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Pb-FREE THERMAL CYCLE ACCELERATION FACTORS

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ABSTRACT
Society is demanding tougher legislation to minimize or even eliminate perceived health risks to people. Since the European Union began drafting requirements in support of RoHS (Restriction of Hazardous Substances), companies have been scrambling to address the critical transition from eutectic SnPb to Pb-free solder for electronic assemblies. Activities have focused heavily on understanding fundamental material properties and their changes during higher temperature processing. The most important question that must be answered is how these new materials will perform in the equivalent customer environment. This paper will discuss the calculation of acceleration factors for different Pb-free solders, comparing results with those for eutectic SnPb, while also evaluating several approaches and their ability to predict field reliability.

Key words: Pb-free, acceleration factor, thermal cycling, field cycles, failure mode.

INTRODUCTION
There has been much debate as to whether fatigue acceleration factors for Pb-free solders can be calculated with the same accuracy that has evolved for eutectic SnPb based solders, upon which there are many years of electronic industry experience.[1] The methodology attempts to predict the life expectancy of materials in a defined customer environment by "accelerating" exposure conditions in a laboratory. On the surface, differences in the materials between Pb-free and SnPb solders would indicate that the two types will perform differently during Accelerated Thermal Testing, ATC, and therefore in the field. This paper will explore those differences and how they contribute to the parameters for calculating an acceleration factor, with an eye toward understanding whether the acceleration factor for Pb-free solder can be calculated with the same degree of accuracy obtained for SnPb solders.

PLASTIC DEFORMATION MECHANISM
Much of the work on Pb-free solders has focused on different approaches to analyzing the progress of plastic deformation, crack propagation and ultimately failure of the solder joints.[2] For SnPb solder there is much data based upon thermal cycling in test and repeated exposure to thermal variations in the field. Most of the plastic deformation is attributed to time-dependent creep in SnPb solder.[3 4 5] Surprisingly enough, while the creep rate in Pb-free solder is significantly slower than in eutectic SnPb alloy, overall, through thermal cycling, the rate of plastic deformation remains approximately the same between the two. This implies that other mechanisms in addition to creep are influencing the material's behavior. Creep is often defined as a time dependent deformation whose response changes with applied load and temperature, usually by shifting the structure or dimension of interest. Hwang[6] describes two different plastic deformation mechanisms which are determined by whether creep or fatigue is the predominant mechanism during stressing. In the case of fatigue, which occurs from repeated loading and unloading, the shape and dimension of the structure play an important role in determining the reliability. With creep, under a load at a given temperature, underlying atomic events will approach a macroscopic result as strain accumulates over the operating time. Several authors have proposed that dimensional changes in Pb-free solders occur at a much slower rate than in SnPb solders despite the changes at the atomic level occurring in the same relative time frame.[3 4 7 8]

ACCELERATION FACTOR
There are numerous approaches for predicting field life through an estimated acceleration factor. Probably the most common and the one that is the basis for most other models is the Coffin-Manson Equation.[3] See equation 1.

$$N(\Delta\varepsilon_p)^n = \text{Const.} \qquad \textbf{Eqn. 1}$$

Where:
N is life in cycles to fail ,
$\Delta\varepsilon_p$ is the plastic strain range per cycle,
n is an empirical constant which for SnPb solder is often considered to be ~1.9.

Equation 1 can also be written as follows for two different plastic strain ranges:

$$N_1(\Delta\varepsilon_{p1})^n = N_2(\Delta\varepsilon_{p2})^n \qquad \textbf{Eqn. 2}$$

Or

$$AF_{CM} = N_1 / N_2 = (\Delta\varepsilon_{p1} / \Delta\varepsilon_{p2})^{-n} \qquad \textbf{Eqn. 3}$$

Where:
AF_{CM} is the acceleration factor between Lab test to Field Use,
N_1 is the number of cycles in the field,
N_2 is the number of cycles in the lab,

$\Delta\varepsilon_{p1}$ and $\Delta\varepsilon_{p2}$ are the plastic strain range in the field and in the lab respectively.

One useful modification to the Coffin-Manson equation is the substitution of plastic strain range with the ratio of change in temperatures during lab testing to the change in temperature in the field. During thermal cycling the change in plastic strain is created by the difference in coefficient of thermal expansion, typically between the components and the PCB, the distance from the neutral point, DNP, of the solder joint and driven by the ΔT of the thermal cycling. These other factors all cancel out in the calculation of acceleration factor with the ratio of ΔTL/ΔTF. For this reason the ΔT ratio is used as an approximation of plastic strain range where the temperature range is much easier to obtain. This is depicted in equation 4.

$$AF_{ModCM1} = (\Delta T_L/\Delta T_F)^n \quad \textbf{Eqn. 4}$$

Another modification made by Clech is to exchange the plastic strain term for a cyclic strain energy term.[9] See equation 5.

$$AF_{ModCM2} = (\Delta W_L/\Delta W_F) \quad \textbf{Eqn. 5}$$

Where ΔW_L is the cyclic strain energy in accelerated thermal cycling testing in the lab and ΔW_F is the cyclic strain energy in the field. Cyclic strain energy is another method to measure the accumulated damage during each thermal cycle of testing or of field life.

Norris and Landzberg made further enhancements to the Coffin-Manson equation adding two more terms which account for the thermal cycle frequency. This approach includes a T_{max} (L) representing the Lab thermal cycle and a T_{Max} (F) for the field. This can be seen in equation 6.[10]

$$AF_{NL} = (\Delta T_L/\Delta T_F)^{B1} (f_F/f_L)^{B2} * \exp(Ea/k(1/T_{Max\,F} - 1/T_{Max\,L})) \quad \textbf{Eqn. 6}$$

Where:
B1 is the material exponent, 1.9 for SnPb solder,
B2 is the frequency exponent, 0.333 for SnPb,
E_a is the Energy of Activation as for the Arrhenius Equation, and
k is Boltzmann's Constant.

Table 1 shows the values for both SnPb and Pb-free solder SnAgCu (SAC), highlighting the differences in parameter values used to complete equation (6) above.

Table 1: Values for SAC solder for the Norris-Landzberg Model[11]

Parameter	SnPb Eutectic	SAC Alloys
B1	2.0	2.3
B2	0.3333	0.3
Ea/k (°K)	1414	4562

Continuing our analysis on methods of calculation, the third term in the Norris-Landzberg Model follows closely the form of the Arrhenius equation shown here:

$$c = Ae^{(-Ea/kT)} \quad \textbf{Eqn. 7}$$

The Arrhenius equation provides the relationship of the rate of reaction to the absolute temperature of the assembly. It can also be used to model the temperature variance of diffusion coefficients and creep rates, as shown in equations 8 and 9, respectively.[12]

$$D = D_0^{(-Qd/RT)} \quad \textbf{Eqn. 8}$$

$$\varepsilon_s = K_2\sigma^{n(-Qc/RT)} \quad \textbf{Eqn. 9}$$

In these relationships Q_d and Q_c are the activation energy constants for solder diffusion and solder creep, respectively. From a pure physics and chemistry perspective activation energy is best described as the amount of energy in excess over the ground state, which must be added to an atomic or molecular system to allow a particular process to take place. Whether the plastic deformation is diffusion related or creep related or a combination of the two, the dependence on absolute temperature would be the same. The third term in the Norris-Landzberg equation above factors in both the maximum lab thermal cycle temperature and the maximum field temperature as it relates to activation energy of the solder.

Pan has made a different modification to the Coffin-Manson equation, very similar to the Norris-Landzberg equation but substituting inverse cyclic dwell time for cycle frequency.[13]

$$AF_{Pan} = (\Delta T_L/\Delta T_F)^{C1} (t_L/t_F)^{C2} * \exp(Ea/k\,(1/T_{Max\,F} - 1/T_{Max\,L})) \quad \textbf{Eqn. 10}$$

There is an obvious similarity between the Norris-Landzberg equation and Pan's equation. In Pan's equation, The variables t_L and t_F replace frequency in the Norris-Landzberg equation with dwell time. This substitution affords us the opportunity to evaluate what weight is placed on cycling frequency as compared with dwell time at the extreme temperatures.

For equation 10, C1 is the material exponent, and C2 is the dwell exponent, for Pb-free solder.[14] The constant values can be found in Table 2.[15]

Table 2: Values for SAC solder alloy for the Pan Model

Parameter	Value
C1	2.65
C2	0.136
Ea/k Deg. K	2185

As we summarize the numerous approaches to calculating acceleration factors, it is interesting to also consider a

derivation of the Arrhenius equation known as the Eyring model, shown in equation 11.[16]

$$AF_{Eyring} = L_U/L_A = T_A/T_U \exp(Ea/k\ (1/T_U - 1/T_A)) \quad \textbf{Eqn. 11}$$

Here L_U and L_A are expected life cycles in use and accelerated testing respectively. E_a is energy of activation and k is Boltzmann's constant. T is absolute temperature in accelerated testing and use. The Eyring model more accurately takes into account how the rate of degradation or time to failure varies with stress, and is commonly used to model acceleration when many stresses are involved.

One additional approach that more closely accounts for the material properties of the solder is that taken by Engelmaier, which expanded the Coffin-Manson into the following: [17]

$$N_{f50} = \tfrac{1}{2}\,(2\varepsilon_f/\Delta D)^m \quad \textbf{Eqn. 12}$$

$$1/m = c_0 + c_1 T_{sj} + c_2 \ln(1 + t_0/t_{dwell}) \quad \textbf{Eqn. 13}$$

$$\Delta D = K(L_d\ (\alpha_s - \alpha_c)\Delta T)/h \quad \textbf{Eqn. 14}$$

Where:
N is the number of cycles for 50% of the population to fail
D is the cyclic strain range,
ε_f is the fatigue ductility constant for the solder,
c is the fatigue ductility exponent,
T_{sj} is the mean cyclic temperature,
t_{dwell} is the dwell time at the peak temperature,
K is the calibration factor,
L_d is the distance to neutral point for the maximum solder joint,
ΔT is the equivalent temperature swing,
h is the solder joint height,
α_s is the Cte for the substrate,
α_c is the Cte for the component,
ΔT is the change in temperature during temperature cycling.

Engelmaier has constants for SnPb solder as well as proposed constants for several different Pb-free solders. [18] See Table 3.

Table 3: Solder Constants for the Engelmaier Model

Solder	Model Parameters				
	ε_f'	c_0	c_1	c_2	t_0
Engelmaier-Wild Creep-Fatigue Model for SnPb Solders					
SnPb	**0.325**	**0.442**	**6.00e-4**	**-1.74e-02**	**360**
Tentative Creep-Fatigue Model Parameters for Pb-Free Solders					
SAC405/ 305	**0.425**	**0.480**	**9.30e-4**	**-1.92e-2**	**500**
SAC205	**0.250**	**0.480**	**9.30e-4**	**-1.92e-2**	**500**
SAC105	**0.225**	**0.480**	**9.30e-4**	**-1.92e-2**	**500**
SnAg	**0.275**	**0.480**	**6.3e-4**	**-1.82e-2**	**400**

As noted above there are several approaches to predicting time to fail and solder joint life, each placing emphasis on a different set of variables. There are many who believe that an acceleration factor for Pb-free solders cannot be calculated and that the reaction is too complex for equations, empirical or otherwise. Pb-free solders have proven to be more sensitive to the aforementioned variables, and care must be taken to recognize and control them so as not to unduly influence the results of a calculation.

MORE ON VARIABLES

Perhaps the most important variable influencing the results of the above calculations is the package type itself. All of the acceleration factor equations can apply to only one package type at a time, of the same size and geometry. One cannot extend learning on one package type to another without extensive testing.[19] This testing is often performed on full assemblies, and typically failure rates on assemblies are dominated by one component such that curve fitting works well. When more than one package is involved with the failure rate, they will need to be analyzed separately to construct a composite failure rate of the different components involved.

T_{Max}; The maximum temperature from cycling is significant for several reasons. From the Norris-Landzberg equation and based upon activation energy and temperature, the rate at which deformation occurs is clearly temperature dependent, and most damage will occur at or near the maximum temperature, where the rate of damage will be much faster. While creep can occur at any temperature, it occurs at a substantially higher rate when the temperature of the solder is more than half of the melting point of the alloy. Using the melting point of SnAg solder and a T_{Max} of 100 Deg. C. the calculation is as follows:

$$(373\ ^oK\ T_{Max}/494\ ^oK\ T_{mp}\ SnAg) = 0.76 > 0.5 \quad \textbf{Eqn. 15}$$

From equation 15, solder creep would be expected to occur under the given conditions. This melting point normalized temperature is called the homologous temperature.

T_{Min} and ΔT; The minimum temperature by itself is not as significant as the differences between the maximum temperatures and the minimum temperatures. These differences, noted as ΔT, drive stress through the differences in coefficients of thermal expansion between the component and the substrate, usually the printed circuit board. As the temperature is cycled and the component and the PCB expand and contract at different rates, stress will be applied to the solder joints as seen through a standard thermal cycle induced hysteresis loop. Pan[13] performed accelerated thermal cycling on samples where the temperature range was 0 – 60 ^oC and 40 – 100 ^oC on the components with a high Cte difference between the component and the PCB. In this case even though the ΔT is the same, the damage was much higher and the number of cycles to fail was much less when cycled at the 40 – 100 ^oC. This would be true for both SnPb and Pb-free solders.

Frequency of temperature change; One of the concerns with testing of Pb-free solders is the frequency at which experiments must cycle to generate temperature change. In an attempt to allay concerns regarding the question of Pb-free solders performing at extended cycle times in the field, Vasudevan et al found that Pb-free solder had an improved reliability performance with a 480 minute extended cycle compared with the Sn-Pb solder with the same cycle time and also found that the failure signature, mode, location and crack formation were the same.[20]

Dwell time, particularly at T_{Max}; Longer dwell times have been found to decrease thermal fatigue life as measured in cycles to failure. In one test with SAC405, SAC305, and SAC105 a 60 minute dwell time had approximately 20-33% less characteristic life compared with the component cycled with a 10 minute dwell time.[21] The same result was found for SnPb solder. These comparisons on different Pb-free solders revealed the importance of dwell time on increased plastic deformation. During the dwell, particularly at higher temperatures, the solder accommodates the stress from the Cte mismatch in cycling causing plastic deformation in the solder. At higher temperatures solder creep/plastic deformation may occur more quickly and so a longer dwell time may actually have less effect since the maximum possible damage per cycle will occur relatively early in the dwell time interval.[22]

Ramp rates; Ramp rate is known to have a weak affect on cycles to fail if any affect at all.[1] Mattila et all completed a study that demonstrated no substantial difference in the number of cycles to fail for two different ramp rates, 8 C^o/Min and vs. 24 C^o/Min. Even though the failure rates did not show change between different ramps, this work did observe failures in the form of a crack propagating at the intermetallic interface for higher ramp rates, as opposed to fails originating in the bulk of the solder for slower ramp rates. For ramp rates of the same order of magnitude, this can be explained by the dependence on Cte between the Cu pad and solder as opposed to the component and the PCB.

Solder surface condition; When processed correctly, SnPb solders appear shiny and pristine. This is in stark contrast to Pb-free solders which are prone to surface roughness and shrinkage cracks, shrinkage voids and crevices. Because cracks may propagate from shrinking crevices that form during solidification of solder, there has been much discussion on their impact on time to fail and product life as it relates to solder joints. On average, surface roughness conditions do not appear to have an impact on component reliability. In cases of higher solder joint stress, cracks have been found to initiate from shrinkage voids or crevices in Pb-free solders. [23]

Preconditioning; One variable that often is not considered is the preconditioning of the sample. Coyle et al reports that preconditioning of SAC solder joints at 125 Deg. C for 500 hours can increase life cycles by about 3%. [24] This by itself is not significant. However, it is significant to note that heating as a treatment for other reasons will not degrade the solder joint reliability or quality.

Ag content; The percentage of silver content has been found to be a significant variable contributing to the reliability of the solder joint.[7] [21] SAC405, SAC305, SAC205, SAC105 and SnCu have all been tested extensively. The fatigue resistance and increase in reliability have been directly related to the amount of Ag in the alloy, which those displaying higher Ag content better than SnCu and those without Ag addition. In fact, SAC 405 showed about a 3x improvement in reliability over SnCu.

PCB surface finish; PCB surface finish is another variable known to affect solder joint reliability, and its effect can be neutral to adverse. Organic surface preservative, OSP, can cause-inclusion voids from out-gassing of the OSP surface finish itself.[25] Immersion Silver surface finish can cause pinholes.[26] Electroless Nickel Gold, ENiG is known to cause embrittlement of the intermetallic interface. This has proven to be true especially in components with high shear strain on the solder joints. During new product introductions it has been observed that first pass yields went from 50% to 95% only by changing the surface finish from ENiG to an OSP finish. The defects were opens at the intermetallic layer on components with a high Cte mismatch between the component and the PCB.

CALCULATIONS

Below are sample calculations utilizing different acceleration methods provided above. The information in the table below will be used for each of the calculations. Where possible they will be made for both SnPb and Pb-free solder alloys.

Table 4: Parameters for example calculations

Parameter	Condition 1	Condition 2	Condition 3
TMax	125 Deg. C	100 Deg. C	60 Deg. C
TMin	-55 Deg. C	0 Deg. C	30 Deg. C
ΔT	180 Deg. C	100 Deg. C	30
Cycles per hour	0.5	1	0.25
Dwell time	10 Min	10 Min	360 Min
K*	1	1	1
h	0.2	0.2	0.2
α_c	3.2 ppm	3.2 ppm	3.2 ppm
α_s	21 ppm	21 ppm	21 ppm
L_d	1.06	1.06	1.06

*Note: K is unknown, calculations assume 1

Examples utilizing the Modified Coffin-Manson with ΔT, Norris-Landzberg, Pan and Engelmaier models:

$$AF_{ModCM1} = (\Delta T_L/\Delta T_F)^n$$

$$AF_{ModCM1SnPb} = (180/100)^{1.9} = 3.1$$

$$AF_{ModCM1Pb\text{-}free} = (180/100)^{2.3} = 3.9 \quad \text{Eqn. 16}$$

Table 5: Modified Coffin-Manson Acceleration Factor

	Cond 1/Cond 2	Cond 1/Cond 3
SnPb	3.1	30
Pb-free*	3.9	62

*Note: No alloy information was provided.

$$AF_{NL} = (\Delta T_L/\Delta T_F)^{B1} (f_F/f_L)^{B2} * \exp(Ea/k(1/T_{Max\ F} - 1/T_{Max\ L}))$$

$$AF_{NLSnPb} = (180/100)^{2.0} (1/0.5)^{0.33} * \exp(1414(1/373 - 1/398)) = 5.2$$

$$AF_{NLPb\text{-}free} = (180/100)^{2.3} (1/0.5)^{0.3} * \exp(4562(1/373 - 1/398)) = 10.3 \quad \text{Eqn. 17}$$

Table 6: Norris-Landzberg Acceleration Factor

	Cond 1/Cond 2	Cond 1/Cond 3
SnPb	5.2	110
Pb-free	10.3	880

$$AF_{Pan} = (\Delta T_L/\Delta T_F)^{C1} (t_L/t_F)^{C2} * \exp(Ea/k(1/T_{Max\ F} - 1/T_{Max\ L}))$$

$$AF_{PanPb\text{-}free} = (180/100)^{2.65} (10/10)^{0.136} * \exp(2185(1/373 - 1/398)) = 6.9 \quad \text{Eqn. 18}$$

Table 7: Pan Acceleration Factor

	Cond 1/Cond 2	Cond 1/Cond 3
Pb-free*	6.9	167

*Note: No alloy information was provided.

Table 8: Engelmaier Model N_{50f} and Acceleration Factor

Solder	180 Deg C ΔT	100 Deg C ΔT	30 Deg C ΔT	Cond 1/ Cond 2 AF	Cond 1/ Cond 3 AF
SnPb	187	481	2160	2.6	11.5
SAC405/ 305	106	222	745	2.1	7.1
SAC205	49	104	370	2.1	7.5
SAC105	42	90	322	2.1	7.6
SnAg	149	387	1710	2.6	11.5

In the above calculations, the Coffin-Manson equation appears to estimate the acceleration factor more conservatively than the other models. It can also be seen that the Norris-Landzberg and Pan equations may be better suited for different situations where in one the frequency of cycling may be a more dominant variable while in the other dwell time may be the more dominant variable.

DISCUSSION

Now that we've summarized several approaches toward calculating acceleration factors, one may question which equation is best suited for various applications. Certainly the easiest to use is the Coffin-Manson modified to use temperature cycles in the field vs. in the lab. For many of the above methods, material properties and constants are required that may not be readily available. Many claims of the accuracy and improvement over the other data analysis methods are found in the literature. [13 27 28 29 30 31 32] The claimed accuracy varies from approximately +/-50% to as good as +/-2%. Often, the accuracy of one method, when applied to another situation is not found to obtain as accurate results as another method tailored to the testing at hand.

The Coffin-Manson equation modified to use temperature instead of plastic strain is easy and straightforward to use. The results appear to be conservative as noted above. All that is required is the exponent, which is reported to be between 1.9 -2. To calculate the energy, plastic strain may require modeling or measurements that are difficult to obtain accurately, and may cast more error into the calculated acceleration factor. Already there are proposed values for the constants used in the Norris-Landzberg and Pan equations, which may be used in the calculation of acceleration factors. Engelmaier has proposed constants for use in his Creep-Fatigue model for several Pb-free solders. It may be worthwhile to use multiple calculation methods as one way of providing a measure of error to the acceleration factor calculation itself. Controlling variables in addition to those accounted for in the acceleration factor equations, such as those mentioned above, may well decide whether or not the outcome is accurate and repeatable.

CONCLUSION

The available literature supports the use of several calculation methods to determine the acceleration factor for extrapolating from lab testing to life expectancy in the field for Pb-free solders. These methods have been used for SnPb solders and are readily extendable to Pb-free with the right constants and variables available in the literature today. As in the case for SnPb, calculations for Pb-free solder will experience similar limitations for extreme strain factors where predictions have in the past fallen short. Many claim with proper use and thoughtful data results within +/- 25% are very achievable.

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