

Lead-Free Solder-Joint-Reliability Model Enhancement

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Abstract

Upon release of electronics products with lead-free (Pb-free) solders starting in 2006 and driven by the EU's RoHS legislation, a few models have been in use by the electronics industry to predict the life of the Pb-free solder joints under product-application conditions based on accelerated testing results. These models, including one published by HP in 2005, have proven to have shortcomings, resulting in any of three probable scenarios: (1) over-design for reliability, (2) earlier-than-predicted field failures, or (3) missed technology opportunities. We have devised an approach to develop and implement improved models for predicting Pb-free solder joint life. This approach comprises: (1) comprehensive review of available published work to create a large data base of test results, (2) application of statistical techniques to analyze this large data base, and (3) the grouping of the data into clusters of comparable packaging attributes and test conditions. Using this new approach, a set of accurate models has been generated that significantly reduce the errors and uncertainties compared to earlier models, greatly enhancing HP's ability to accurately predict Pb-free solder-joint life based on test data.

Key words: Acceleration Factor, Sn-Ag-Cu (SAC) solders

1. Introduction

Solder joint thermal fatigue failures may occur in electronic products over times ranging from months to many years, so designers must quantitatively account for this potential failure mode. Common practice is to perform accelerated thermal cycle (ATC) experiments using appropriate test vehicles and an "acceleration model" to map the test-failure distribution to the more benign conditions in the field. Results of this analysis are then compared to product requirements so that design and procurement decisions can be made.

One of the most common and useful acceleration models is the Norris-Landzberg (NL) model [1], which is based on a modified Coffin-Manson equation [2] for low cycle fatigue. The most common form of the NL model with constants for eutectic Sn-37Pb solder is:

$$AF = \frac{N_o}{N_t} = \left(\frac{f_o}{f_t} \right)^{\frac{1}{3}} \left(\frac{\Delta T_t}{\Delta T_o} \right)^2 \exp \left[1414 \left(\frac{1}{T_{\max, o}} - \frac{1}{T_{\max, t}} \right) \right] \quad (1)$$

where AF is the acceleration factor, N is thermal fatigue life, ΔT is temperature range, f is the thermal cycling frequency, and $T_{\max}$ is the peak temperature attained during thermal cycling. The subscripts "o" and "t" in the equation refer to operating (field) and test (accelerated) conditions, respectively.

Since the transition to lead-free Sn-Ag-Cu (SAC) solders, the industry has been investigating the applicability of the NL model (among others) to this new class of solders with no consensus on the appropriate constants. In 2005, Hewlett-Packard (HP) published constants for the NL model based on a set of internal data, resulting in Eq.2 [3].

$$AF = \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o} \right)^{2.65} \left(\frac{t_t}{t_o} \right)^{0.136} \exp \left[2185 \left(\frac{1}{T_{\max, o}} - \frac{1}{T_{\max, t}} \right) \right] \quad (2)$$

As described by Pan, et al. [3], this model was expected to perform best for temperatures in the range of 0 to 100 °C.

Since then, others have investigated the accuracy of this model against an ever-increasing body of ATC data on SAC solders [4-6]. These studies revealed large errors in predicted AFs versus experimental data in many cases and that using the NL model with constants for eutectic Sn-Pb (Eq. 1) gave much better (and more conservative) predictions than the HP model.

Finally, Dauksher [7] also studied the application of the NL model to Pb-free solder joints. Eq.3 gives the equation derived in their study:

$$\frac{N_2}{N_1} = \left(\frac{\Delta T_1}{\Delta T_2} \right)^{1.75} \left(\frac{t_1^{hot}}{t_2^{hot}} \right)^{1/4} \exp \left(\frac{1600}{T_2^{MAX}} - \frac{1600}{T_1^{MAX}} \right) \quad (3)$$

where t^{hot} = the sum of ramp+dwel times for the hot portion of each thermal cycle.

Thus, a variety of AF models currently exist for Pb-free SAC solder joints, including NL models using widely different constants. Since these models cannot all be correct, selecting any particular one may result in any of three possible scenarios: (1) over-design for reliability, (2) earlier-than-predicted field failures, or (3) missed technology opportunities. To address this, HP undertook the study described here to better understand the variability in the data and how it affects the NL model for Pb-free solder joints. Our approach comprises: (1) comprehensive review of available published work to create a large data base of test results, (2) application of statistical techniques to analyze this large data base, and (3) grouping of the data into clusters of comparable packaging attributes and test conditions. The ultimate objectives were to establish a firm set of SAC alloy NL constants together with a quantitative

understanding of the uncertainty in applying the model to reliability predictions.

2. Data Collection and Sub-Group Differentiation

The object of this study was to research and analyze “all” available and relevant reliability data (HP internal, open/public domain, and those from consortia to which HP belonged) to further improve HP’s NL model. The scope of the work was constrained to only SAC solder joints and those without any added dopants (e.g., Ni, Bi, Sb, or others). The term “relevant” refers to the data subset that was *useable* (same PCA test-vehicle with multiple ATC testing conditions). To access the so-called *useable* data, over 100 references were reviewed, from which 41 contained useable data. After careful review and removal of all redundant data, 22 references rendered unique sets of useable data [8 to 29]. The data from these different references related to SAC solder joints with Ag concentrations of 3-4%, and Cu concentrations of 0-1%. Data on Sn-Pb controls were also analyzed but discussion of these data is outside the scope of this article.

Let’s look at the general form of the NL equation with the coefficients a, b, and c:

$$AF = \frac{N_o}{N_t} = \left(\frac{\Delta T_t}{\Delta T_o} \right)^a \left(\frac{t_t}{t_o} \right)^b \exp \left[c \left(\frac{1}{T_{\max, o}} - \frac{1}{T_{\max, t}} \right) \right] \quad (4)$$

The error, E, in AF is defined:

$$\text{Error} = E = [(AF_t - AF_c) / AF_t] * 100 \quad (5)$$

where,

AF_t = acceleration factor from “**test**” data

AF_c = acceleration factor “**calculated**” from Eq.4.

Based on a series of analyses in deriving the NL-model coefficients for all the useable data in the 22 references, it was determined that the error E as defined above has a large range over all the input data, which encompassed different PCAs, package styles, and ATC conditions. For the latter, “condition 1” is defined to have temperatures in the range of -25°C to +100°C, while “condition 2” has temperature limits outside this range. The key to the new modeling effort was special framing of all the useable data. This involved proper clustering of the data into different sub-groups, followed by analysis of

the individual sub-group data. The analysis of the sub-group data was an iterative process. First, sub-groups were selected and their respective NL modeling coefficients were determined by numerical fitting. Then, the statistics of the corresponding data distributions and the resulting errors E were calculated. The sub-groups were then adjusted and re-subjected to the same analyses and calculation of E. The goals of this iterative process were: 1. derivation

of the NL-model coefficients, 2. minimization of E, and, 3. maximization of the sub-group size. This process was followed until the final sub-groups were determined that met goals 2 and 3. The steps within this approach, including some example cases, are discussed in detail elsewhere [31]. The first three columns of Table-1 list the nine subgroups resulting from this analysis.

High-Level PCA/Test SubGroup	High-Level PCA/Test SubGroup Description	N (Sample Size for Derivations of the new individual AFs)	Coefficients of the New Individual NL Models for SAC		
			a	b	c
1	FCoB_ATC cond 1&2	58	2.15	0.063	1211
2	PBGA, FlexBGA, QFN_ATC cond 1&2	16	1.26	0.02	3503
3	CSP_ATC cond 1&2	10	2.86	0.077	4532
4	LCCC, CBGA_ATC cond 1	67	1.07	0.18	4286
5	HITCE-CBGA_ATC cond 1	4	2.54	0.088	1972
6	LCCC_ATC cond 2	25	1.92	0.12	5.9
7	TSOP, TQFP_ATC cond 1&2	8	2.14	0.21	273.6
8	C-SOP_ATC cond 2	21	0.66	0.087	2718
9	Chip Res. or Caps_ATC cond 1&2	31	2.19	0.16	980
10	ALL PCAs & ATC Conditions	240	1.84	0.11	2167

Signifies that coefficients suitable for the reflected one of the two ATC conditions

Table-1: NL Coefficients for the derived models

3. Error Analyses and Comparisons for Different Models

The values of Error (Eq.5) from each of the sub-group data in Table-1, were calculated after final determination of constants a, b, and c in the NL-equation (Eq.4). The results were compared against three other models as follows:

- The HP-05 model (Eq.2),
- The recently-published model by Avago (Eq.3), and
- The model for Sn-37Pb (Eq.1), which is also the model recently-published by Intel for lead-free solder joints [6].

The Error values for the four different models were calculated independently, primarily because the terms accounting for the cycling exposure times were different among the models (e.g., the base for exponent "b" in Eq.4 is the ratio of hot-dwell-times while for Eq.1 it is the ratio of cycle-frequencies). Prior to discussion of the errors resulting from the application of the 4 different models to all sub-groups, let's briefly review the significance of the sign of the error.

4. Significance of Sign of Error

When the AF from test data is larger than that calculated from the model, the error is positive. In this case, reliability is under-predicted, which could lead to unnecessary over-design. Obviously, the larger the departure above zero, the more conservative is the reliability prediction and the design supporting it. The under-prediction of reliability may lead to rejection of technology opportunities that could otherwise be viable, leading to potentially higher costs during the product lifecycle. Such predictions are termed "conservative." In contrast, when the calculated AF is larger than that observed from the actual tests, the error is negative and reliability is over-predicted. The more negative the error, the higher the risk of having earlier-than-predicted failures. Such predictions are termed "non-conservative."

5. Individual and Collective Models

In the modeling, two paths were evaluated. **Path-1:** In this approach, different sets of constants (a, b, c) were derived for the respective 9 sub-groups. **Path-2:** In this approach, one set of constants was derived for the "collective" set of data for all sub-groups.

6. Comparative Error Analyses, Path-1

In this section, the comparative error-analyses results for one of the 9 sub-groups is presented (the remainder are covered in the Appendix-A).

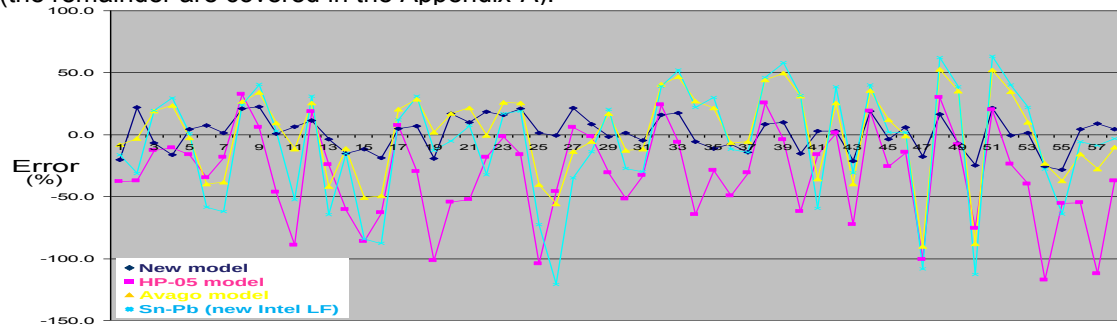


Figure-1: Comparative error-analyses results for Subgroup-1 (FCoB w/o UF for ATC-cond's 1&2)

	Error-New FCoB	Error-HP05 FCoB	Error-Avago FCoB	Error-Intel FCoB
StDev	14	37	34	46
Max	22	33	53	63
Min	-28	-117	-90	-121
Range	51	150	143	184

Table-2: Simple Statistics relative to the data of Figure-1 (values in %)

The curves in Figure-1 reflect the errors obtained for sub-group A, which is that of Flip-Chip on Board (FCoB) assemblies without underfill (UF), subjected to both sets of ATC conditions. The 58 ticks on the x-axis represent the individual data points for this sub-group, and the fluctuations in the y-axis represent the "Error" as defined in Eq.5.

Figure-1 shows that the new model for sub-group-A data has the tightest error range and is well balanced around the zero line. The HP-05 model exhibits one of the worst results among the four models for sub-group-A data, and is heavily biased in the negative (non-conservative) territory. Errors for the Avago & Intel models are slightly lower and higher (respectively) than those of the HP-05 model, yet not nearly as low as the errors in the new sub-group model.

Table-2 provides a simple statistical analysis of the data of Figure-1. The error range for the new sub-model is 51%, vs. 150% for HP-05, 143% for Avago, and 184% for Intel.

Since the individual sub-models were derived to achieve Gaussian error distributions, all the sub-group variance terms (except for the two with low sample sizes) are valid, which allows construction of confidence limits for the variances. Therefore the standard deviations given in Table-2 show the significant advantage of the new model over the other three.

Analogous to Table-2, the error statistics for the other 8 sub-models are presented in Appendix-A (Tables A1 through A8). All the individual results demonstrate a significant improvement in error and related variance offered by the new individual models compared to the other 3 models.

7. Comparative Error Analyses, Path-2

Figure-2 presents the error analyses results of all 9 subgroups together.

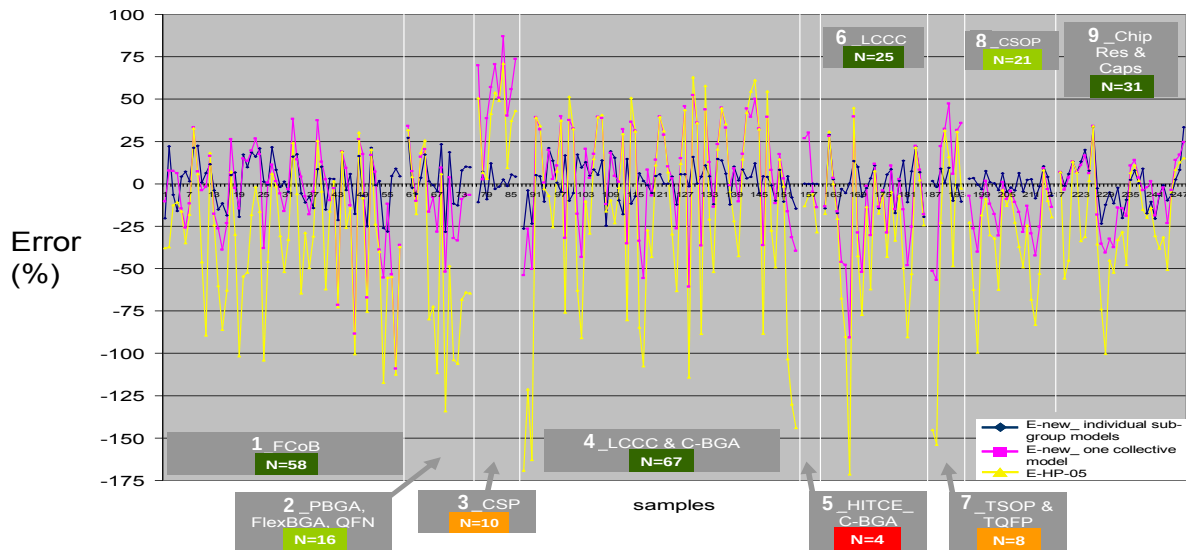


Figure-2: Comparative error-analyses results for Subgroups 1 through 9, over all packages and ATC conditions 1 & 2

Note the 9 different zones, separated by the vertical white lines. Within these zones, the white annotations in the darker grey boxes signify the sub-groups in those zones, followed by the corresponding color-highlighted sub-group sample-sizes (number of NL equations input to the modeling).

Three different errors are compared in Figure-2:

- the dark blue represents the new “*individual*” sub-group models from Path-1,
- the magenta represents the new single “*collective*” model from Path-2 and,
- the yellow is for the HP-05 model

High-Lev PCA/Test SubGroup	High-Lev PCA/Test SubGroup Description ATC cond-1: -25 to 100C ATC cond-2: -25>T >= -65 AND T>100* (* in tests leading to HP-05 paper, actual nominal-T's of 100 were slightly >100C; for these, ATC-cond was still chosen as 1)	Use Category	Worst <u>Use</u> Environ						Accelerated <u>Testing</u> Environ						AF				
			T_{min}	T_{max}	ΔT	t_D	t_{Rmp}	Cycles/Day	T_{min}	T_{max}	ΔT	t_D	t_{Rmp}	Cycles/Day	Proposed New NL Model for SAC	HP-2005 NL Model for SAC	Avago New NL Model for SAC	Classic NL Model for SnPb	Model On ALL Data
			°C	°C	°C	Hrs	Min		°C	°C	°C	Min	Min						
2	PBGA, FlexBGA, QFN_ATC cond 1&2	Consumer	0	60	60	12	fast	1	0	100	100	15	10	29	5.4	4.6	1.8	1.4	3.4
2	PBGA, FlexBGA, QFN_ATC cond 1&2	Computers	15	60	45	2	fast	4	0	100	100	15	10	29	8.1	12.6	4.6	4.1	6.9
2	PBGA, FlexBGA, QFN_ATC cond 1&2	Telecom	-40	85	125	12	fast	1	-40	125	165	15	10	29	3.5	2.3	1.1	0.9	2.0

Table-3: An example of NL-modeling results for Sub-group 2

The parameters under the “Worst Use-Environments” and the “Accelerated Testing Environments” are simple adoptions from [30], chapter-17. Under the AF sets of columns in

As noted earlier, the new *collective* model is expectedly not as good as the individual models, yet it is still significantly better than the HP-05 model.

8. Example of Modeling Results for Sub-groups B&C

Table-3 illustrates the application of the new *individual* model (alongside 4 other models) for sub-group 2, which is the PBGA, FlexBGA, QFN under ATC-conditions 1&2, to determine AFs for the different use categories of consumer, computers, and telecom.

Table-3, the acceleration factors for the five different models are given. These AFs do not include a safety factor. For example, consider the mid-row which highlights the computer

category. The new *individual* model gives an AF of 8.1 while that of the *collective* model is 6.9, and the HP-05 model gives 12.6. Thus, both the individual and collective models developed in this study provide significantly more conservative and more accurate results than the HP-05 model. Further, the accuracy of the new models is superior to that of the Avago and Intel models.

9. NL-Coefficients for the “individual” models vs. the “collective” model

The last three columns of Table-1 summarize all 9 *individual* sub-group model coefficients, as well as those of the single *collective* model. As noted earlier, the coefficients vary considerably among the sub-groups.

Use of the above modeling coefficients are currently performed with the understanding that the applications should comply with the PCA and ATC-condition attributes from the reference data feeding into the model derivations.

10. Conclusions

A new set of Norris-Landzberg coefficients has been derived for lead-free solder joints based on published and consortia data. The coefficients are demonstrated to have strong dependencies on package type, as well as ATC test conditions. Criteria imposed in the derivations included:

- all available data included (except for few demonstrated outlier cases),
- minimization of the Errors (between AF from tests, and AF from derived models)
- maximization of the sub-group sample sizes

In the derivations of all 9 sets of sub-group model coefficients, the achieved Error ranges were within about +/-25%. The error ranges were demonstrated to be significantly tighter than those of 4 other models considered.

The new models offer opportunities for application of more accurate acceleration factors compared to HP’s 2005 model, or the Avago or Intel models, depending on the PCA and ATC conditions. The large non-conservative predictions in HP’s previous model (based on limited data of the time) are eliminated.

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Appendix-A: Comparative Analyses of the Errors, Path-1 (Sub-Groups 2 – 9)

Subgroup-2_PBGA, FlexBGA, & QFNs, for ATC-cond's 1&2:

	Error_New PBGA, FlexBGA, QFN	Error_HP05 PBGA, FlexBGA, QFN	Error_Avgs PBGA, FlexBGA, QFN	Error_Intel PBGA, FlexBGA, QFN
StDev	15	54	14	18
Max	27	32	38	36
Min	-28	-134	-6	-23
Range	55	166	44	60

Table-A1: Simple Statistics relative to the data of Subgroup-2 (values in %)

Subgroup-6_LCCC, for ATC-cond.-2 only:

	Error_New LCCC	Error_HP05 LCCC	Error_Avgs LCCC	Error_Intel LCCC
StDev	12	46	21	26
Max	29	45	28	32
Min	-20	-171	-53	-67
Range	48	216	82	99

Table-A5: Simple Statistics relative to the data of Subgroup-6 (values in %)

Subgroup-3_HP's CSPs only, for ATC-cond's 1&2:

	Error_New CSP	Error_HP05 CSP	Error_Avgs CSP	Error_Intel CSP
StDev	7	23	27	31
Max	12	71	90	88
Min	-11	3	-4	-14
Range	23	68	94	102

Table-A2: Simple Statistics relative to the data of Subgroup-3(values in %)

Subgroup-7_TSOP, TQFP, for ATC-cond.'s 1&2:

	Error_New TSOP, TQFP	Error_HP05 TSOP, TQFP	Error_Avgs TSOP, TQFP	Error_Intel TSOP, TQFP
StDev	7	75	21	17
Max	9	32	30	10
Min	-10	-154	-28	-41
Range	20	185	58	51

Table-A6: Simple Statistics relative to the data of Subgroup-7 (values in %)

Subgroup-4_LCCC & C-BGA, for ATC-cond.-1 only:

	Error_New LCCC & CBGA	Error_HP05 LCCC & CBGA	Error_Avgs LCCC & CBGA	Error_Intel LCCC & CBGA
StDev	11	60	32	40
Max	21	63	54	56
Min	-26	-169	-71	-93
Range	47	232	124	148

Table-A3: Simple Statistics relative to the data of Subgroup-4 (values in %)

Subgroup-8_CSOP, for ATC-cond.-2 only:

	Error_New C-SOP	Error_HP05 C-SOP	Error_Avgs C-SOP	Error_Intel C-SOP
StDev	5	28	18	28
Max	10	8	20	27
Min	-9	-99	-41	-63
Range	19	107	62	90

Table-A7: Simple Statistics relative to the data of Subgroup-8 (values in %)

Subgroup-5_HP's HITCE-CBGA, for ATC-cond.-1 only:

	Error_New HITCE-CBGA	Error_HP05 HITCE-CBGA	Error_Avgs HITCE-CBGA	Error_Intel HITCE-CBGA
StDev	0.0568	10	34	50
Max	0.0986	-6	39	34
Min	0.0001	-28	-36	-74
Range	0.0985	22	76	109

Table-A4: Simple Statistics relative to the data of Subgroup-5 (values in %)

Subgroup-9_Chip Res., Caps, for ATC-cond.'s 1&2:

	Error_New Chip Res., Caps	Error_HP05 Chip Res., Caps	Error_Avgs Chip Res., Caps	Error_Intel Chip Res., Caps
StDev	14	30	17	22
Max	34	34	48	49
Min	-23	-100	-20	-41
Range	57	134	67	90

Table-A8: Simple Statistics relative to the data of Subgroup-9 (values in %)