IMAPS Chesapeake-area
Winter Technical Symposium
Wednesday, January 27, 2010
3:00 - 6:50 pm

Effect of Temperature Cycling Parameters (Dwell and Mean Temperature) on the Durability of Pb-free solders

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What is CALCE?

http://www.calce.umd.edu

Center for Advanced Life Cycle Engineering (founded 1987) is dedicated to providing a knowledge and resource base to support the development and sustainment of competitive electronic components, products and systems.

Focus areas:
- Physics of Failure
- Design of Reliability
- Accelerated Qualification
- Supply-chain Management
- Obsolescence
- Prognostics

Center Organization
16 research faculty
5 technical staff
60+ PhD students
30+ MS students
11 visiting scholars

Education
- MS and PhD programs
- International visitors
- Web seminars
- Short courses for industry

Electronic Products and Systems Consortium
- Risk assessment, management, and mitigation for electronics

Prognostics and Health Management Consortium
- Techniques based on data trending, physics-of-failure, and fusion

CALCE
Center for Advanced Life Cycle Engineering for Electronic Products and Systems

Research Contracts
- Large scale programs
- Medium to long-term durations
- Contractual agreements

Examples:
Software development,
testing,
training programs

Lab Services
- Small to medium scale
- Rapid response
- Examples:
  Failure analysis,
  measurement,
  design review,
  supplier assessment

Standards
Putting CALCE research to work for industry
- Examples:
  IEEE
  GEIA
  IPC
  JEDEC
  IEC

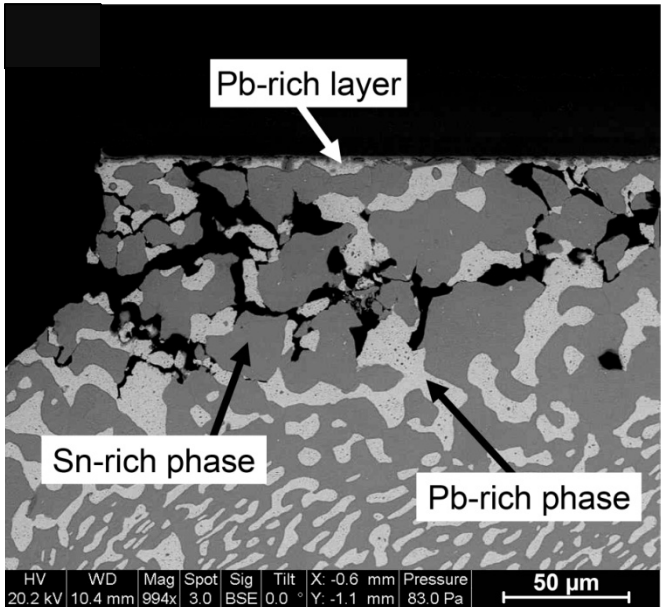
CALCE Clients

- Alcatel-Lucent
- Agilent Technologies
- Amkor
- Arbitron
- Arcelik
- ASC Capacitors
- ASE
- Arbitron
- Astronautics
- Atlantic Inertial Systems
- AVI-Inc
- Axsys Engineering
- Battelle
- Branson Ultrasonics
- Brooks Instruments
- Capricorn Pharma
- Cascade Engineering
- AMSAA Reliability Branch
- Boeing
- BAE Systems
- Cisco Systems, Inc.
- Crane Aerospace & Electronics
- Curtiss-Wright Corp
- CDI
- De Brauw Blackstone Westbroek
- Dell Computer Corp.
- EIT, Inc.
- Embedded Computing & Power
- EMCORE Corporation
- EADS – AirBus
- EMC
- Emerson Advanced Design
- Emerson Appliance Controls
- Emerson Appliance Solutions
- Emerson Electric Co.
- Emerson Network Power
- Emerson Process Management
- Ericsson AB
- Daimler
- Dell Computer Company
- DRS EW Network Systems, Inc.
- Essex Corporation
- Exponent, Inc.
- Fairchild Controls Corp.
- Filtronic Comtek
- GE Fanuc Embedded Systems
- GE Global Research
- General Dynamics – AIS
- Goodrich Control Systems
- General Motors
- Guideline
- Hamlin Electronics Europe
- Hamilton Sundstrand
- Harris Corp
- Honda
- Honeywell
- Howrey, LLP
- Huawei
- Intel
- Instituto Nokia de Technologia
- Juniper
- Johnson and Johnson
- Kimball Electronics
- L-3 Communication Systems
- LaBarge, Inc
- Lansmont Corporation
- Laird Technologies
- Liebert Power and Cooling
- LM Aero - Ft. Worth Site
- Lockheed Martin
- Lutron Electronics
- Maxion Technologies, Inc.
- Motorola
- Joint Strike Fighter Program
- Mobile Digital Systems, Inc.
- n-Code
- NASA Goddard Space Flight
- NetApp
- nCode International
- Nokia Siemens
- Northrop Grumman
- NXP Semiconductors
- Ortho-Clinical Diagnostics
- PEO Integrated Warfare
- Petra Solar
- Philips
- Philips Medical Systems
- Pole Zero Corporation
- Pressure Biosciences
- Raytheon Company
- Rendell Sales Company
- Research in Motion
- RNT, Inc.
- Rolls Royce
- Rockwell Automation
- Rockwell Collins
- Qualmark
- Samsung Electro-Mechanics
- Samsung Mechtronics
- Samsung Memory
- Samsung Techwin
- S.C. Johnson Wax
- Sandia National Labs
- SanDisk
- Schlumberger
- Schweitzer Engineering Labs
- Seagate Technologies
- Selex-SAS
- Sensors for Medicine and Science, Inc.
- SiliconExpert
- Space Systems Loral
- SolarEdge Technologies
- Starkey Laboratories, Inc
- Sun Microsystems
- Symbol Technologies, Inc
- Team Corp
- Team Pacific Corporation
- Tech Film
- Tekelec
- Teradyne
- The Bergquist Company
- The University of Michigan
- Tin Technology Inc
- TruePosition, Inc.
- Toshiba
- TRW Automotive
- TÜBİTAK Space Technologies
- U. K. Ministry of Defence
- U. S. AMSAA
- U. S. ARL
- U. S. Naval Surface Warfare Center
- Vectron International, LLC
- Vestas
- Weil, Gotshal & Manges LLP
- Whirlpool Corporation
- WiSpry, Inc.
- Woodward Governor

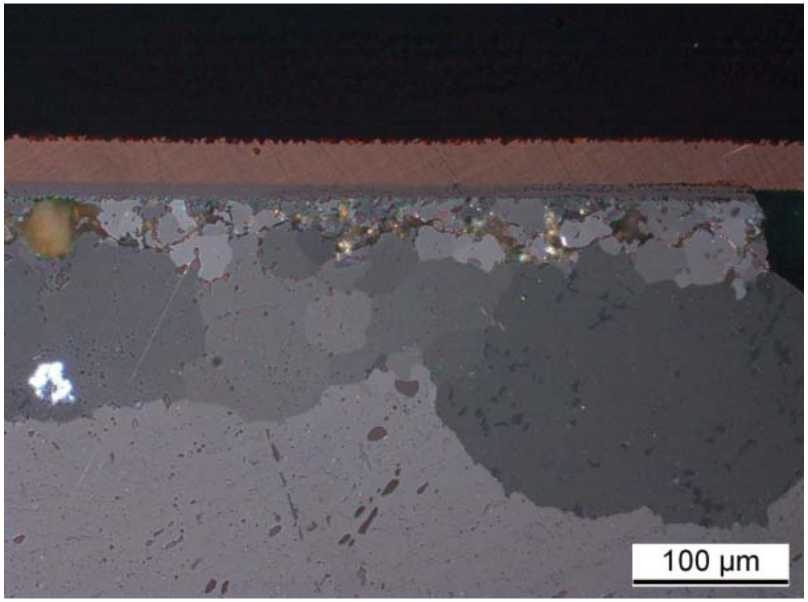
Lead-free Impact on Mission/Life Critical Systems

- New manufacturing and support challenges
  - New and diverse material set
  - **Mixed lead and lead-free materials**
  - Reprocessed parts (Re-balling and **Hot Solder Dip**)
  - Repair materials/processes
- New failure mechanisms
  - Tin whiskers
  - Pad cratering
  - Creep corrosion
  - Drop fragility
- **Unproven qualification methods**

Cyclic Fatigue Durability – SAC vs SnPb



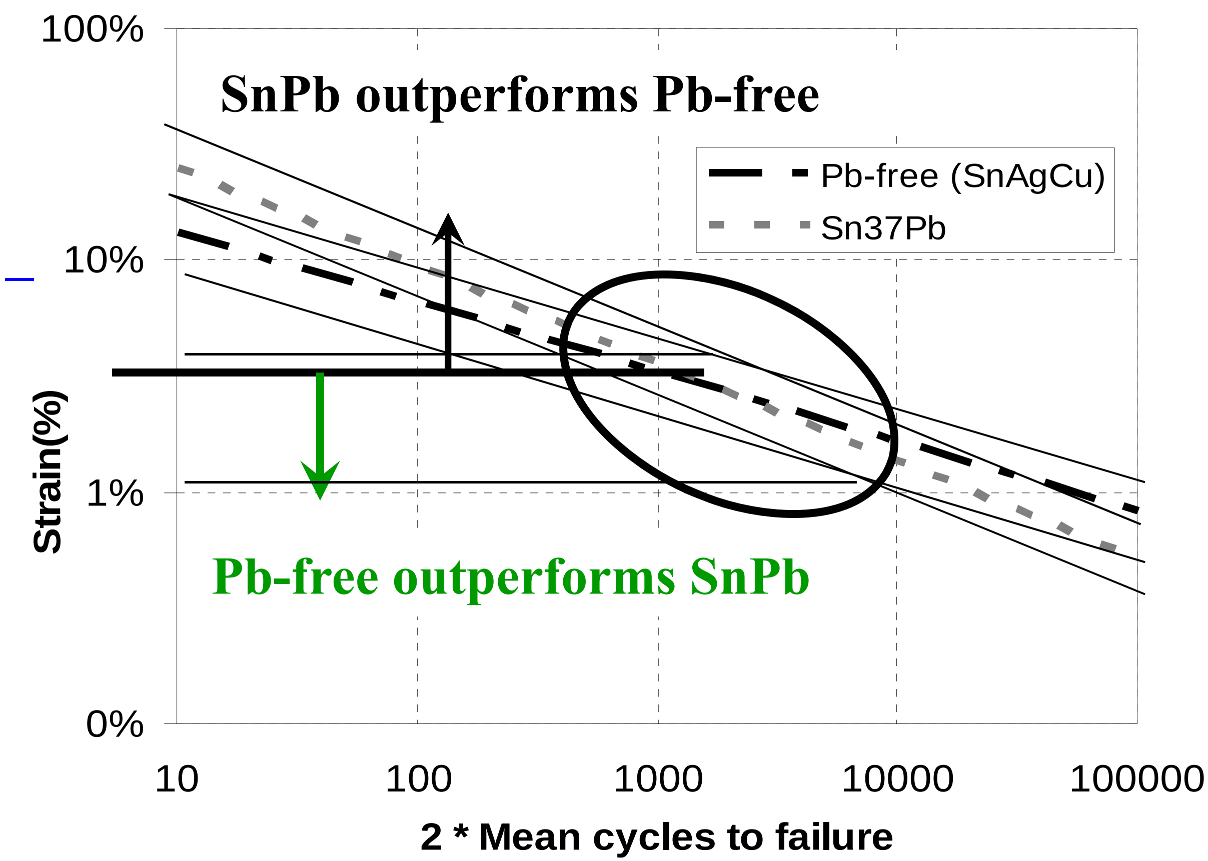
Sn37Pb



SAC

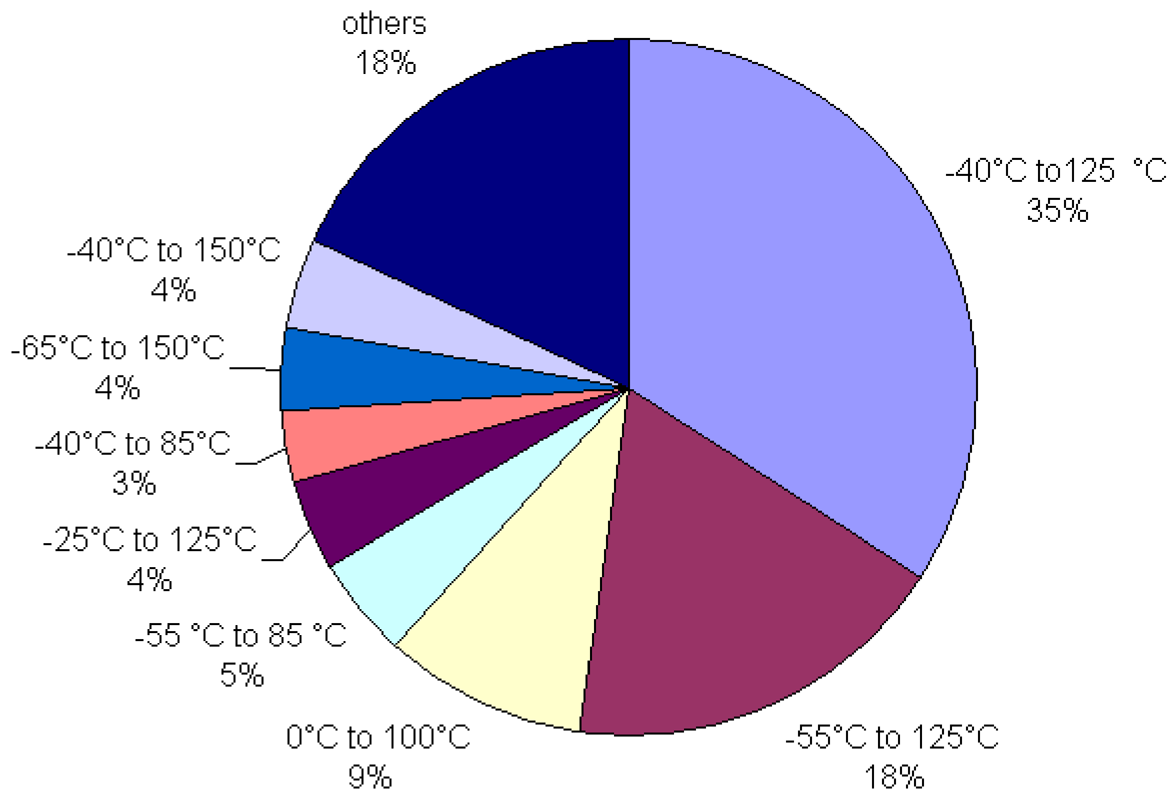
Under cyclic stress tin-lead solder exhibits grain coarsening (enlargement), crack formation and growth. For lead-free SAC solder, the structure exhibits grain formation due to recrystalization which results in finer grains that separate at grain boundaries resulting in crack growth.

Durability of Solder under a Temperature Cycle



Crossing point likely to shift due to temperature cycle parameters (i.e. mean temperature, temperature range, dwell time, and ramp rate)

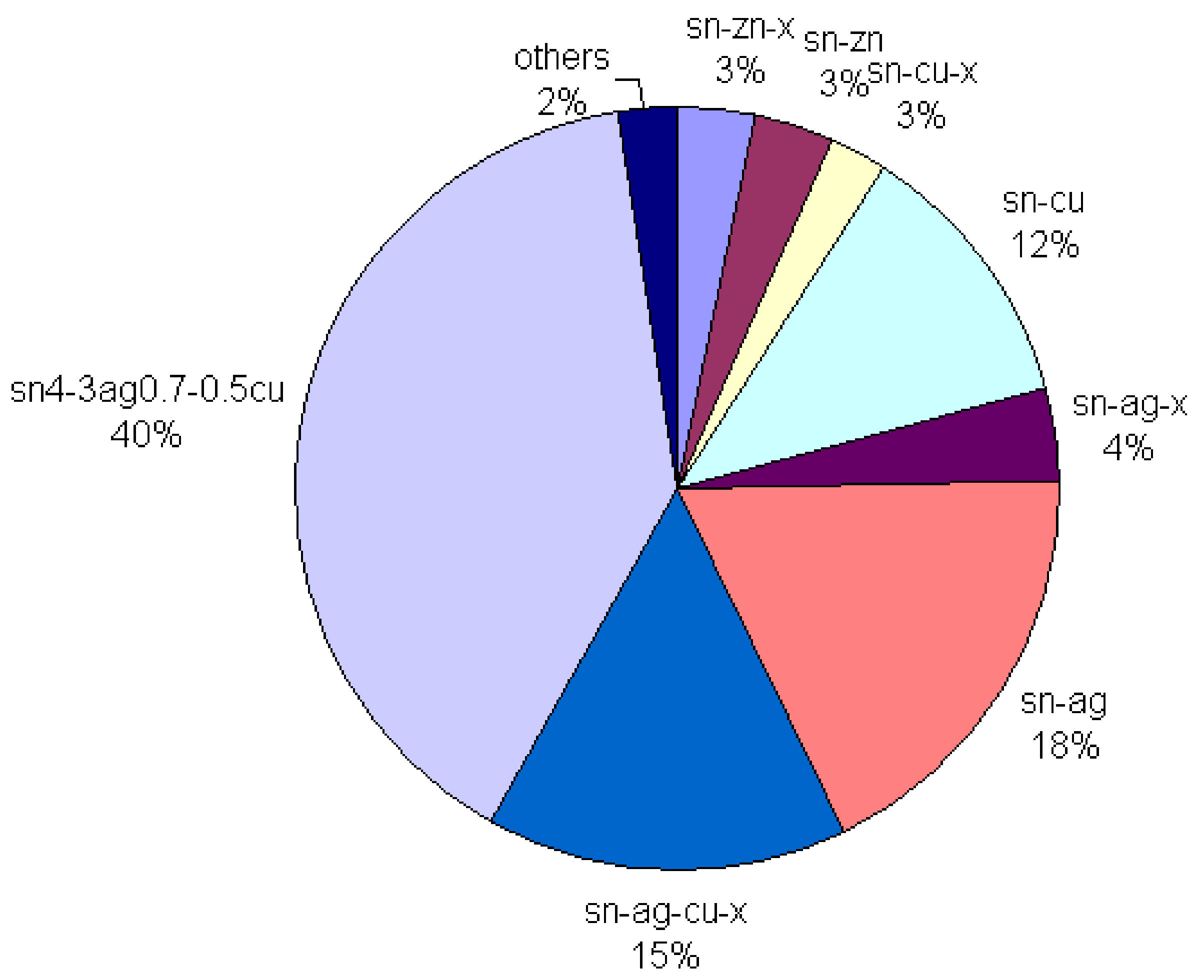
IEEE Reported Temperature Cycle Test Conditions
2004 to 2008



- **73% of reported temperature cycling fell in the range of -55 to 125C**

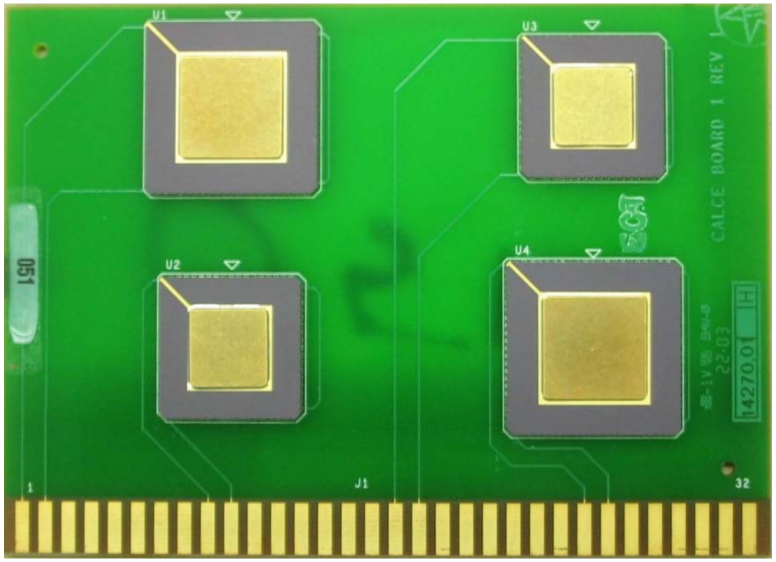
Based on reviewed of IEEE literature

IEEE Resources
Solders Under Investigation
2004-2008



- **Tin silver copper solder remain the most studied**
- **Tin silver alloys identified in 77% of articles**
- **Tin copper alloys identified in 15%**

Test Specimen and Test Details



Packages Under Test

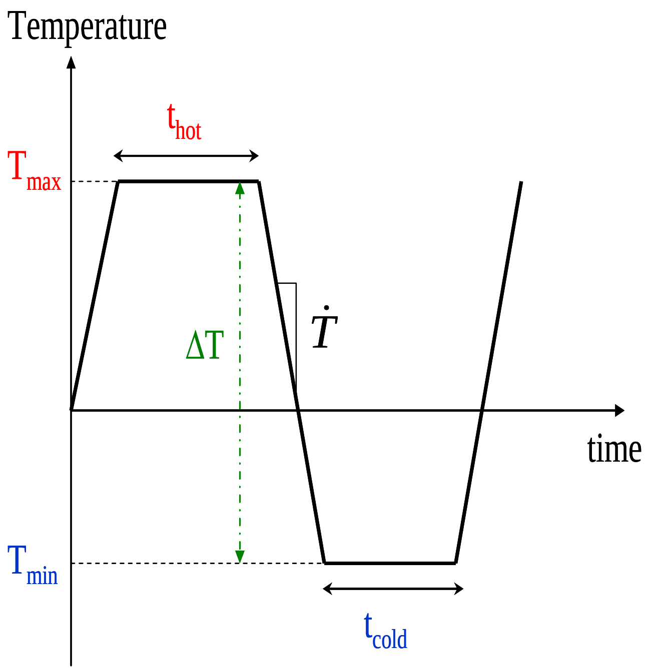
- 68-pin LCCC: 24mm × 24mm
- 84-pin LCCC: 30mm × 30mm
- PCB Board: 130 x 93 x 2.5 mm, FR4

- **Solders Completed**
  - Indium SMQ 230 Sn95.4/Ag3.9/Cu0.7
  - Indium SMQ 230 Sn96.5/Ag3.5
  - Indium SMQ 92J Sn63/Pb37
  - Indium SMQ92J Sn61.5/Pb 36.5/Ag2 (SPA)
  - Aim Sn96.5Ag3.0Cu0.5 w/254 flux (SAC305)
  - Aim SN100C Sn/Cu/Ni(.5) w/254 flux SN

Sample Sized and Monitoring

- 16 samples in each test condition
- Resistance of each chip is monitored by a data logger.
- Temperature is recorded at the center of each card.
- Test continues until 100 % failure occurs.
- Cross sectioning was performed on failed test specimens to verify a solder interconnect failure.

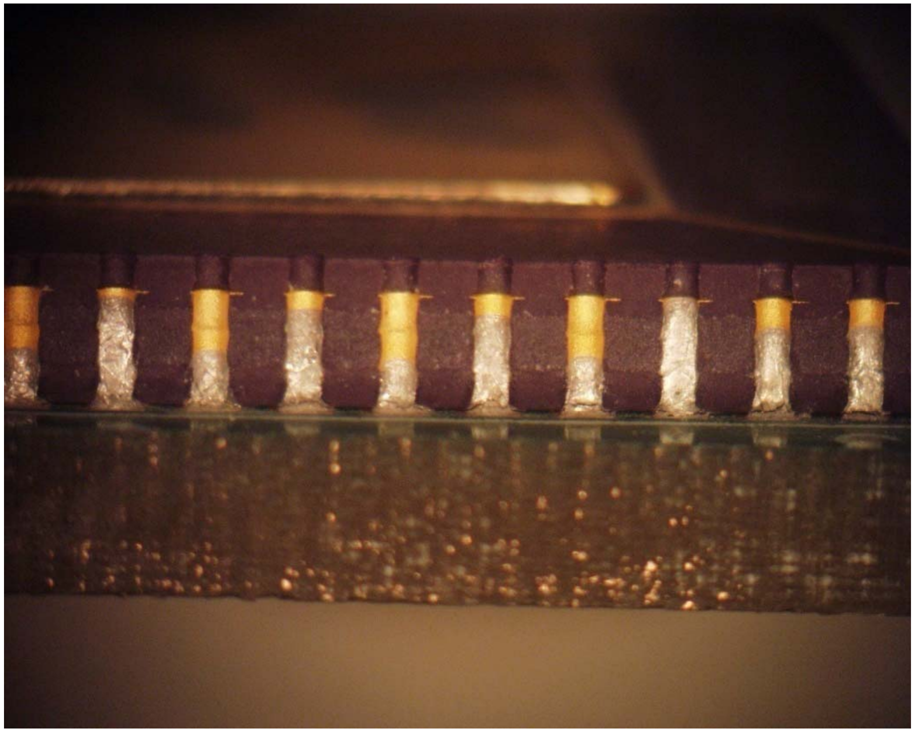
Test Matrix



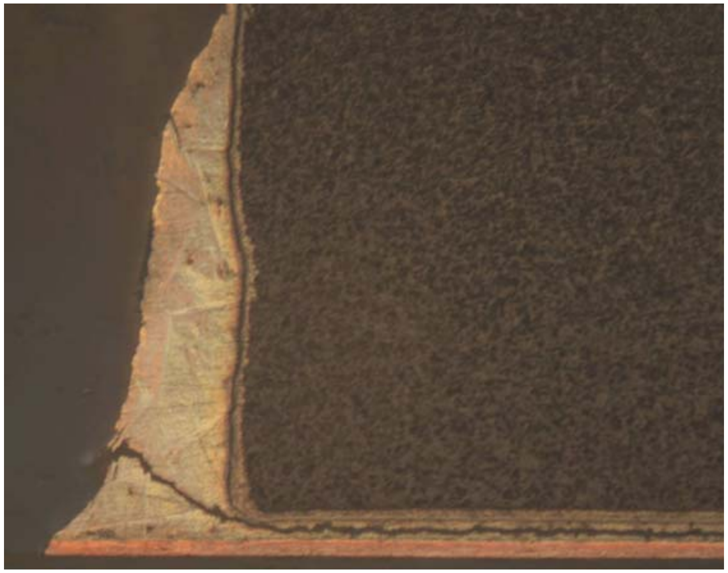
Test	Min. Temp. (°C)	Max. Temp. (°C)	Temp. range (°C)	Dwell Time at Max temp* (min)	Solders
1	0	100	100	15	All
2	-25	75	100	15	All
3	25	125	100	15	All
4	0	100	100	75	All
5	25	125	100	75	All
6	-25	75	100	75	All
9	-50	50	100	15	All
10	-25	75	100	120	SAC305, SN100C, SnPbAg
11	-25	75	100	75[2]	SAC305, SN100C, SnPbAg

***Dwell at minimum temperature is set to be 15 minutes.**
[2]For this run, the low end temperature will be extended and max dwell will be fixed at 15 minutes

Failure Analysis



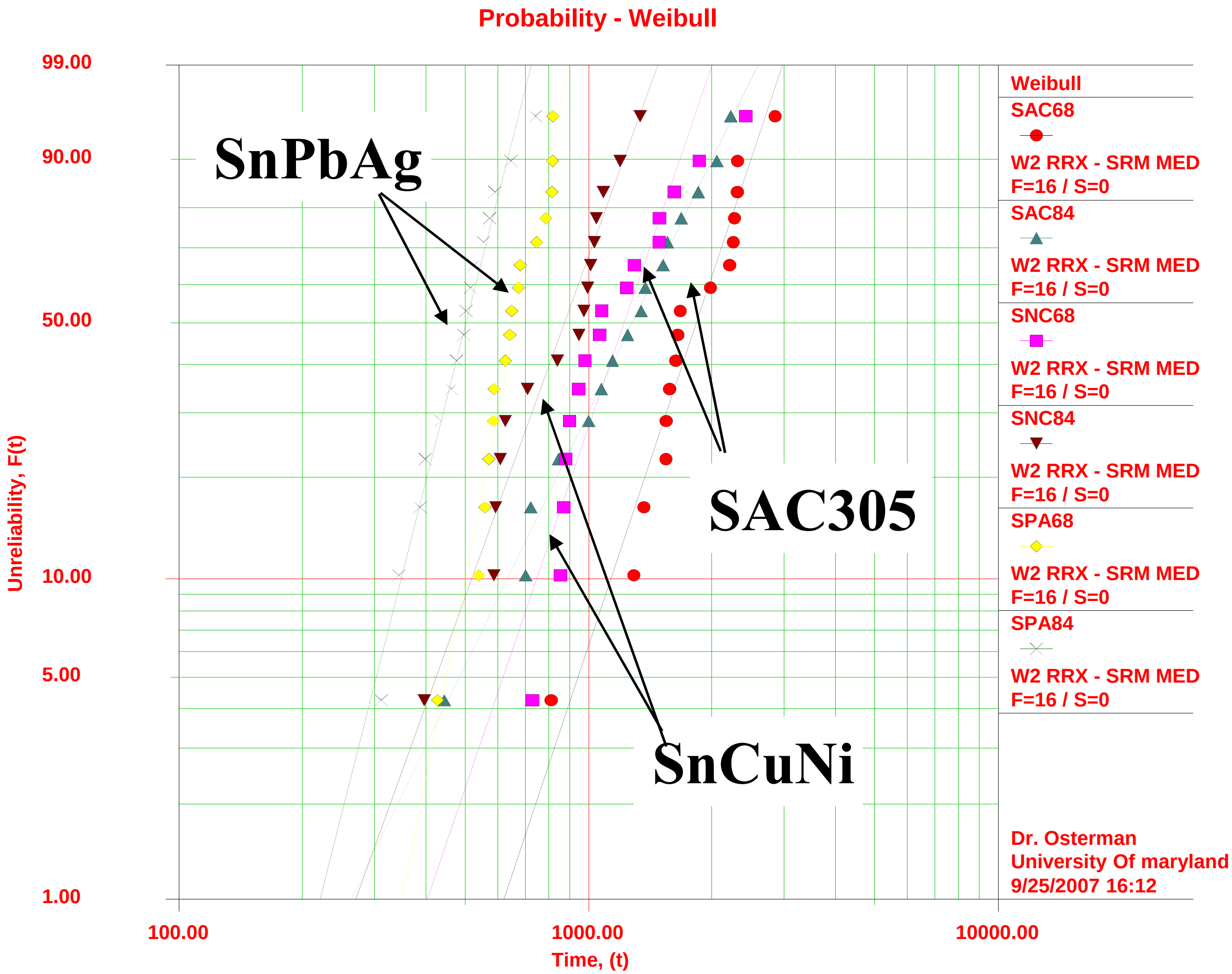
Side view of cracked solder interconnects for a 68 IO CLCC



Typical crack path observed in failed specimens

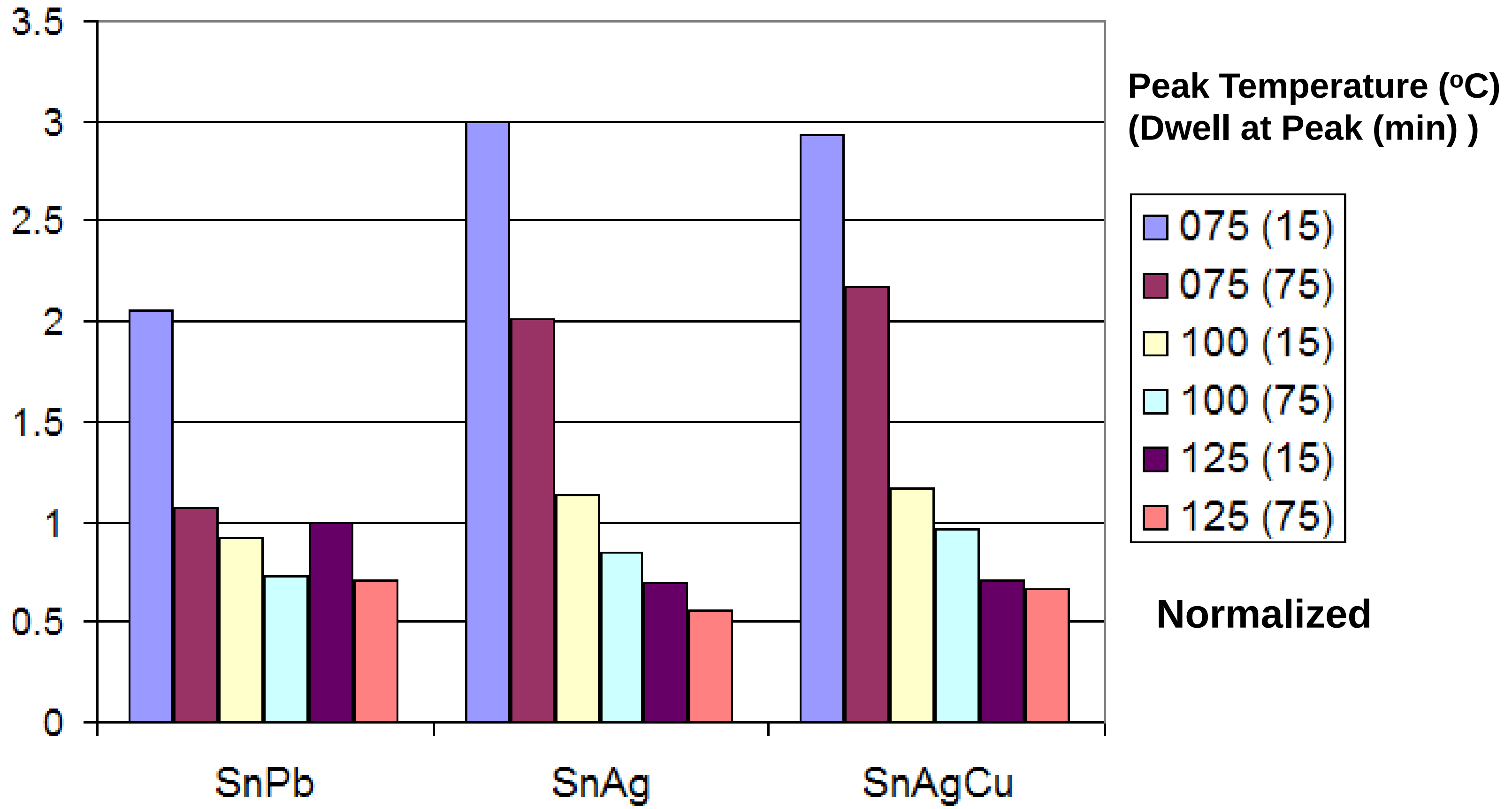
Visual and optical examination of failure sites clearly identifies solder cracking as root cause of monitored resistance failure.

-50 to 50 °C (Dwell 15 min)



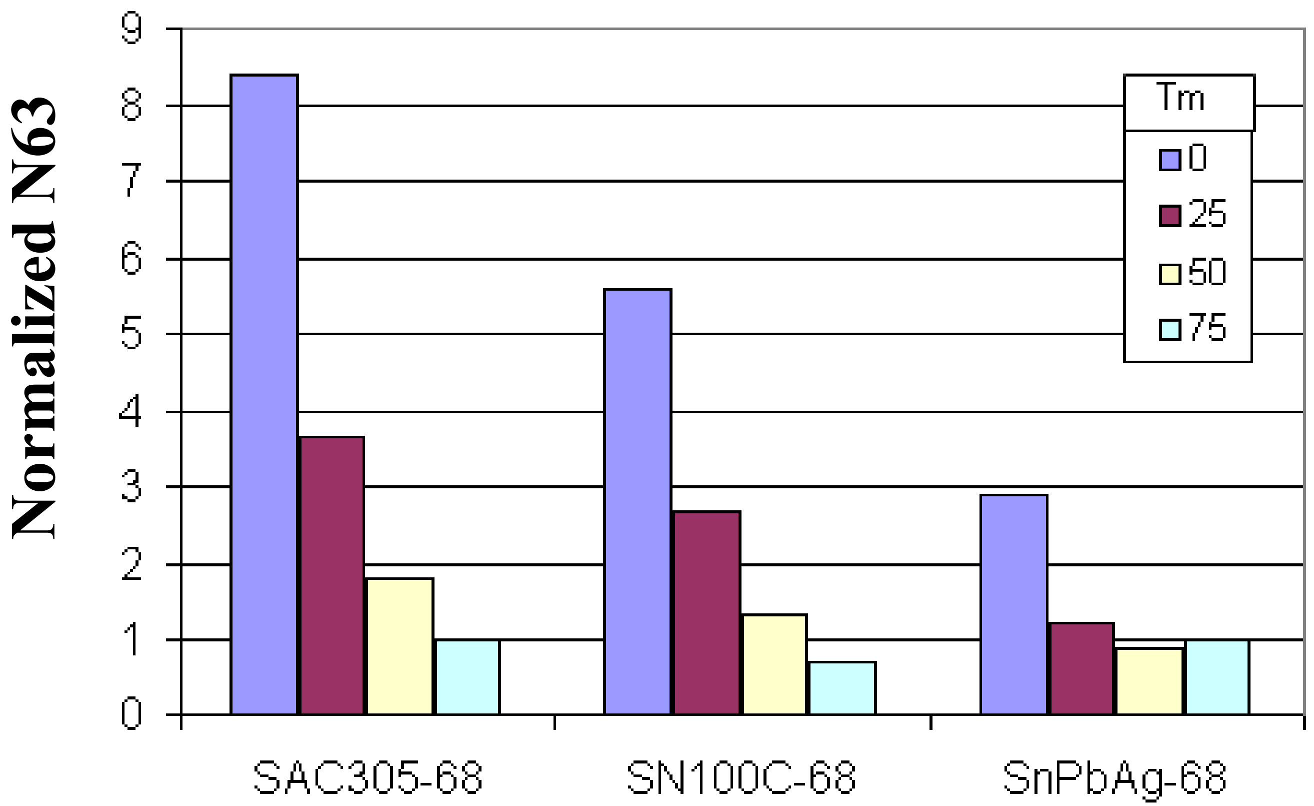
SAC305 found to have longer life than SN100C and SnPbAg solders under temperature cycle loading.

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.

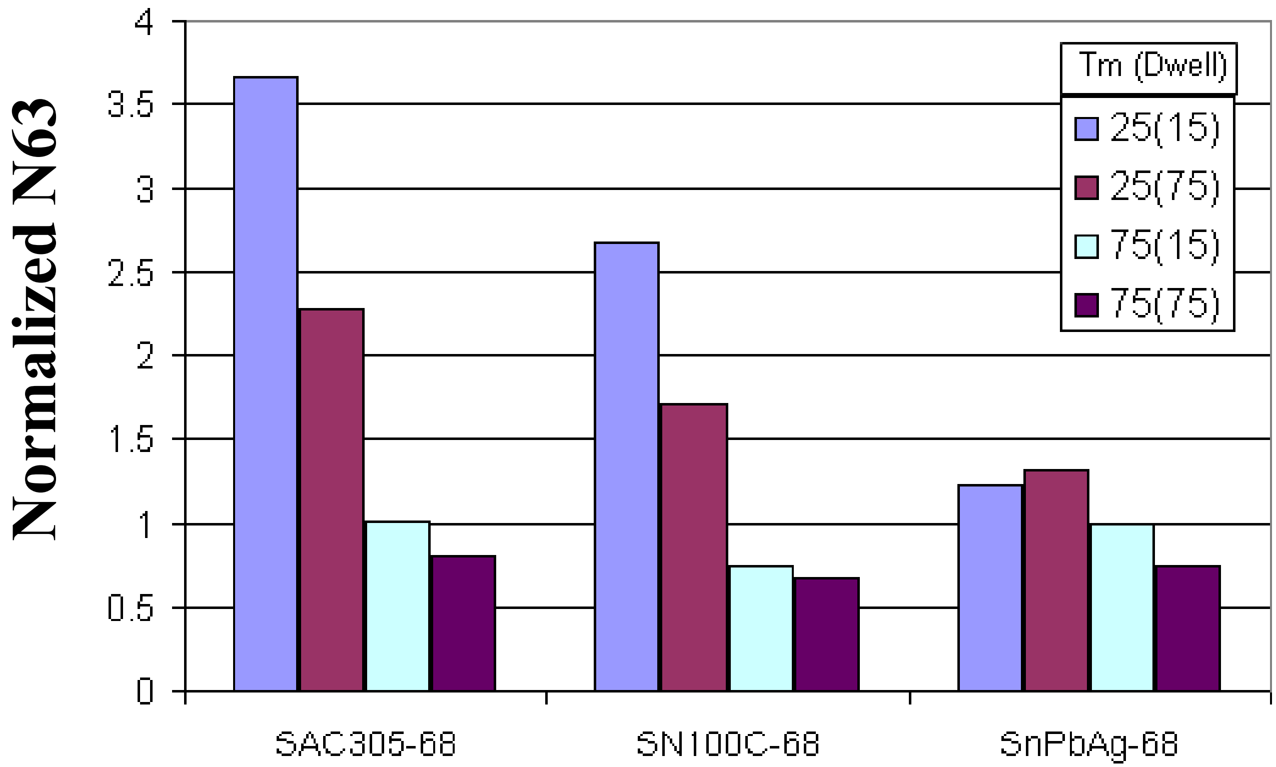
Comparison of Cyclic Mean Temperature on a fixed 100 ^{o}C Temperature Range Cycle (15 minute dwell)



ΔT=100^{o}C
Mean Temp
Dwell time 15 min.

With the exception of the tin-lead-silver (SnPbAg) solder, solder interconnect life increased as the cyclic mean temperature was reduced.

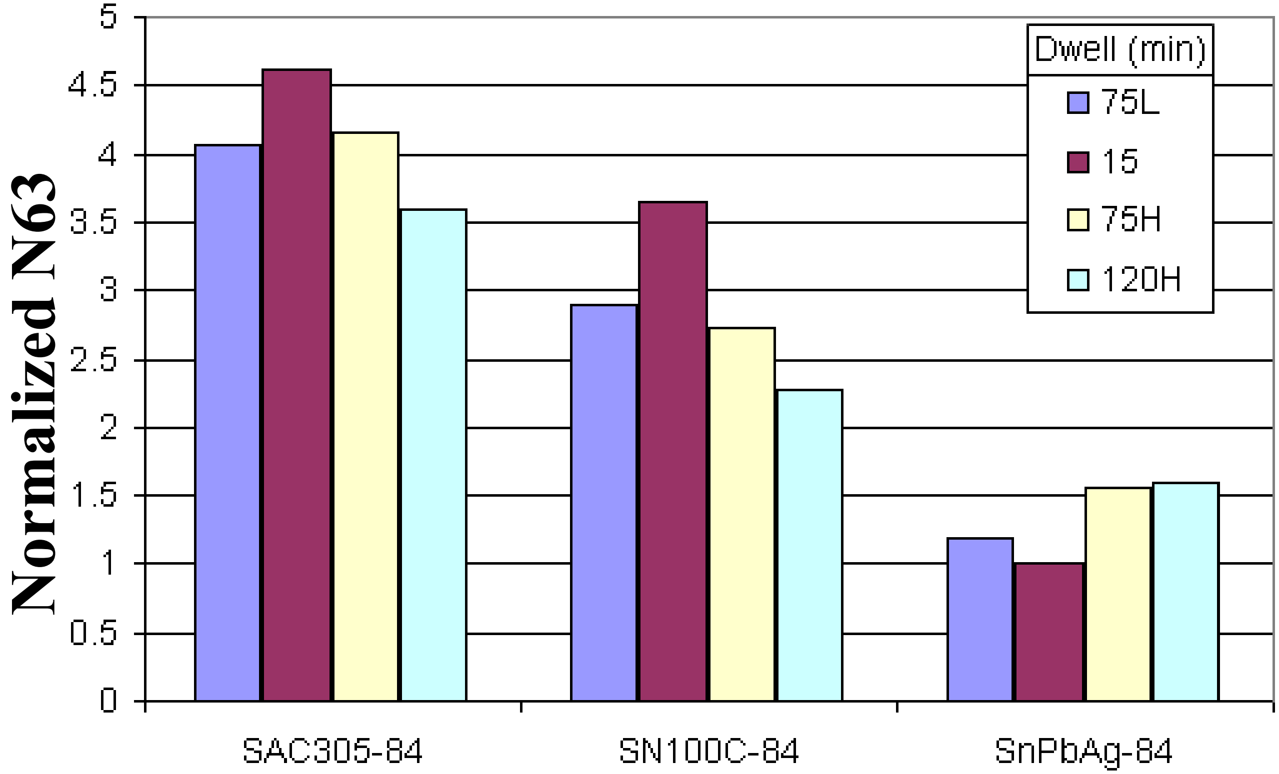
Impact of Cyclic Mean Temperature and Dwell



ΔT=100°C
Mean Temp
(dwell time)

Dwell has a larger effect when the medium cyclic temperature is lower. The SnPbAg results are puzzling.

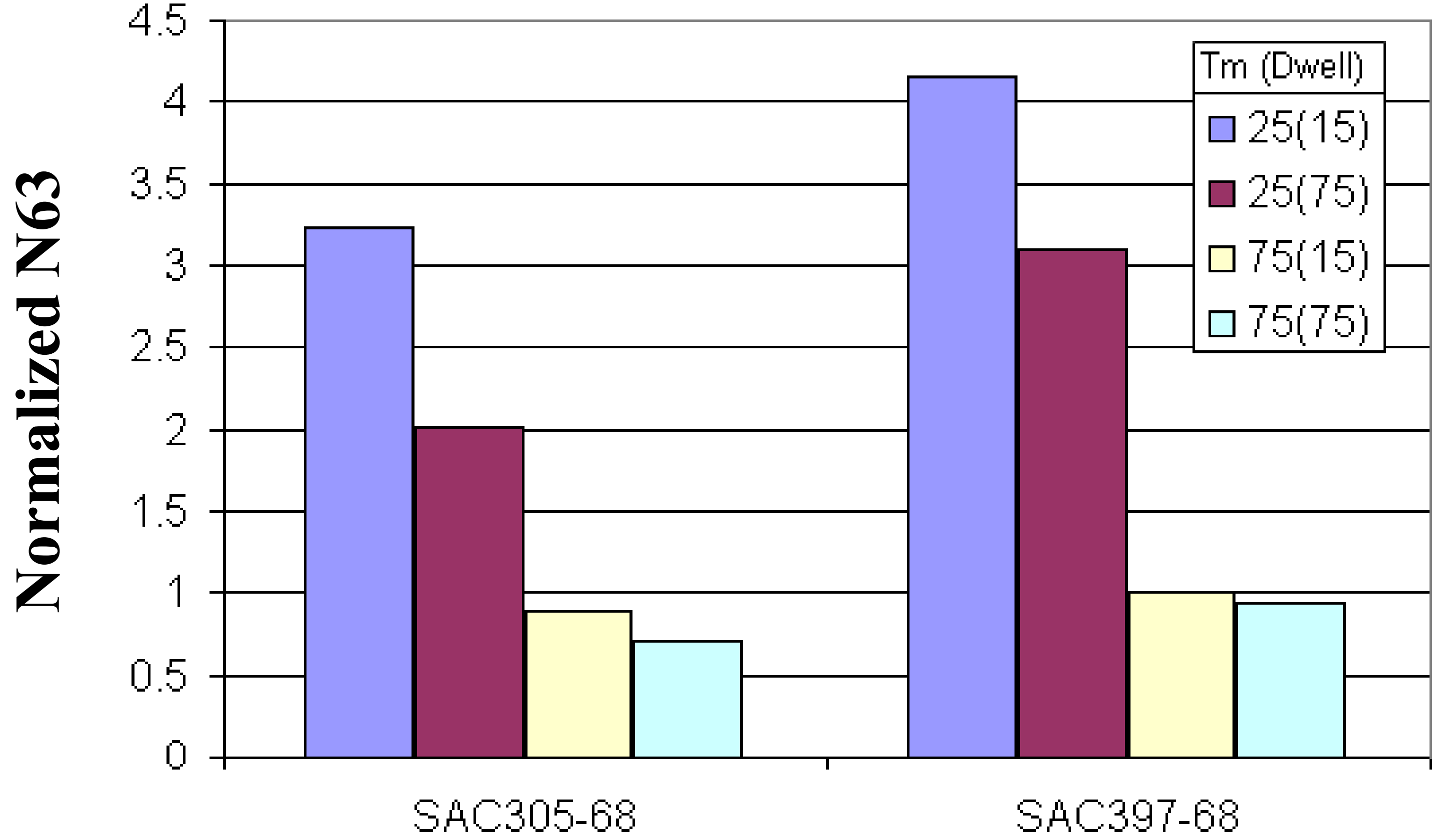
Impact of Dwell on a -25 to 75 °C Temperature Cycle



ΔT=100°C
Tm=50°C

Low temperature dwell had a stronger reduction in life than anticipated. For tin-lead-silver (SnPbAg), dwelling for 75 minutes at -25 C was more damaging than dwell at 75 minutes at 25C. The lowest life for SnPbAg occurring with the 15 minute dwell was also unexpected.

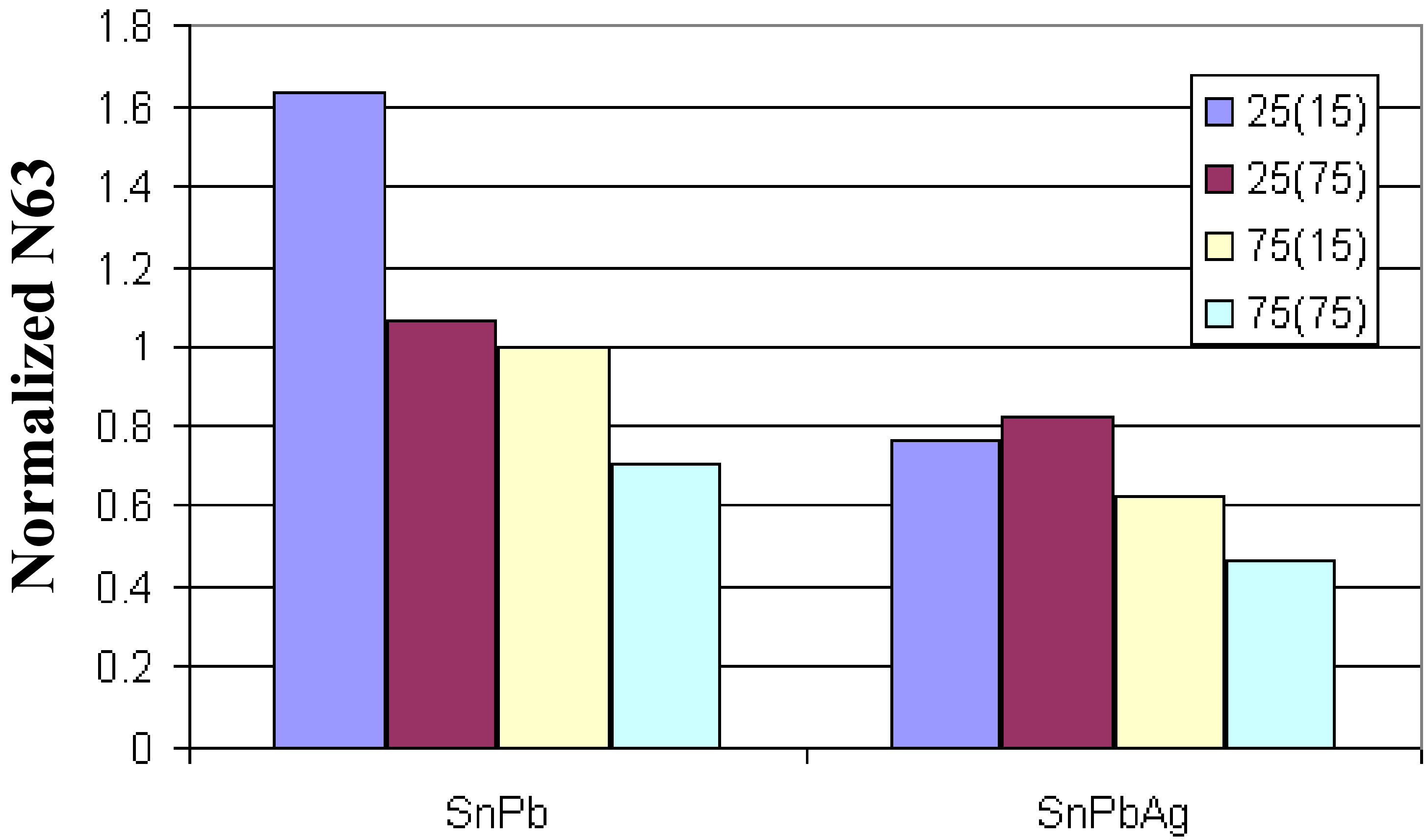
SAC305 versus SAC397



$\Delta T=100^{o}C$
Mean Temp
(dwell time)

With the exception of 75(15), SAC 305 is slightly less reliability than SAC 397 under temperature cycle loads.

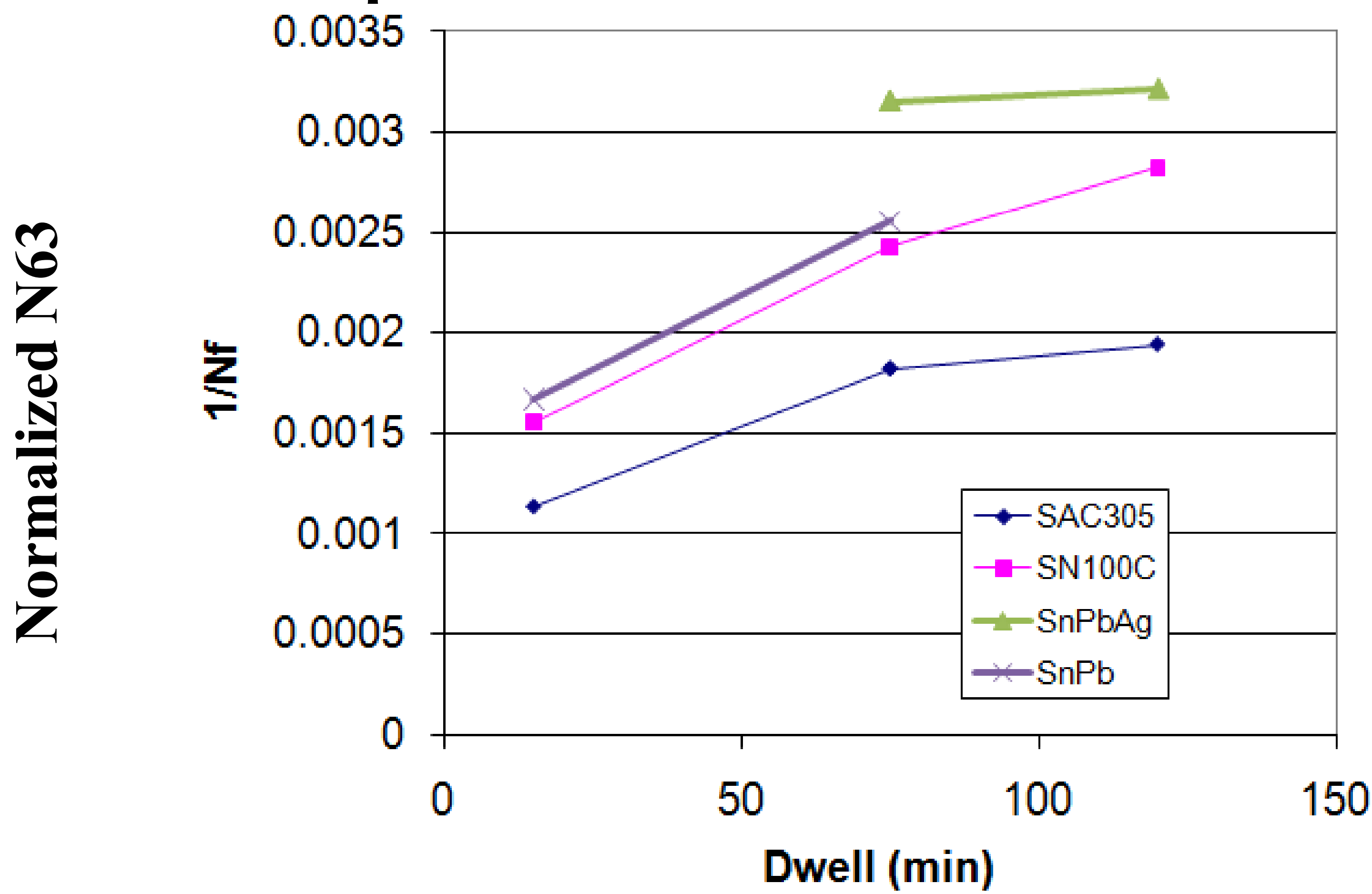
Sn37Pb versus Sn36Pb2Ag



ΔT=100°C
Mean Temp
(dwell time)

Sn37Pb performed better than Sn36Pb2Ag in all completed tests.

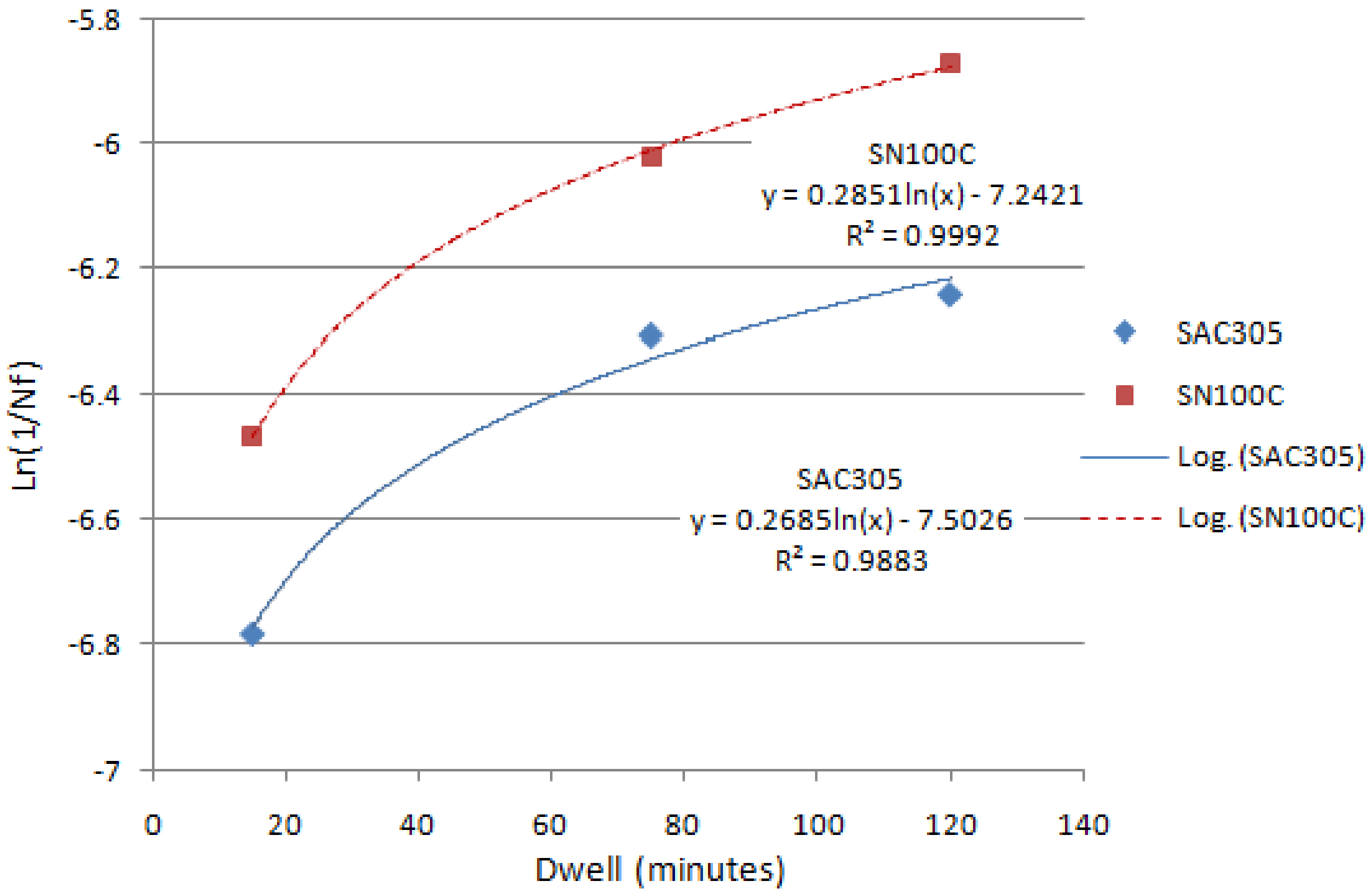
Impact of Dwell on Tested Solders



ΔT=100°C
Mean Temp
(dwell time)

All solders show a dwell effect on the -25 to 75C test to dwell. Tin-lead based solder showed a reduced effect after 60 minutes compared to SAC205 and SN100C.

Impact of Extended Dwell on Fatigue Life



Solder Fatigue Life Models

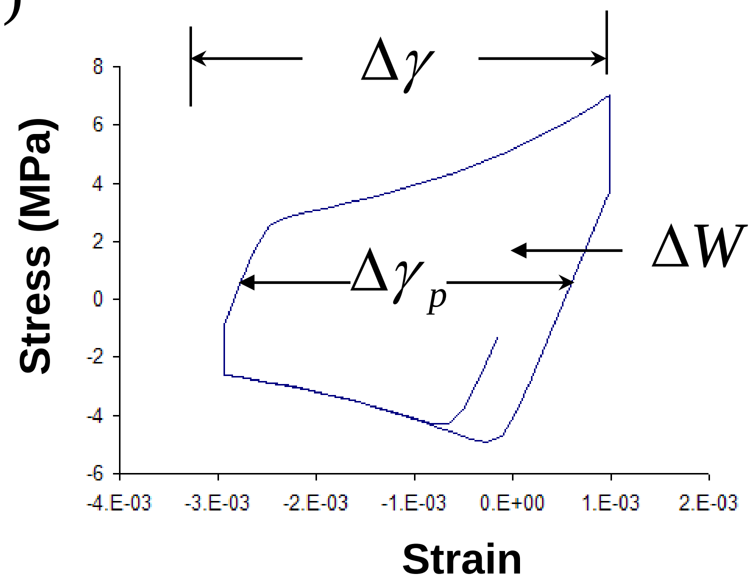
- Strain Range Model (Engelmaier)

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

- Inelastic Energy (Darveaux)

$$\frac{dA}{dN} = C\,(\Delta W)^b$$

- Energy Partitioning (Dasgupta)



$$Energy = U_e + W_p + W_{cr} = U_o N_{fe}^{\,b'} + W_{po} N_{fp}^{\,c'} + W_{co} N_{fc}^{\,d'}$$

- Partitioned Creep Strain/Energy (Syed)

$$Nf = \left(0.02E_{GBS} + 0.063E_{MC}\right)$$

Fitted Strain Range Model Parameters

Solder Parameters	SnPb	SAC397	Sn3.5Ag
c_o	-0.502	-0.347	-0.416
c_1	-7.34E-04	-1.74E-03	-2.10E-03
c_2	1.45E-02	7.83E-03	1.40E-02
ε_{f*} [1]	2.25	3.47	2.25
R^2	0.898	0.966	0.980

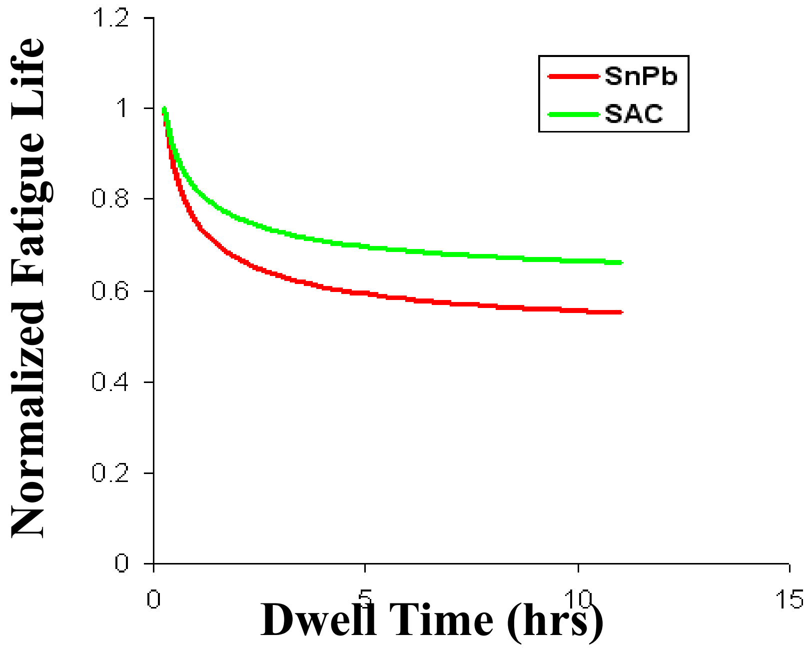
$$N_f = \frac{1}{2}\left(\frac{L\Delta T}{2e_f^{[1]}}\right)^{\frac{1}{c}}$$

ε_f = Constant

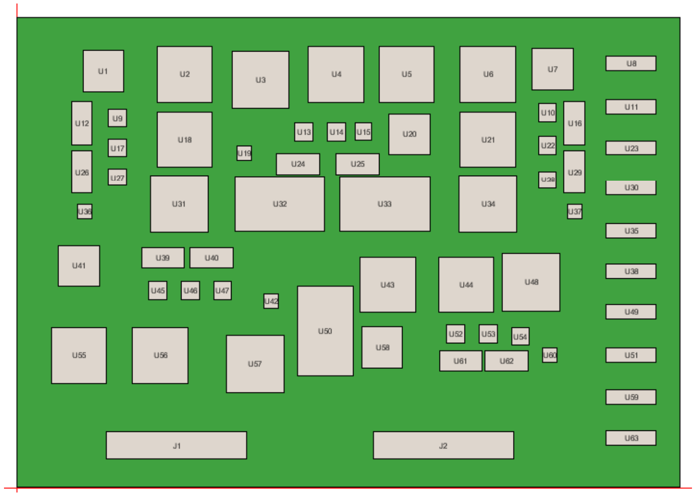
$$c = c_0 + c_1 T_{sj} + c_2 \ln\left(1 + \frac{360}{t_d}\right)$$

[1] The fatigue ductility constant was derived only considering the neutral distance length of the package. This value must be adjusted with respect to the cyclic temperature range, CTE mismatch between the package and the board, and the effective solder joint height.

A Strain Range Based Model for Life Assessment of Pb-free SAC Solder Interconnects , M. Osterman, A. Dasgupta, B. Han, *56th Electronic Component and Technology Conference*, pp. 884 - 890, May 30-June 2, 2006

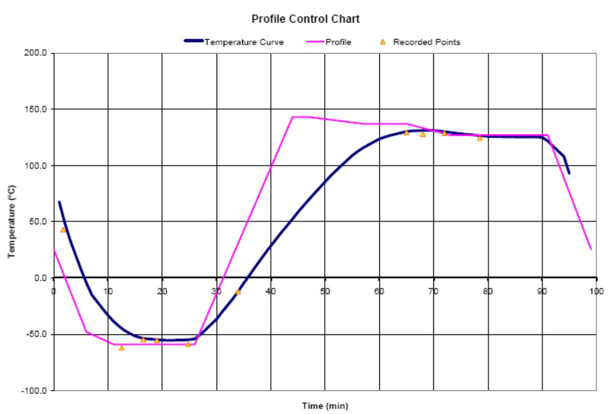


Validation of Strain Range Solder Interconnect Fatigue Life Model

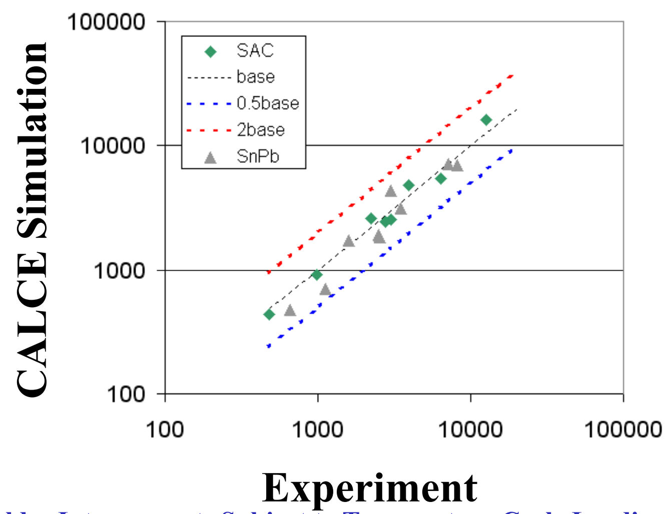


calcePWA Model

2 mm thick board contained PBGA, TSOP, TQFP, CLCC packages. The simulation model was based on test vehicle used under the JGPP/JCAA Pb-free Solder Test Program. Separate sets of test assemblies were subjected to a -55 to 125^{o}C and a -20 to 80^{o}C temperature cycle conditions

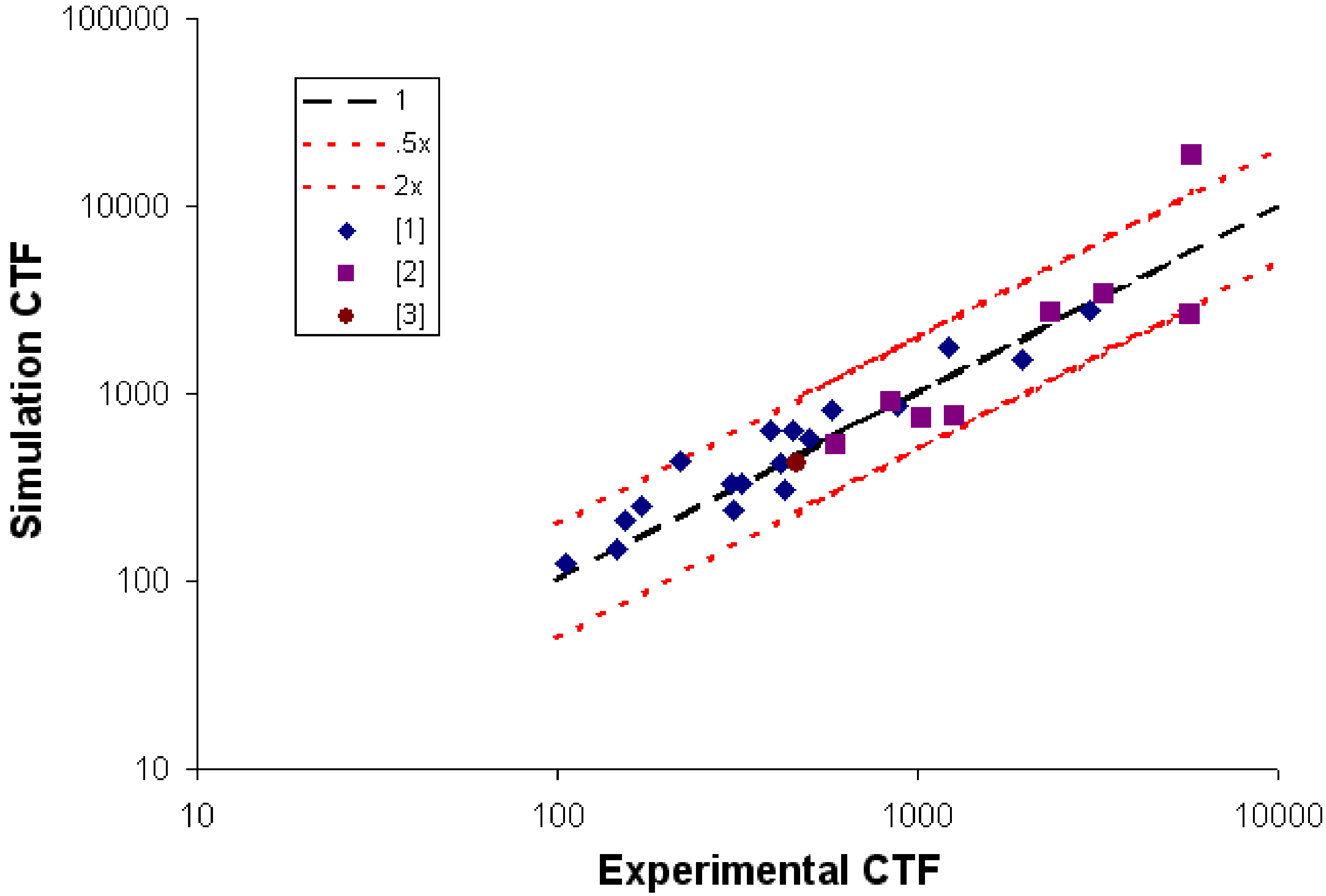


-55 to 125 C test



M. Osterman and M. Pecht, Strain Range Fatigue Life Assessment of Lead-free Solder Interconnects Subject to Temperature Cycle Loading, *Soldering & surface Mount Technology*, Vol. 19, No. 2, pp. 12-17, 2007.

Model vs Experiment Data for SN100C



1. M. Osterman, C07-06 CALCE EPSC Project, 2007
2. J. Arnold, N. Blattau, C. Hillman, K. Sweatman, Reliability Testing of Ni-Modified SnCu and SAC305 – Accelerated Thermal Cycling, SMTA International 2008, pp 187-190, Aug. 2008
3. M. Osterman, C08-08 CALCE EPSC Project, 2008

Acceleration Factors

$$AF = \frac{N_{use}}{N_{test}}$$

Norris – Landzberg Acceleration Factor Model for Collapsed Bump Solder Interconnects

$$AF = \left(\frac{f_f}{f_t}\right)^m \left(\frac{\Delta T_t}{\Delta T_f}\right)^n \exp^{\frac{E_a}{K}\left(\frac{1}{T_f}-\frac{1}{T_t}\right)}$$

SnPb solder, C4, m=-0.33, n=1.9, Ea/K=1414 [1]

SAC solder, BGA, CSP, TSOP, m=0.132 (here f is replaced with dwell time), n=2.65, Ea/K=2185 [2]

SAC solder, m=0.33, n=1.9, Ea/K=1414 [3]

[1] K. C. Norris and A. H. Landzberg, "Reliability of controlled collapse interconnections", IBM J. Res. Develop., May 1969, pp. 266-271,

[2] N. Pan et al, "An Acceleration Model for Sn-Ag-Cu Solder Joint Reliability under Various Thermal Cycle Conditions", Proc. SMTA, 2005, pp. 876-883

[3] V. Vasudevan and X. Fan, An Acceleration Model for Lead-Free (SAC) Solder Joint Reliability under Thermal Cycling, 2008 ECTC, May 2008, pp. 139-145.

Acceleration Factor Comparison - SN100C

Part Type	ΔT dwell	AF	AF CALCE (Nf/Nt)	Error	AF $(\Delta Tf/\Delta Tt)^{1/c}$	Error	AF N-L	Error
	-40 to 125 °C	1.00	1.00	0	1.00	0	1.00	0
R2512	25 to 125°C td=10 min	2.15	1.40	-0.348	3.42	0.594	3.20	0.493
R2512	25 to 125°C td=30 min	1.42	1.69	0.192	3.53	1.488	3.21	1.261
R2512	25 to 100°C td=10 min	9.64	4.95	-0.486	7.93	-0.177	4.94	-0.487
TSOP	25 to 125°C td=10 min	2.30	3.71	0.616	3.42	0.489	3.20	0.394
TSOP	25 to 125°C td=30 min	3.24	4.65	0.434	3.53	0.091	3.21	-0.009

Examination of acceleration factor estimation with data from ref. 2. CALCE model over estimates acceleration with leaded parts (leaded formulation may be issue). Unadjusted Norris-Landzberg provides relatively good correlation

Conclusions

- Under temperature cycle loading, SAC 305 solder is slightly less durable than SAC379.
- Under temperature cycle loading, SnPbAg solder is slightly less durable than SnPb.
- Under temperature cycle loading, SN100C is less durable than SAC305.
- Lowering the medium cycle temperature dramatically increases the fatigue life of tested lead-free solders.
- Extended low temperature dwell for the temperature cycle -25 to 75 ^{o}C is more damaging than expected, particularly for SnPbAg.
- For maximum temperature of 125^{o}C, dwell time increase from 15 to 75 minutes found to have little effect.
- The tests revealed that extended low temperature dwell for the temperature cycle range of -25^{o}C to 75^{o}C was more damaging than expected, particularly for SnPbAg.
- The impact of dwell was found to be more significant when the median cyclic temperature shifted from 75^{o}C to 25^{o}C. Extending the dwell from 15 minutes to 120 minutes did not result in SAC305 having a lower durability than SnPbAg. Test data also supported the finding that dwell has a logarithmic response to dwell time.