"Filling in the Gaps in Lead-Free Reliability Modeling and Testing"

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IPC Midwest Technical Conference
Schaumburg, IL, September 23, 2009

Session S01: Lead-free Model Cage Match

Summary

This presentation discusses critical material properties and test data that are often overlooked in the introduction of new lead-free solder alloys, but are critical to alloy comparison and the development of life predictive models and acceleration factors. Common gaps in property and test database are identified (e.g., lack of creep data at low to medium stress and cold temperature, insufficient data under mildly accelerated test conditions). The importance of variations in temperature variables (cold and hot temperatures) as well as dwell times is also discussed. Examples of thorough test conditions and test databases that have been used for the development of SAC305, SAC387/396 acceleration factors are presented. It is concluded that the "winning" alloys - i. e. alloys that end-users can work with – are those that are fully characterized in terms of metallurgy (including at interfaces) and mechanical / physical properties & their evolution; are robust enough under both thermal and mechanical loading conditions; and come with an extensive reliability test database and validated reliability models & acceleration factors.

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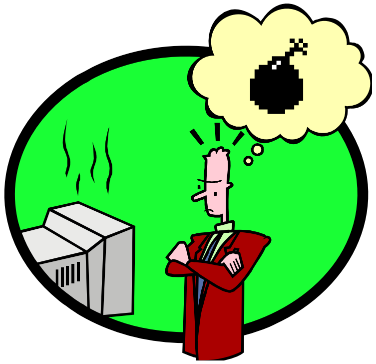
Topics

- Some material & modeling issues / gaps that have surfaced with the advent of lead-free solders:
  - Issues are not rank-ordered by significance level
  - List is NOT EXHAUSTIVE (e.g. drop conditions & vibration are not addressed in this presentation)

Topics (continued)

1. Lack of cold temperature creep data
2. Lack of low stress creep data
3. Few, if any, thermal cycling hysteresis loop measurements on real boards
4. Temperature-dependence of solder CTEs
5. Experimental AFs are component / assembly dependent (some popular, algebraic AF models are not)
6. TC cycles-to-failure saturate with increasing dwell times
7. Some AF models do not capture this effect (# 6)
8. Need variable T_{min}, T_{max} and dwell times for life prediction and AF model development.
9. Different rank ordering at low vs. high “stress” conditions
10. TC life model development is a lengthy process

What has changed with Pb-free?



- Many alloys and mixed assembly compositions
- New microstructures and intermetallics
  - In SAC family, low number of grains & anisotropy
- Dwell time considerations are important for alloys that are more creep resistant than SnPb
- Reliability under drop conditions is requiring more attention than in the past

……..

Pb-free Alloy Proliferation

Mixed Assemblies (SnPb + LF*)

* LF = Lead Free

MIXED LF BALLS & LF PASTE
e.g.: SAC105 Balls + SAC305 Paste

SACX™ (0.01-1.5%Ag, 0.08-20%Bi, 0.02-1.5%Cu,…)

Sn9Zn
SnZnBi
SnBiX
SnIn…

SAC <u>405, 396, 387</u>, 305, 310, 266, 205, 105, 101…

Sn0.7Cu
SnCu + Ni
Sn0.7Cu0.05Ni

LF35 = Sn1.2Ag0.5Cu

SAC+

SACT

OTHERS …

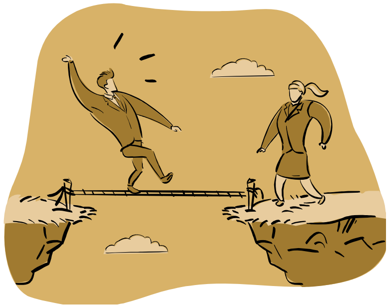
S3XNI = SAC305 + Ni + In

SACN (SAC + Ni)
Sn2.5Ag0.8CuSb0.5
SACB
Sn3.4Ag1.0Cu3.3Bi

\+ Au Co Ca Ce Cs Mg Se RE…

July 1, 2006

Why are there gaps?



- Soft solders have a complex behavior
  - It took decades for industry to get a grasp of SnPb SMT reliability
- “Trial and error” has been the dominant approach.
  - Several proposals since 1992 (NCMS first lead-free project)
  - “Commercial” segments of industry have to “build and ship”
- Unfortunately (IMHO), material properties (physical & mechanical) come last.
  - Emphasis has been on strength, often at room temperature and at an unspecified rate.
    - Why do we need higher strength?
    - Solder joints are not intended to be load-carrying members and should not be subjected to direct mechanical loads.
  - **Ductility is as / or more important than strength for solders**
  - In hindsight, upfront & thorough characterization of thermo-mechanical properties of solders could have reduced the number of “trial & error” cycles.

Issue # 1: Lack of Cold Temperature Creep Data

- Most creep data (creep rates, rupture times etc…) is at room temperature and above
- Cold temperature data suggests a possibly different creep mechanism at cold temperatures
  - See example in next slide

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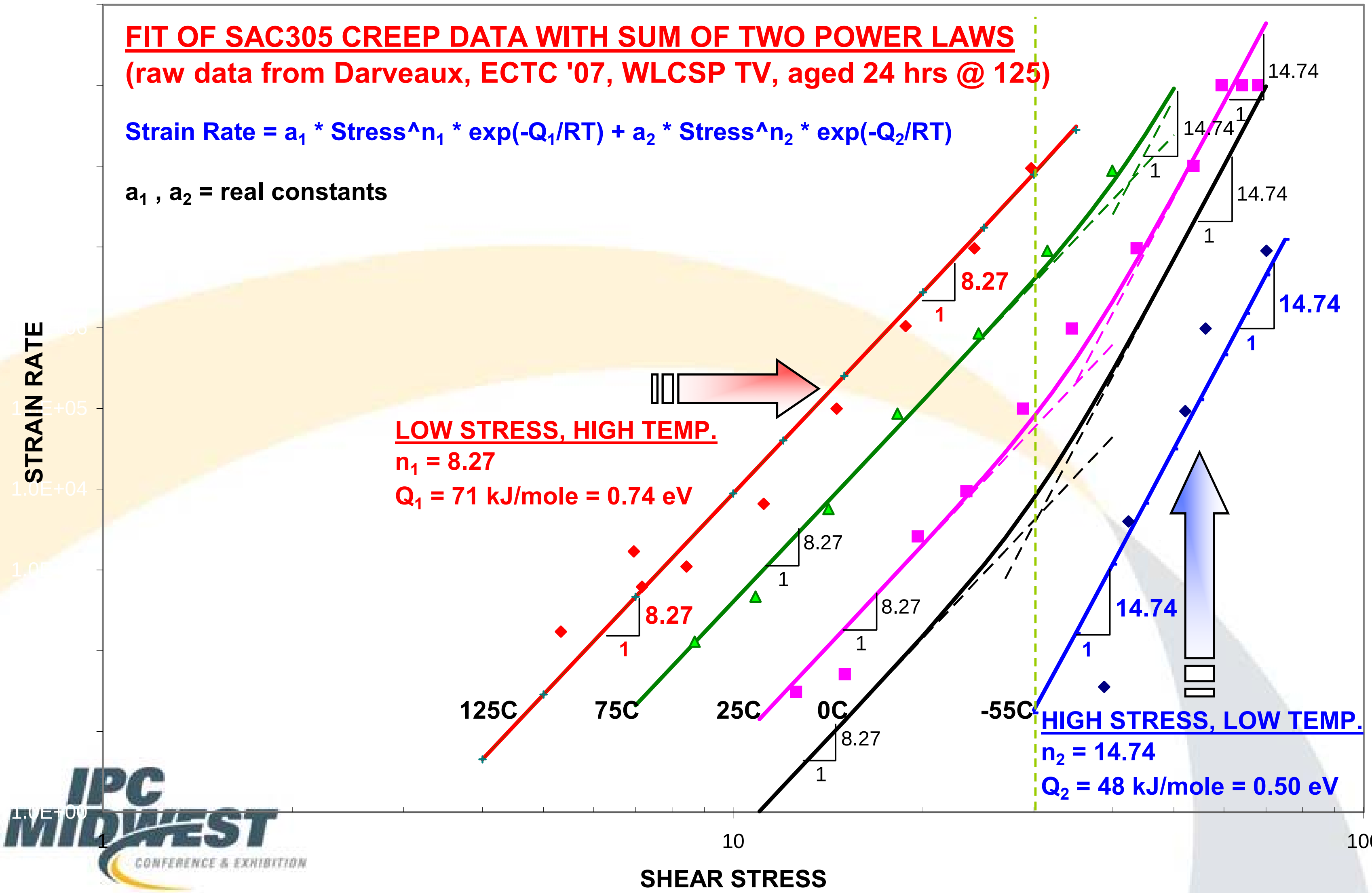
Example: A Different Creep Mechanism at Cold Temperatures?



Issue # 2: Lack of Low Stress Creep Data

- A lot of creep data (creep rates, rupture times etc…) is at 10-20 MPa or above
  - Under many use conditions, maximum stresses are lower.

Table 1. Test Matrix

Temperature (ºC)	Shear Stress (MPa)	Shear Strain Rate (1/s)
20 (RT)	15,20,25,30	1E-6, 1E-5, 1E-4, 1E-3, 1E-2
50	15,20,25	1E-5, 1E-4, 1E-3, 1E-2
75	10,15,20	1E-5, 1E-4, 1E-3, 1E-2
100	10,15,20	1E-5, 1E-4, 1E-3, 1E-2

Example of SAC305 Creep Test Conditions (Herkommer et al., EPTC '08)

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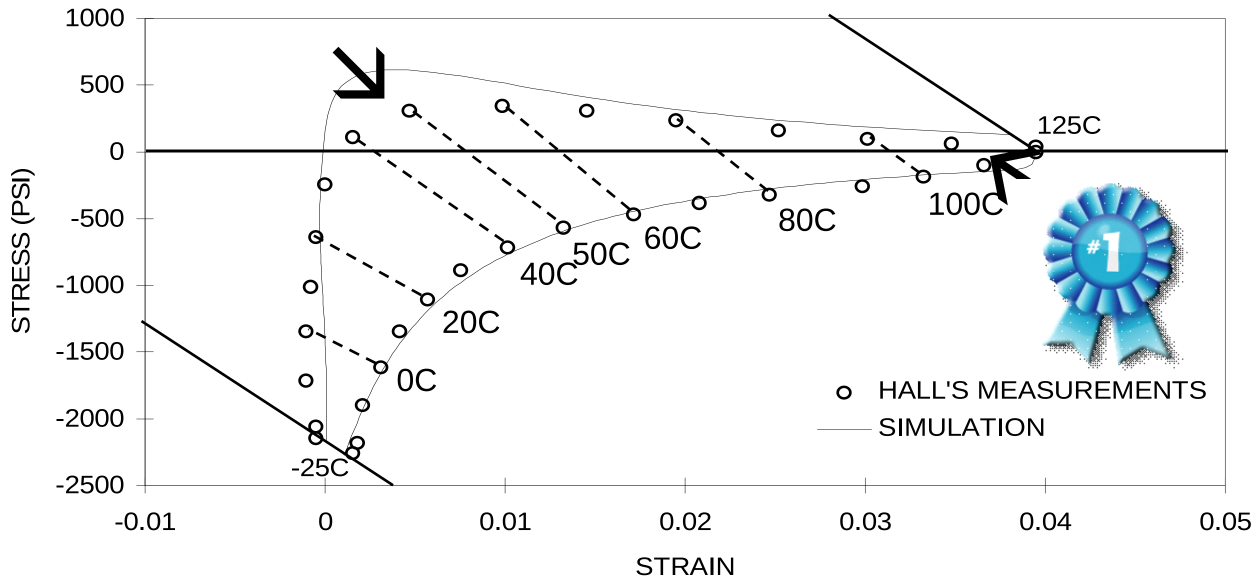
Issue # 3: Few, If Any, Measured Hysteresis Loops for Lead-Free Assemblies under TC Conditions



- Hall's test vehicle: 25 mil pitch 84 I/O LCCC on FR-4
  - 0.5ºC/min ramps, 120 min dwells

- P. M. Hall's (AT&T) hysteresis loops gave SIGNIFICANT, QUANTITATIVE insight in the thermo-mechanical response of SnPb board assemblies
  - Hall's data has been used extensively to validate stress / strain analysis models for SnPb assemblies

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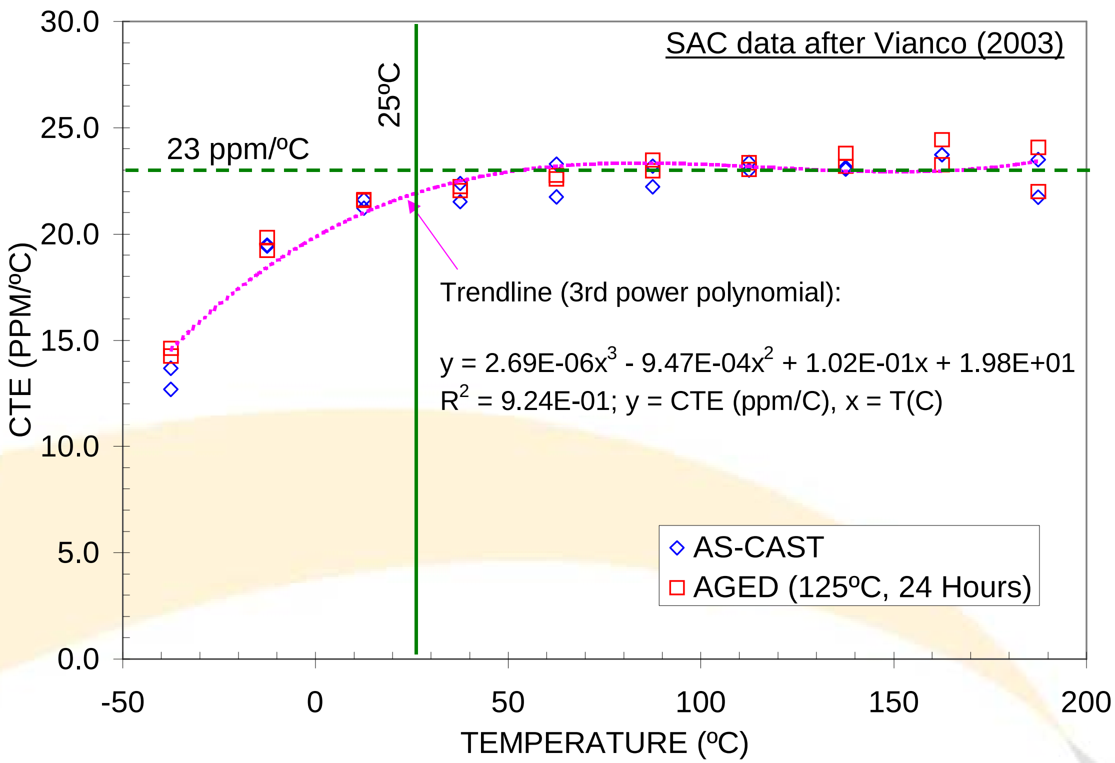
Issue # 4: Lack of CTE Measurements



- It is often assumed that CTE of Sn-based solders ~ 23-24 ppm/°C.
- In range -50ºC to -25ºC, CTE of SAC396 is as low as 12.7 ppm/ºC.

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Issue # 5: Acceleration Factors (AFs) are Assumed to Be Component Independent

- Some popular, closed-form AFs only account for temperature profile parameters
- Test data & FEA models suggest that AFs vary with component / assembly type
- E.g.: in the case of SnPb and SAC305 assemblies, AFs vary by over 2.3 X depending on component type.

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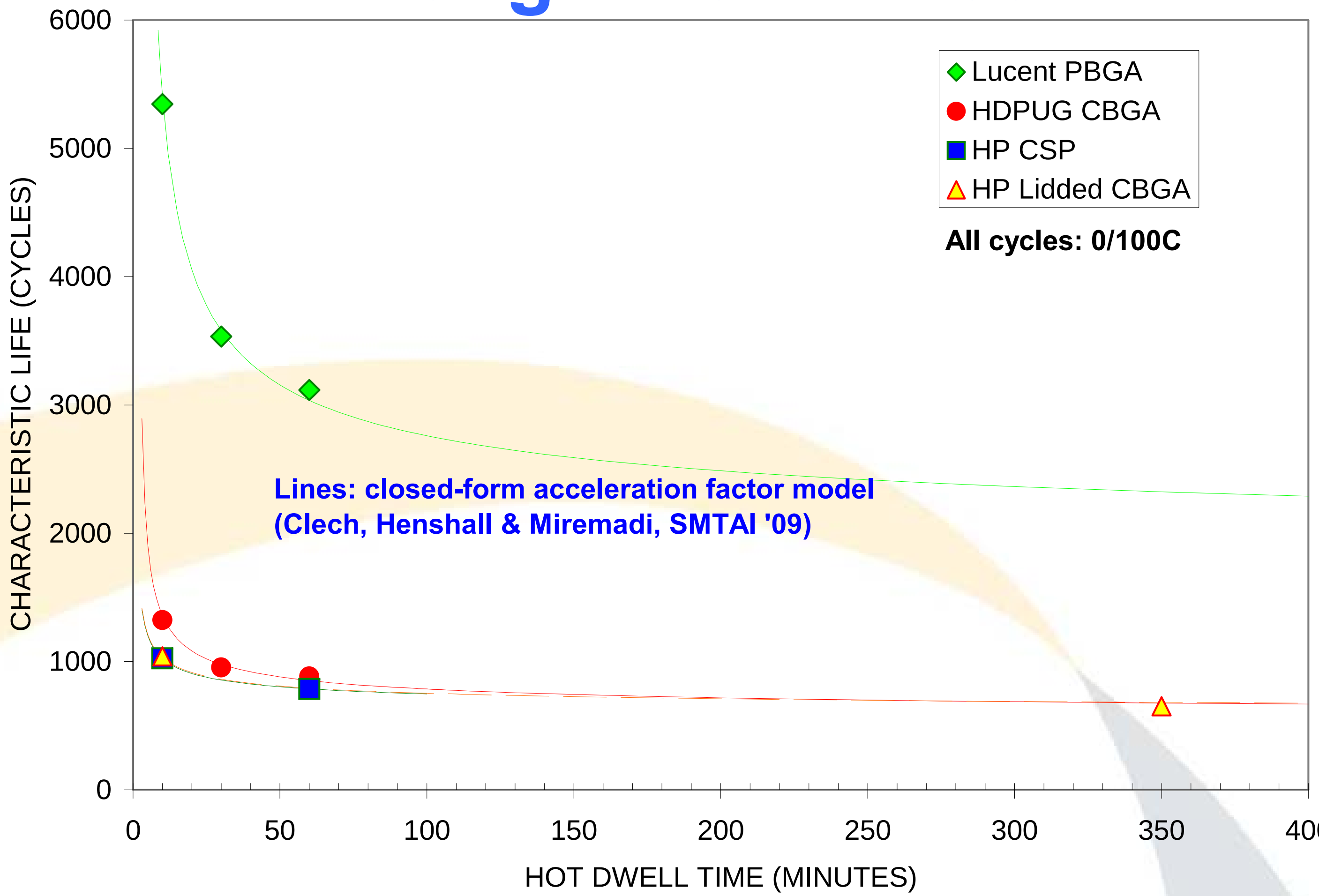
Example: Component -Dependent Experimental AFs

Solder	Source Component	Test Condition "1" N1 (cycles)	Test Condition "2" N2 (cycles)	AF = N2/N1	Largest AF ratio
	HP SMTAI 2005	**0/100C, 10 min. dwells, 10C/min.**	**40/100C, 10 min. dwells, 10C/min.**		
SAC	TSOP B	3071	9455	**3.08**	
SAC	TSOP A	1843	6849	3.72	
SAC	HiCTE CBGA with lid	850	3202	3.77	
SAC	60 I/O CSP	1025	4497	**4.39**	**1.43**
	Lucent J. of SMT 2001	**-40/125C, 5 min. dwells, 16.5C/min.**	**0/100C, 5 min. dwells, 10C/min.**		
SnPb	Flex CSP A	605	760	**1.26**	
SnPb	Flex CSP B	674	884	1.31	
SnPb	Flex CSP D	1961	3986	2.03	
SnPb	Flex CSP E	683	1398	2.05	
SnPb	BGA F	1853	4287	2.31	
SnPb	BGA G	3363	9018	2.68	
SnPb	BGA H	2330	6908	**2.96**	**2.36**
	Lucent J. of SMT 2001	**0/100C, 5 min., 20C/min.**	**0/100C, 5 min. dwells, 10C/min.**		
SnPb	Flex CSP E	1526	1398	**0.92**	
SnPb	Flex CSP B	936	884	0.94	
SnPb	BGA G	9219	9018	0.98	
SnPb	BGA F	4046	4287	1.06	
SnPb	Flex CSP D	3706	3986	1.08	
SnPb	BGA H	6381	6908	1.08	
SnPb	Flex CSP A	662	760	**1.15**	**1.25**

- Test AFs show a strong component / assembly dependence
  - For a given pair of conditions, AFs vary by as much as 2.36 X (maybe more) depending on component / assembly type.
  - Norris-Landzberg type of models do not account for this effect.

Issue # 6: Cycles to Failure Saturate with Long Dwell Times



- To figure out how fast saturation occurs, need thermal cycling failure data as a function of dwell time

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Issue # 7: Models Need to Show Saturation of Cycles to Failure with Dwell Times

- Pan / HP Model (SMTAI'05)

$$AF = \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o}\right)^{2.65} \left(\frac{t_t}{t_o}\right)^{0.136} \exp\left[2185\left(\frac{1}{T_{\max,o}} - \frac{1}{T_{\max,t}}\right)\right]$$

  - Subscripts: "o" = operating conditions, "t" = test conditions
  - t_t and t_o are dwell times
  - **N (cycles to failure) go as (1 / Dwell)$^{0.136}$ → 0 when dwell time → ∞**

- Error margins: ~ +/- 50% (Pan, SMTAI'05)
  - Also found outliers

- "It is desirable to continue to update the constants in the acceleration model once more SAC ATC data are available in the future to make it more inclusive", Ning Pan et al. (SMTAI'05)

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Issue # 8: AFs & Test Conditions

- Common Thermal Cycling (TC) / Thermal Shock (TS) conditions, with various dwell times:
  - 0/100°C, -40/125°C, -55/125°C
- Independent test variables:
  - T_{max} = 100°C or 125°C
  - T_{min}: -55°C to 0°C
- Above is OK for product reliability testing assuming Acceleration Factors (AFs) are reliable
- AF = f(T_{min} ‘s, T_{max} ‘s, cold dwell, hot dwell….)

  - **For AF or model development, we need test data for cycles with T_{max} < 100°C, T_{min} > 0°C**

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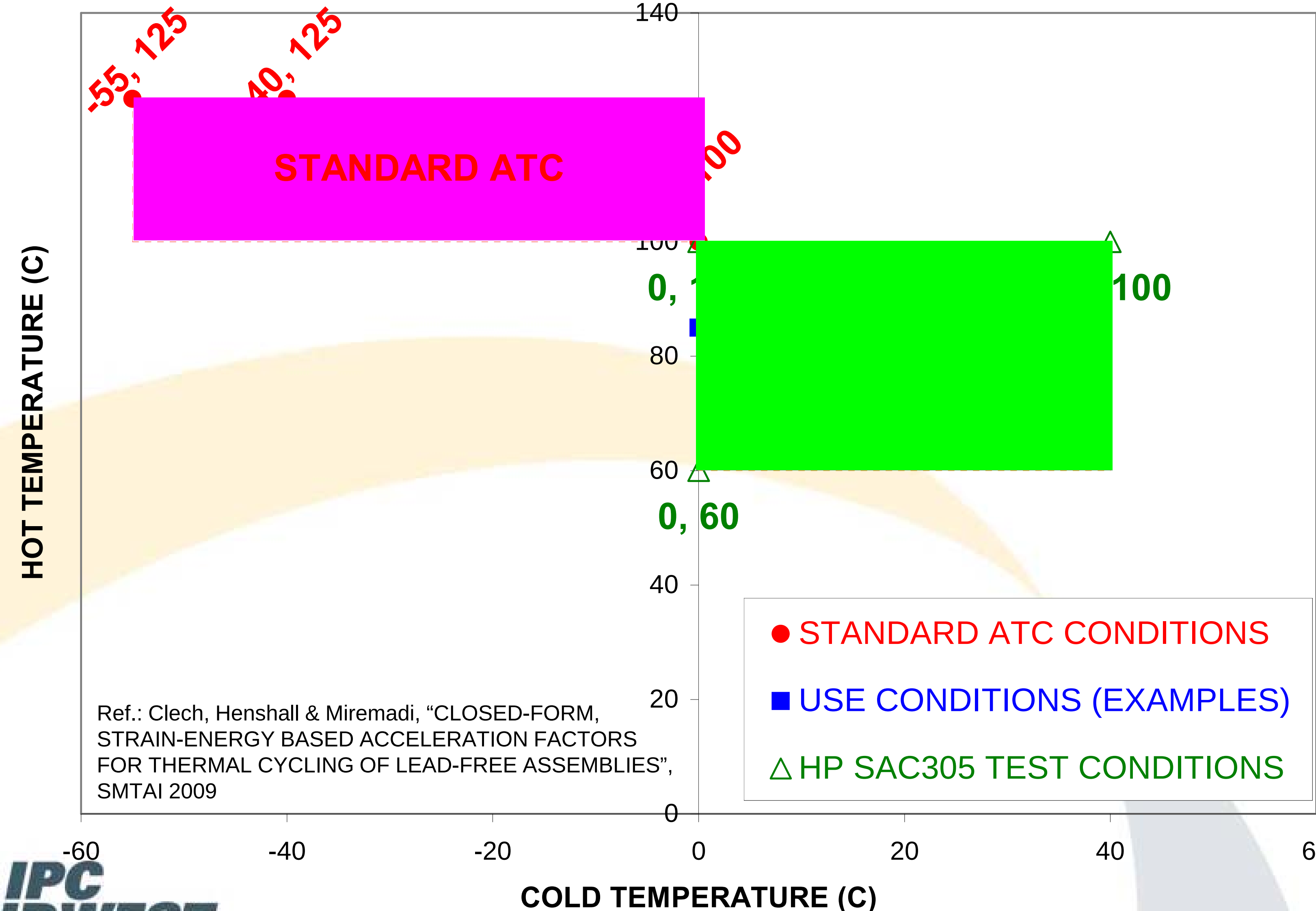
Example: Test Condition Matrix with Variable Dwells, T_{min} & T_{max}

SAC305 test conditions from Pan et al., SMTAI '05

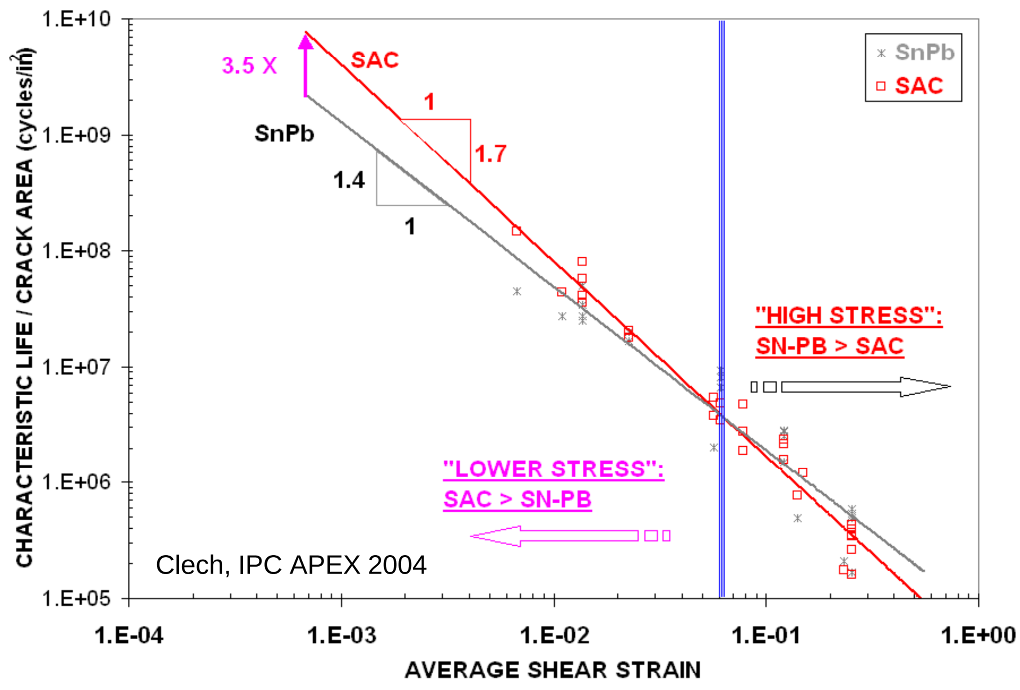
Row #	Component Type	Condition 1 ("harshest") Given Parameters Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	ramp rate (C/min.)	Condition 2 ("mildest") Given Parameters Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	ramp rate (C/min.)
1	HP Lidded HiCTE CBGA	0	100	10	10	10	0	60	10	10	10
2	HP Lidded HiCTE CBGA	0	100	10	10	10	40	100	10	10	10
3	HP Lidded HiCTE CBGA	40	100	10	10	10	0	60	10	10	10
4	HP Lidless HiCTE CBGA	0	100	350	350	10	0	100	10	10	10
5	HP 60 I/O CSP	0	100	60	60	10	0	100	10	10	10
6	HP 60 I/O CSP	0	100	10	10	10	40	100	10	10	10
7	HP 60 I/O CSP	0	100	60	60	10	40	100	10	10	10
8	HP 60 I/O CSP	0	100	10	10	10	0	60	10	10	10
9	HP 60 I/O CSP	0	100	60	60	10	0	60	10	10	10
10	HP 60 I/O CSP	40	100	10	10	10	0	60	10	10	10
11	HP TSOP A	0	100	10	10	10	40	100	10	10	10
12	HP TSOP B	0	100	10	10	10	40	100	10	10	10
13	HP 60 I/O CSP	-25	125	10	10	10	0	100	10	10	10
14	HP 60 I/O CSP	-25	125	10	10	10	0	60	10	10	10
15	HP 60 I/O CSP	-25	125	10	10	10	0	100	60	60	10
16	HP 60 I/O CSP	-25	125	10	10	10	40	100	10	10	10
	Max. Value	**40**	**125**	**350**	**350**	**10**	**40**	**100**	**60**	**60**	**10**
	Min. Value	**-25**	**100**	**10**	**10**	**10**	**0**	**60**	**10**	**10**	**10**

- **Range of independent variables:**
  - **T_{min}: -25 to 40°C**
  - **T_{max}: 60 to 125°C**
  - **Dwell times: 10 to 350 min.**

Example (continued): how close are test and use conditions?



Issue # 9: Low vs. High Stress Conditions



- Rank-ordering of alloys depends on thermal cycling conditions
  - Test results have to be extrapolated to use conditions to estimate whether product reliability requirements are met
- *"Performance comparison from only one accelerated test maybe misleading - <u>At least two test conditions should be used</u>"*
  - A. Syed, Workshop on Modeling and Data Needs for Lead-Free Solders, sponsored by NEMI, NIST, NSF and TMS, TMS Meeting 2001

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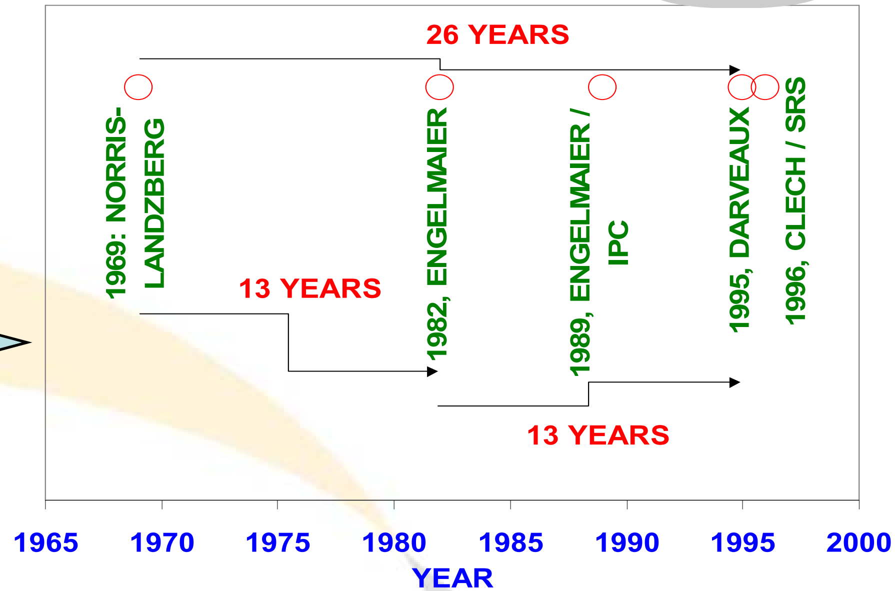
Issue # 10: Thermal Cycling Model Development Takes Time

- The Sn-Pb experience:
  - Historical timeline of SnPb model development (examples of SnPb thermal cycling reliability models).
  - ~ 30 years of model development for SnPb.
  - Other models exist but are kept internal / proprietary (e.g. AT&T CSMR model, CALCE model…).



- Why does it take so long?
  - Complete, thorough data (e.g. CTEs) is not always available

Other Issues or Gaps

- Need to characterize Ductile-to-Brittle transition temperature (fracture energy vs. temperature from Charpy test) for all new alloys
  - SAC alloys show a sharp transition from ductile to brittle
- Creep data needs to be fully exploited:
  - Emphasis is often on "steady state" or minimum creep rates
  - Primary creep can be significant
  - Rupture times are also of interest but are rarely reported on
- Limited or incomplete thermal cycling data for new alloys
  - SAC305 & 405 joints are not the same in terms of creep, thermal cycling etc…
  - Board and component CTEs are not routinely measured
- Limited vibration data for new alloys

Conclusions

- From a technical perspective, the “winning” alloys:
  - Are fully characterized in terms of metallurgy (including at interfaces) and mechanical / physical properties & their evolution
  - Are robust enough under both thermal and mechanical loading conditions
  - Come with an extensive reliability test database and validated reliability models & acceleration factors.

- ~~The devil~~ reliability is in the details

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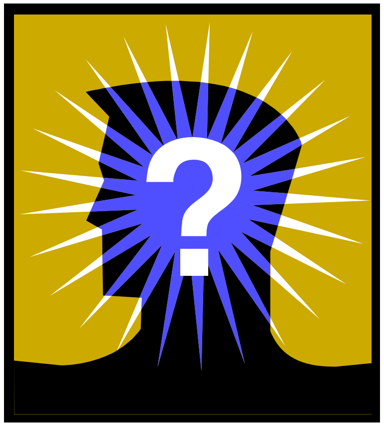

Thank You For Your Time & Attention

COMMENTS / QUESTIONS?