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# Early-Indicators for Failure-Prognosis of Electronics under Shock, Vibration and Thermo-mechanical Loads

## *Task ID: NNA08BA21C*

INTEGRATED VEHICLE HEALTH MANAGEMENT


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# Outline

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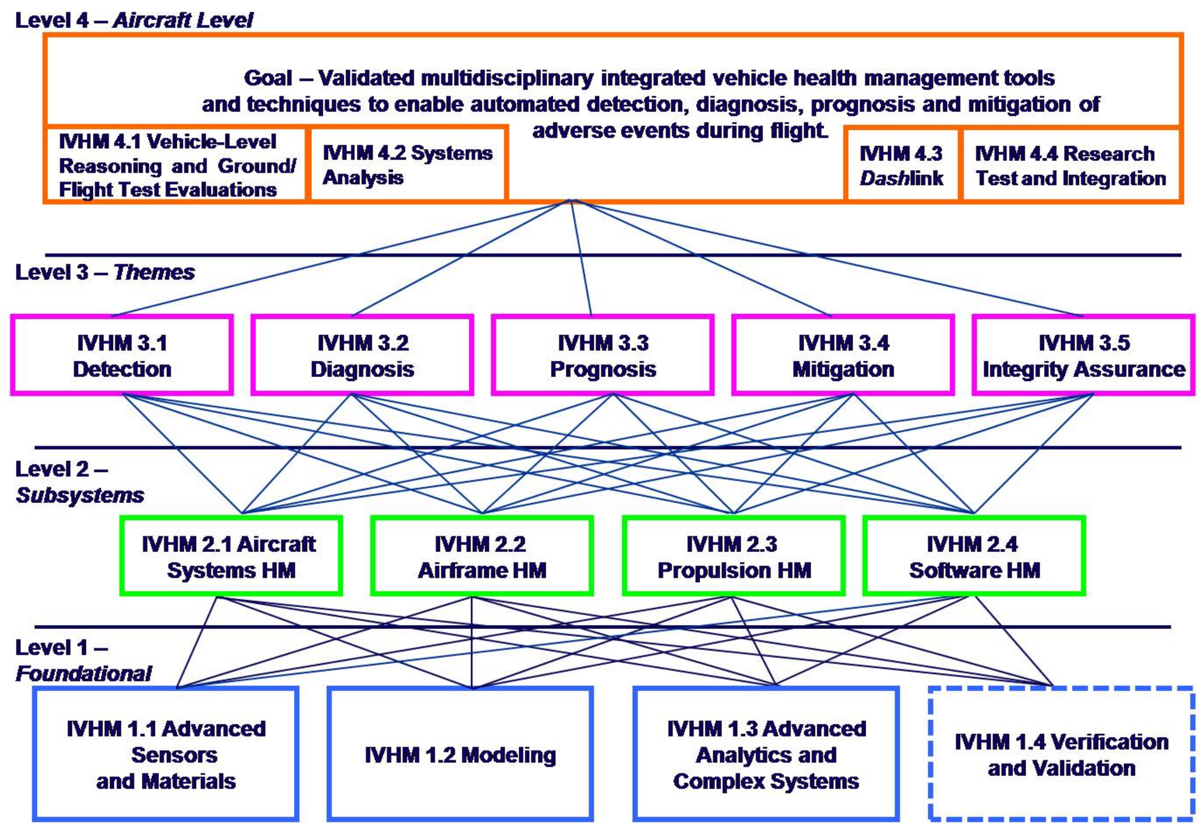
- Problem Statement
- Background
- IVHM milestones(s) being addressed
- Approach
- Results
- Conclusions
- Future Plans



# Problem Statement

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Develop the Prognostic Health Management for electronics subjected to multiple cyclic thermo-mechanical loads, shock and vibration loads typical of deployed electronics.

Residual Life Assessment and decision support methods for re-deployment, operational readiness of systems based on accrued damage.

Develop the mathematical relationships correlating physical damage and feature-set for electronic systems in various harsh environment applications.

Statistical Assessment of response-repeatability for healthy components versus components with impending damage.

***Relationship to Adverse Events Table***
Slow Progression Fault: Very hard to detect, gradual degradation in performance

# Background

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BIST gives ability to self-test and diagnose electronics with minimal interaction from external test equipment but limited insight into reliability [Chandramouli96, Drees04, Hassan92, Williams83, Zorian94]

Fuses and Canaries used for detecting and controlling faults in electronic system and restoring normal operating conditions are reactive diagnostic tools. [Anderson04, Mishra02 ].

Life-prediction models assume pristine systems, require acquisition and storage of environmental data, limited ability to predict life in complex environments.

Damage pre-cursors based on micro-structural evolution, time and spectral techniques for health monitoring of electronics. [Lall04[a-d], 05[a-b], 06[a-f], 07[a-e], 08[a-f] ].

# IVHM Milestones Addressed

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*IVHM 2.1: Aircraft Systems Health Management*

Development of methods that will enable detection, diagnostics, prognostics, and mitigation strategies for systems, including but not limited to electromechanical systems, avionics, electrical power systems, and electronics.

*Relationship to IVHM Goal:*

Current program focuses on development of early indicators of damage for prognostication of electronics

*Program Duration: 3-Years*

*Current Location in Time-Line: Near-end of Year-2*

# Approach: cave³ PHM Framework

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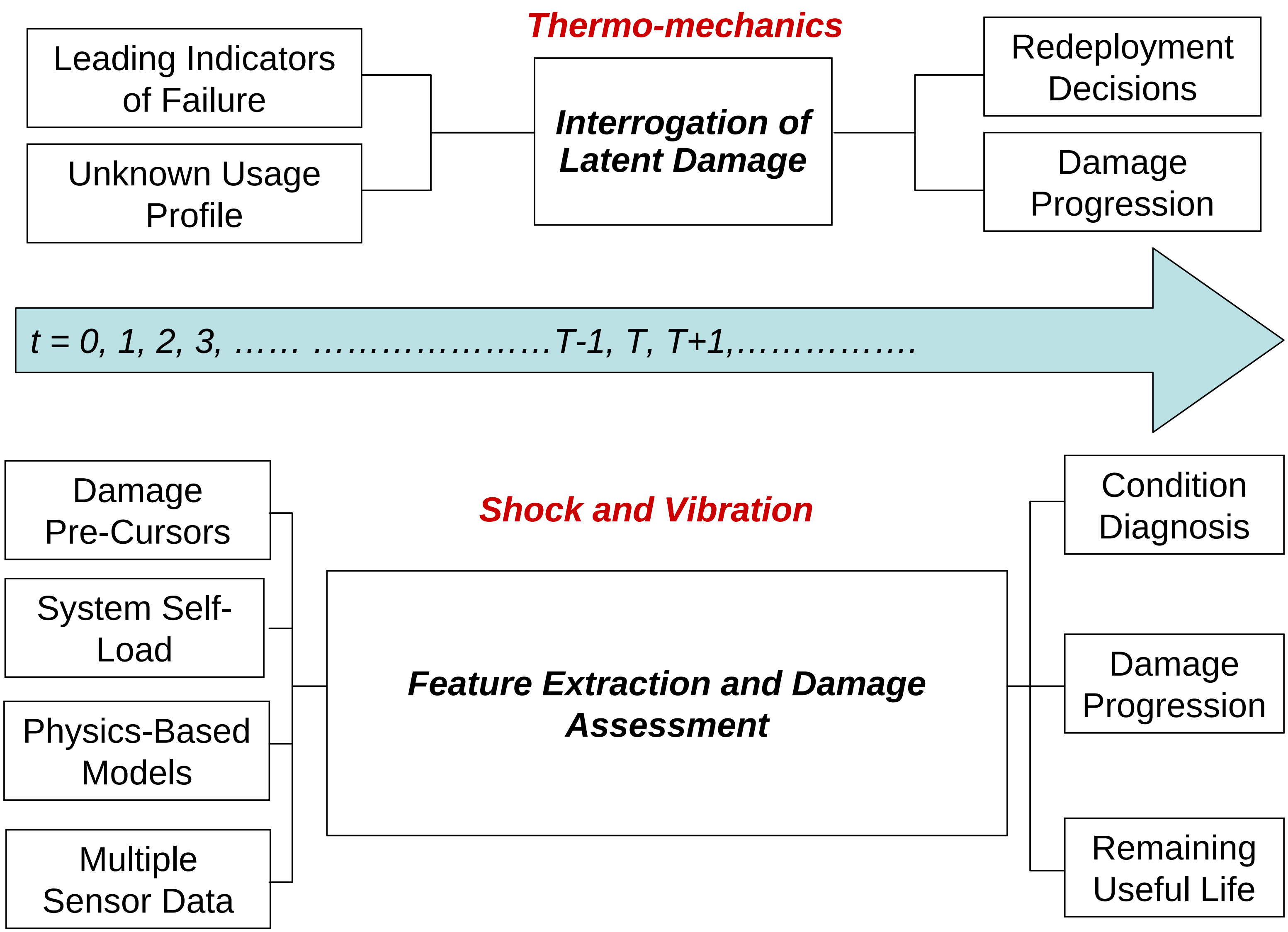

# Test Vehicle-A

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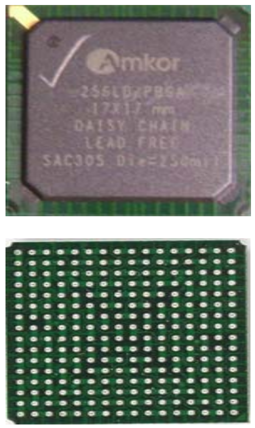
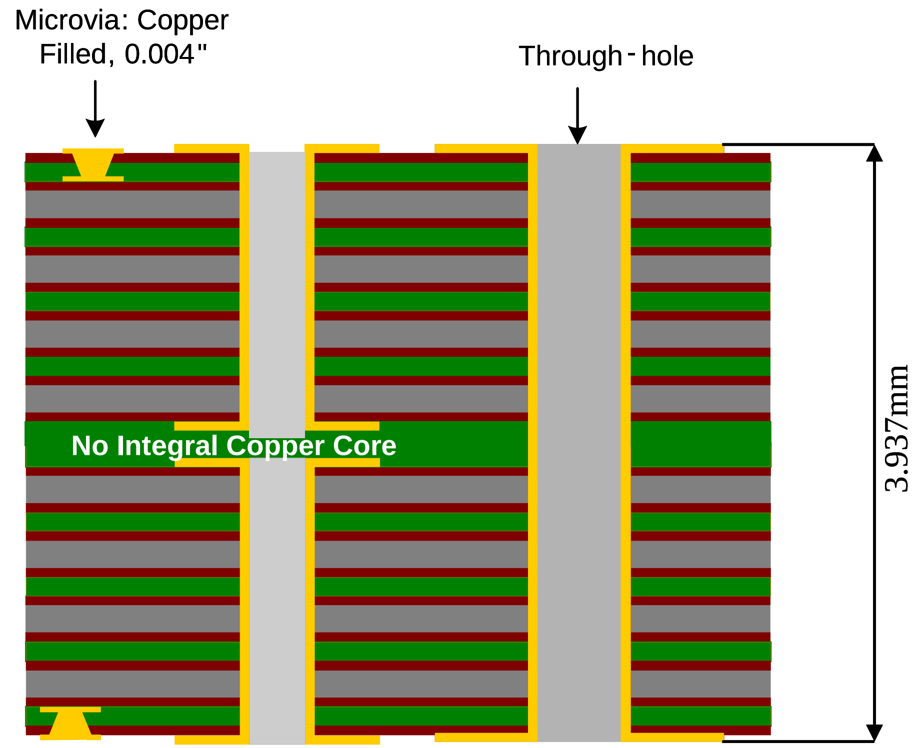



*256 PBGA*


*100 CABGA*

| | | |
|---|---|---|
| Solder | Sn3Ag0.5Cu | Sn3Ag0.5Cu |
| Package Size (mm) | 17 x 17 | 12 x 12 |
| Package Type | PBGA | CABGA |
| I/O Count | 256 | 100 |
| I/O Pitch (mm) | 1 | 0.8 |
| Ball Diameter (mm) | 0.5 | 0.5 |
| Die Size (mm) | 7.94 | 5.58 |
| P/D ratio | 2.14 | 2.15 |
| Board Finish | ENIG | ENIG |
| Substrate Pad Type | NSMD | NSMD |




***Board Assembly , No-Core***

The assemblies have been subjected to relatively harsh thermal cycle (TC-1) temperature ranging from -55°C to 125°C, 2.5 hours/cycle followed by a milder thermal cycle (TC-2) temperature from 0°C to 100°C, 16 minutes Dwell and 8 minutes ramp.

# Test Vehicle-B and C

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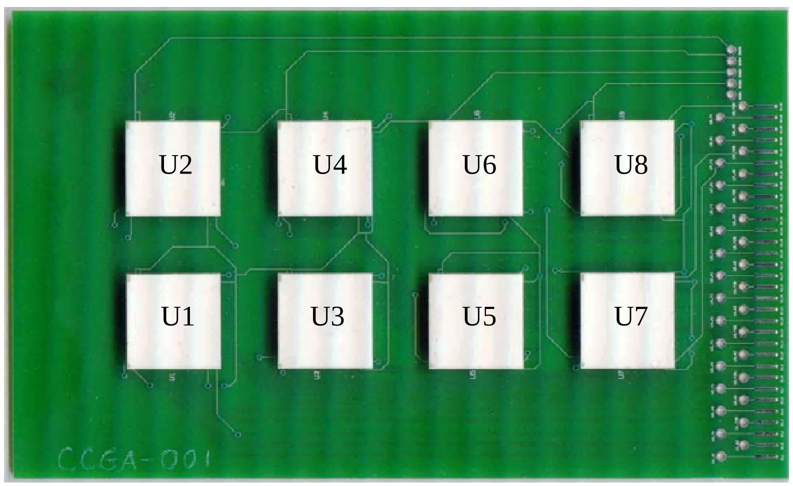
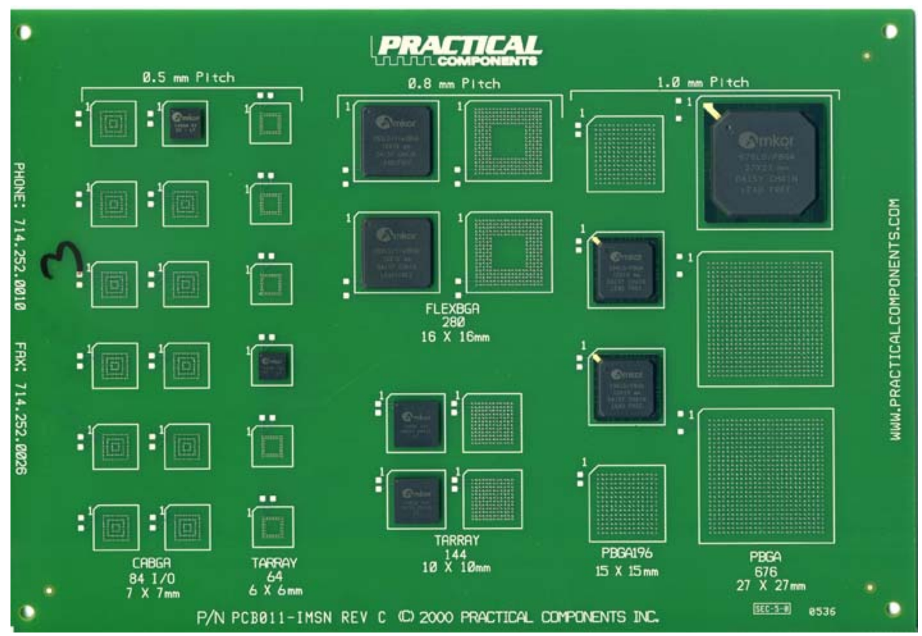
| Parameter | CCGA Cu-Columns | CBGA SnPb | CBGA Hi-Pb | CBGA SAC305 |
|---|---|---|---|---|
| Solder | Sn15/Pb85 | Sn63/Pb37 | Sn10/Pb90 | SAC305 |
| Length | 21 mm | 21 mm | 21 mm | 21 mm |
| Width | 21 mm | 21 mm | 21 mm | 21 mm |
| Thickness | 2.4 mm | 2.4 mm | 2.4 mm | 2.4 mm |
| I/O | 400 | 400 | 400 | 400 |
| Pitch | 1 mm | 1 mm | 1 mm | 1 mm |
| Ball Dia | 0.6 mm | 0.6 mm | 0.6 mm | 0.6 mm |
| Jt Height | 2 mm | 0.6 mm | 0.6 mm | 0.6 mm |

| | 6 mm Tape Array | 7 mm Chip Array | 10 mm Tape array | 15 mm PBGA | 16 mm Flex BGA | 27 mm PBGA |
|---|---|---|---|---|---|---|
| I/O | 64 | 84 | 144 | 196 | 280 | 676 |
| Pitch (mm) | 0.5 | 0.5 | 0.8 | 1 | 0.8 | 1 |
| Die Size (mm) | 4 | 5.4 | 7 | 6.35 | 10 | 6.35 |
| Substrate Thick (mm) | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 | 0.36 |
| Pad Dia. (mm) | 0.28 | 0.28 | 0.30 | 0.38 | 0.30 | 0.38 |
| Substrate Pad | NSMD | NSMD | NSMD | SMD | NSMD | SMD |
| Ball Dia. (mm) | 0.32 | 0.48 | 0.48 | 0.5 | 0.48 | 0.63 |




*Test Vehicle-B*




*Test Vehicle-C*

# Multiple Thermal-Environments

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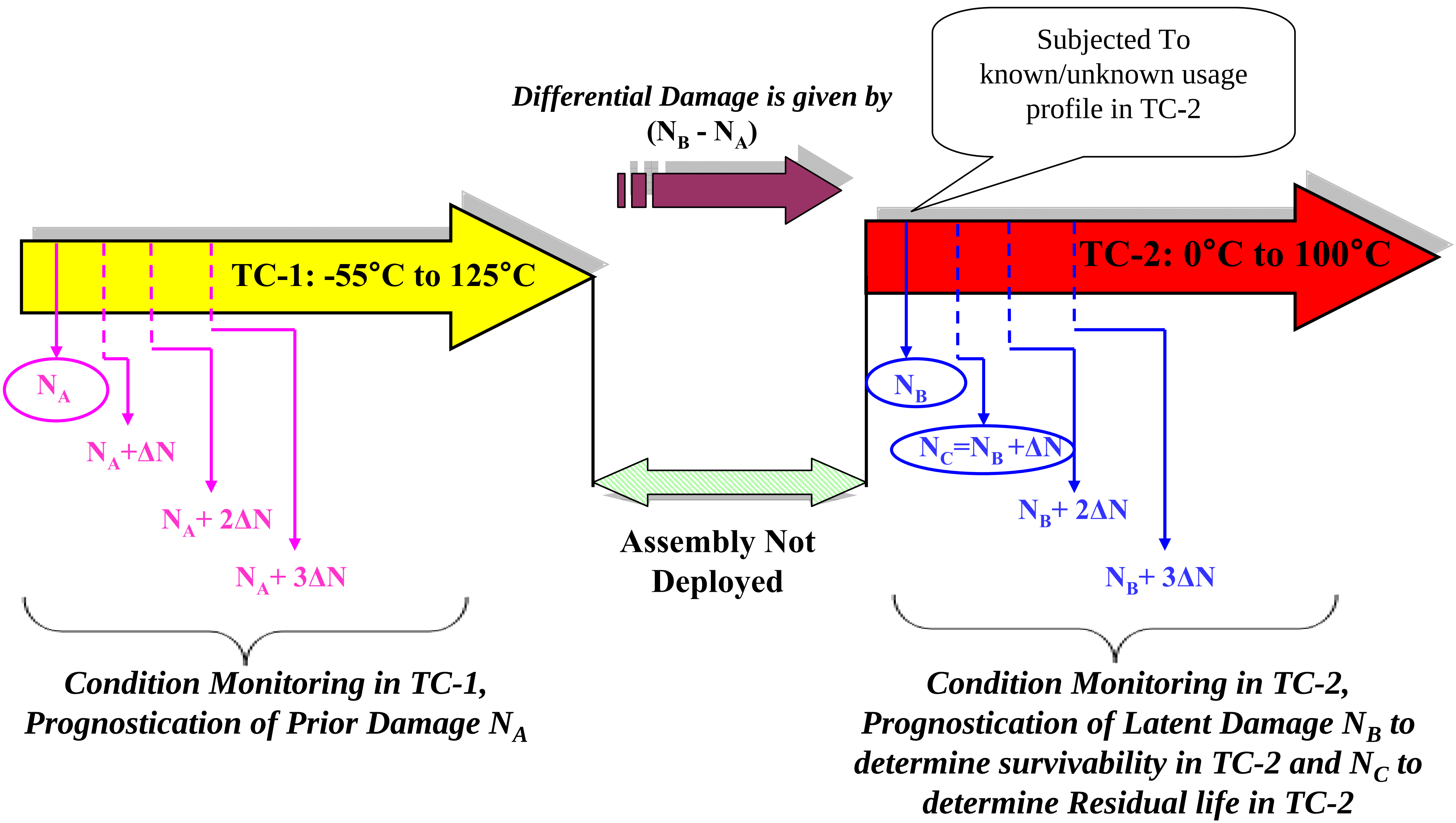

# Multiple Thermal-Environments

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*Previously, it has been shown that……….*

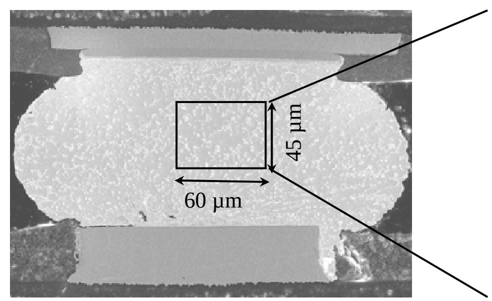
Rate of change in phase growth parameter [d(lnS)/d(lnN)] is valid damage proxy for prognostication of thermo-mechanical damage in solder interconnects and assessment of residual life [Lall 2004[a], 2005[a], 2006[c,d], 2007[c,e], 2008[c,d]].

Damage proxy [d(lnS)/d(lnN)] is related to the microstructural evolution of damage by the following equation:

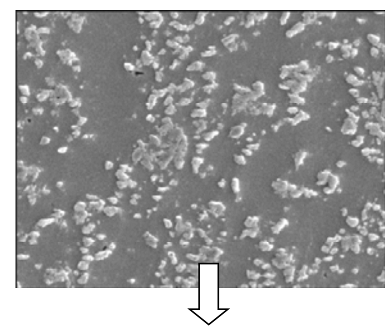
$$S = g^4 - g_0^4 = a(N)^b$$

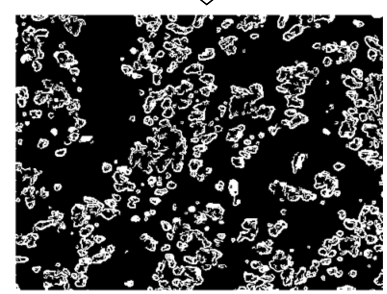
$$\ln S = \ln\left(g^4 - g_0^4\right) = \ln a + b \ln N$$

$$\frac{d(\ln S)}{d(\ln N)} = b$$



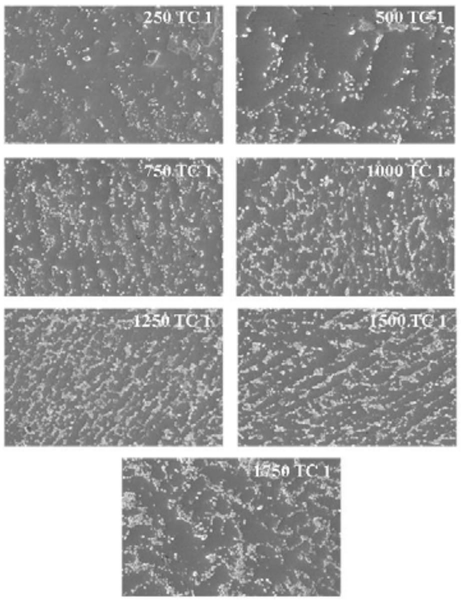

*$Ag_3Sn$ phases in 96.5Sn3.0Ag0.5Cu solder microstructure*



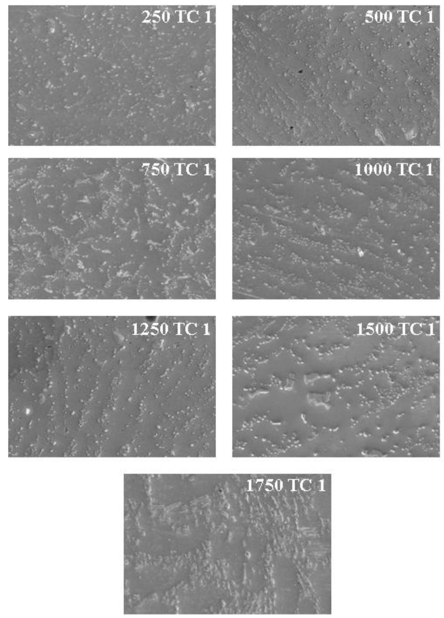


*Gray scale mapped image*

# Effect of ΔT Magnitude



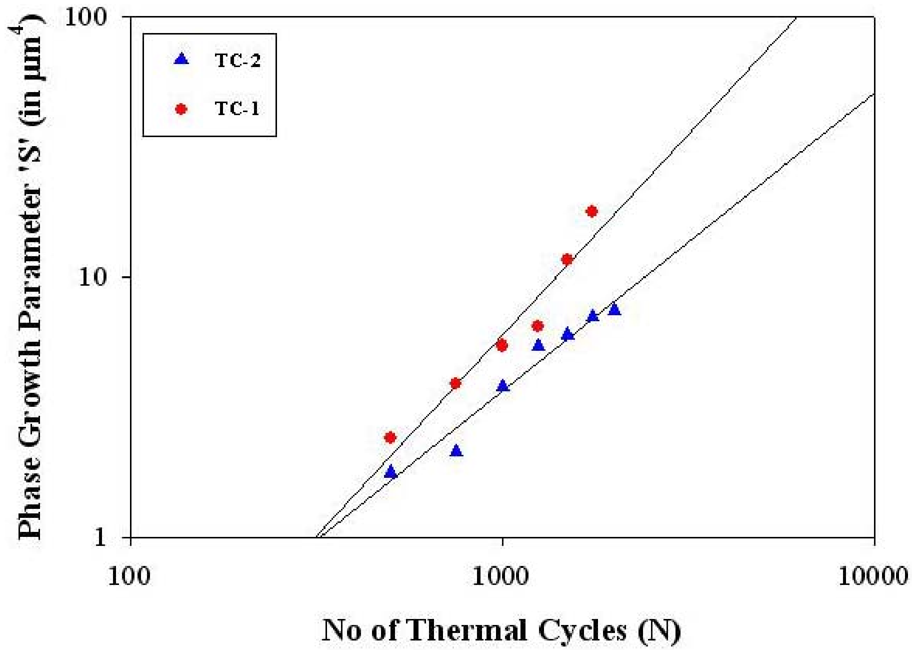

*SEM backscattered images, -55ºC to 125ºC, 96.5Sn3.0Ag0.5Cu solder, **100 I/O CABGA**, magnification 750x*




*SEM backscattered images, -55ºC to 125ºC, 96.5Sn3.0Ag0.5Cu solder, **256 I/O CABGA**, magnification 750x*

Phase growth vs number of thermal cycles for 96.5Sn3.0Ag0.5Cu solder, **256 I/O PBGA**, subjected to

TC-1 (-55ºC to 125ºC)
TC-2 (0ºC to 100ºC)



# Case-1: Prior Damage in TC-1

Assembly has been ***subjected to $N_A$ cycles in environment TC-1***

Assembly is ***withdrawn from service*** and interrogated for damage state.

Prior ***accrued damage*** sustained by the system in TC-1 prognosticated.

***Subscript "p" appended at end of each prognosticated parameter.***

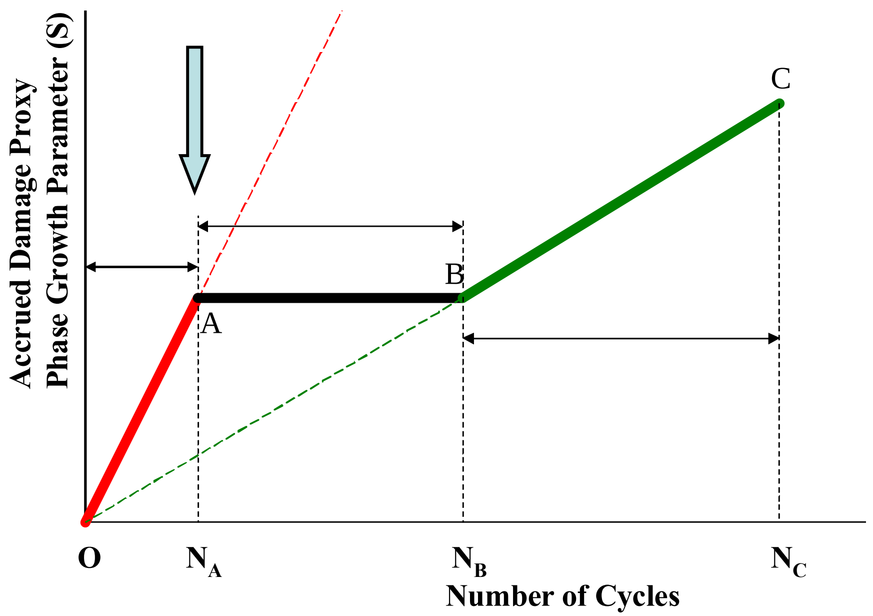
***$g_{0p}$, $a_p$, $b_p$, $N_{Ap}$.***

$$S_A = g_A^4 - g_0^4 = a(N_A)^b$$

$$S_{A+\Delta N} = g_{A+\Delta N}^4 - g_0^4 = a(N_A + \Delta N)^b$$

$$S_{A+2\Delta N} = g_{A+2\Delta N}^4 - g_0^4 = a(N_A + 2\Delta N)^b$$

$$S_{A+3\Delta N} = g_{A+3\Delta N}^4 - g_0^4 = a(N_A + 3\Delta N)^b$$



# Case-1: Prior Damage in TC-1

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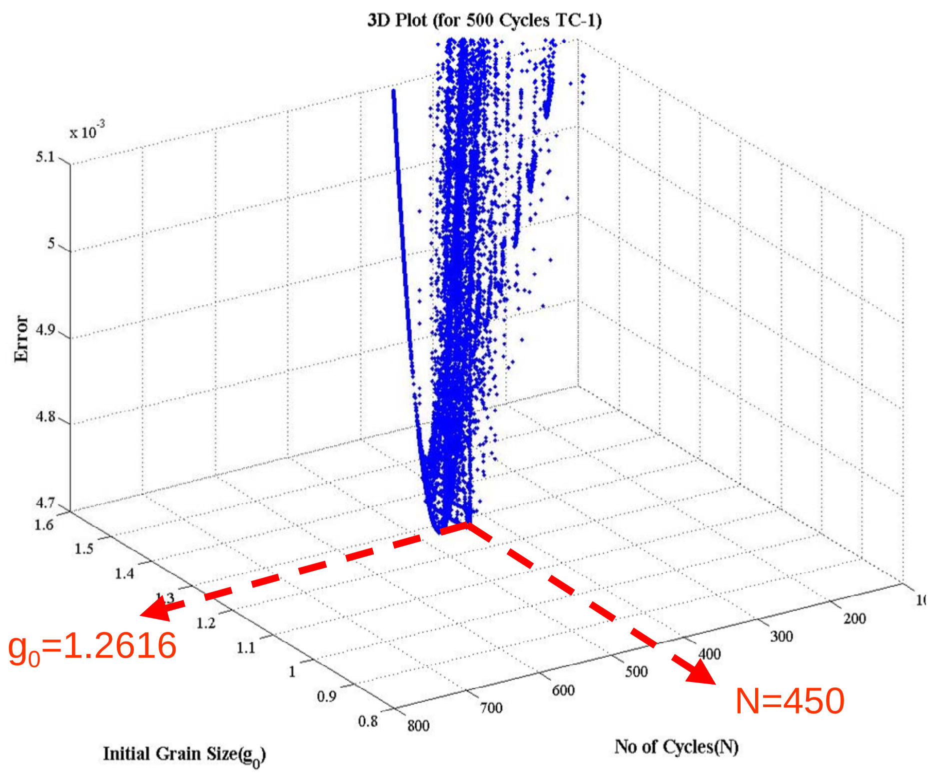
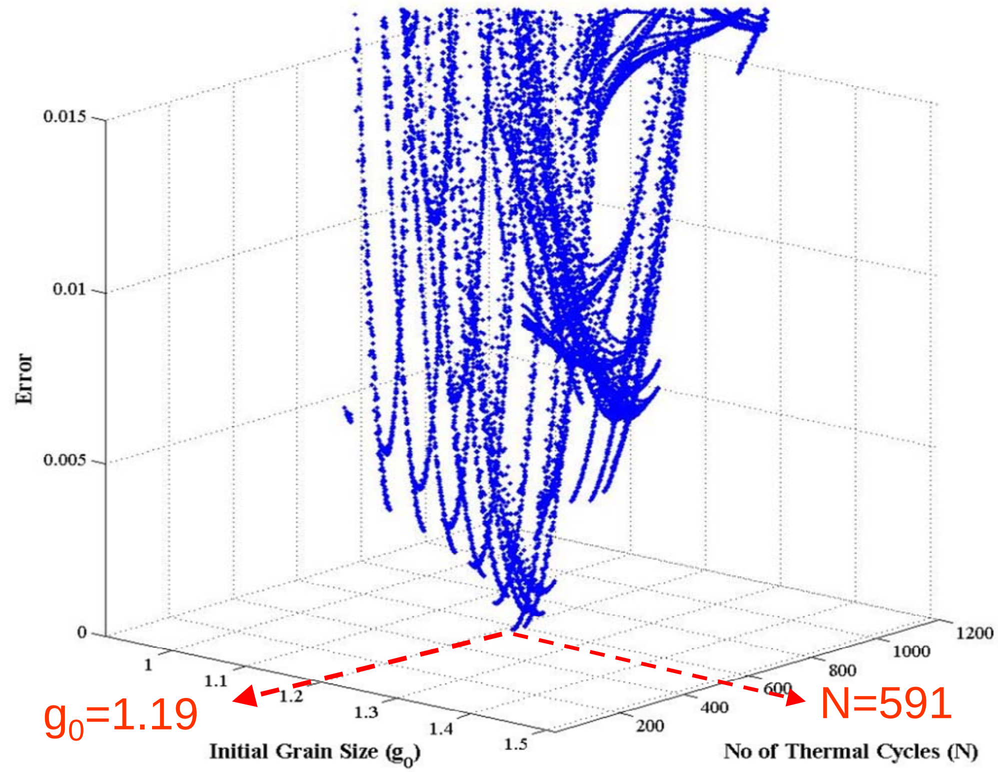
Assembly ***subjected to known but undisclosed 500 cycles in environment TC-1***

| Cycle Count | Cycle 'N' | | | Initial Grain Size '$g_0$' (μm) | | |
|---|---|---|---|---|---|---|
| | Expt Data | LM Alg | % Error | Expt Data | LM Alg | % Error |
| 100 I/O CABG | 500 | 430 | -14 | 1.258 | 1.076 | -14.5 |
| 256 I/O BGA | 500 | 591 | 18.2 | 1.065 | 1.262 | 18.5 |




*-55ºC to 125ºC, SAC305, 100 I/O CABGA*




*-55ºC to 125ºC, SAC305, 256 I/O CABGA*

# Case-2: Operational Readiness in TC-2

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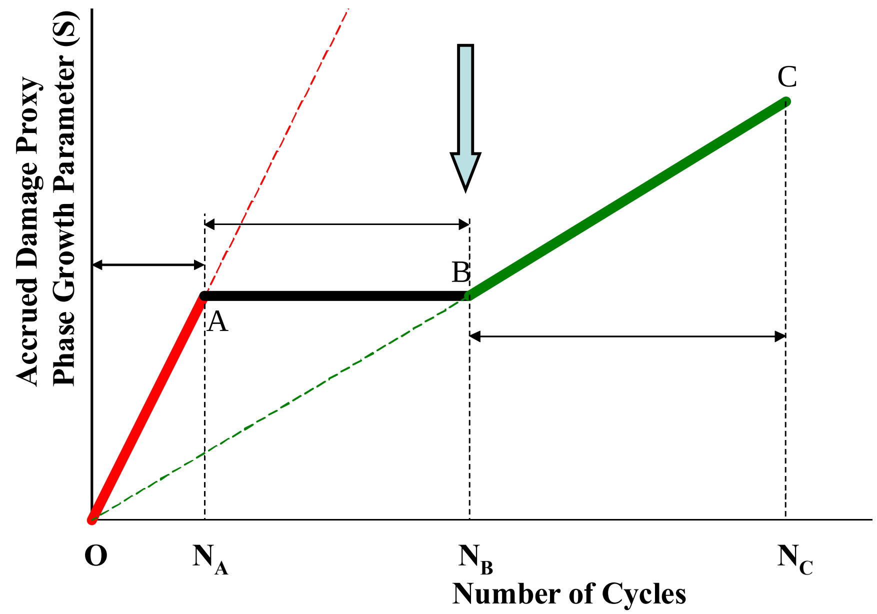
Assess ***operational readiness*** of the electronic assembly in TC-2.

Prognostic sensor cells are subjected to a ***small period*** of exposure of TC-2.

Assembly prognosticated for ***equivalent prior damage*** TC-2

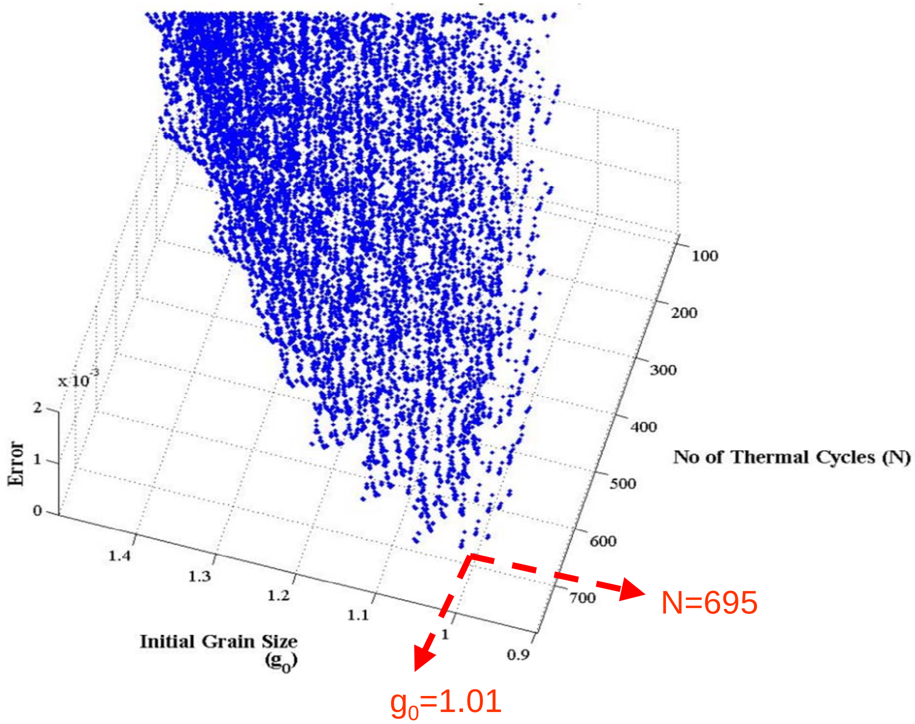



| Cycles | | 100 I/O CABGA | 256 I/O PBGA |
|---|---|---|---|
| a (TC-2) | | 6.90E-03 | 1.30E-03 |
| b (TC-2) | | 0.9757 | 1.1462 |
| $g_0$ | | 1.258 | 1.065 |
| $g_A = g_B$ | | 1.591 | 1.386 |
| Experimental Data | Cycles of TC-1 | 500 | 500 |
| | Cycles of TC-2 | 662 | 708 |
| | $\Delta D_e (N_B - N_A)$ | 162 | 208 |

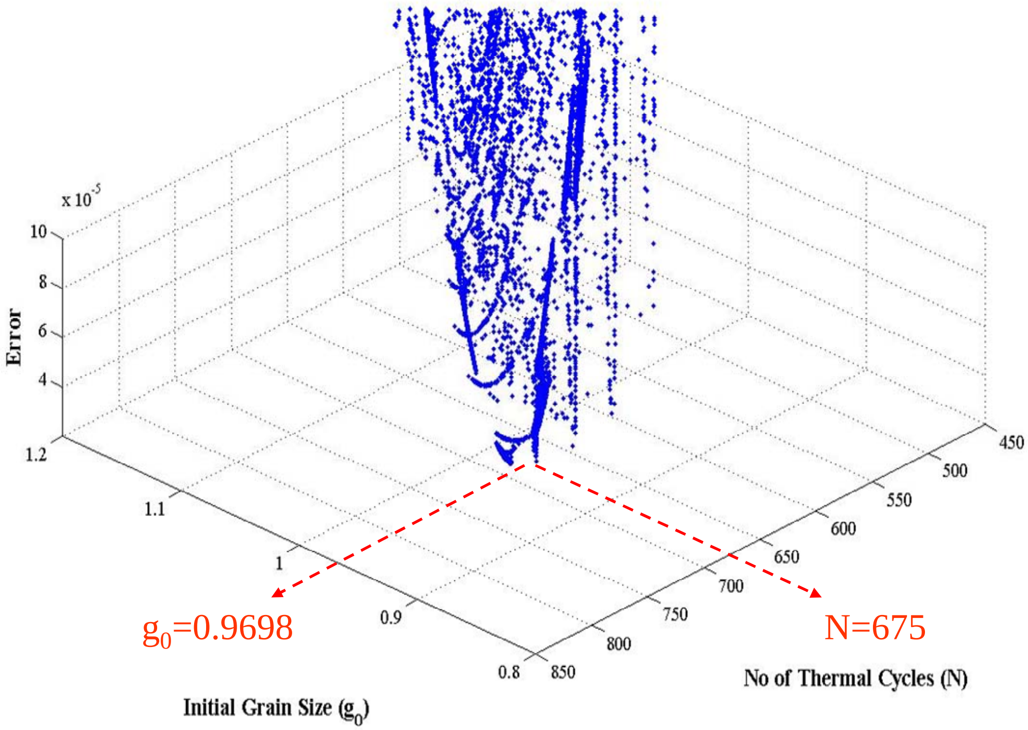
# Case-2: Operational Readiness in TC-2

A small subset of assemblies subjected to TC-2.

Samples from the condition monitoring cells exposed to a second environment TC-2 and withdrawn in 50 cycle increments




*-55ºC to 125ºC, SAC305, 100 I/O CABGA*




*-55ºC to 125ºC, SAC305, 256 I/O CABGA*

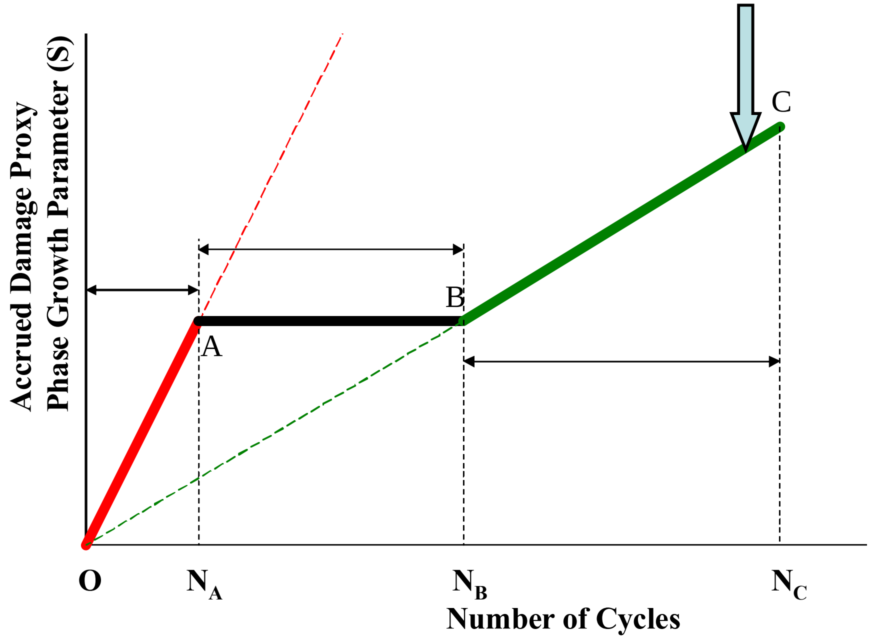
# Case-3: Residual Life in TC-2

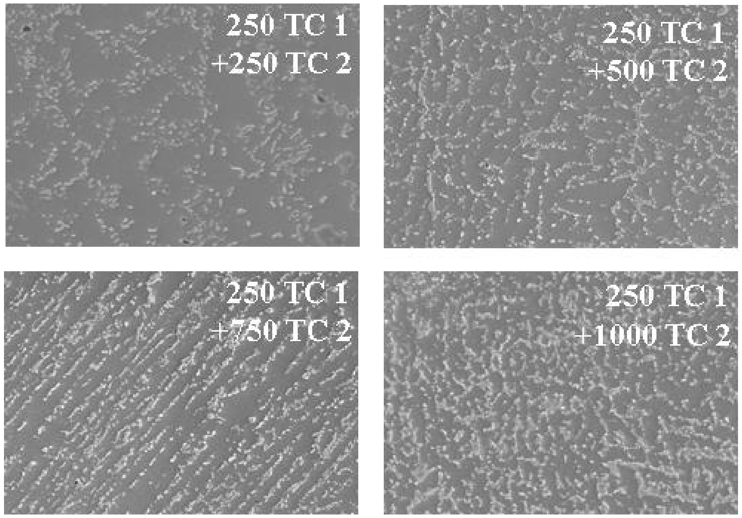
Assembly was ***deployed in TC-1***, and then ***re-deployed in TC-2***.

Assembly prognosticated for ***prior damage*** TC-1 and TC-2

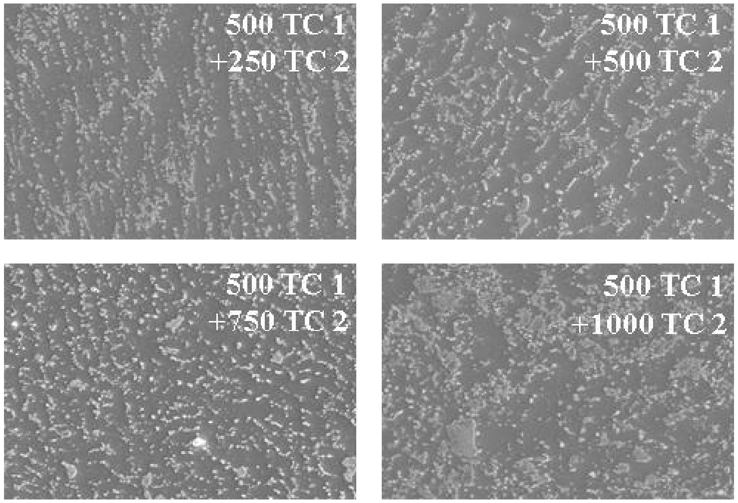
Differential damage subtracted to account for the sequential thermal exposures.

$$N_C - N_B = N_{CP} - \Delta D - N_{AP}$$




***250 Cycles** of TC-1 + (x-cycles) of TC-2, SAC305, 256 PBGA, 750x*




***500 Cycles** of TC-1+( x-cycles) of TC-2, SAC305, 256 PBGA, 750x*

# Case-3: Residual Life in TC-2

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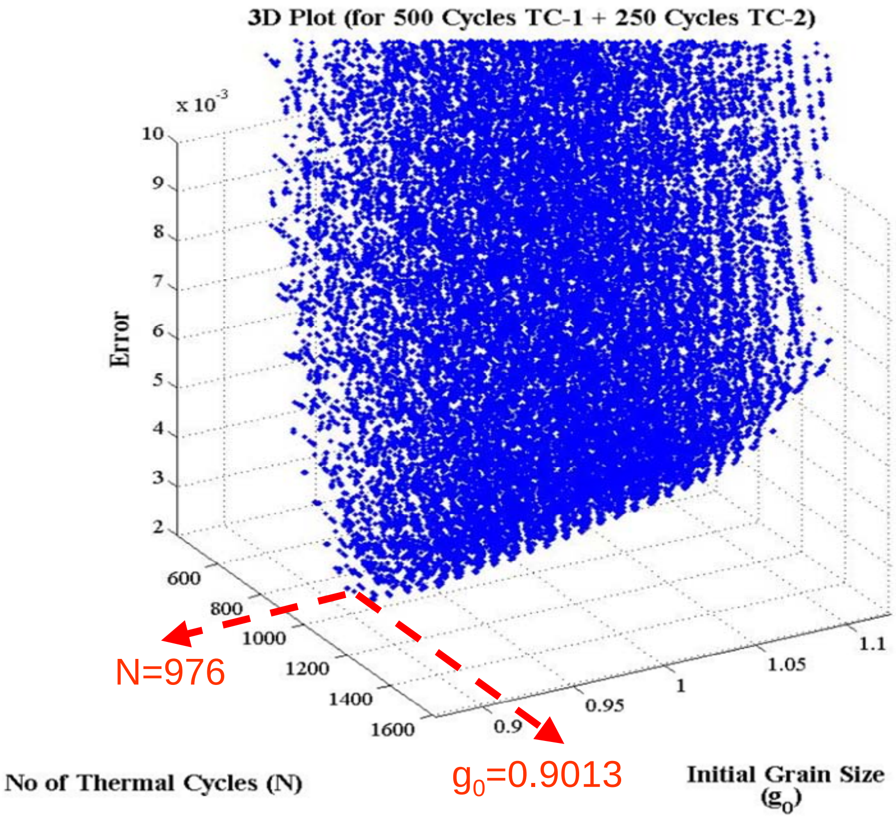
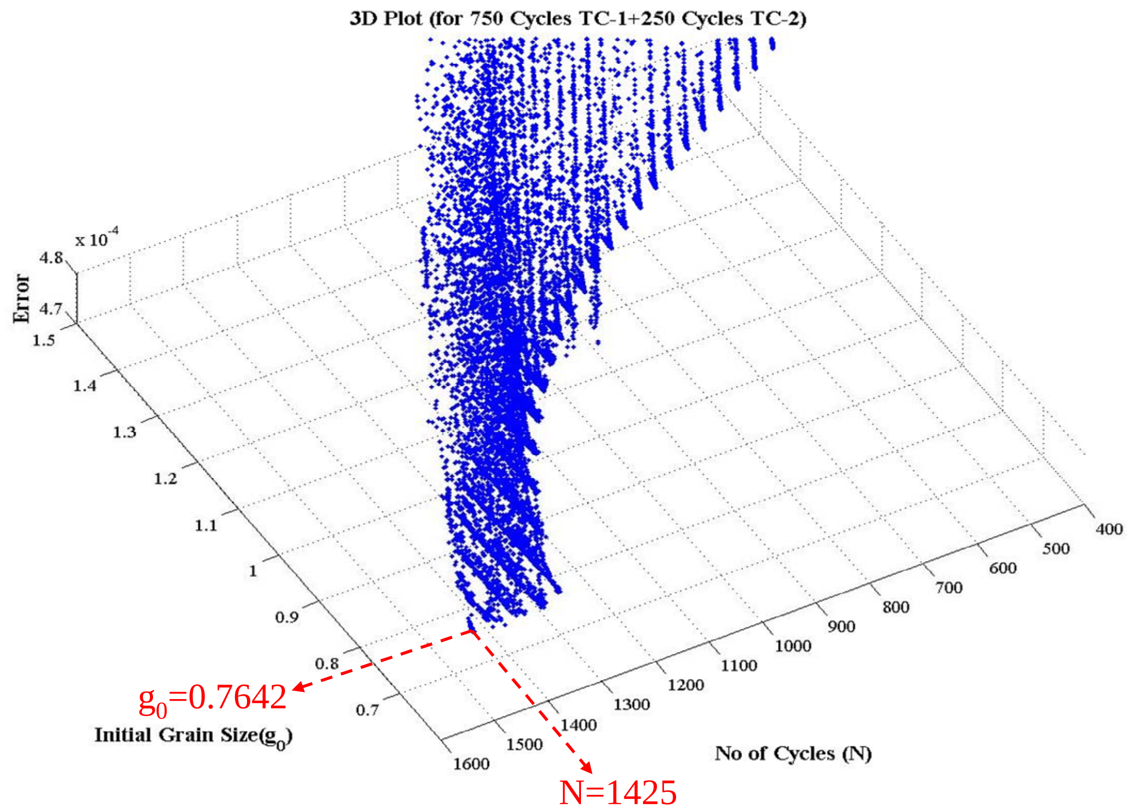
Samples from the condition monitoring cells exposed to a second environment TC-2 and withdrawn in 50 cycle increments

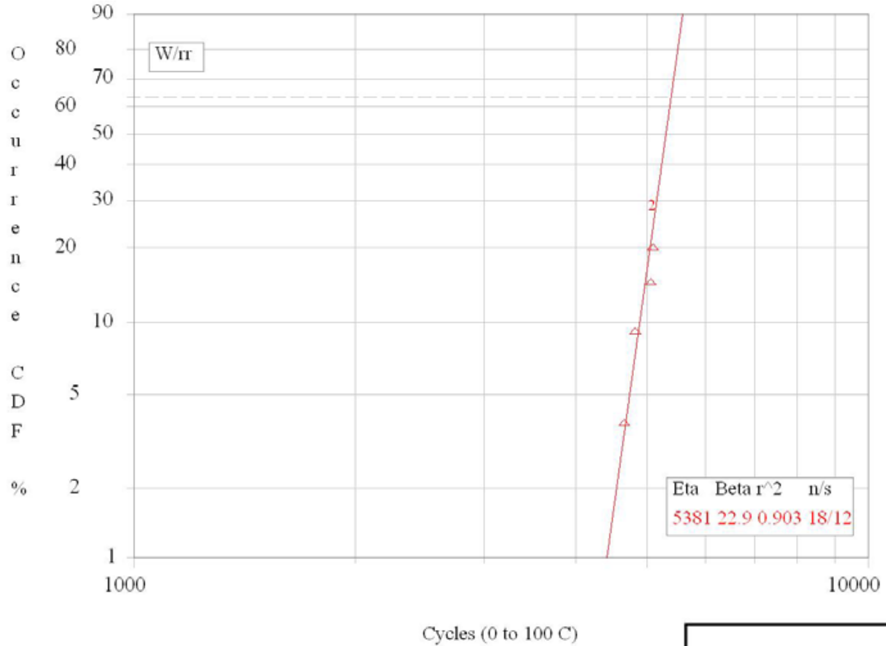



*256 PBGA 96.5Sn3.0Ag0.5Cu Solder subjected to 500 Cycles TC-1 + 250 Cycles TC-2.*




*256 PBGA 96.5Sn3.0Ag0.5Cu Solder subjected to 750 Cycles TC-1 + 250 Cycles TC-2.*

# Case-3: Residual Life in TC-2




| Cycle count | Prognosticated Cycles | $N_{1\%}$ | RL |
|---|---|---|---|
| Damage in TC-2 | 695 | 4866 | 4171 |

***Calculation of $N_{1\%}$ from Weibull plot of failure data.***

| | Cycle Count | $N_{Cp}$ | $\Delta D_p$ $(N_{Bp} - N_{Ap})$ | $N_{Ap}$ | Experiment $N_C$-$N_B$ | Prognostication $N_{Cp}$-$N_{Bp}$ $= N_{Cp}$-$\Delta D_p$- $N_{Ap}$ |
|---|---|---|---|---|---|---|
| 256 I/O BGA | 500 TC1 +250 TC2 | 976 | 175 | 430 | 250 | 371 |
| 256 I/O BGA | 750 TC1 + 250 TC2 | 1425 | 495 | 710 | 250 | 220 |

# Part-I: Summary and Conclusions

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PHM approach has been developed for interrogation of damage state of electronics subjected to multiple thermal environments.

Approach is based on leading indicators of failure derived from micro-structural evolution of damage in second-level interconnects.

Case studies have been presented to demonstrate the ability of the approach for assessment of accrued damage and the residual life after exposure to multiple environments.

Prognosticated latent damage correlates with experimental results for leadfree alloys in area-array packaging.

Correlation demonstrates that the presented leading indicators based PHM technique can be used to interrogate the system state in multiple environments.

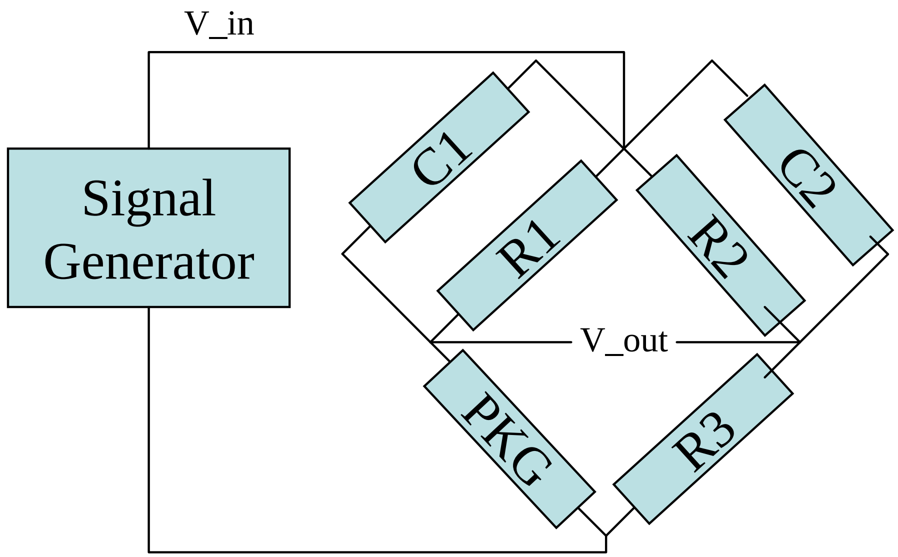
# Approach: Shock & Vibration

Interconnect resistance characteristics have been used to determine leading indicators of failure

Phase shift of resistance spectroscopy output signal is used instead of magnitude

Drop and vibration environments have been investigated

Data is collected on BGA components at varying frequencies



# Phase Sensitive Detection

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$$V_{REF} = V_1 \sin(\omega_1 t + \theta_1)$$
$$V_{SIG} = V_2 \sin(\omega_2 t + \theta_2)$$

Read in Signals

$$V_{PSD} = (V_{REF})(V_{SIG})$$
$$V_{PSD} = \frac{V_1 V_2}{2}\begin{bmatrix}\cos((\omega_1 - \omega_2)t + \theta_1 - \theta_2) \\ -\cos((\omega_1 + \omega_2)t + \theta_1 + \theta_2)\end{bmatrix}$$

Multiply Reference Signal by Test Signal with Noise

$$V_{PSD} = \frac{V_1 V_2}{2}\left[\cos(\theta_1 - \theta_2) - \cos(2\omega t + \theta_1 + \theta_2)\right]$$

DC Signal

AC Signal

Implement Low Pass Filter

Output Signal Proportional to Magnitude of Test Signal

$$V_L \sin\left(\omega_L t + \theta_{ref} + 90^\circ\right)$$

# Theoretical vs Experimental

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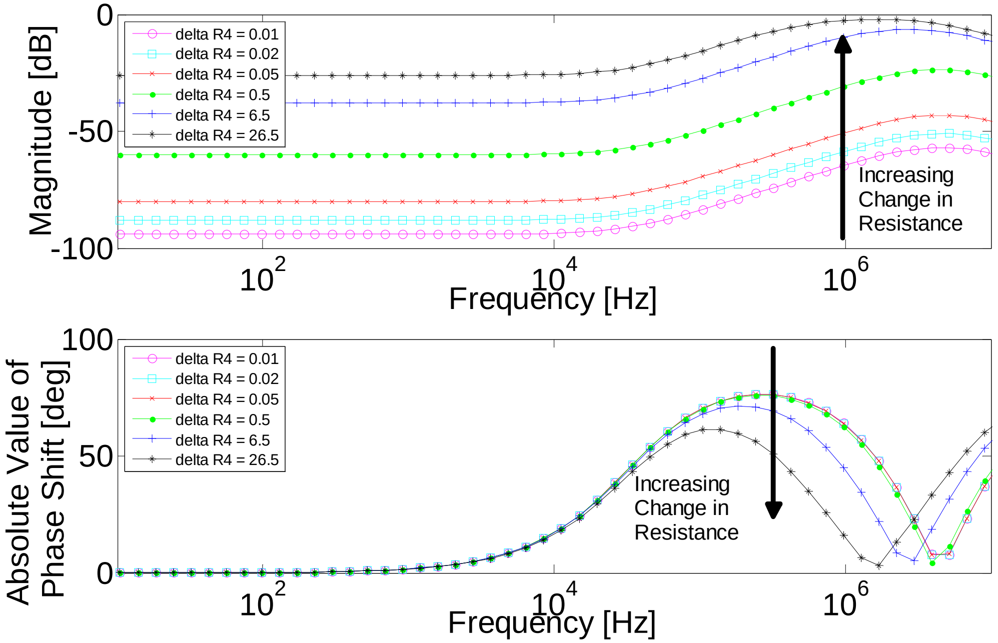
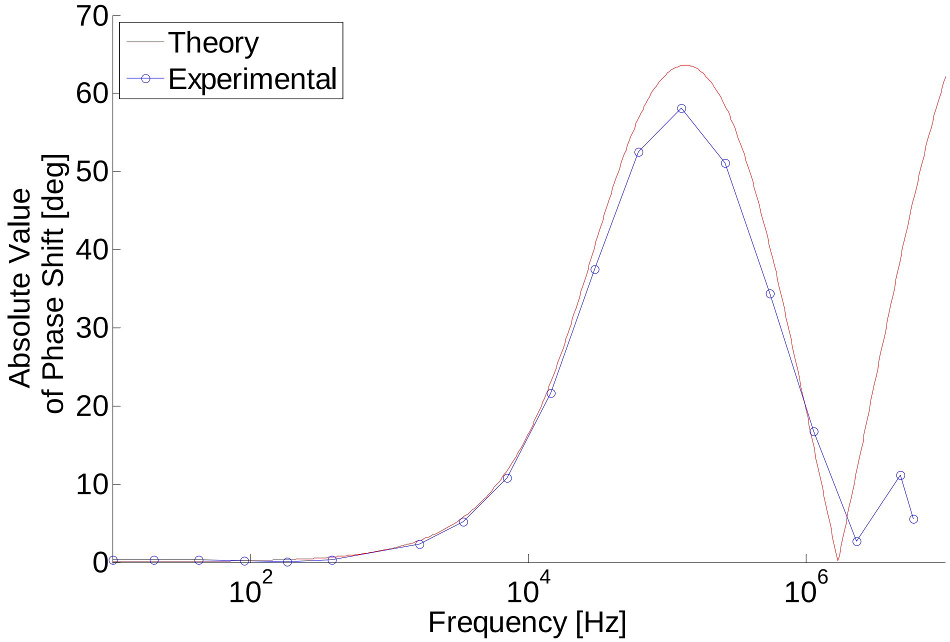
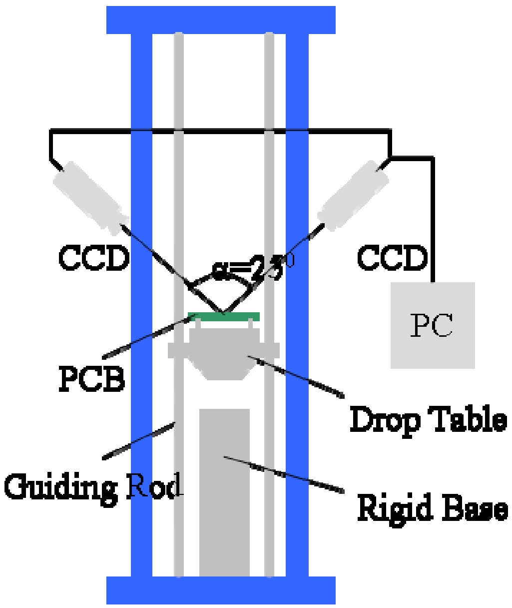


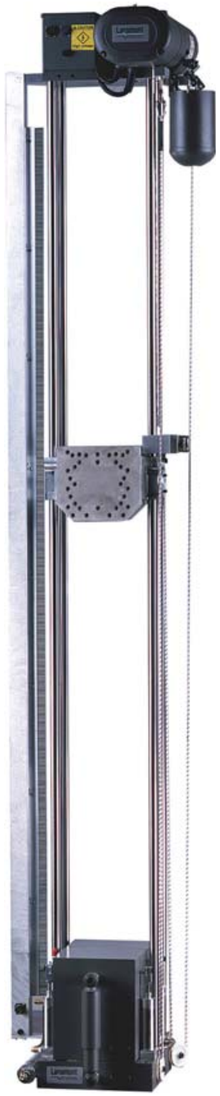

*Bode Plots of Theoretical Transfer function. Arrows indicate trends of increasing resistance of the package*

# Test Setup
## *- Shock and Vibration*

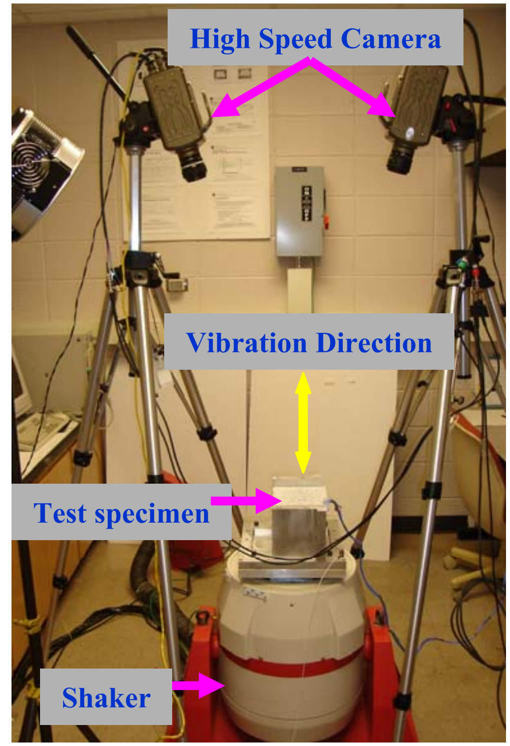
1500G's, 0.5 ms
Packages face down
10M Samples/second

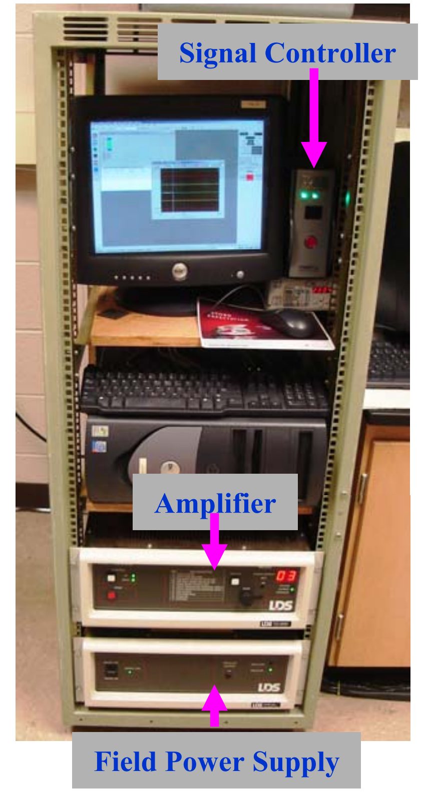


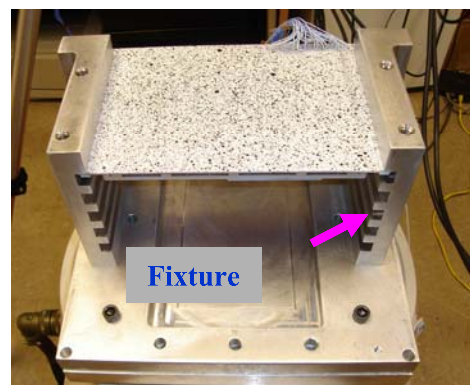

*Drop tower and high speed digital cameras for digital image correlation*

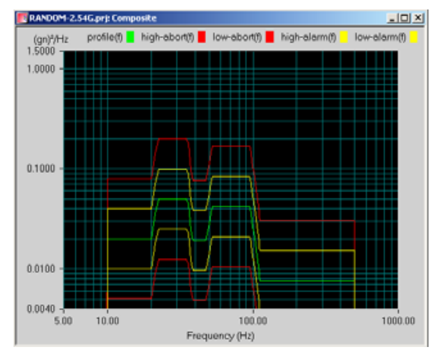


*Lansmont Model 23 Shock Test System*

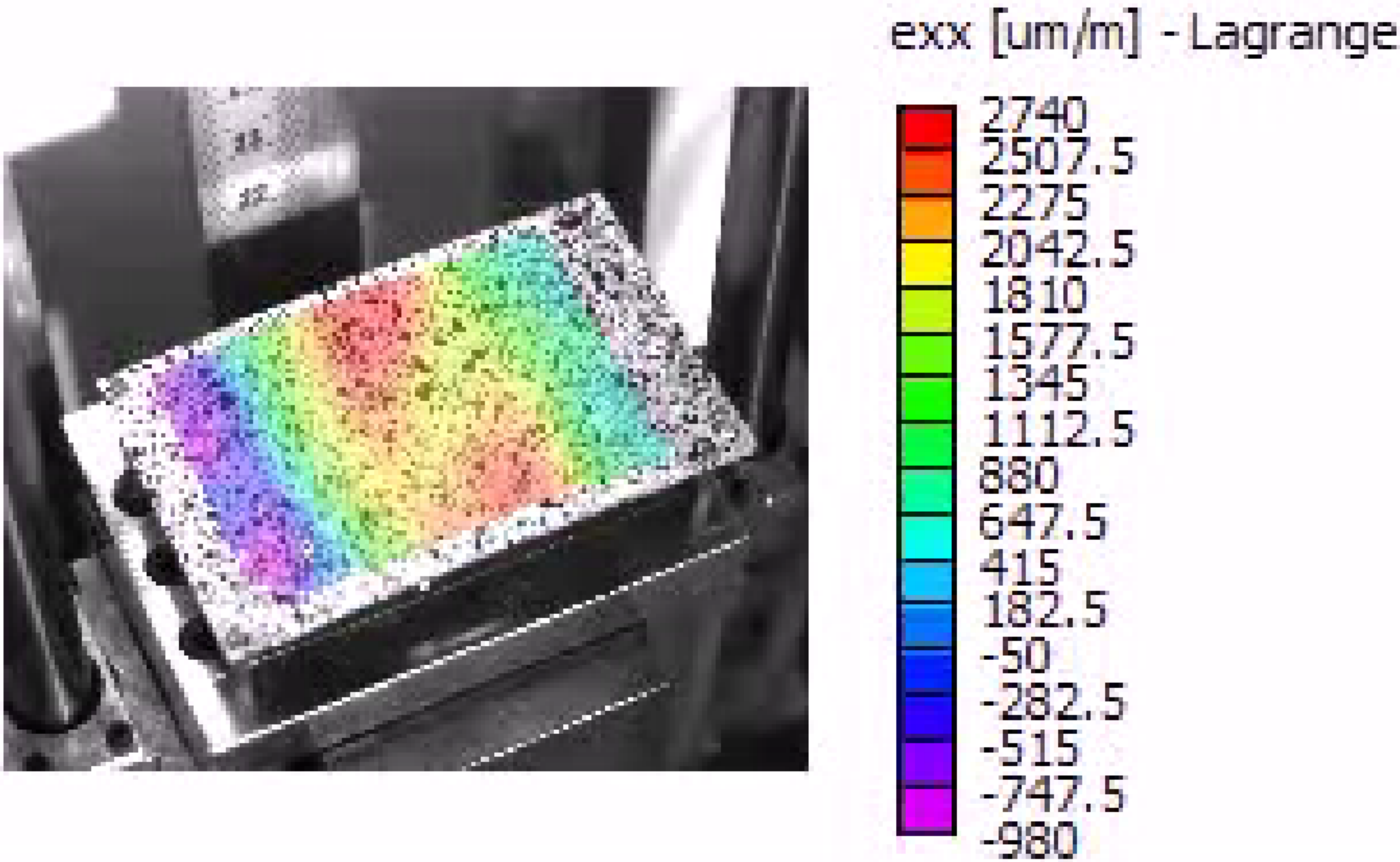



Random Profile from 12-500 Hz at 2.54 Grms


exx [um/m] - Lagrange
2740
2507.5
2275
2042.5
1810
1577.5
1345
1112.5
880
647.5
415
182.5
-50
-282.5
-515
-747.5
-980

# Definition of Failure

## *- Electrical Continuity x Peak Magnitude*

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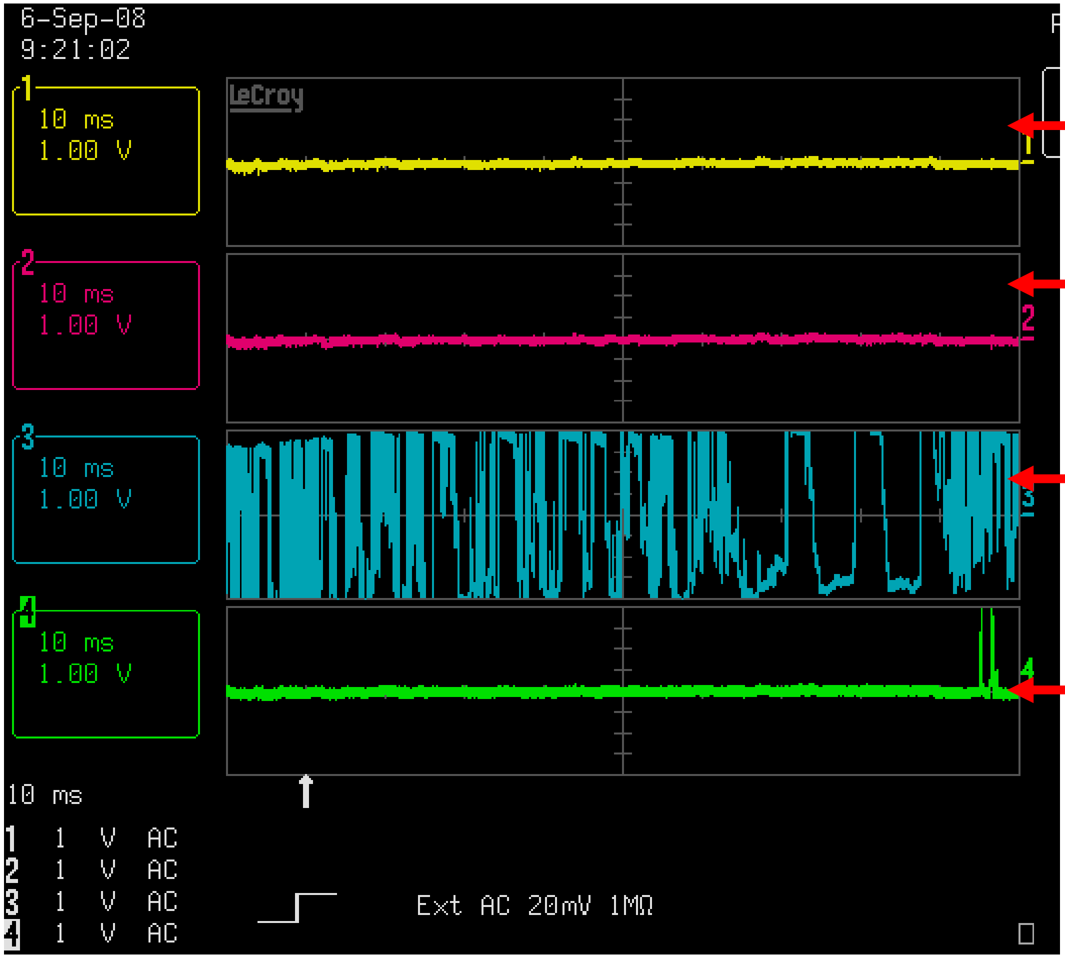
U1

U2

U3

U4




No failures ⇨ 0 pts

No failures ⇨ 0 pts

23 x 5V failures ⇨ 115 pts

2 x 5V failures ⇨ 10 pts

*Electrical Continuity Output from DSO, and failure metric calculation*

# Statistical Assessment of Damage
## *- Vibration, CV vs. Time (127 KHz)*

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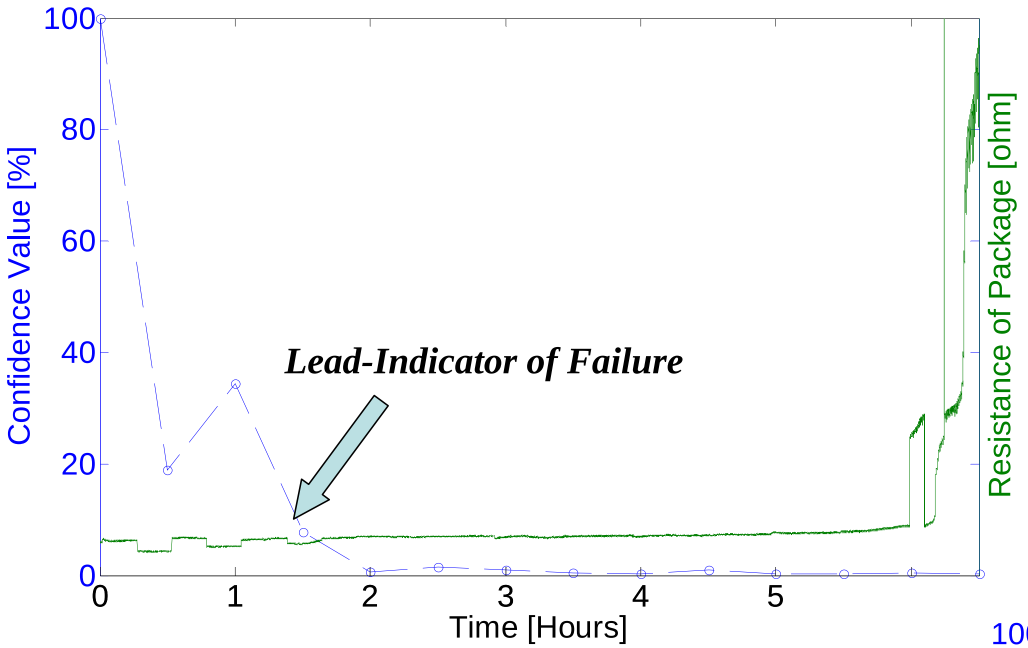
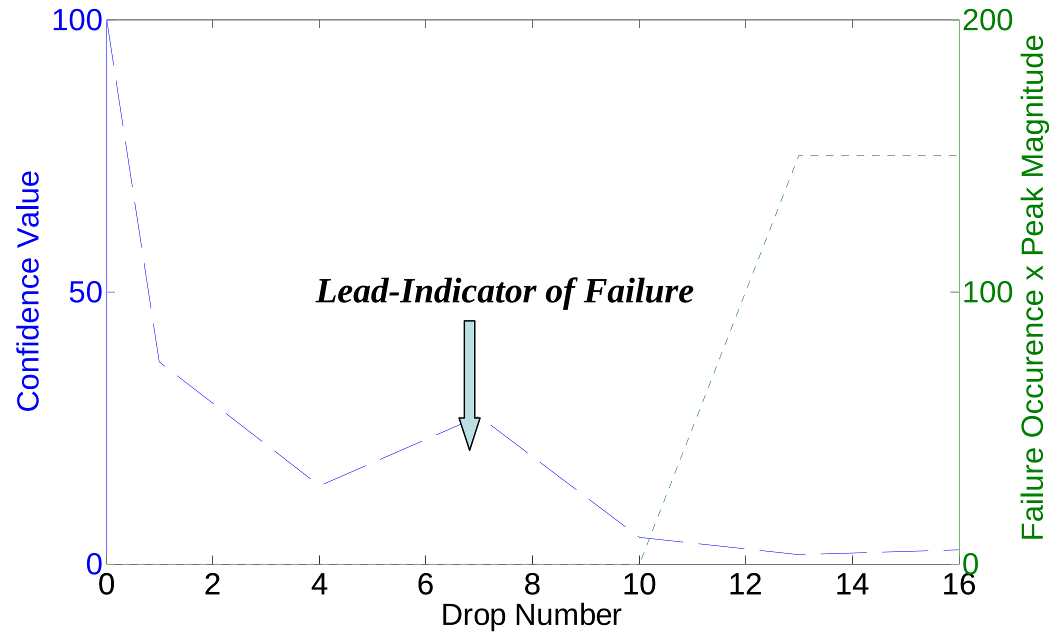



*Phase shift as a lead indicator of failure (Test Board-B, PBGA676,127kHz)*

*Confidence value as a lead indicator of failure during a drop test (Test Board-B, PBGA676)*



# Effect of Interconnect Architecture

## *- All Interconnects (Package U4, 6MHz)*

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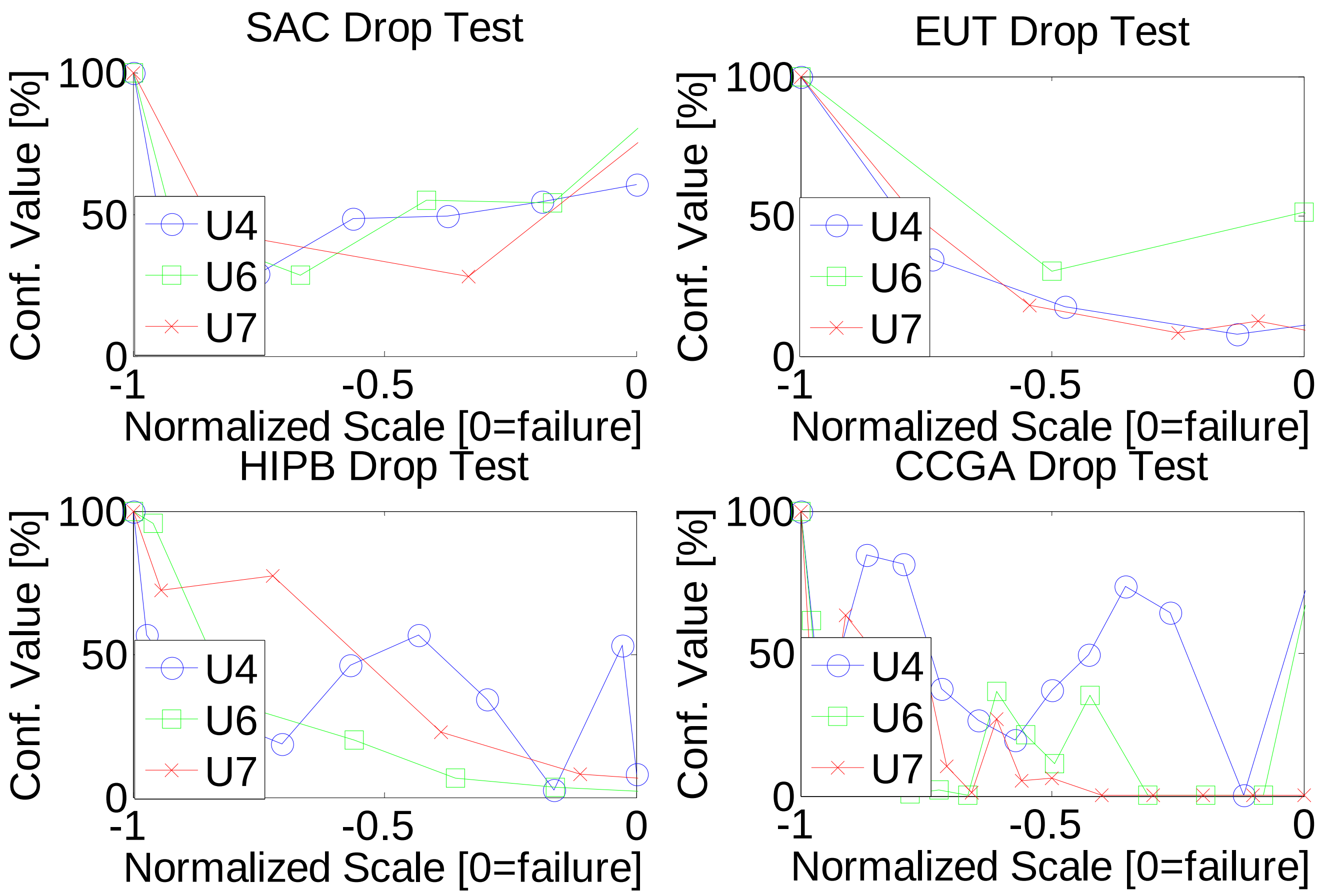


*Degradation of confidence value during drop test of packages U4,U6 and U7 on a normalized scale for all interconnects. U4 is shown with blue circles, U5 is shown with green squares and U6 is shown with red crosses (Test Board-A, 6MHz)*

# Threshold for Prognostic Distance

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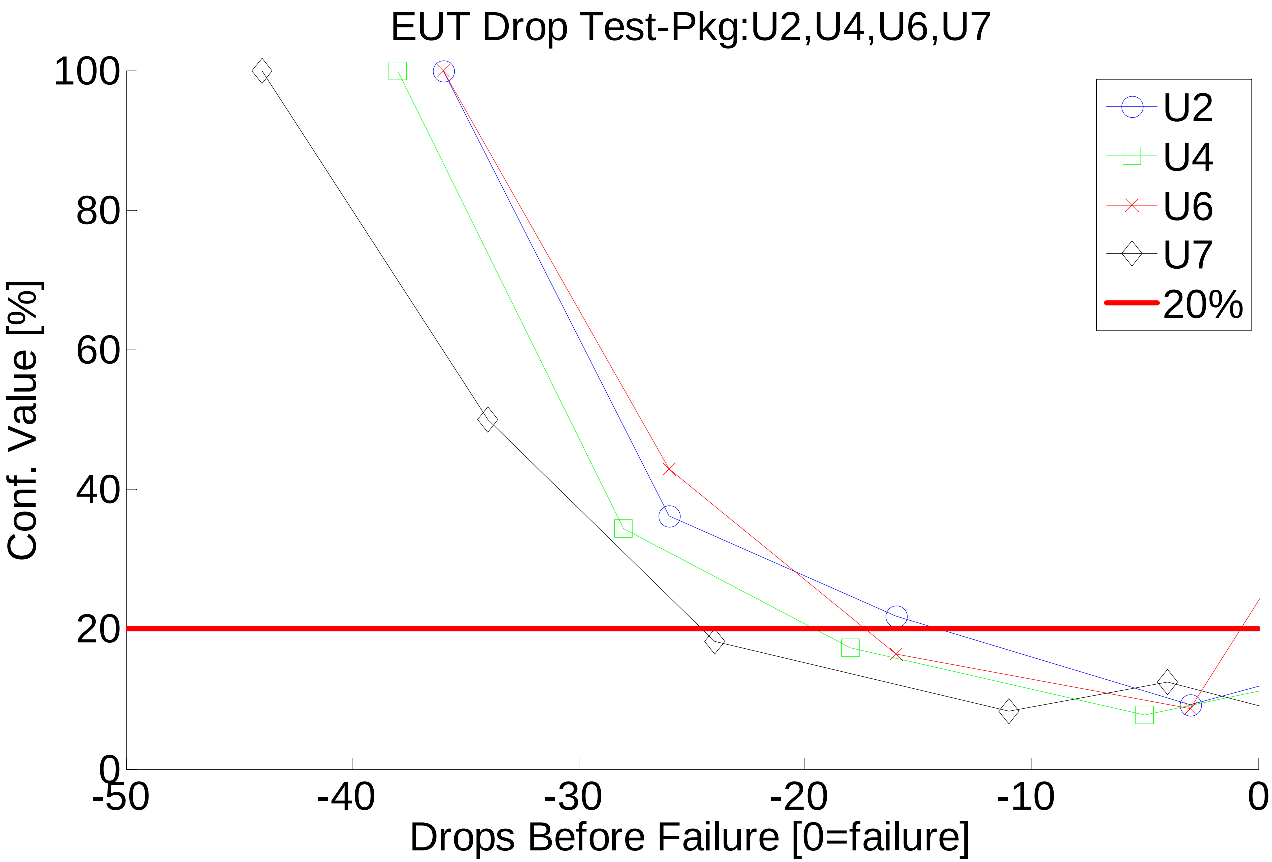
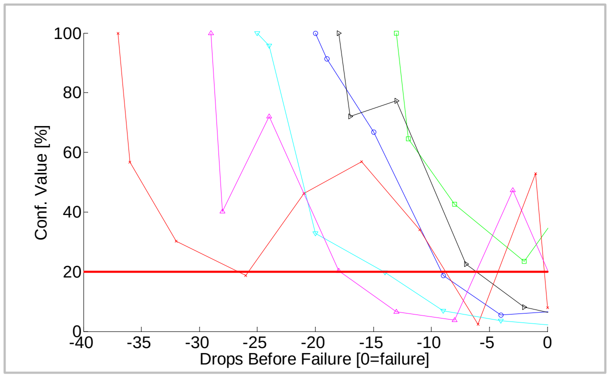
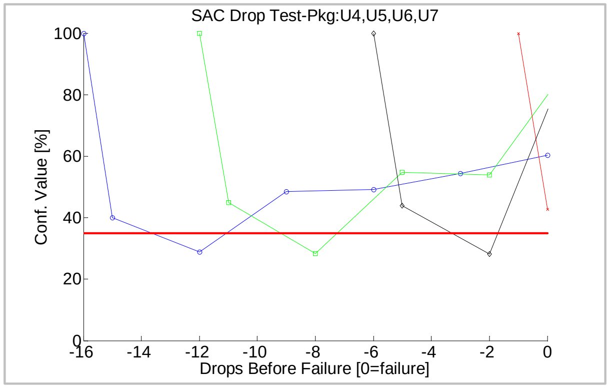



*Method for determining prognostic distance using a threshold value shown in red. Each trace is a individual package. (Test Board-A)*

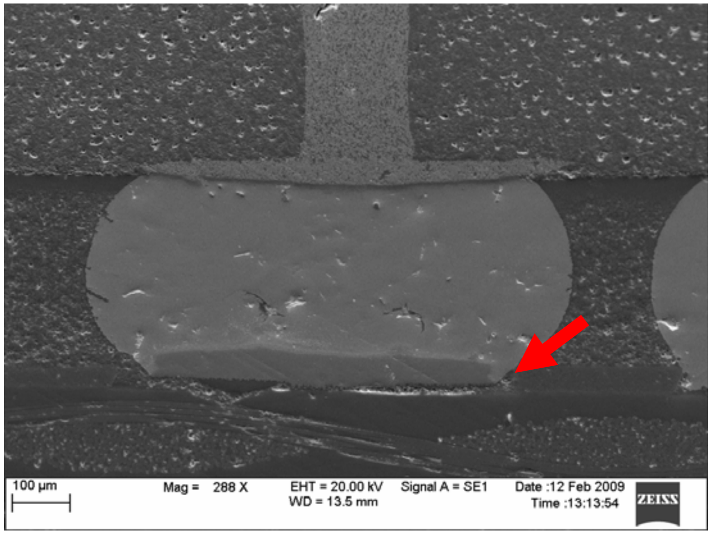
# Prognostic Distance

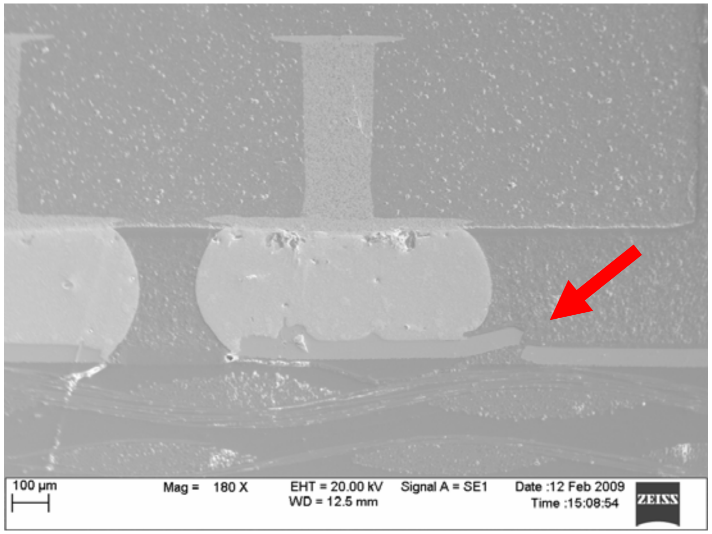
## > *CV vs Time (2.33MHz, 6 MHz)*

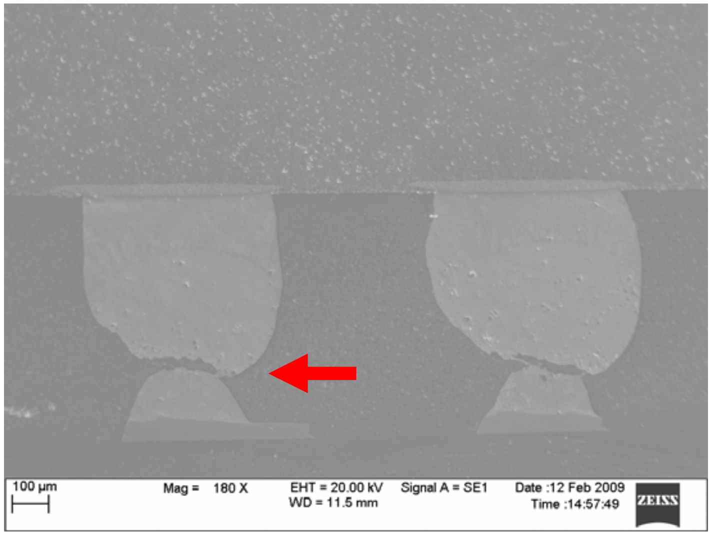
| Interconnect Type | Frequency | Threshold Confidence Value (%) | Average Prognostic Distance (No of Drops) | Std. Deviation (No of Drops) | False Positives |
|---|---|---|---|---|---|
| SAC305 | 2.33MHz | 50 | 8.33 | 5.03 | 0 |
| 63Sn37Pb | 2.33MHz | 70 | 23.75 | 13.43 | 0 |
| 90Pb10Sn | 2.33MHz | 85 | 18.17 | 10.65 | 0 |
| Cu-CCGA | 2.33MHz | 30 | 22.75 | 10.9 | 0 |

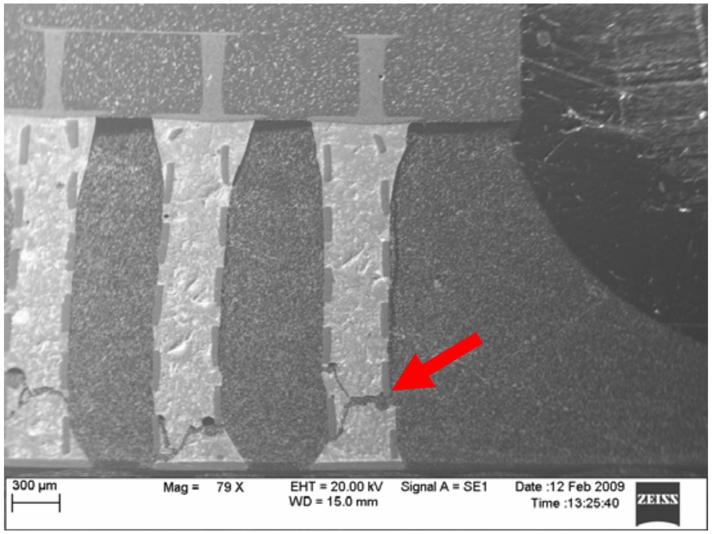
| Interconnect Type | Frequency | Threshold Confidence Value (%) | Average Prognostic Distance (No of Drops) | Std. Deviation (No of Drops) | False Positives |
|---|---|---|---|---|---|
| SAC305 | 6 MHz | 35 | 9 | 4 | 0 |
| 63Sn37Pb | 6 MHz | 20 | 18.75 | 4.65 | 0 |
| 90Pb10Sn | 6 MHz | 25 | 13.17 | 9.85 | 0 |
| Cu-CCGA | 6 MHz | 30 | 43.5 | 23.39 | 0 |

# Failure Modes



# Part-II: Summary and Conclusions

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A technique based on resistance measurements of solder interconnects has been developed to derive damage pre-cursors for electronic assemblies

Measurements of prognostic distance exhibit that the presented techniques can be used for early detection of impending failure in electronics

Prognostic distances have been quantified for various interconnects, and all have been shown to be positive

The trade off between prognostic distance and the propensity of a false positive have been shown to be inversely proportionate using this technique