Thermal Cycle Reliability Study of Vapor Phase BGA Solder Joints

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Abstract
Prior to committing production boards to vapor phase soldering, we performed an evaluation to assess reliability and evaluate the vacuum soldering option. The reliability of vapor phase processed BGA solder joints, with and without vacuum applied, was evaluated by means of a test vehicle circuit board assembly. The test vehicle was designed with daisy chain nets through multiple solder joints. These were designed with all of the solder balls in a chain having a similar distance from neutral point, so this factor could be part of the reliability assessment. The boards were temperature cycled for 8250 cycles of -5 to 95°C, by which time all of the outermost daisy chains had failed. The number of cycles-to-failure was analyzed using Weibull plots and characteristic life was calculated.

Introduction
While convection reflow is the standard method for the surface mount process, there is thermal variation across a large board and there are smaller temperature margins within the tighter process window for Pb-free soldering. It can be difficult to achieve minimum temperatures in highly dense areas without over-heating less dense areas on the same PCA. Vapor phase reflow provides an advantage in limiting the maximum temperature on the PCA to the vapor temperature of the heating fluid. Vacuum applied in the vapor phase process allows for reduction in the amount of voiding found. The reliability of vapor phase with and without vacuum is not well known and the objective of this study was to evaluate this.

The Test Vehicle
The test vehicle board was designed to hold a single BGA, as seen in Figure 1, for the purpose of evaluating a number of material or process options.

Figure 1 - Test Vehicle Board

The PCB and BGA were designed to have eight daisy chain continuity circuits for resistance measurment testing. A diagram of the continuity circuit layout is shown in Figure 2.

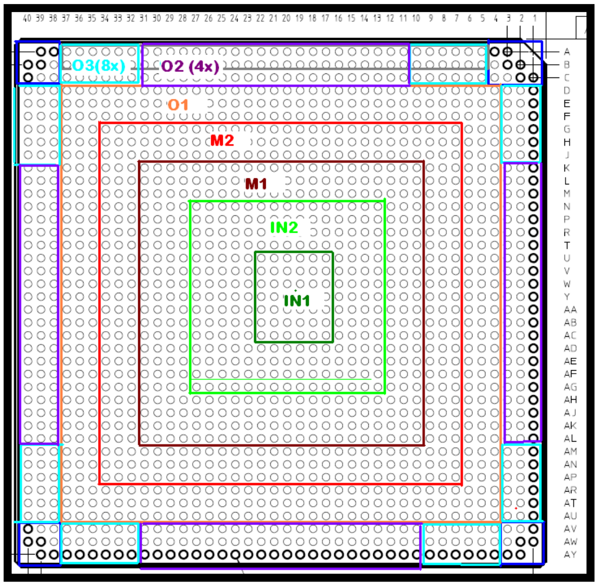


Figure 2 - Continuity Circuit Locations

All solder balls within the named areas are included in the daisy chain circuit. O4, O3, and O2 include the outermost 3 rows and columns. O4 is comprised of 3 of the 4 corner areas. The 4th corner area was not used in this study because it is part of an independent, high frequency circuit. M2 and M1 include the next 6 rows and columns heading inwards. IN2 and IN1 are two daisy chains covering the inner 16 rows and columns in the center of the BGA package.

The BGA in this experiment is a 40x40 mm full array configuration. It is 1.5 mm thick and constructed of multilayer ceramic with a high CTE of 12.3 ppm/^{o}C. The PCB is 8 layers, 62 mils thick, and made of high Tg laminate with a CTE of 13 to 14 ppm/^{o}C.

Table 1 – Test Vehicle Definition

BGA die size (mm)	10.6 x 10.6 x 0.635
BGA substrate (mm)	41 x 41 x 1.5
BGA solder pad dia. (mm)	0.600 (NSMD)
BGA solder pad metallization	ENIG (0.1 - 0.5um Au over 3.0 – 7.0um Ni)
BGA solder ball pitch (mm)	1.0
BGA solder ball array	40 x 40, 1594 connections
SAC305 s/b dia. (mm)	0.650
PCB material	8 layer ISOLA PCL-370HR 1 oz copper
PCB size (mm)	127 x 140 x 1.57
PCB surface finish	Immersion Ag
PCB solder pad dia. (mm)	0.609 (NSMD)

Nine test vehicle boards were assembled: four in a vapor phase oven with the vacuum option turned off, four in a vapor phase oven with the vacuum turned on, and one in a standard convection reflow oven as a control sample. The vacuum option is available for the purpose of reducing voids in solder joints. The vacuum is pulled during reflow causing gas trapped within the molten solder to expand and break through the surface of the solder. Then air pressure is returned to the chamber and residual voids shrink to a smaller size.

Figure 3 shows overlapping solder profiles for vacuum (dashed line) and no-vacuum settings. The profile with vacuum has a slightly longer time above liquidus, 72 seconds vs. 65, as the board is held in the vacuum chamber under IR heaters to keep it molten.

Figure 3 - Solder profiles overlapped: no-vacuum (solid) and with vacuum (dashed)

This reliability evaluation was performed as our initial investigation of vapor phase soldering, and the vacuum process parameters were not optimized. X-ray inspection showed numerous small voids in the solder balls of all boards, with the vapor phase soldered BGAs having noticeably more voids than the convection soldered board. Boards soldered with the vacuum process had some solder bridging between adjacent solder balls. One sample board had enough short circuits due to bridging that it was not included in the subsequent thermal cycling.

Thermal Cycling

Electrical resistance measurements of the daisy chain circuits in each sample part were recorded prior to thermal cycling, and at 250 cycle intervals. Temperature cycling was performed for 8250 cycles, from -5°C to +95°C for the majority of cycles. A dual chamber machine was used with each chamber set permanently to one of the temperature limits. The rack of boards was moved quickly between chambers every 15 minutes.

Daisy chain circuit failure at each interval was defined as an increase in measured resistance of more than 10%. Table 2 shows the measurement cycle in which each daisy chain became a failure. Solder joints that were farthest from the center of the substrate (longest DNP - Distance from the Neutral Point), were observed to be the earliest failures. The eight daisy chain circuits per sample part are listed in the table in order of longest to shortest DNP: O4 (corners), O3, O2, O1, M2, M1, IN2, and IN1.

Table 2 - Number of Thermal Cycles to Failure (>10% Resistance Change)

DC net	O4	O3	O2	O1	M2	M1	IN2	IN1
No-Vac 1	4250	5000	5750	7250	7750	7750	-	7750
No-Vac 2	5000	5000	6250	8250	-	-	-	-
No-Vac 3	4500	5750	7250	-	-	-	-	8250
No-Vac 4	4500	5000	6750	7500	-	8250	8250	8250
Vac 1	3750	5000	6000	7250	-	-	7750	8250
Vac 2	4500	5000	6250	7750	8250	8250	-	8250
Vac 3	4250	5000	6250	7750	8250	-	8250	-
Convection	4500	5750	6750	8250	8250	-	8250	8250

'-'indicates daisy chain net did not fail

Figure 4 has a Weibull plot of vacuum versus no-vacuum on the four outermost daisy chain nets. The four innermost (shortest DNP) daisy chain nets had few failures, and are not shown.

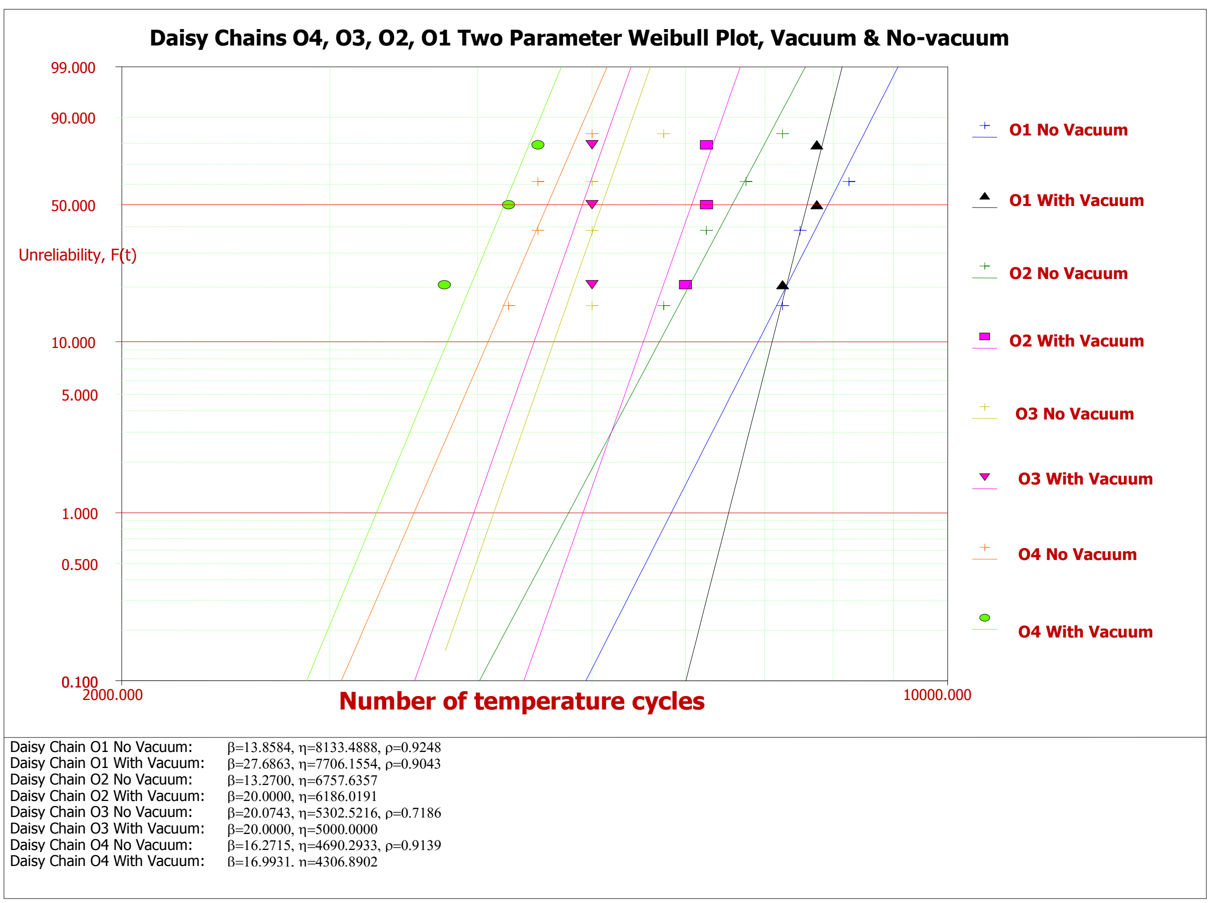
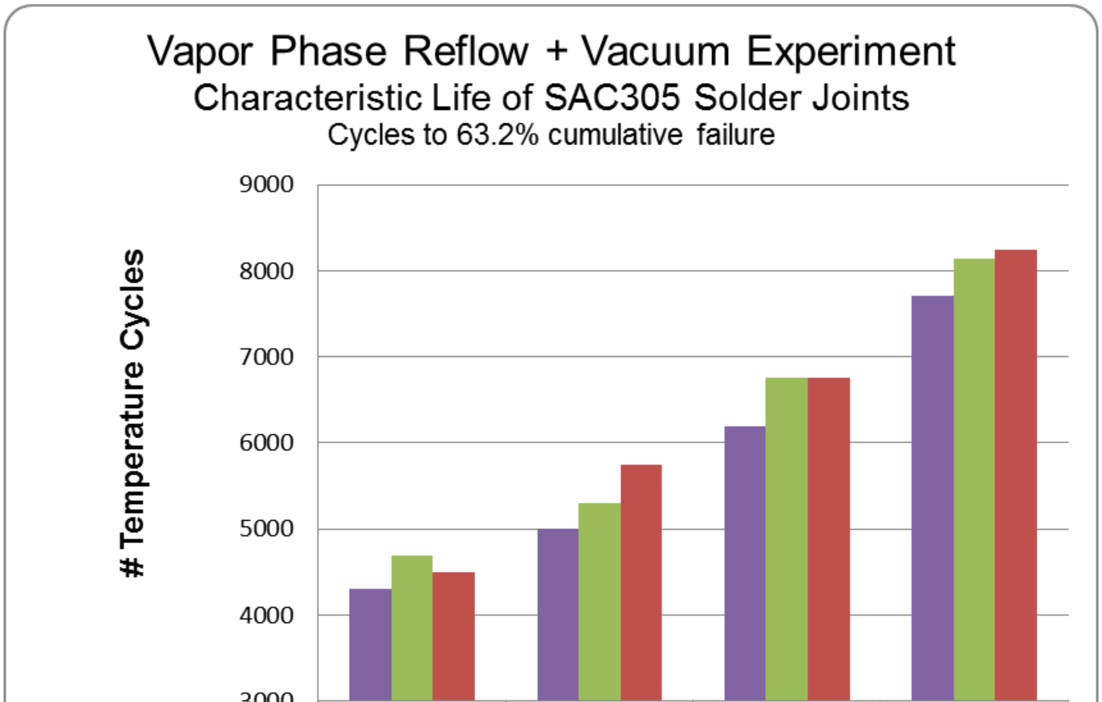


Figure 4 - Weibull Plot –Four Outermost Daisy Chain Nets; Vacuum versus No-Vacuum

From the Weibull plot, Eta (η) values [characteristic life - number of cycles to failure with 63.2% probability of failure] for each daisy chain net are used in Figure 5 to directly compare vacuum and no-vacuum sample types.



	O4	O3	O2	O1
VACUUM (n=3)	4307	5000	6186	7706
NO VACUUM (n=4)	4690	5303	6758	8133
Std. Reflow (n=1)	4500	5750	6750	8250

Figure 5 - Summary of Experimental Results

Characteristic life data from this experiment demonstrates that SAC305 solder joints made with vapor phase reflow and vacuum processing have slightly less temperature cycling reliability. The one sample of standard convection reflow is also included as a single data point (not characteristic life), and appears to have the highest reliability in this particular dataset.

Several factors are important to consider when using this dataset, and any of the Weibull probability analyses in the report. The dataset may limit the ability to draw significant conclusions, or make statistical comparisons between different processes. Factors that limit statistical analysis include:

1. Right censored (suspended) sample data: daisy chain nets on some samples did not fail at 8250 cycles
2. Interval censored sample failure data: groups of sample daisy chain net failures at 250 temperature cycle intervals, not individual sample daisy chain net failures at a specific number of temperature cycles
3. Small sample size: some regression correlations were not possible.

As a result of these factors, there is a wide range of Beta (β - slope) values and low regression coefficients (ρ).

Reliability Comparison

To further understand the experimental results, another reliability analysis was performed. Characteristic life was analyzed for daisy chain circuits in all eight test vehicle samples, regardless of sample type (vacuum, no-vacuum, or convection reflow). The new Weibull probability analysis combines daisy chain net O4, then O3, then O2,…, ending with IN2, to be representative of the reliability of SAC305 solder joints with the same DNP for all samples.

A Weibull plot for seven of the eight combined daisy chain nets is shown in Figure 6. The innermost daisy chain net, IN1, did not have enough failures to generate non-deterministic Weibull statistics.

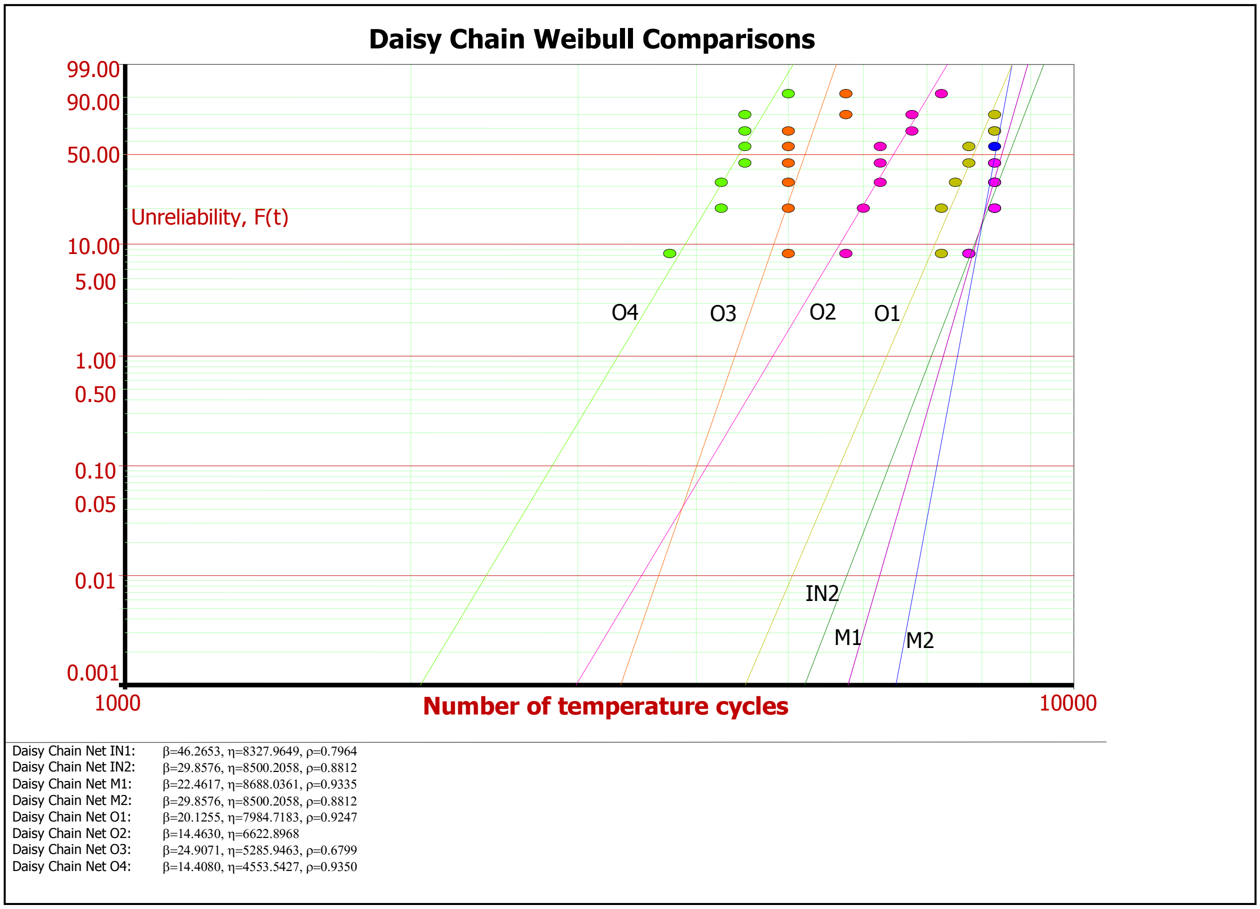


Figure 6 - Weibull Plot of Combined Samples (vac + no-vac + convection) Individual Daisy Chain Nets

Distance From Neutral Point

As expected, the characteristic life of the daisy chain nets decreases as their distance from the center of the BGA increases. The outer daisy chain nets failed in order. However, on some boards, certain inner and middle daisy chains failed by the end of test even though other inner and middle chains still had not. The longest distance of all of the solder balls in the daisy chain circuit from the neutral point is plotted in Figure 7. Plotted on the same graph is the calculated characteristic life.

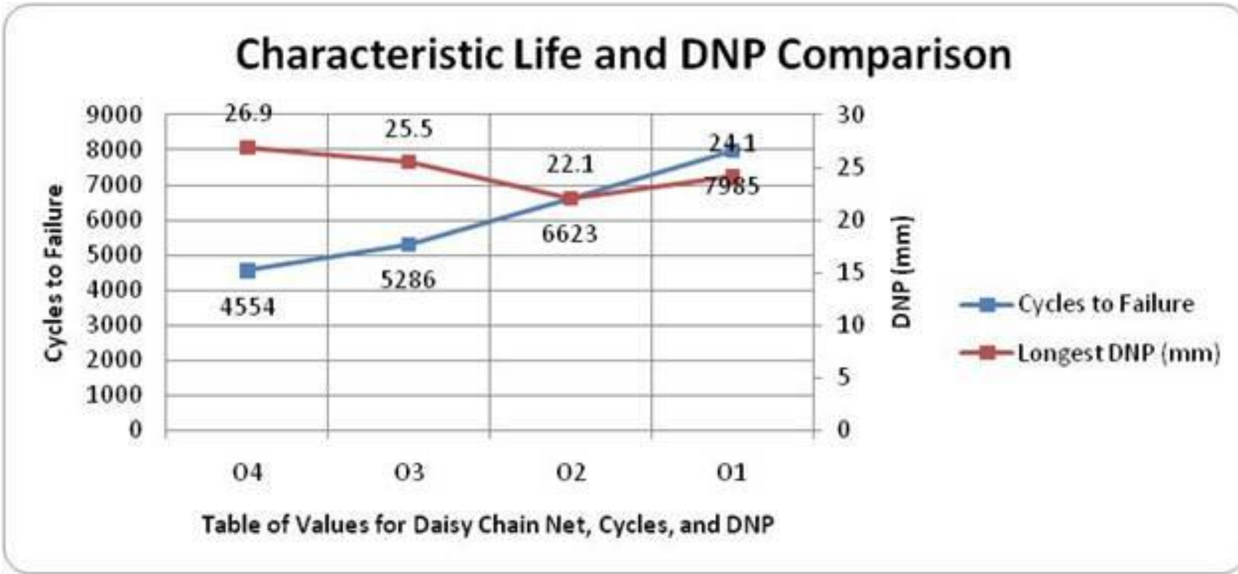


Figure 7 - Comparison of Characteristic Life and DNP for Test Vehicles

The graph shows that the longest DNP for circuit O1 is actually longer than that for O2: 24.1 mm vs. 22.1 mm. However, the O2 net failed first. This is because the O2 daisy chain includes solder balls along the outer rows of the BGA which makes them more vulnerable to the stress once the corner balls in the O4 circuits have failed.

Cross Section

One part was cross sectioned to observe the nature of the interconnect failure. An example failed solder ball is shown in an SEM image in Figure 8. The break is through the bulk solder and at the intermetallic interface to the BGA substrate. This is the typical fracture seen on other solder balls. Some fracturing was also observed in the bulk solder down near the PCB interface, but none of these were found to have propagated too far.

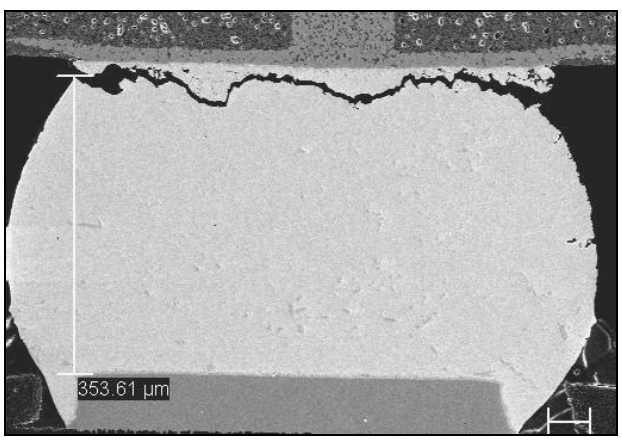


Figure 8 - Cross Section of Solder Joint Fracture

Conclusions

Referring to Figure 4, the sample sizes were not large enough to show that the characteristic life is statistically different between the different reflow methods. The reason is that the 90% confidence bounds surrounding Weibull plot lines for the vacuum process and no-vacuum process results overlap, and therefore don't show statistically significant differences. What can be stated is that the differences are consistent for each reflow method across four outermost daisy chain nets as shown in Figure 5, and have the appearance of indicating realistic values expected for larger sample sizes. The reason for the vacuum soldered board showing shorter apparent characteristic life than the other samples isn't fully understood yet, but it is not suspected to be caused by the slightly longer time-above-liquidus in the profile. This difference appears negligible and the values are well within recommended limits. Further destructive analyses of the solder joints may shed some light on this.

There is an instance of a statistically significant difference in two populations within this dataset. Vapor phase no-vacuum daisy chain net O3 has a characteristic life of 5303 cycles and a DNP of 25.5mm. For the same boards, net O4 has a characteristic life of 4690 cycles and a DNP of 26.9mm. At a 90% confidence level O3 sample data represents a population with characteristic life that is not part of the population represented by O4 sample data. The longer characteristic life of O3 is therefore attributed to a shorter DNP.

Acknowledgements
In appreciation for all their efforts to generate the data for this reliability report: Albert Yeh and Brian Dahl of Agilent Technologies, Inc.
In appreciation for the solder processing of the circuit boards: Venture Manufacturing Services, Inc.

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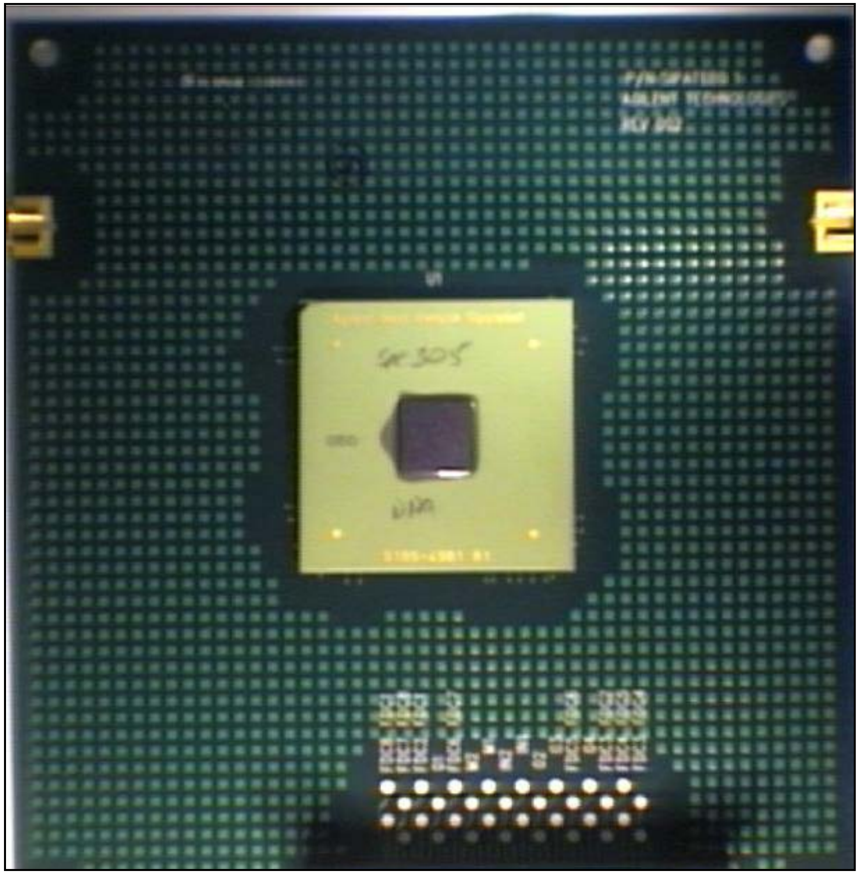
The Reliability Evaluation

- Custom, single BGA, daisy chain test vehicle board
- Four soldered in vapor phase without vacuum
- Four soldered in vapor phase with vacuum
- One control sample soldered in convection oven
- Thermal Cycling
  - -5ºC to +95ºC, every 15 minutes
  - dual chamber, with immediate transport between temperatures
  - 8250 cycles with readpoints at 250 cycle intervals
- Weibull analysis for characteristic life

Why Vapor Phase?

- Pb-free thermal process window is tight for large, dense PCAs and sensitive components
- In convection, minimum acceptable solder temperature at cold spots can result in very hot spots elsewhere
- In vapor phase, peak temperature <u>everywhere</u> is limited by the boiling point of the heating fluid
- A vacuum option is available for reducing voids

The Test Vehicle Design

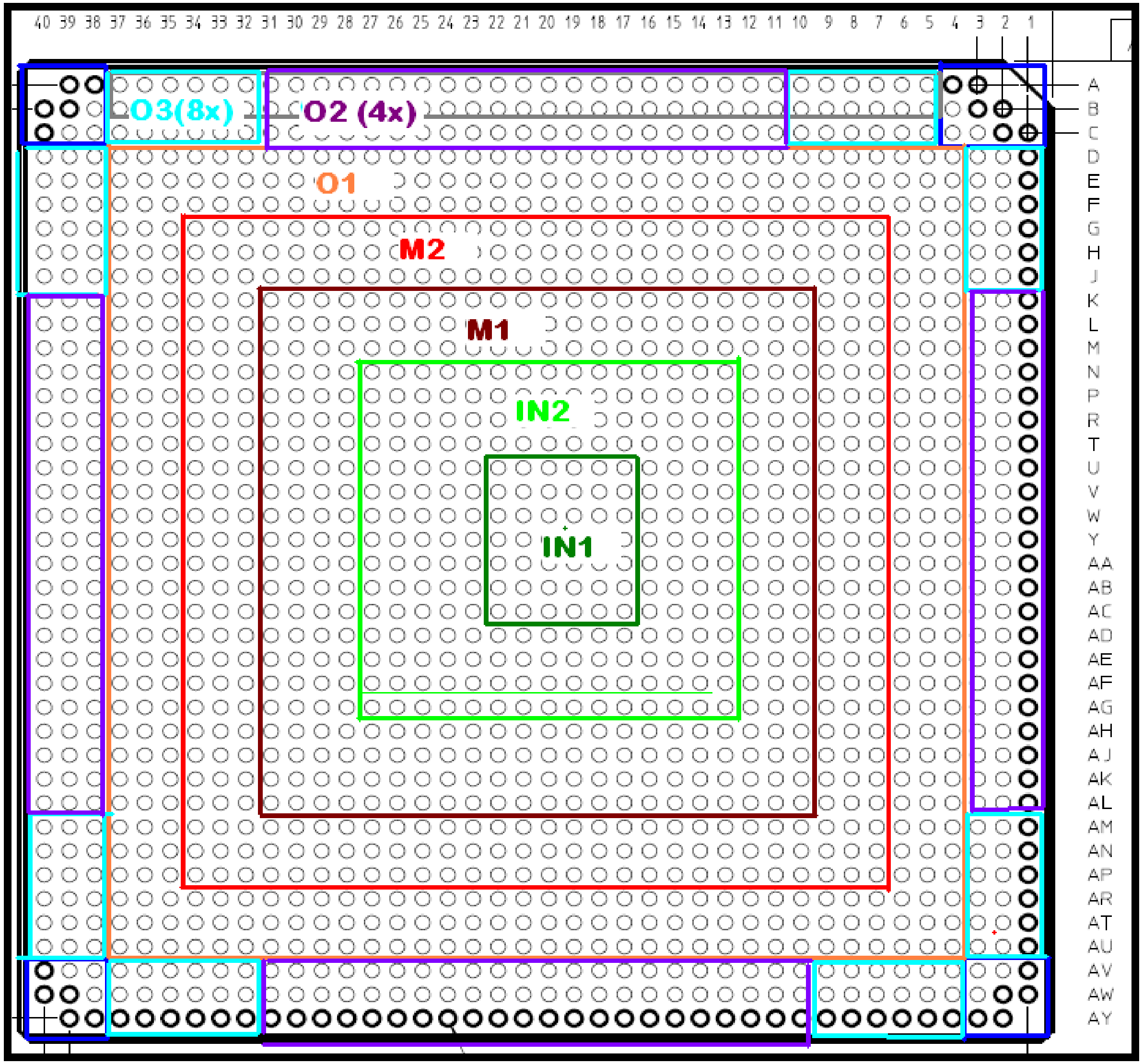


12.2 ppm/ºC CTE Ceramic BGA soldered to 13 ppm/ºC CTE PCB

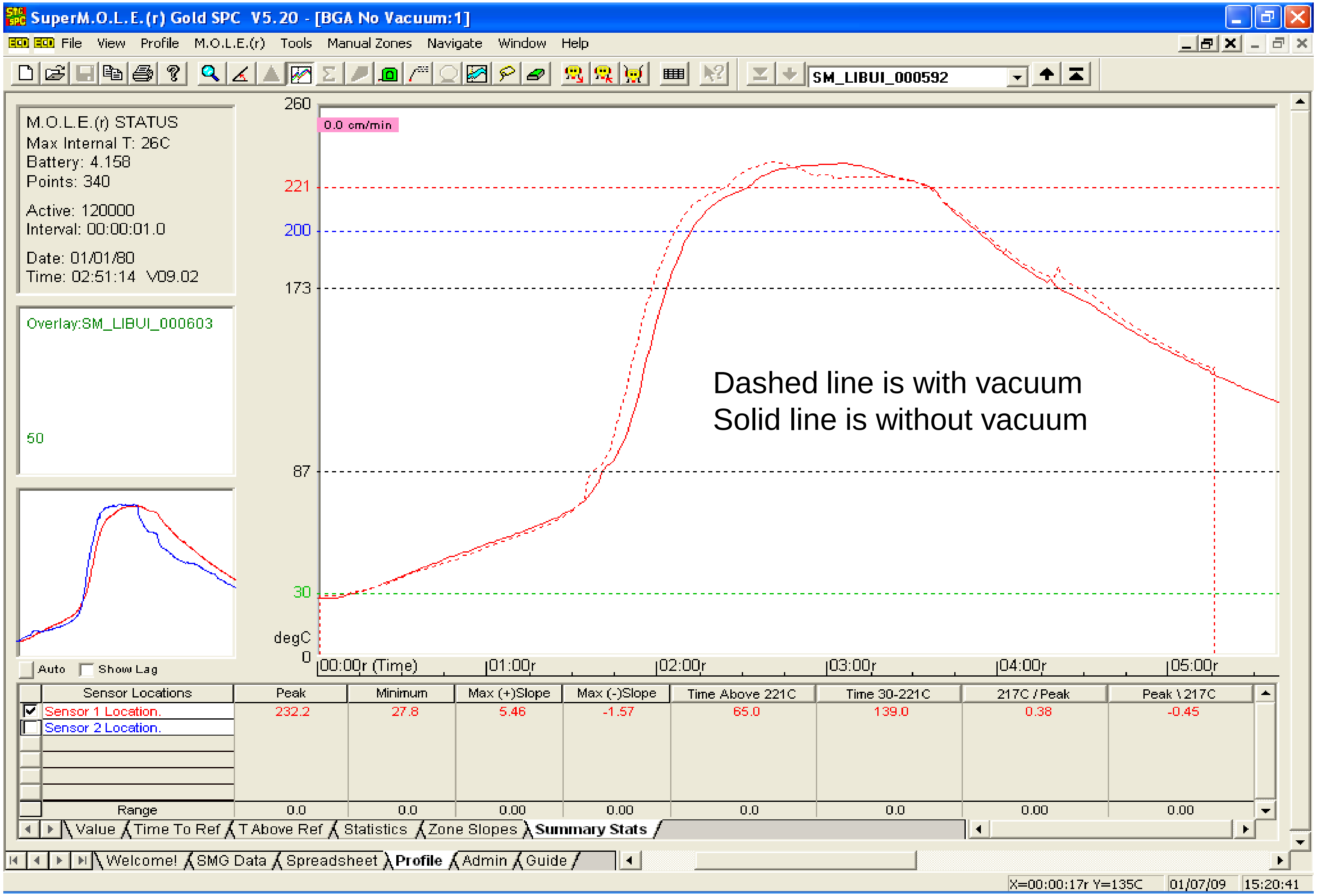
Test Vehicle Definition

BGA die size (mm)	10.6 x 10.6 x 0.635
BGA substrate (mm)	41 x 41 x 1.5
BGA solder pad dia. (mm)	0.600 (NSMD)
BGA solder pad metallization	ENIG (0.1 - 0.5um Au over 3.0 – 7.0um Ni)
BGA solder ball pitch (mm)	1.0
BGA solder ball array	40 x 40, 1594 connections
SAC305 s/b dia. (mm)	0.650
PCB material	8 layer ISOLA PCL-370HR 1 oz copper
PCB size (mm)	127 x 140 x 1.57
PCB surface finish	Immersion Ag
PCB solder pad dia. (mm)	0.609 (NSMD)

8 Daisy Chain Circuit Nets in Ceramic BGA



Vapor Phase Reflow Profiles



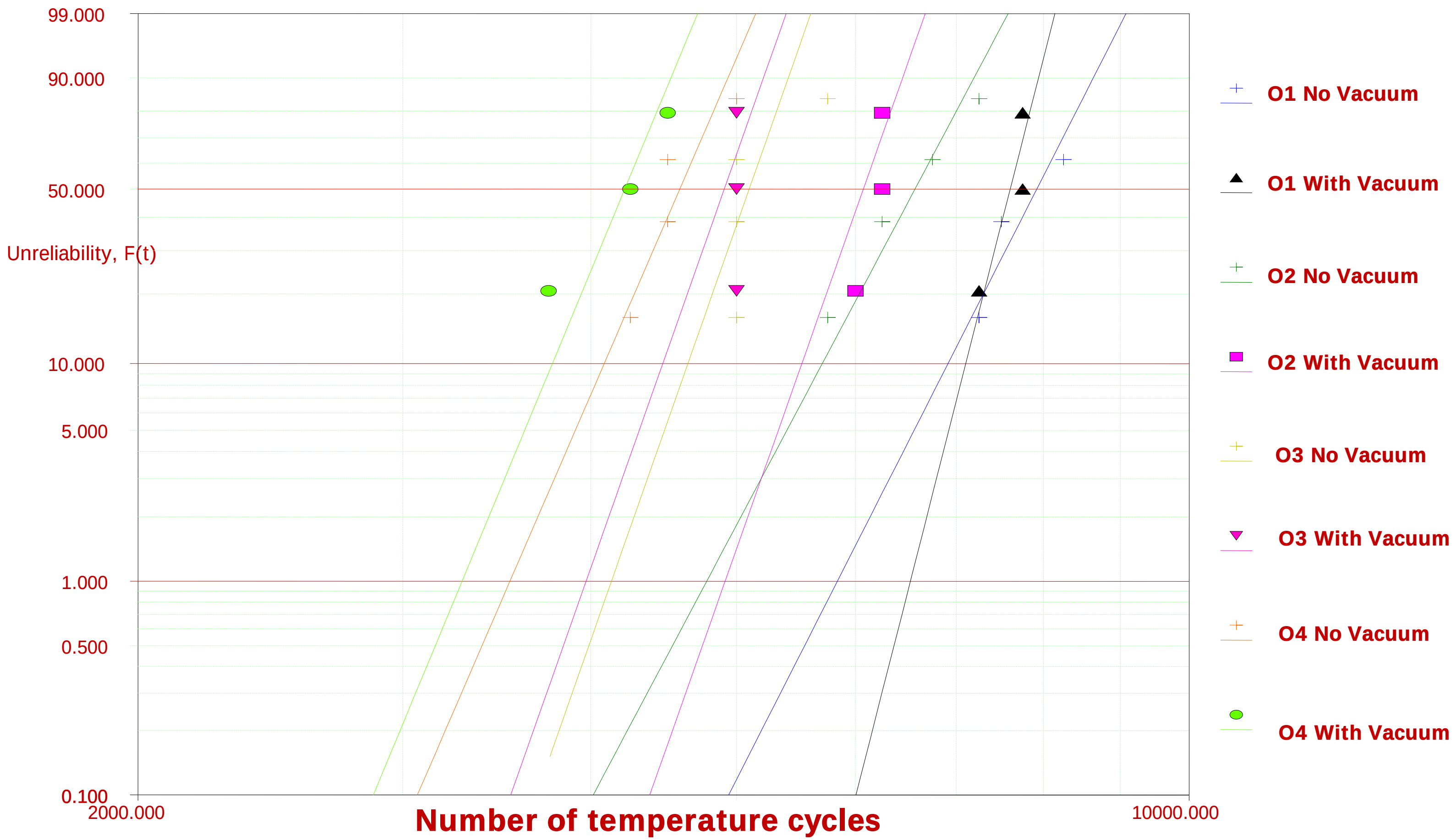
Number of thermal Cycles to Failure

Defined as > 10% Resistance Change

DC net	O4	O3	O2	O1	M2	M1	IN2	IN1
No-Vac 1	4250	5000	5750	7250	7750	7750	-	7750
No-Vac 2	5000	5000	6250	8250	-	-	-	-
No-Vac 3	4500	5750	7250	-	-	-	-	8250
No-Vac 4	4500	5000	6750	7500	-	8250	8250	8250
Vac 1	3750	5000	6000	7250	-	-	7750	8250
Vac 2	4500	5000	6250	7750	8250	8250	-	8250
Vac 3	4250	5000	6250	7750	8250	-	8250	-
Convection	4500	5750	6750	8250	8250	-	8250	8250

'-'indicates daisy chain net did not fail

Daisy Chains O4, O3, O2, O1 Two Parameter Weibull Plot, Vacuum & No-vacuum



Daisy Chain O1 No Vacuum:	β=13.8584, η=8133.4888, ρ=0.9248
Daisy Chain O1 With Vacuum:	β=27.6863, η=7706.1554, ρ=0.9043
Daisy Chain O2 No Vacuum:	β=13.2700, η=6757.6357
Daisy Chain O2 With Vacuum:	β=20.0000, η=6186.0191
Daisy Chain O3 No Vacuum:	β=20.0743, η=5302.5216, ρ=0.7186
Daisy Chain O3 With Vacuum:	β=20.0000, η=5000.0000
Daisy Chain O4 No Vacuum:	β=16.2715, η=4690.2933, ρ=0.9139
Daisy Chain O4 With Vacuum:	β=16.9931, η=4306.8902

Dataset Factors to Consider

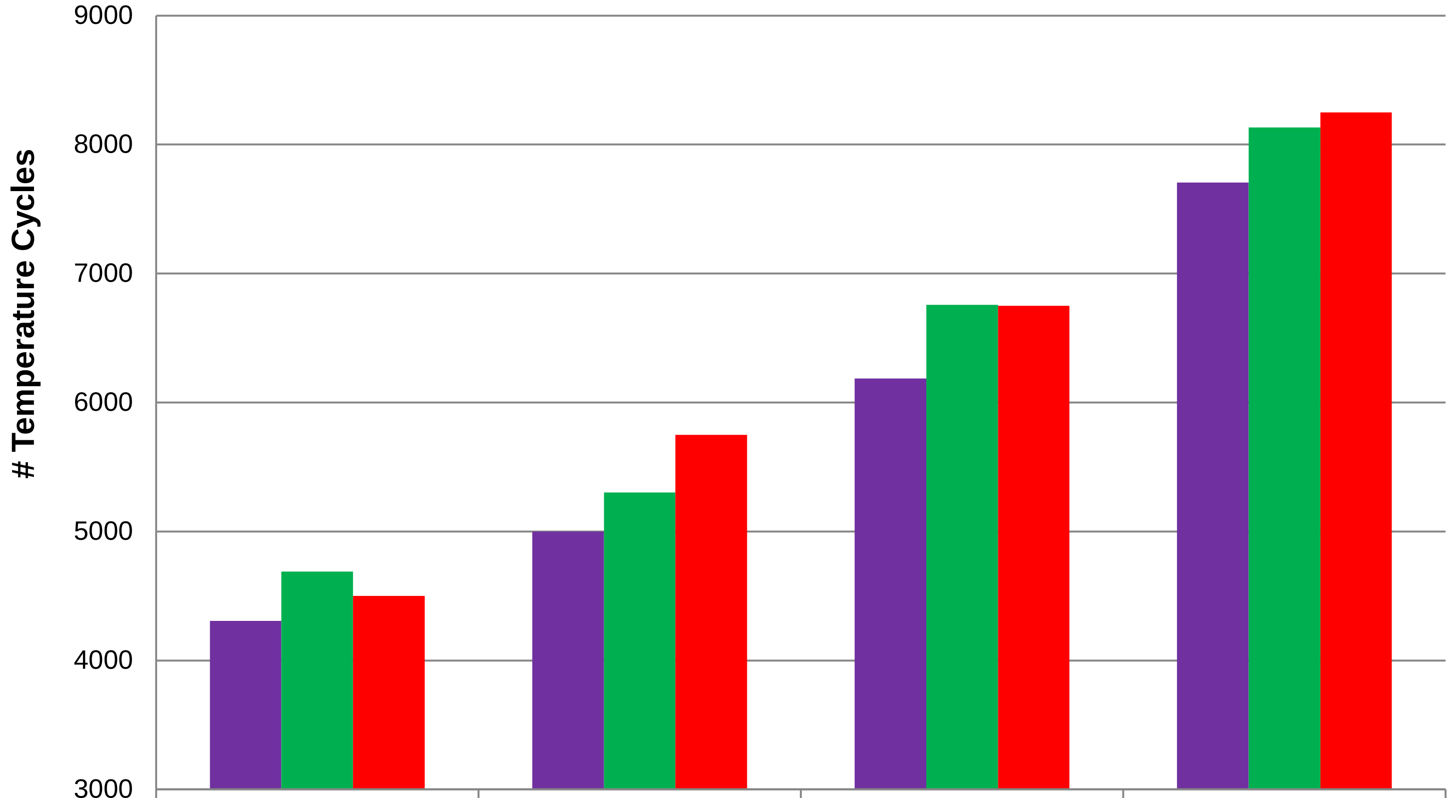
1. Right censored (suspended) sample data: daisy chain nets on some samples did not fail at 8250 cycles
2. Interval censored sample failure data: groups of sample daisy chain net failures at 250 temperature cycle intervals, not individual sample daisy chain net failures at a specific number of temperature cycles
3. Small sample size: some regression correlations were not possible.

As a result of these factors, there is a wide range of Beta (β - slope) values and low regression coefficients (ρ).

Vapor Phase Reflow + Vacuum Experiment

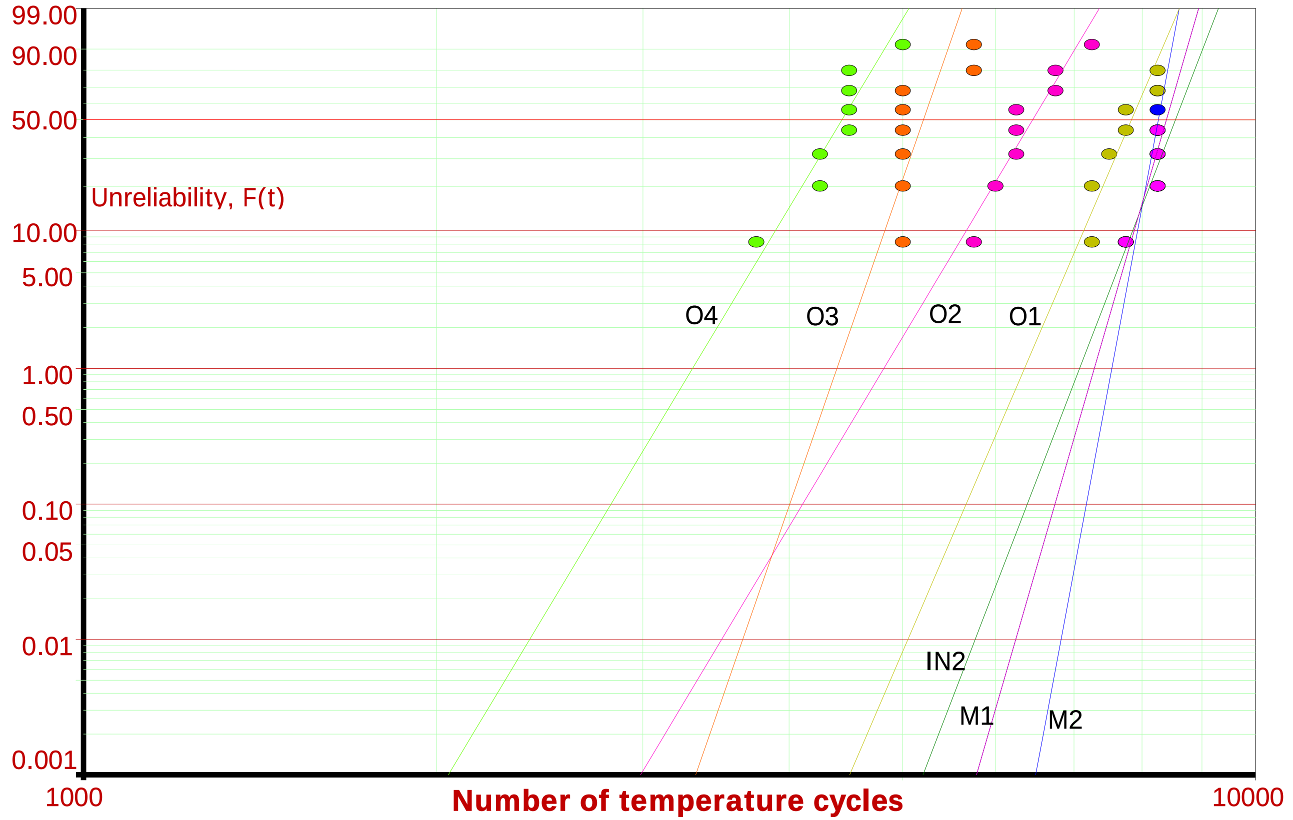
Characteristic Life of SAC305 Solder Joints

Cycles to 63.2% cumulative failure

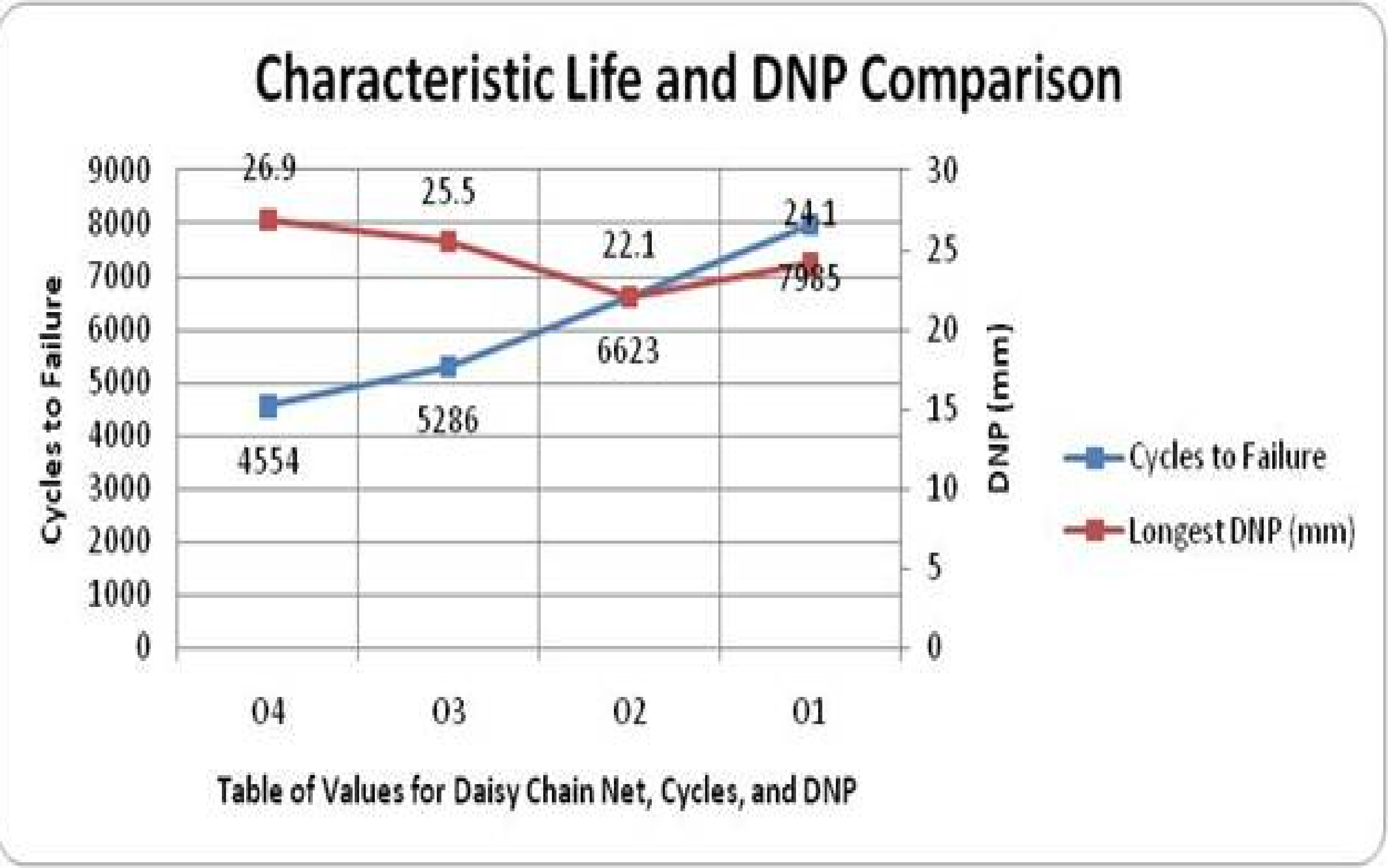


	O4	O3	O2	O1
VACUUM (n=3)	4307	5000	6186	7706
NO VACUUM (n=4)	4690	5303	6758	8133
Std. Reflow (n=1)	4500	5750	6750	8250

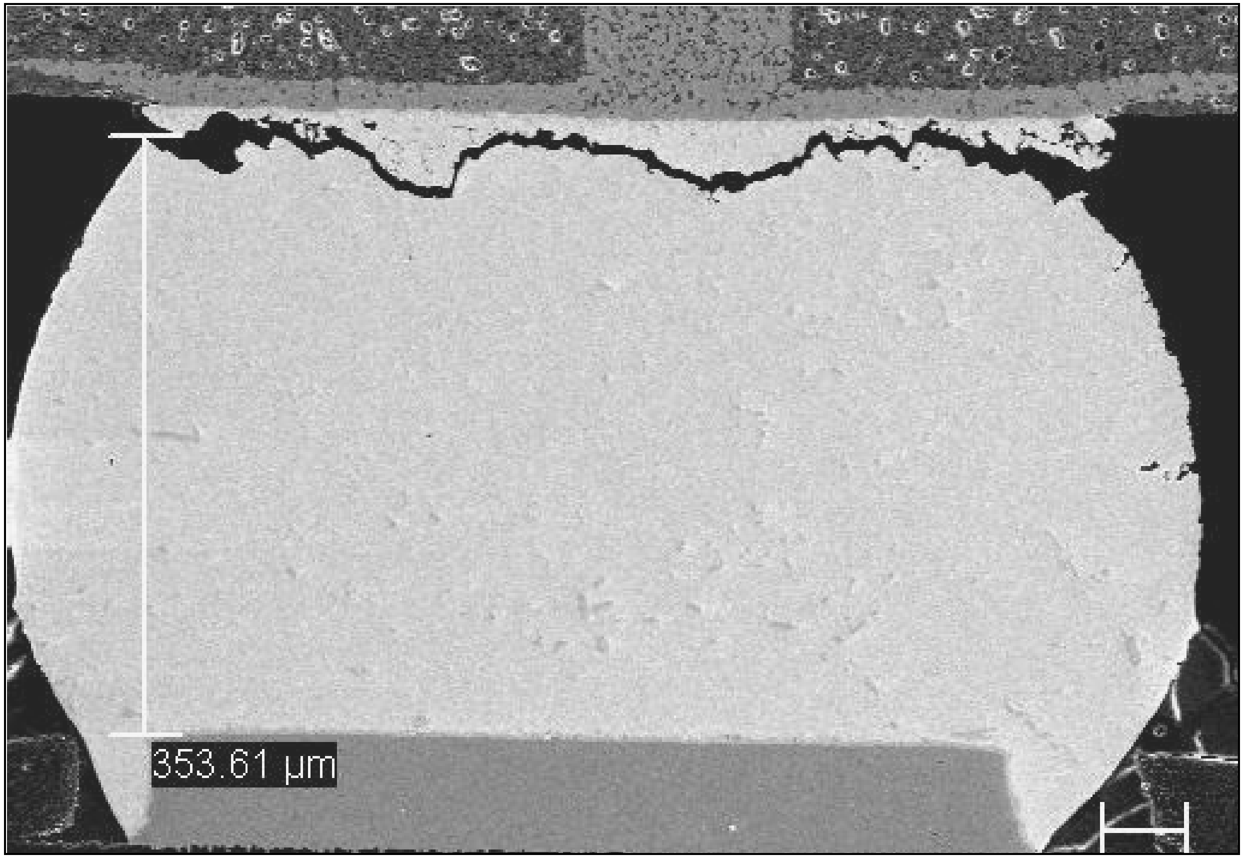
Daisy Chain Weibull Comparisons



Daisy Chain Net IN1:	β=46.2653, η=8327.9649, ρ=0.7964
Daisy Chain Net IN2:	β=29.8576, η=8500.2058, ρ=0.8812
Daisy Chain Net M1:	β=22.4617, η=8688.0361, ρ=0.9335
Daisy Chain Net M2:	β=29.8576, η=8500.2058, ρ=0.8812
Daisy Chain Net O1:	β=20.1255, η=7984.7183, ρ=0.9247
Daisy Chain Net O2:	β=14.4630, η=6622.8968
Daisy Chain Net O3:	β=24.9071, η=5285.9463, ρ=0.6799
Daisy Chain Net O4:	β=14.4080, η=4553.5427, ρ=0.9350


Characteristic Life and DNP Comparison
Cycles to Failure
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
DNP (mm)
30
25
20
15
10
5
0
26.9
25.5
22.1
24.1
4554
5286
6623
7985
04
03
02
01
Table of Values for Daisy Chain Net, Cycles, and DNP
Cycles to Failure
Longest DNP (mm)

Cross Section of Solder Joint Fracture



Conclusions

- Characteristic life, therefore reliability, was very good for all samples in this evaluation and was consistent with an Avago study of similar material sets and test vehicle geometries in a convection soldering evaluation.
- Characteristic life decreases with distance from neutral point.
  - O4 and O3 nets are statistically different in this dataset at a 90% confidence level.
- For the same DNP, boards soldered with vacuum had shorter characteristic life calculations, but the result was not statistically significant .
  - This dataset does not show vacuum soldered and no-vacuum solder boards to be different populations.
- Although the sample size was small, the results from the outer four daisy chains are very self-consistent and expected to realistically approximate a larger sample size.