CLOSED-FORM, STRAIN-ENERGY BASED ACCELERATION FACTORS FOR THERMAL CYCLING OF LEAD-FREE ASSEMBLIES

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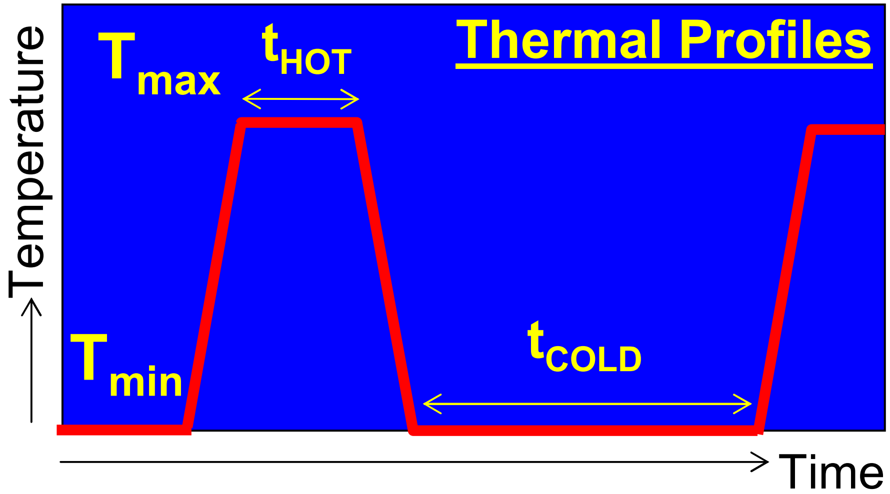
Main Objective



How do we extrapolate from test to field conditions?

$$N_{field} = AF \times N_{test}$$

AF = Acceleration Factor
N's = Cycles To Failure

- Objective: Develop a strain-energy based, algebraic AF model for lead-free assemblies:

$$AF = f(T_{min}\text{'s}, T_{max}\text{'s}, t_{Hot}\text{'s}, t_{Cold}\text{'s}\ldots)$$

that meets the requirements given in the next slide.

Relevant Facts And Requirements

- **FACTS**

1. Cycles to failure (N_f) saturate with long dwell times ($t_D = t_{Hot}$ or t_{Cold}).

2. Hot and cold dwell times can be different in test and are rarely the same in use.

3. AFs are solder, component / assembly dependent.

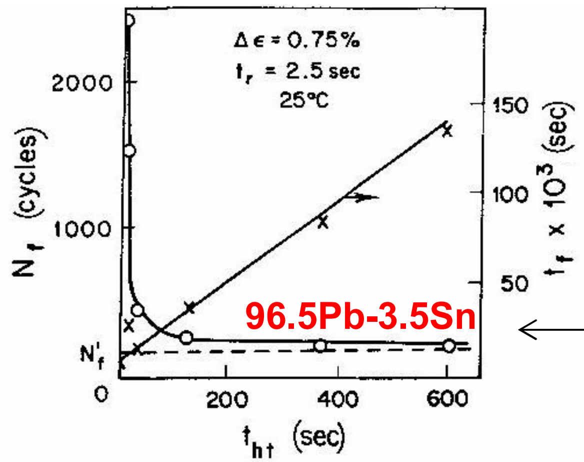
- **REQUIREMENTS**

1. AF model must satisfy the limiting condition:
   - When t_D's → ∞, for a given set of other cycling parameters, Nf → constant ≠0 and is independent of t_D.

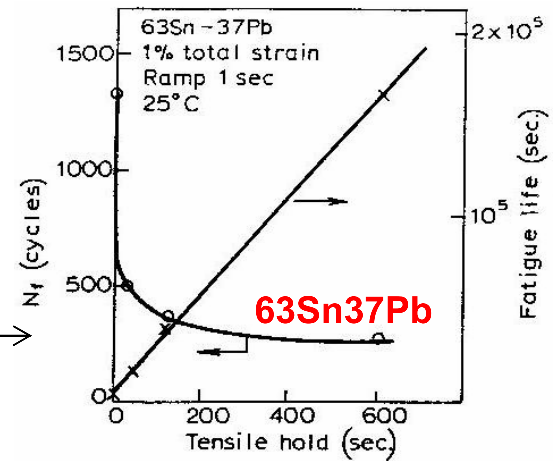
2. AF has different hot and cold dwell time variables: t_{HOT}, t_{COLD}.

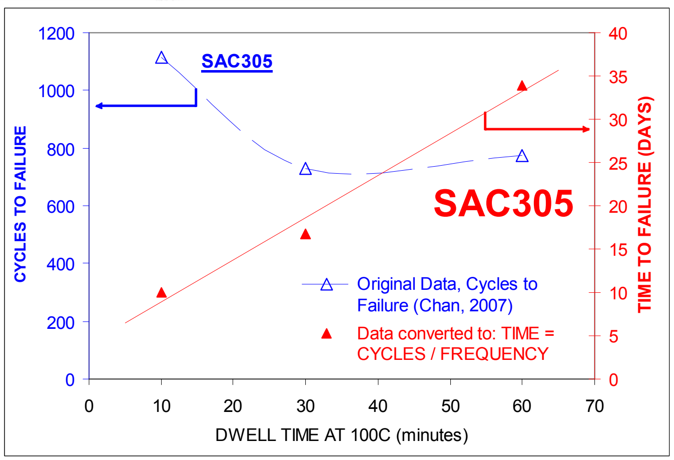
3. AF accounts for solder, component & board geometry and material properties.

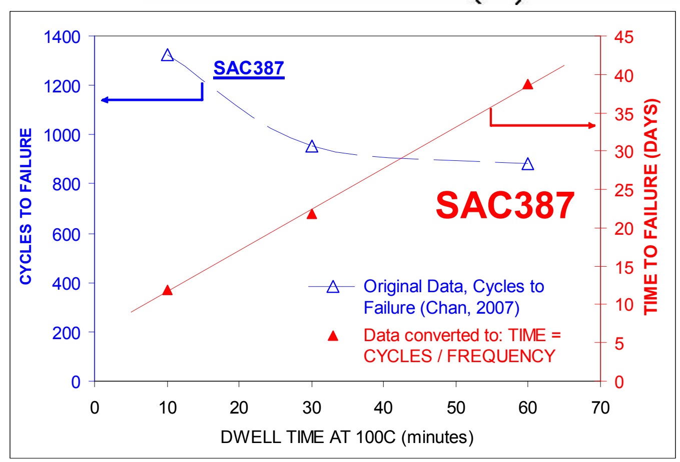
Cycles to Failure Saturate with Long Dwell Times (examples)



Ref.: Veyman et al.
Northwestern U.



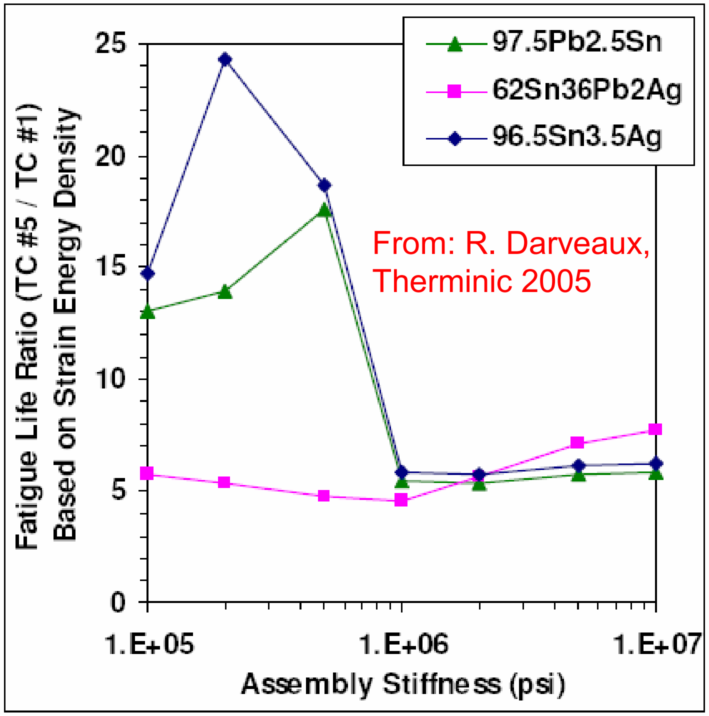




Note: When dwell times are long enough, and within the experimental range, Time to Failure ($t_f = N_f$ / Frequency) is linear with dwell time.

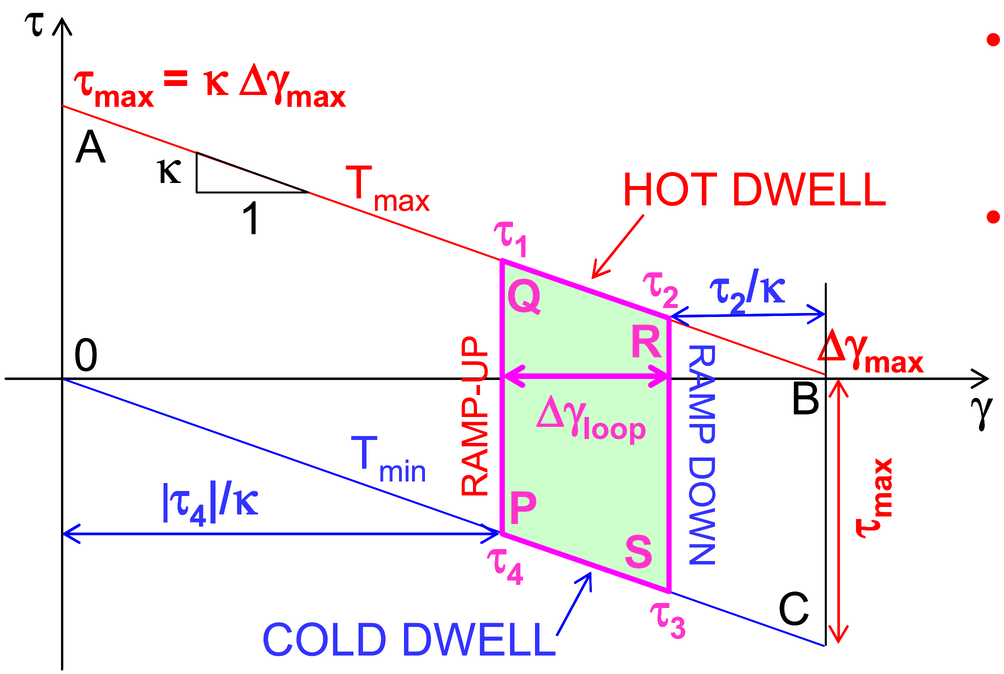
AFs Are Component / Assembly Dependent (examples)

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**



- **Experimental**
  - AFs vary by as much as 2.3 X depending on component type.
- **Hysteresis loop models**
  - AFs vary by as much as 4 X depending on stiffness.

Model Assumptions Allowing Closed Form Approximation



- Approximate stress/strain loop as a parallelogram.
- Main assumptions:
  - Solder creep rates follow a simple power law:

$$\dot{\gamma}_C = A_0 \cdot \tau^n \cdot e^{-\frac{Q'}{T}}$$

n = stress exponent; Q' = Q/R (Q = activation energy, R = gas constant)

  - There is some stress-reduction at T_{hot} and T_{cold} (dwell times can't be zero).

- Cycles to failure go as the inverse of cyclic strain energy (loop area):

$$N_f \propto \left(\frac{1}{\Delta W}\right)^s$$

with fatigue exponent s ~ 1.

Strain Energy Solution

- For a given assembly, strain energy or area PQRS goes as:

$$\Delta W \propto \Delta T^2 - c \cdot \Delta T \cdot \left[\left(\underbrace{t_{Hot} e^{-\frac{Q'}{T_{\max}}}} \right)^{-m} + \left(\underbrace{t_{Cold} e^{-\frac{Q'}{T_{\min}}}} \right)^{-m} \right]$$

Temperature-compensated dwell times

- Model has 3 temperature-independent constants:
  - m, Q' = Q/R and "c".

Cycles-to-Failure Model

- For a given assembly, cycles to failure go as:

$$N_f \propto \frac{1}{\Delta T^2 - c \cdot \Delta T \cdot \left[\left(t_{Hot} e^{-\frac{Q'}{T_{\max}}} \right)^{-m} + \left(t_{Cold} e^{-\frac{Q'}{T_{\min}}} \right)^{-m} \right]}$$

assuming a fatigue exponent s = 1 for SAC305.

- 3 constants:
  - Two solder creep constants: m = 1/(n-1), Q' = Q/R.
  - A "constant" or parameter "c" for component / assembly dependence.

AF Formula

- For a given assembly, AF = N_2 / N_1 (or N_{use}/N_{test}):

$$AF = \left(\frac{\Delta T_1}{\Delta T_2}\right)^2 \frac{1 - c \cdot \Delta T_1^{-1}\left[t_{Cold,1}^{-m} e^{\frac{Q''}{T_{\min,1}}} + t_{Hot,1}^{-m} e^{\frac{Q''}{T_{\max,1}}}\right]}{1 - c \cdot \Delta T_2^{-1}\left[t_{Cold,2}^{-m} e^{\frac{Q''}{T_{\min,2}}} + t_{Hot,2}^{-m} e^{\frac{Q''}{T_{\max,2}}}\right]}$$

where Q” = mQ’ = mQ/R.

- For long dwells: $N_f \rightarrow \frac{1}{\Delta T^2}$ and $AF \rightarrow \left(\frac{\Delta T_1}{\Delta T_2}\right)^2$
  - Dwell time saturation requirement is met.
  - Model converges to a Coffin-Manson relationship.

SAC305 Solder Constants

	Condition 1 ("harshest")					Condition 2 ("mildest")							
	Given Parameters					Given Parameters					Test 1	Test 2	Exp. AF
	Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	ramp rate (C/min.)	Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	ramp rate (C/min.)	N1 = alpha (cycles)	N2 = alpha (cycles)	N2/N1
HP 60 I/O CSP	0	100	60	60	10	0	100	10	10	10	787	1025	**1.30**
	0	100	10	10	10	40	100	10	10	10	1025	4497	**4.39**
	0	100	60	60	10	40	100	10	10	10	787	4497	**5.71**
	0	100	10	10	10	0	60	10	10	10	1025	17497	**17.07**
	0	100	60	60	10	0	60	10	10	10	787	17497	**22.23**
	40	100	10	10	10	0	60	10	10	10	4497	17497	**3.89**
Max. Value	40	100	60	60	10	40	100	10	10	10	4497	17497	**22.23**
Min. Value	0	100	10	10	10	0	60	10	10	10	787	1025	**1.30**

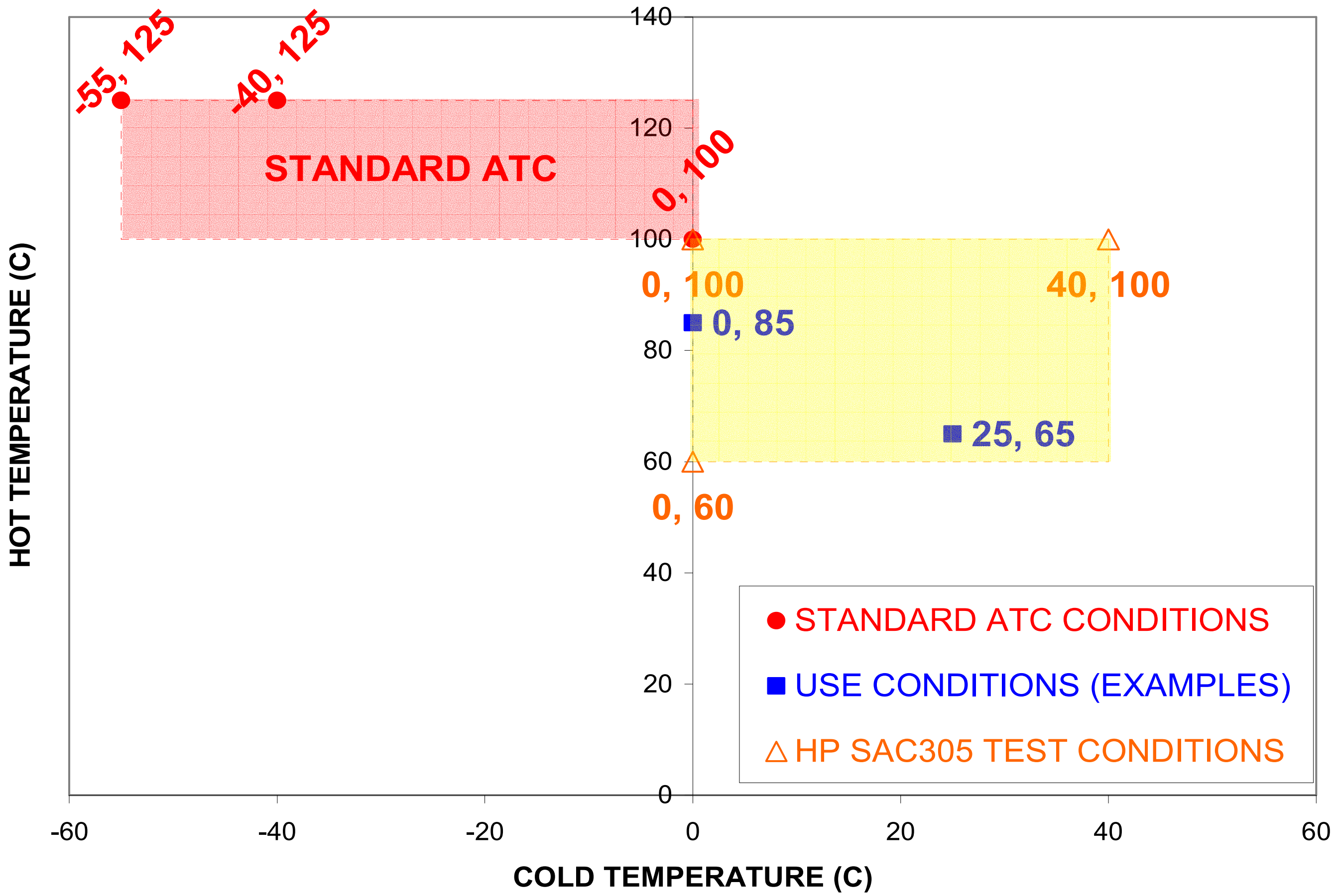
Note: Data from Pan et al., SMTAI 2005, except for 0/60°C characteristic life which is from HP's database.

- Fit model to SAC305 database for single component type (60 I/O CSP) that was tested under the most encompassing range of thermal cycling variables.
  - T_{min}: 0 to 40°C, T_{max}: 60 to 100°C, dwell times: 10-60 minutes
  - Experimental AFs: 1.3 to 22.2.
- For SAC305, get m = 0.19275, Q" = 705.5 deg. K
  - n = 6.2, Q = 30.4 kJ/mole

SAC305 Model Discussion

- Current version of model for SAC305 is limited to temperatures in the range 0°C to 100°C
  - Plots of SAC305 minimum creep rates versus stress show significantly higher slopes at cold temperatures, e.g.: -55°C SAC305 data, Darveaux et al., ECTC 2007.
  - Thus, assumption of single power-law creep, which is needed for closed-form strain-energy solution, is violated at very cold temperatures.
- This is not an issue in 60Sn40Pb version of model (see later slides) where a single power-creep law applies across the test database with temperatures from -20°C to 130°C.

Comparison of T_{min} and T_{max} Under Test and Use Conditions



- Data are needed for intermediate values of T_{min} and T_{max} (other than standard ATC conditions) to validate models at temperatures closer to use conditions.

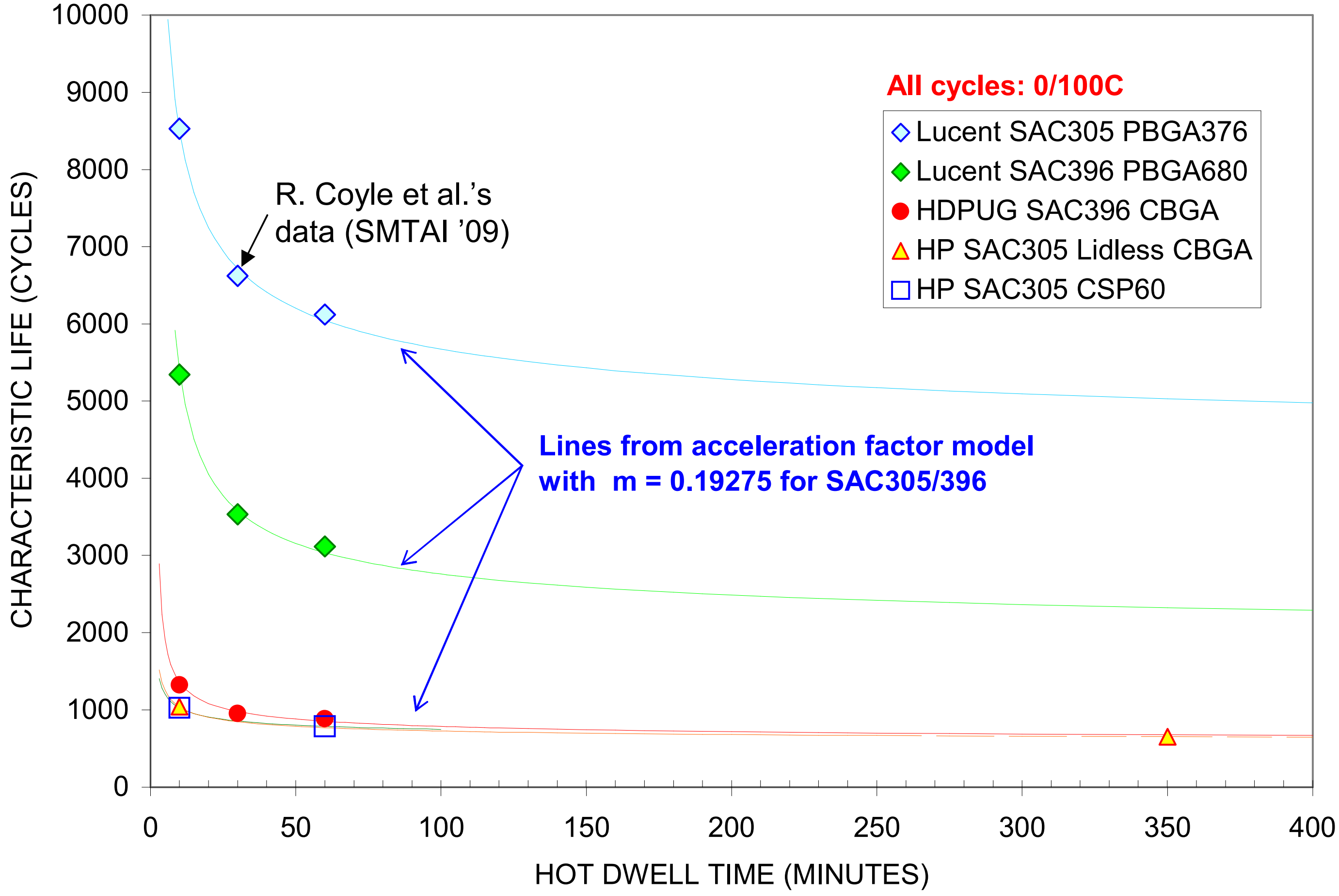
60Sn40Pb Solder Constants

		Condition 1 ("harshest")				Condition 2 ("mildest")				Test Data			Predictions	
		Given Parameters				Given Parameters				Test 1	Test 2	Test AF		
Row #	TEST PAIR	Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	Tmin ('C)	Tmax ('C)	Cold Dwell (min.)	Hot Dwell (min.)	N1 = alpha (cycles)	N2 = alpha (cycles)	N2/N1	Calculated AF	Error = (Test AF / Calculated AF) - 1
1	D & C	25	85	23	5	25	85	15.9	2.1	1030	1186	1.15	1.03	-10.40%
2	D & B	25	85	23	5	25	65	63.6	18.4	1030	2177	2.11	2.14	1.34%
3	D & A	25	85	23	5	25	65	13.4	2.1	1030	2543	2.47	2.52	2.06%
4	C & B	25	85	15.9	2.1	25	65	63.6	18.4	1186	2177	1.84	2.08	13.10%
5	C & A	25	85	15.9	2.1	25	65	13.4	2.1	1186	2543	2.14	2.44	13.91%
6	B & A	25	65	63.6	18.4	25	65	13.4	2.1	2177	2543	1.17	1.18	0.72%
7	E & A	25	125	14.3	2.15	25	65	13.4	2.1	417	2543	6.10	6.81	11.68%
8	E & B	25	125	14.3	2.15	25	65	63.6	18.4	417	2177	5.22	5.79	10.88%
9	E & C	25	125	14.3	2.15	25	85	15.9	2.1	417	1186	2.84	2.79	-1.96%
10	E & D	25	125	14.3	2.15	25	85	23	5	417	1030	2.47	2.70	9.42%
11	F & A	25	125	27	2	25	65	13.4	2.1	352	2543	7.22	6.91	-4.31%
12	F & B	25	125	27	2	25	65	63.6	18.4	352	2177	6.18	5.88	-4.99%
13	F & C	25	125	27	2	25	85	15.9	2.1	352	1186	3.37	2.83	-15.99%
14	F & D	25	125	27	2	25	85	23	5	352	1030	2.93	2.74	-6.24%
15	F & E	25	125	27	2	25	125	14.3	2.15	352	417	1.18	1.02	-14.31%
16	G & A	25	125	45	2	25	65	13.4	2.1	352	2543	7.22	6.97	-3.48%
17	G & B	25	125	45	2	25	65	63.6	18.4	352	2177	6.18	5.93	-4.17%
18	G & C	25	125	45	2	25	85	15.9	2.1	352	1186	3.37	2.85	-15.27%
19	G & D	25	125	45	2	25	85	23	5	352	1030	2.93	2.77	-5.43%
20	G & E	25	125	45	2	25	125	14.3	2.15	352	417	1.18	1.02	-13.58%
21	G & F	25	125	45	2	25	125	27	2	352	352	1.00	1.01	0.86%
22	H & A	-20	130	3.8	4	25	65	13.4	2.1	375	2543	6.78	6.88	1.52%
23	H & B	-20	130	3.8	4	25	65	63.6	18.4	375	2177	5.81	5.85	0.79%
24	H & C	-20	130	3.8	4	25	85	15.9	2.1	375	1186	3.16	2.82	-10.88%
25	H & D	-20	130	3.8	4	25	85	23	5	375	1030	2.75	2.73	-0.54%
26	H & E	-20	130	3.8	4	25	125	14.3	2.15	375	417	1.11	1.01	-9.10%
27	H & F	-20	130	3.8	4	25	125	27	2	375	352	0.94	1.00	6.08%
28	H & G	-20	130	3.8	4	25	125	45	2	375	352	0.94	0.99	5.18%
	Max. Value	25	130	63.6	18.4	25	125	63.6	18.4	2177	2543	7.22	6.97	13.91%
	Min. Value	-20	65	3.8	2	25	65	13.4	2	352	352	0.94	0.99	-15.99%

Ref.: Ceramic Chip Carrier (CCC) data from Sherry & Hall (1986), test profiles from Clech et al. (1987)

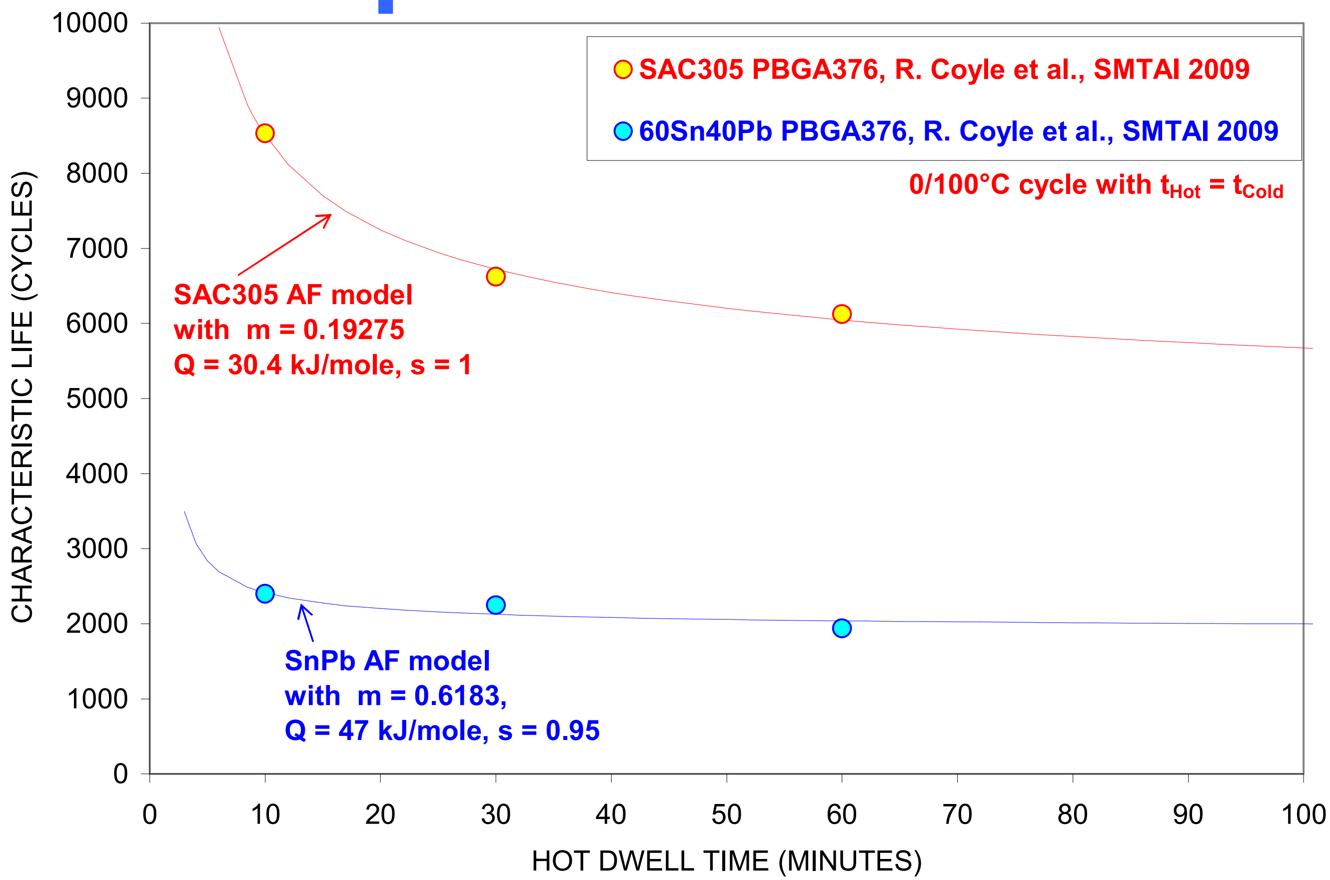
- Fit model to SnPb database for single component type (CCC)
- Get: s = 0.95 (fatigue exponent), n = 2.6, Q = 47.1 kJ/mole
  - Agrees with creep constants for grain boundary creep in SnPb.

AF Model Captures Dwell Time Effects for SAC305/396



- Saturation of cycles to failure with dwell times is more rapid for assemblies with large CTE mismatch

Dwell Time Effects: SAC305 & SnPb Comparison



- AF model captures dwell time effects for both SnPb & SAC305
  - Saturation is more rapid for SnPb than for SAC305

Application Example: SAC305 HiCTE CBGA Assembly

SAC305 AFs: Experimental AFs vs. Predicted AFs

Test Conditions & Experimental AFs			Model / Predicted AFs		
# 1	# 2	AF	Pan	Present Model	Engelmaier
0/100C	0/60C	7.301	7.825	7.209	5.234
0/100C	40/100C	3.767	3.872	3.802	2.699
40/100C	0/60C	1.938	2.021	1.896	1.711

Model references: Pan et al., SMTAI 2005; Engelmaier, Global SMT & Packaging, Dec. 2008.

Table 8. Comparison of test and predicted AF for SAC305 HiCTE CBGA assemblies.

- Different models give different results!
  - Use several models and best judgment.

Application Example: SAC305 HiCTE CBGA Assembly (cont'd)

Use Conditions	Models and Calculated AFs		
T_{min} / T_{max}	Pan	Present	Engelmaier
25C/65C	11.647	6.425	5.078
0C/65C	3.217	1.958	1.943
25C/85C	2.772	2.204	1.728
0C/85C	1.101	1.021	0.904

Model references: Pan et al., SMTAI 2005; Engelmaier, Global SMT & Packaging, Dec. 2008.

Table 9. Calculated AFs for SAC305 HiCTE CBGA assemblies, going from ATC (0/100°C, 10 minute dwells) to use conditions at 1 cycle/day and with dwell times of 710 minutes (cold and hot).

- Discrepancy between models increases with smaller ΔT's.
  - Again, use several models and best judgment.

Another Important Requirement

- Make it VERY CLEAR under which conditions the model has been validated, including thermal cycling parameters and solder composition.
  - Model parameters are empirical.
  - There is no guarantee that an empirical model applies beyond the range of experimental data to which the model was fit.

SAC305 AF Model Summary

SAC305 Acceleration Factor: AF = N_2/N_1 , e.g. “2” = ”Use Conditions”, “1” = “Test Conditions”

$$AF = \left(\frac{\Delta T_1}{\Delta T_2}\right)^2 \left[\frac{1 - c\cdot\Delta T_1^{-1}\left(t_{cold,1}^{-0.19275}\cdot e^{705.5/T_{\min,1}} + t_{hot,1}^{-0.19275}\cdot e^{705.5/T_{\max,1}}\right)}{1 - c\cdot\Delta T_2^{-1}\left(t_{cold,2}^{-0.19275}\cdot e^{705.5/T_{\min,2}} + t_{hot,2}^{-0.19275}\cdot e^{705.5/T_{\max,2}}\right)}\right]$$

- t’s are dwell times in minutes (possibly different for cold and hot).
- T’s are temperature extremes in Kelvin (T_{max} & T_{min} for cold and hot, respectively).
- ΔT is the temperature swing for a given cycle: $\Delta T = T_{max} - T_{min}$.

CONDITIONS FOR USE OF MODEL: **Solder constants are for SAC305 assemblies.**

- “c” is a component/assembly dependence factor. Average “c” = 3.9188 across HP’s SAC305 database. For a given assembly, more realistic values of “c” are obtained by fitting the model to accelerated test data.
- **Temperatures are in the range 0°C to 100°C in HP’s database**
  - T_{min} is in the range 0°C to 40°C and T_{max} in the range 60°C to 100°C.
  - Thus, ΔT’s have to be greater than 20°C for model to remain in empirical range.
- Dwell times are from 10 to 350 minutes in HP’s database.
  - Test frequencies were from 2 to 120 cycles/day. Probably OK at 1 cycle/day.
  - Ramp rates in HP’s database were 10°C/minute.

The above conditions cover the extent of parameters in HP’s SAC305 test database. Use of the model beyond those conditions should be handled cautiously to minimize the dangers associated with extrapolating beyond the empirical range over which the model was fitted to hard data.

Conclusions

- Closed-form strain energy based AF model has been developed for SAC305/396 assemblies.
  - Form of model was not guessed at, but comes out of simplified stress/strain loop analysis.
  - Solder creep constants show up directly in AF formulation.
  - Model captures dwell time effects and meets requirement of saturation of cycles to failure with long dwell times.
- The SAC305/396 AF model is currently limited to temperatures in the range 0°C to 100°C.
- Use more than one AF model and compare results. Need multiple tools in our reliability “toolkit”, depending on management goals.
- Future work: further testing of model; extension to harsher conditions and other solder compositions.

Thank You For Your Time & Attention

COMMENTS / QUESTIONS?