc server test vehicle board (TV2)
      - Sn/Pb and LF
      - Fully enabled
  - Thermal Cycling
    - ❖ -25°C to 100°C
    - ❖ 1, 4, and 8 hr cycle times
    - ❖ *In situ* electrical continuity monitoring



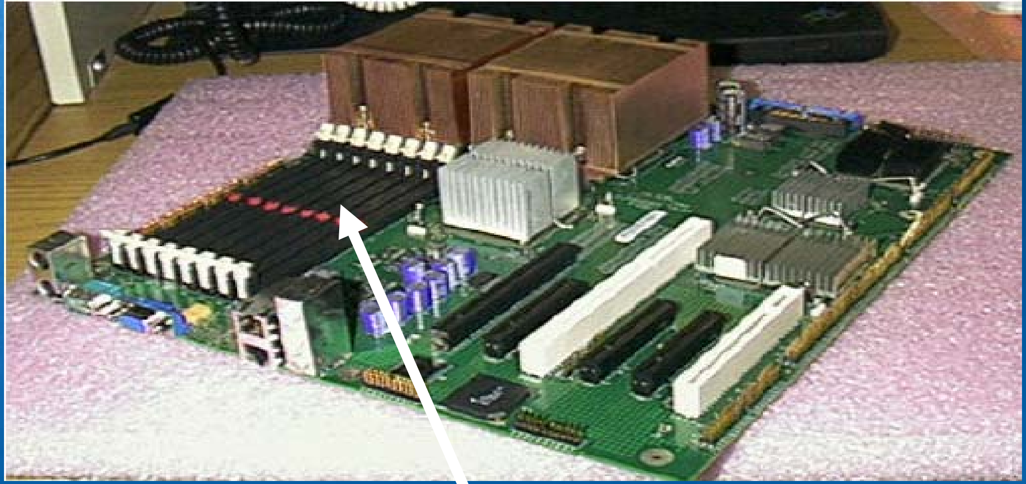


- **Hypothesis: SAC405 ≥ PbSn**

Description of Test Vehicles



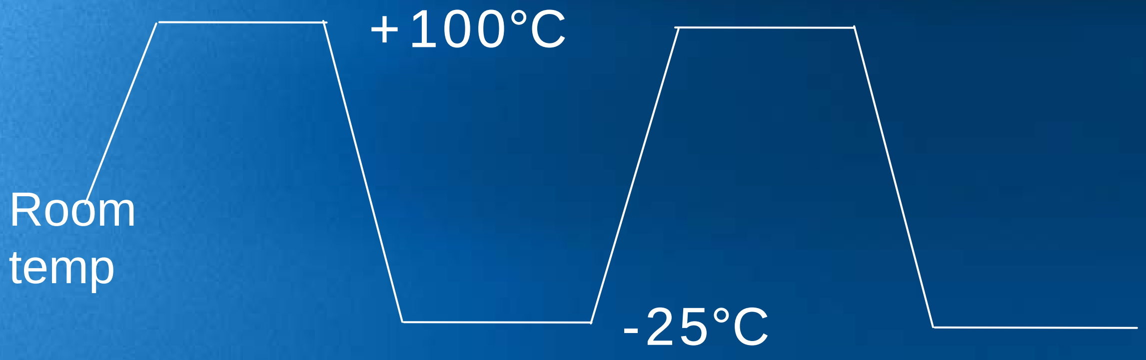
Motherboard (TV1)
with LGA socket and
0.8 mm pitch FCBGA



Server motherboard (TV2) with LGA
sockets and 1.0 mm pitch FCBGA

Thermal solution
Assembly

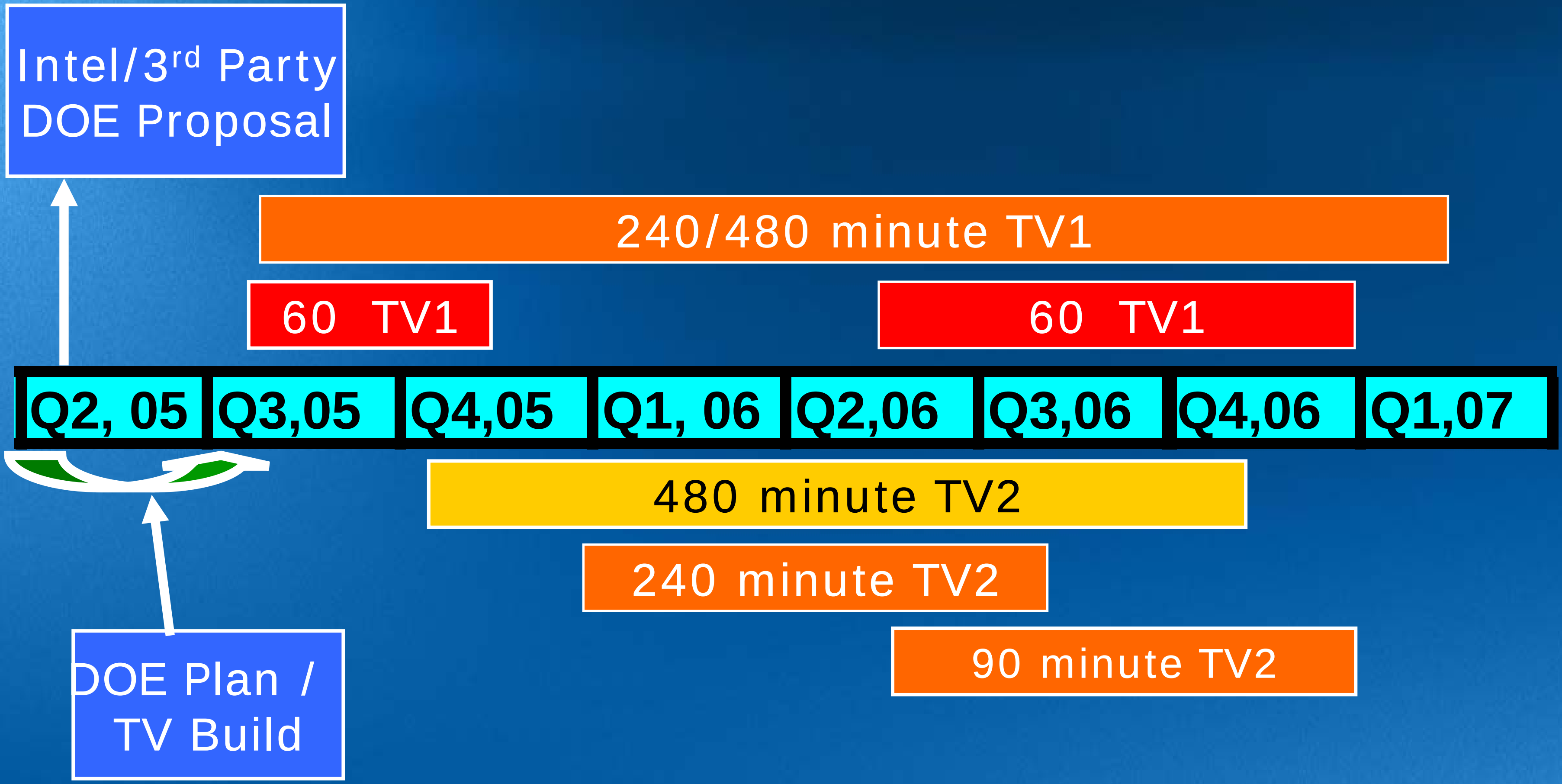
Temp Cycle Profiles



- Temperature range: -25°C to 100°C

Cycle Time	Cycle Time	Ramp Time
1-hour	60min	8min
4-hour	240min	31min
8-hour	480min	31min

Dwell Time Study Timeline



Intel/3rd Party DOE Proposal

240/480 minute TV1

60 TV1

60 TV1

Q2, 05 | Q3,05 | Q4,05 | Q1, 06 | Q2,06 | Q3,06 | Q4,06 | Q1,07

480 minute TV2

240 minute TV2

90 minute TV2

DOE Plan / TV Build

PbSn vs. Pb-free 1.0mm FCBGA

-15 to 125°C, 90 min dwell

Package Size: 37.5 mm sq

Die size: 11.7 X8 mm, 4 Layer

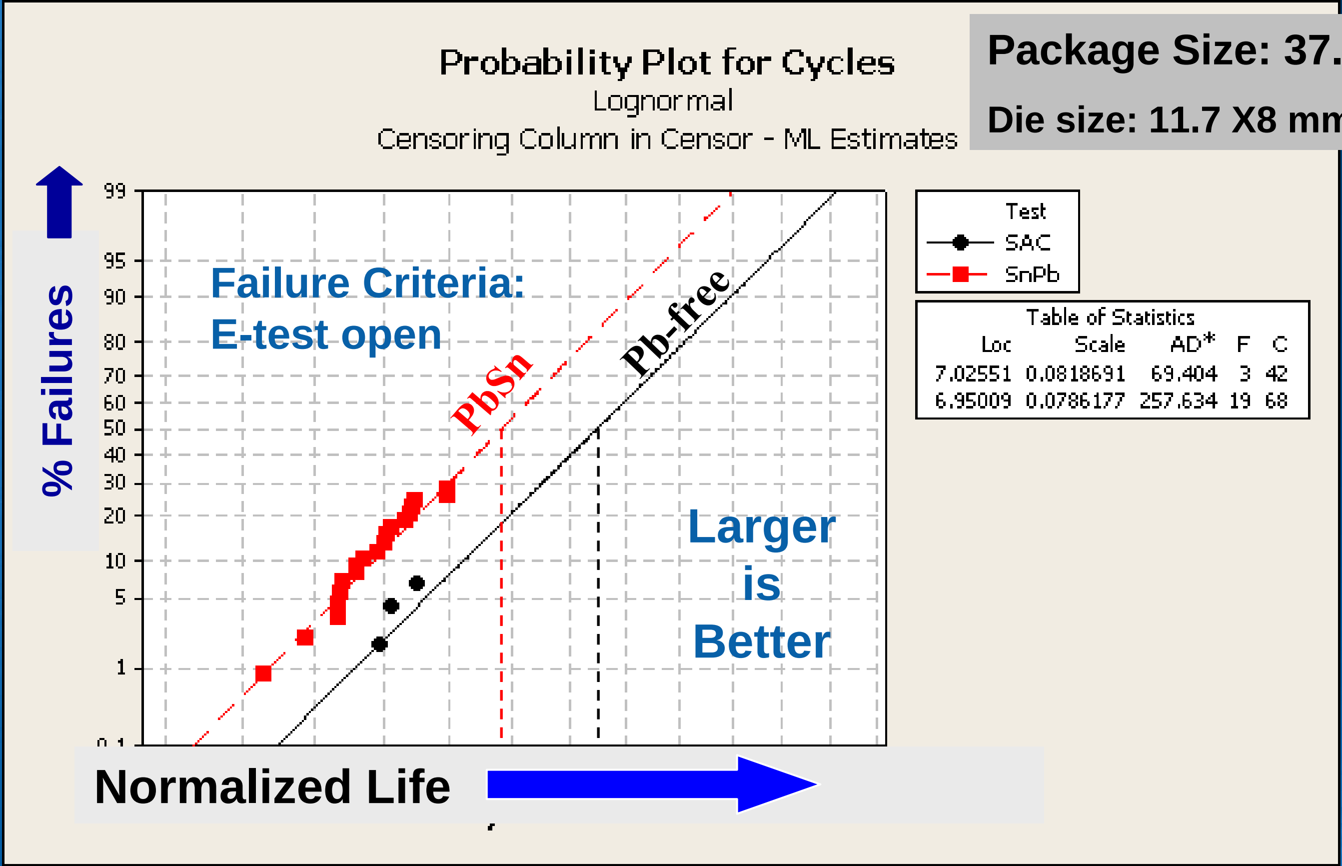


Table of Statistics

Loc	Scale	AD*	F	C
7.02551	0.0818691	69.404	3	42
6.95009	0.0786177	257.634	19	68

- **At 90 min dwell Pb-free performed better than PbSn**

Vasudevan etal “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

Results for Dwell Time Effect Study ^

Long Dwell Time Temp Cycle Results

Test Vehicle	Cycle Time	Solder Alloy	# of Cycles Completed	E-test Cumulative Solder Joint Fails	
				socket	FCBGA
TV Design 1	1 hr	Pb	2480	5/10 fails	0/7 Fail
		LF	2480	1/10 Fails	0/7 fail
	4 hr	Pb	2407	2/9	1/9
		LF	2407	1/9	0/9
	8 hr	Pb	1121	0/8	0/8
		LF	1121	0/8	0/8
TV Design 2	1.5 hr	Pb	846	8/16	0/8
		LF	846	5/16	0/8
	4 hr	Pb	1044	0/8	0/4
		LF	1044	0/10	0/5
	8 hr	Pb	925	9/10	1/5
		LF	925	4/10	0/5

➢ **LF (SAC405) solder showed improved fatigue performance and no early LF failures observed in all legs of the DOE**

^ Vasudevan etal "Solder fatigue creep performance of LF (SAC) solder", ECTC 2007

Socket "Y" Temp Cycle Results (-25°C to 100°C 1 hr cycle time)

Socket Size: 37.5 mm sq

PCB pad size: 20 mm

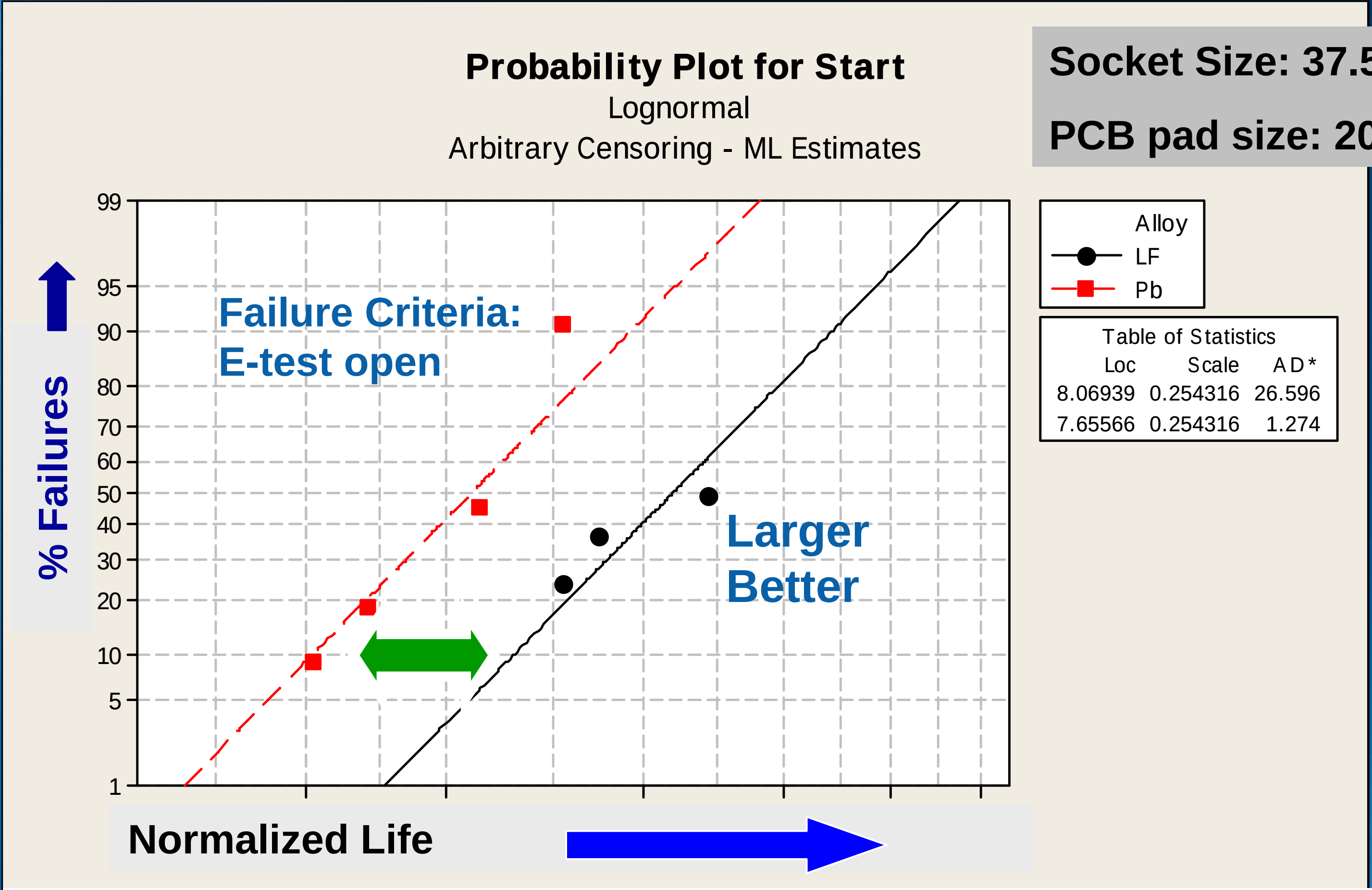


Table of Statistics

Loc	Scale	AD*
8.06939	0.254316	26.596
7.65566	0.254316	1.274

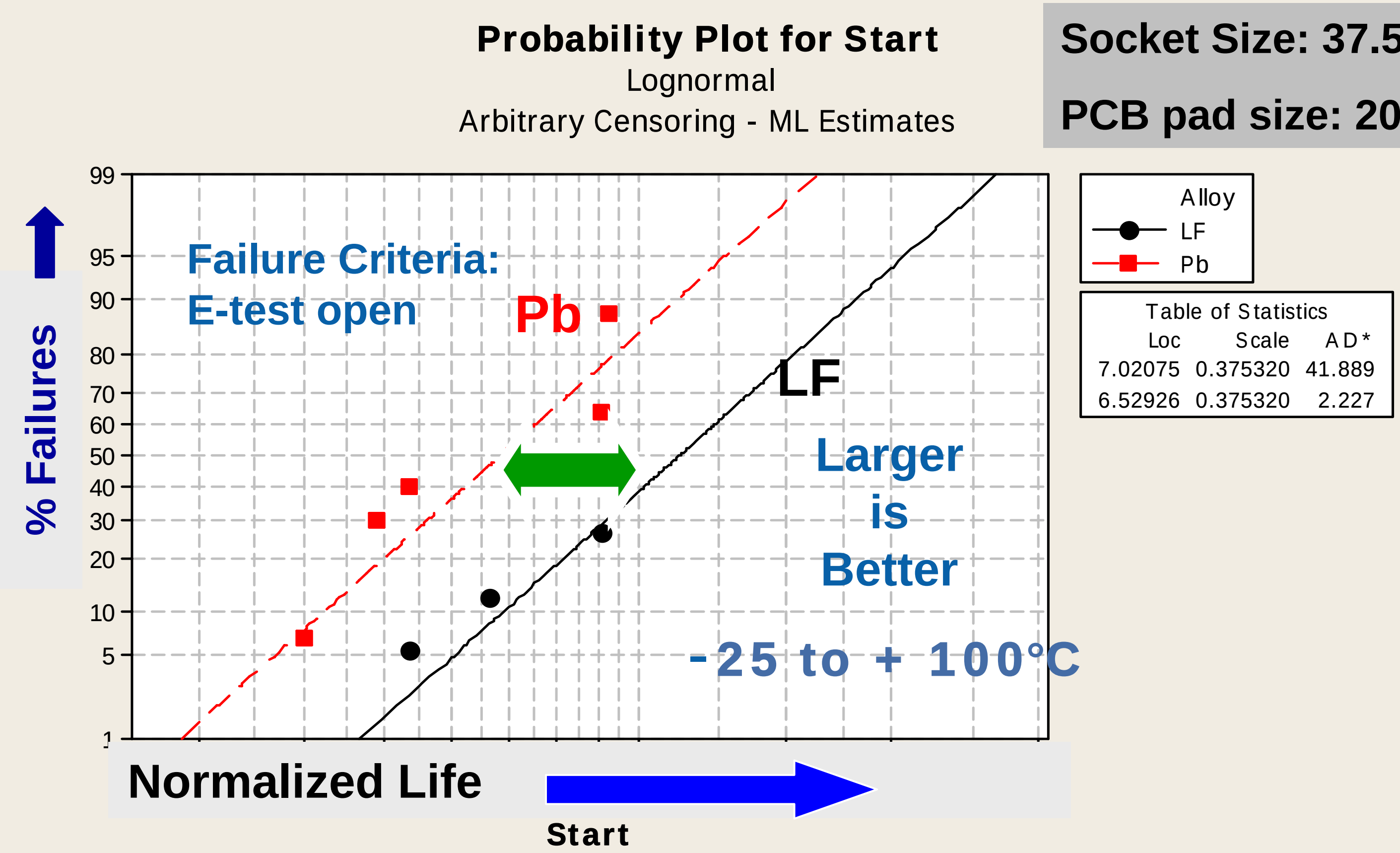
- **Pb-free solder showed better solder fatigue performance compared to PbSn**

Vasudevan etal "Solder fatigue creep performance of LF (SAC) solder", ECTC 2007

Socket X 480 Minute Temp Cycle Results

Socket Size: 37.5 mm sq

PCB pad size: 20 mm



Failure Criteria:
E-test open

Larger is Better

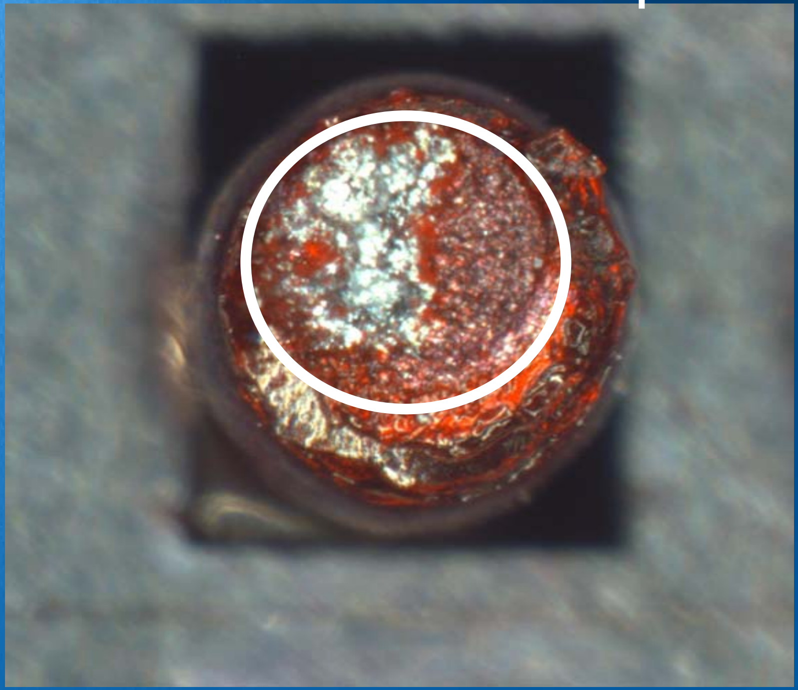
-25 to + 100°C

- LF (SAC405) solder showed improved fatigue performance at 8 hrs cycle time
- No reliability issues observed with LF fatigue creep

Vasudevan etal “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

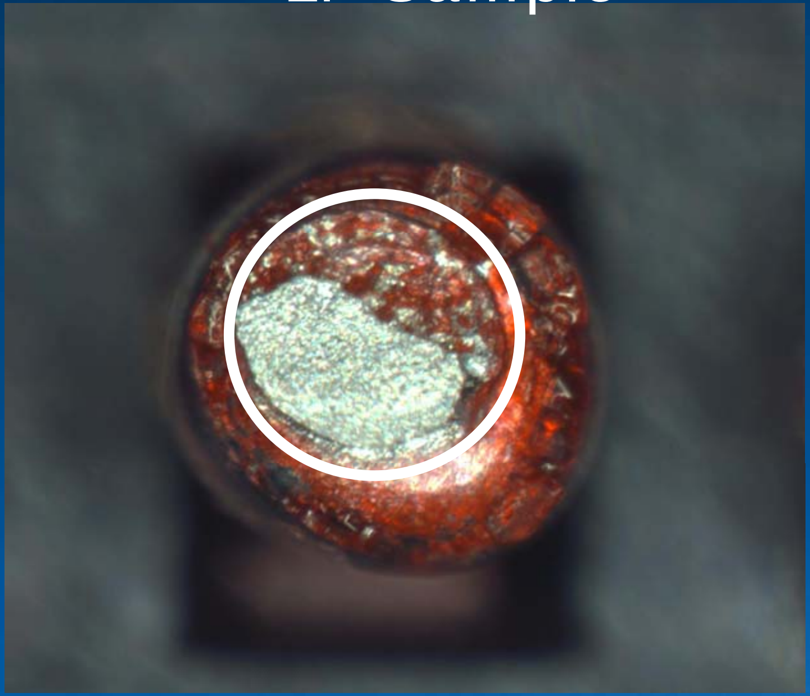
Socket Y 480 Minute Cycle Time After 1121 Cycles

Sn/Pb Sample



Max solder crack ~75%

LF Sample

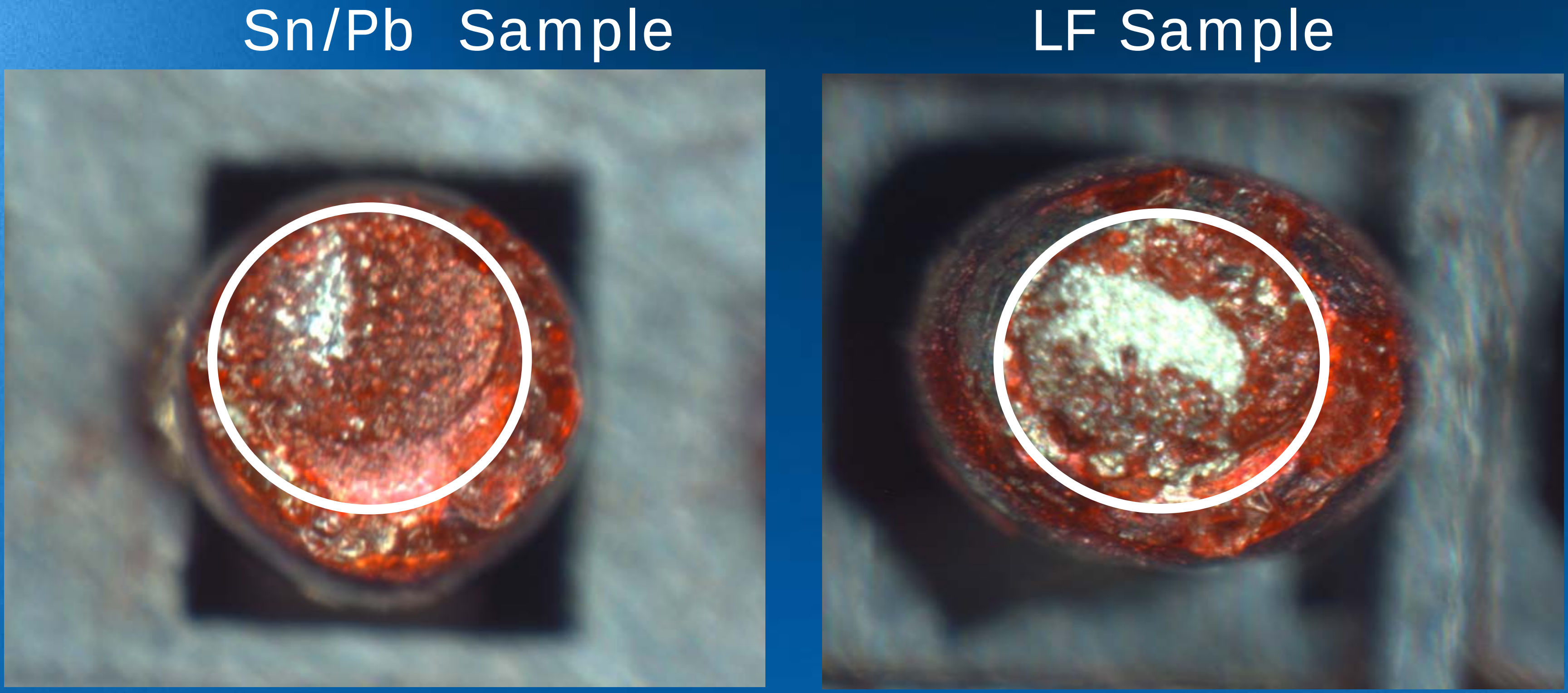


Max solder crack < 40%

- **LF samples showed smaller solder crack size (worst case) compared to Sn/Pb at extended dwell**

Vasudevan etal “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

Socket Y 240 Minute Cycle Time Dye Penetrant Results After 1900 Cycles

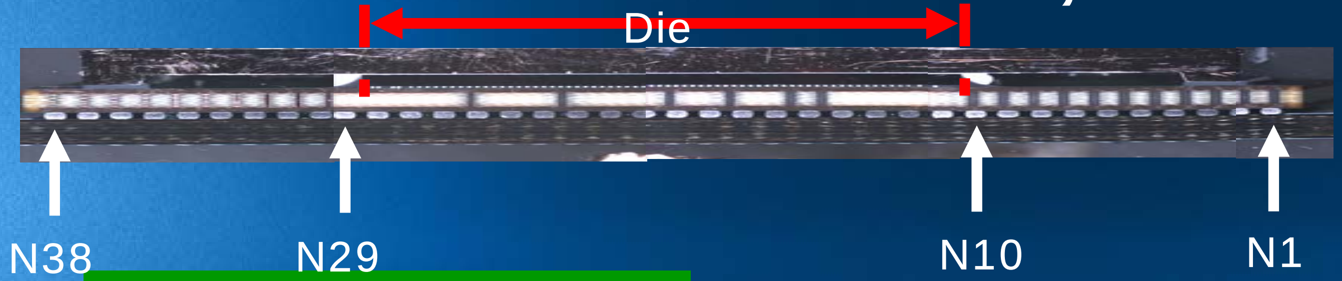


Max solder crack ~90%

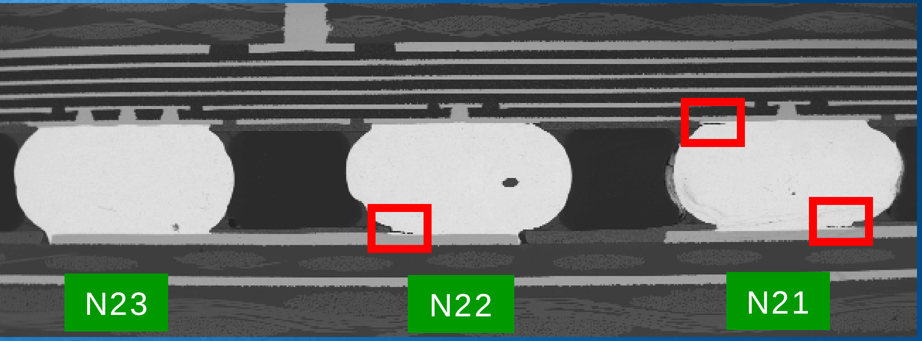
Max solder crack ~70%

- **LF samples showed smaller solder crack size (worst case) compared to Sn/Pb at extended dwell**

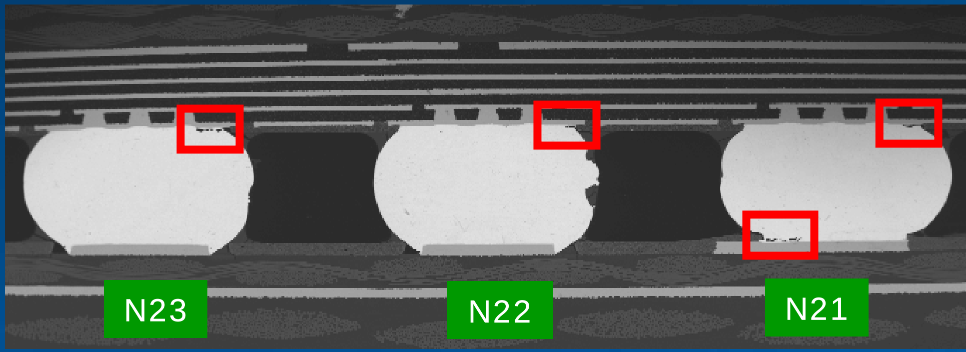
Effect of Dwell time, SJ X-section



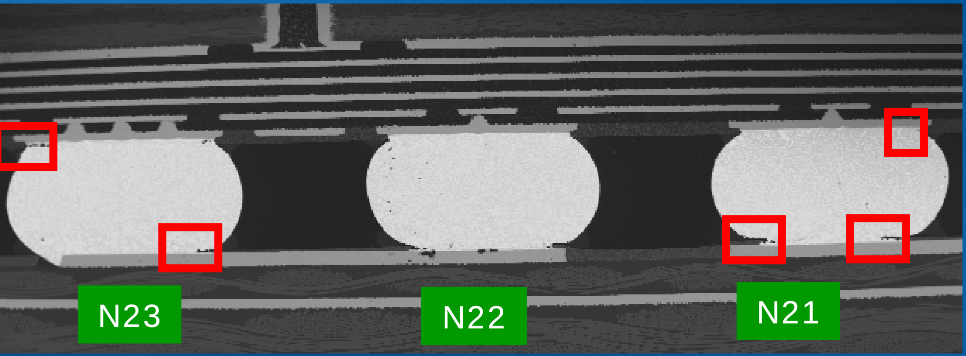
1399 Cycles, LF 90 min



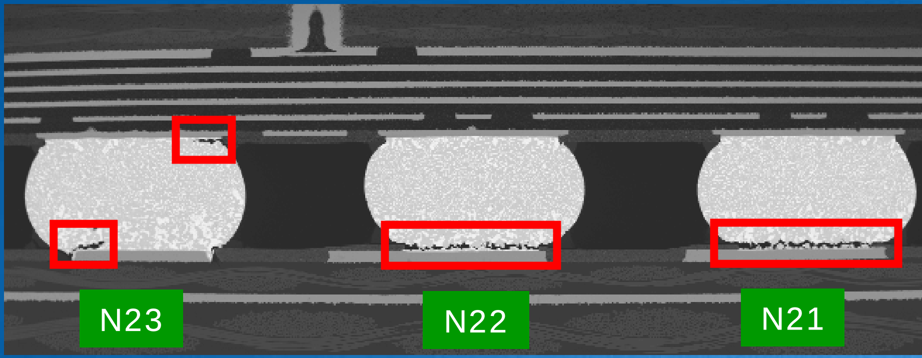
1320 Cycles, LF, 480 min



1300 Cycles, Pb-Sn, 90 min

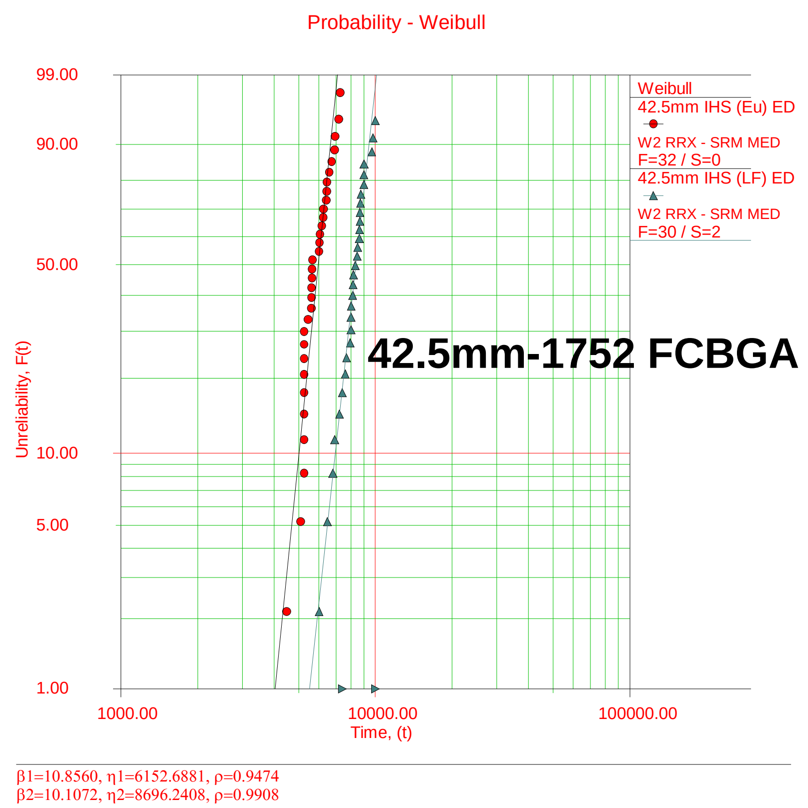


1248Cycles, Pb-Sn, 480 min

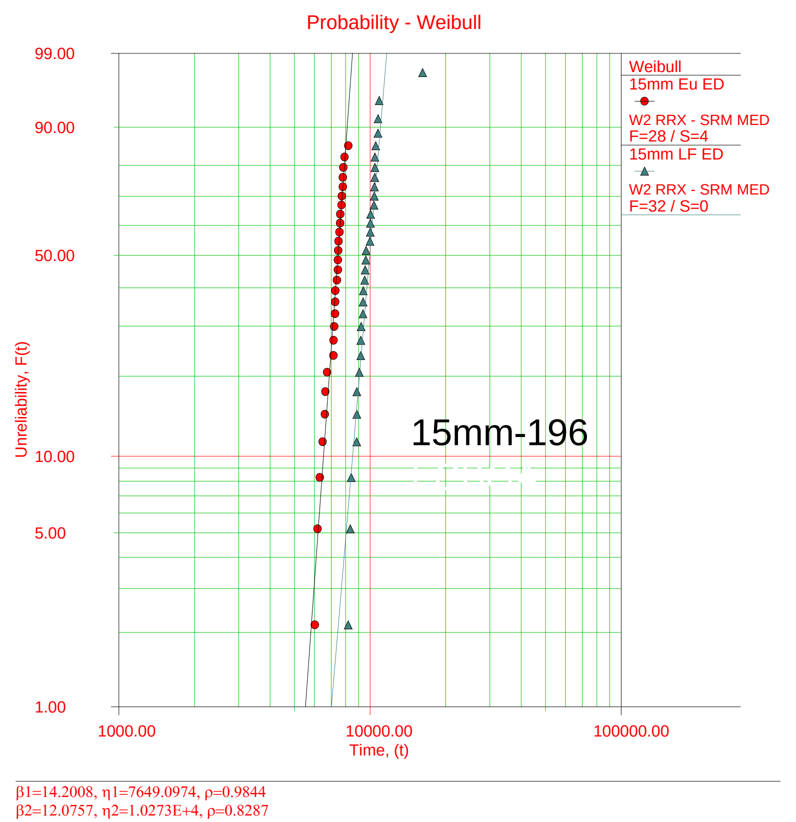


Vasudevan etal “Solder fatigue creep performance of LF (SAC) solder”, ECTC 2007

FCBGA Temp cycle results (0 to +100 º C)



Metallurgy	Characteristic Life	Beta
Eutectic	6153	10.6
Pb-Free	8696	10.1



Metallurgy	Characteristic Life	Beta
Eutectic	7649	14.2
Pb-Free	10273	12.1

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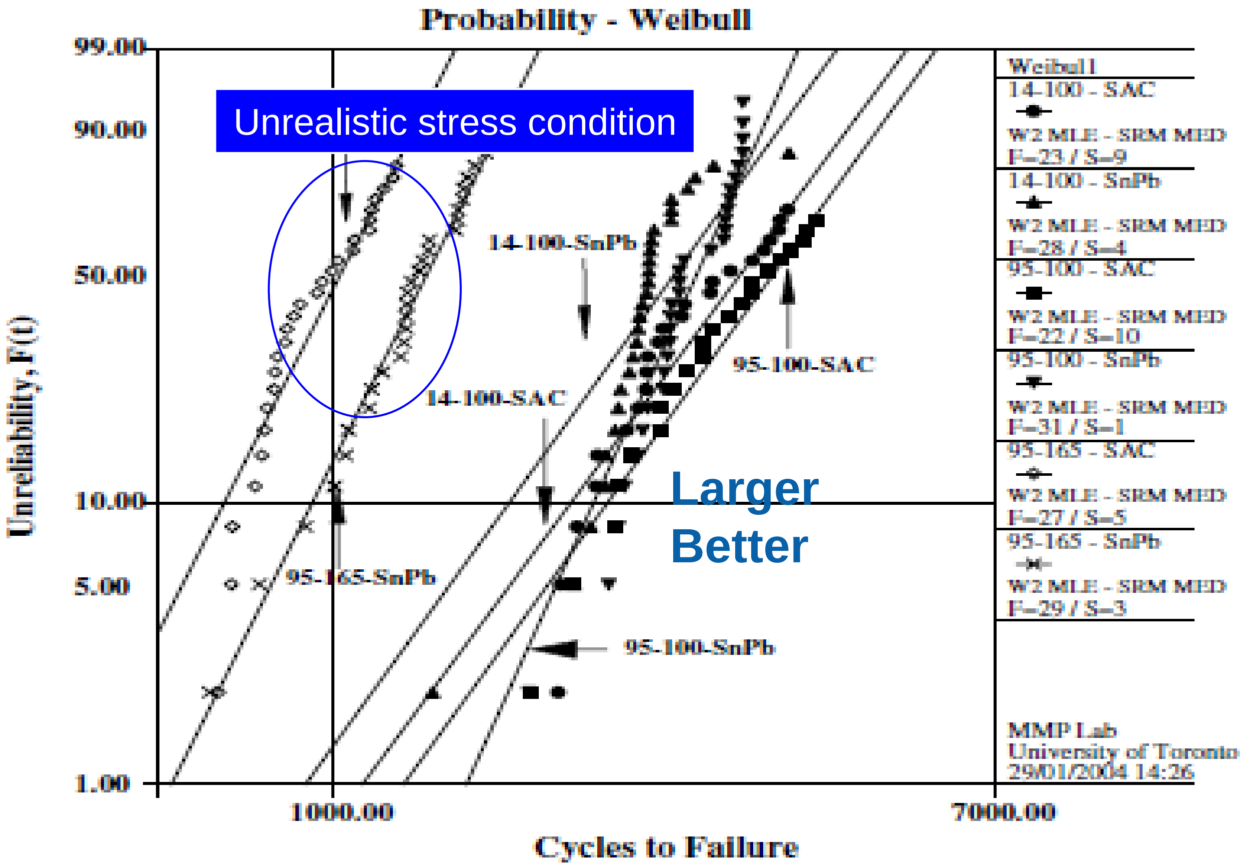
Effect of Temperature on Solder Fatigue

Y. Qi et al. / Microelectronics Reliability 46 (2006) 574–588



Source:

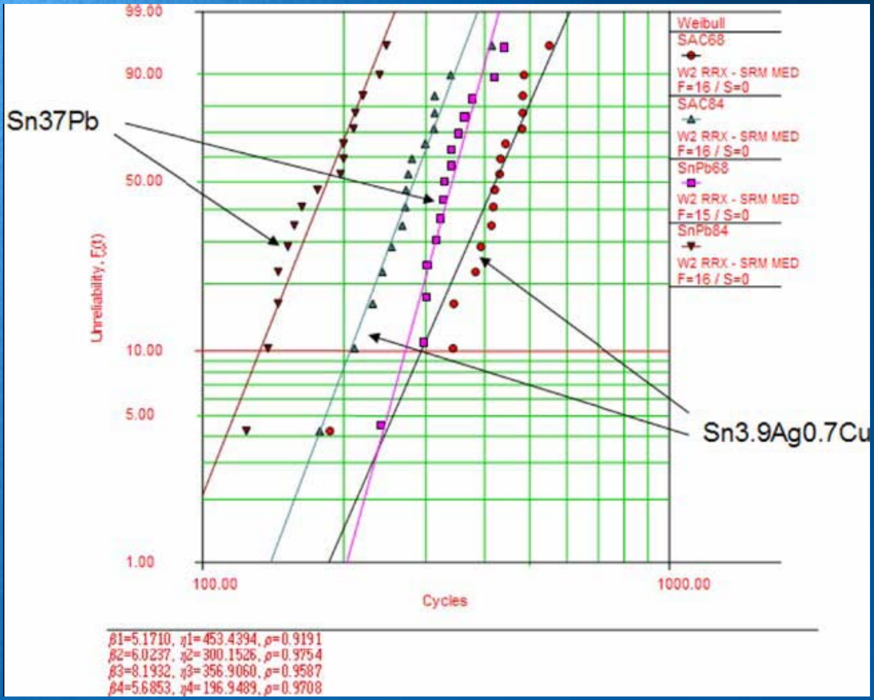
Yan Qi a, Rex Lam a, Hamid R. Ghorbani a, Polina Snugovsky b, Jan K. Spelt a, .

Microelectronics Reliability 46 (2006) 574–588

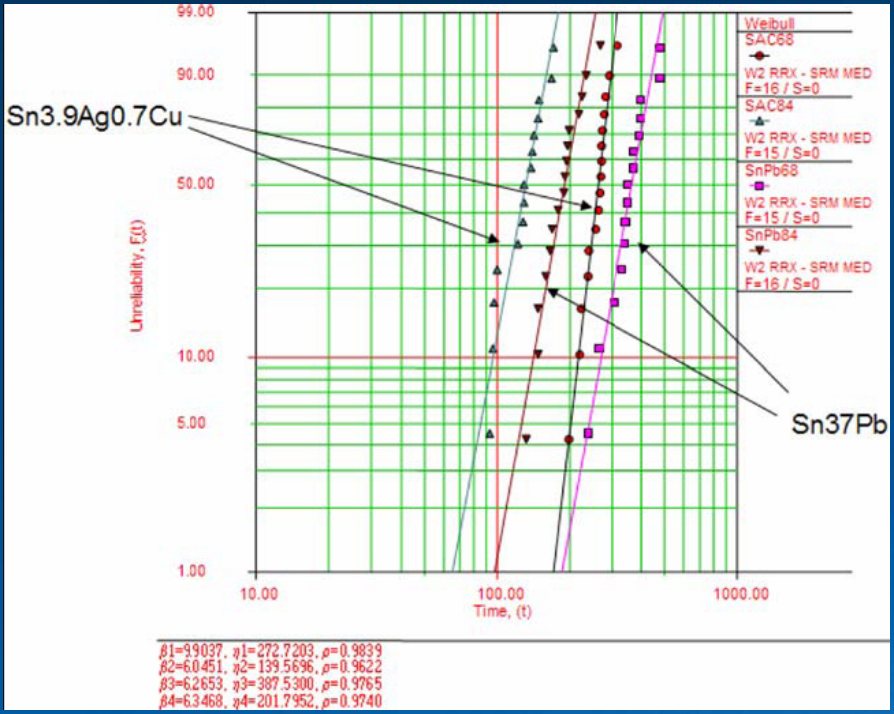
- **Pb-free performed better in normal temp cycle testing which is typical of use condition, but performed worse in extreme test condition unrealistic for telecom central offices & data centers**

Ceramic LCC Solder fatigue Results (*)

* Reference: Michael Osterman Æ Abhijit Dasgupta “Life expectancies of Pb-free SAC solder interconnects in electronic hardware” “ J Mater Sci: Mater Electron (2007) 18:229–236



Temp Cycle: 0 to 100°C



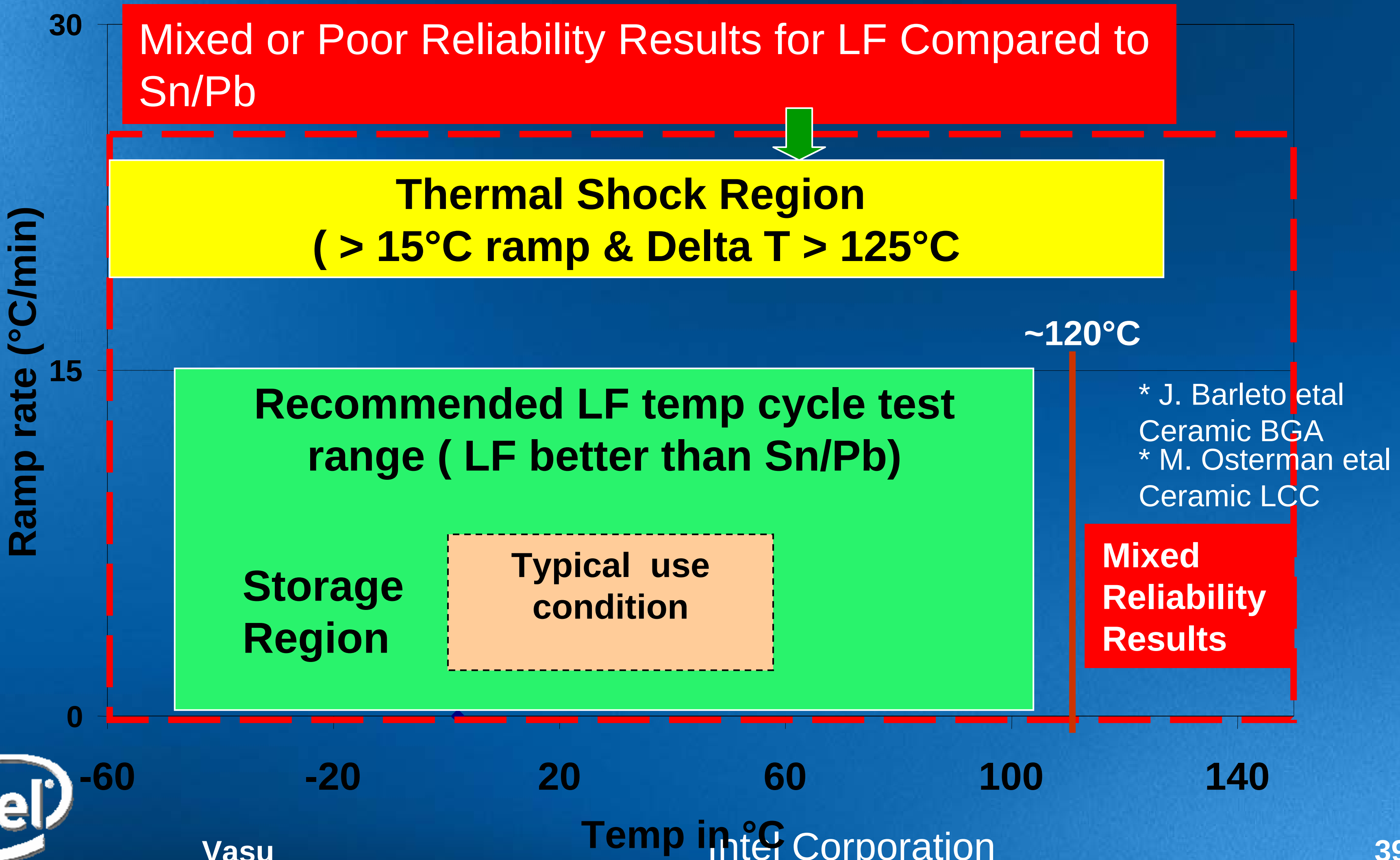
Temp Cycle: 25 to 125°C

- **In head-to-head tests:**
  - **Pb-free performed better than SnPb with Tmax up to 100°C**
  - **SnPb performed better than Pb-free with Tmax over 120°C**

LF Temp Cycle Data Analysis

Temp Cycle Test Recommendation: Tmax <110°C and ramp rate < 15°C/min (IPC spec)

**Y, Qi etal



Mixed or Poor Reliability Results for LF Compared to Sn/Pb

Thermal Shock Region
(> 15°C ramp & Delta T > 125°C

~120°C

Recommended LF temp cycle test range (LF better than Sn/Pb)

Storage Region

Typical use condition

* J. Barleto etal Ceramic BGA
* M. Osterman etal Ceramic LCC

Mixed Reliability Results

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Reliability Tests for Pb-free Solder Joints

Stress Test	Reason	Status
Temp Cycle at -40 to 85°C, ΔT = 125°C -25 to +100°C, ΔT = 125°C	Solder fatigue	Completed / Passed ✓
Bake 150°C for 1000 hrs	Diffusion and IMC growth	Completed / Passed ✓
Temp / Humidity (85°C / 85% RH) unbiased For 1000 hrs	Corrosion for Trace and via	Completed / Passed ✓
Board Level Shock (50 g) & Vibration (3.13 g Rms)	Shipping and handling	Completed / Passed ✓

- ➢ **Pb-free solder passed the established baseline reliability testing**

Summary

- Extensive reliability testing has been done for Intel LF packages
- Intel LF packages showed improved fatigue performance compared to eutectic solder
- Intel recommends the use of SAC405 for applications where long-term reliability is a critical factor
- Temp cycle test data indicates that LF (SAC 405) out-performs eutectic solder even with long dwell time thermal cycling
- SAC405 products with proper process control exceeds the reliability of SnPb products
- Temp cycle test conditions can modulate the LF performance and convergence in temp cycle test needed
- Recommended temp cycle condition for LF : Temperature range between -40 and + 100 ^{0} C and ramp rate less than <15 ^{0} C/Min.

Q & A