Product Life-Cycle Management and Decision Support Models for Area-Array Electronics in Extreme Environments

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Objective

Development of a tool which can be used for appropriate selection and deployment of area-array packages in harsh environments.

Motivation

Scarcity of models for turn key approach, for making trade-offs between geometry and materials and quantitatively evaluating the impact on reliability.

Component Obsolescence, multiple suppliers, product platforms, die shrink, and underfills.

Existing standards, publications do not address a complete set of system-level material and design parameters.

First-order models typically address single effects only.

State-of-Art

Previous studies have shown the,

Effect of material and geometric parameters on reliability of flip-chip on organic laminate printed circuit boards [Yeh et al., 1996, Popelar, 1998].

2-D analysis of geometry and architecture parameters for trade-off studies [Lu 2000].

Non-linear finite element models [Darveaux 1996, Gustafsson 2000, Lall 2004]

First-order closed form models [Engelmaier 1984, Clech 1996, Vandevelde 1998].

Scope of the Guidelines

Aid for understanding the sensitivity of component reliability to geometry, package architecture, material properties and board attributes.

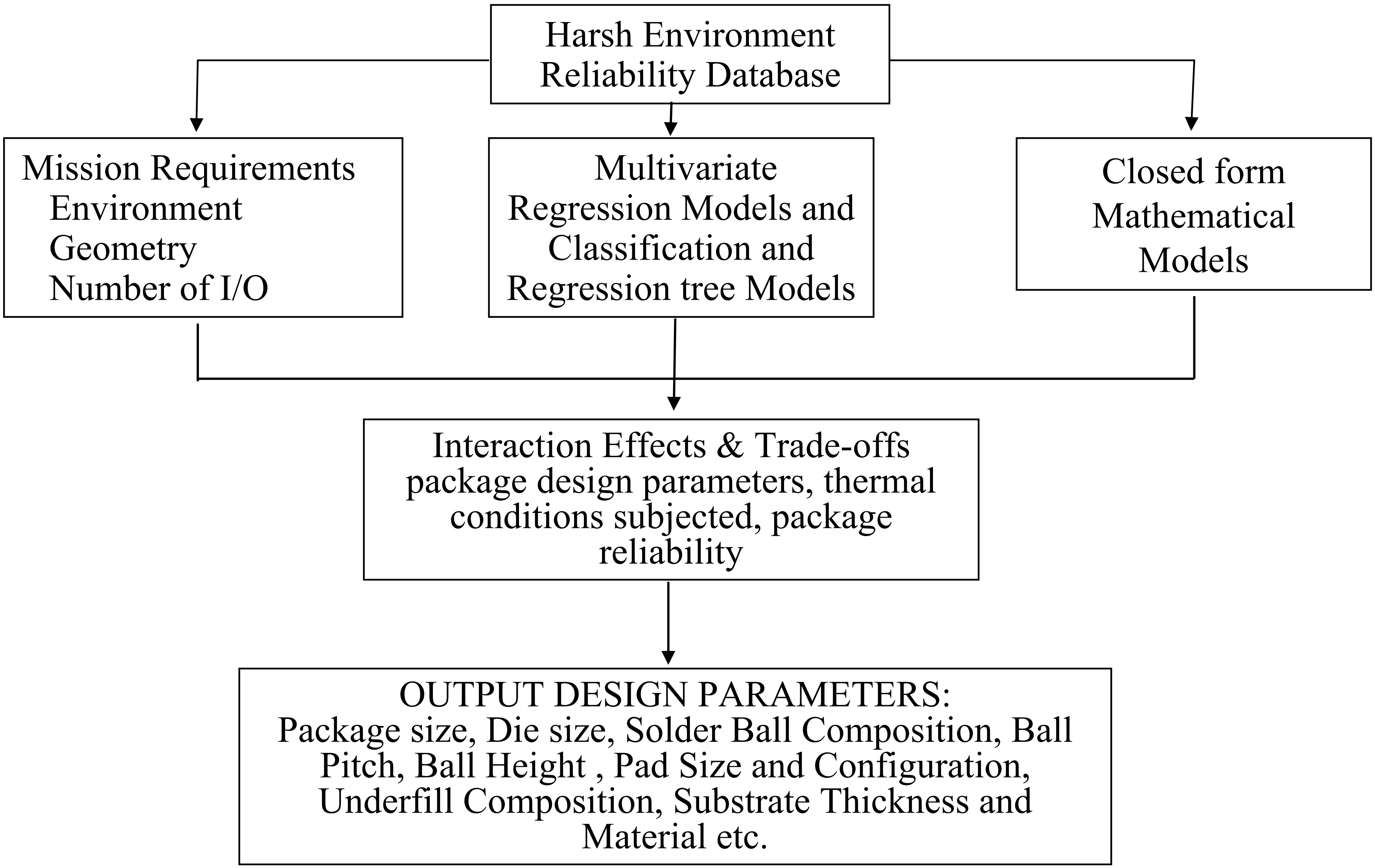
Tool for doing trade-offs between geometry, materials and quantitatively evaluating the impact on reliability.

Does NOT specify –

The required level of component reliability for use in various mission critical applications.

A comprehensive library of every component that can be used in harsh environments.

Structure


Harsh Environment Reliability Database
Mission Requirements
Environment
Geometry
Number of I/O
Multivariate Regression Models and Classification and Regression tree Models
Closed form Mathematical Models
Interaction Effects & Trade-offs
package design parameters, thermal conditions subjected, package reliability
OUTPUT DESIGN PARAMETERS:
Package size, Die size, Solder Ball Composition, Ball Pitch, Ball Height , Pad Size and Configuration, Underfill Composition, Substrate Thickness and Material etc.

Thermal Profiles

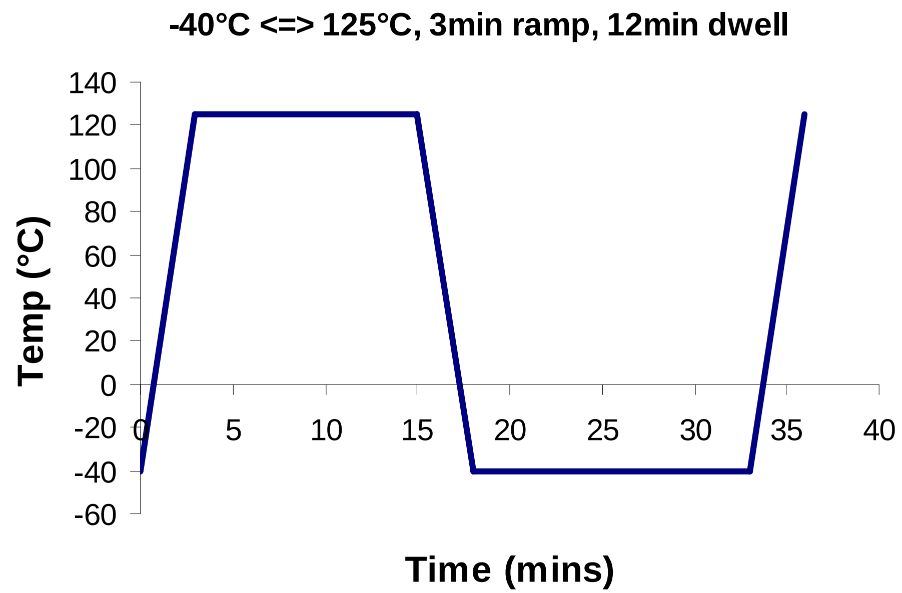
-40°C to 125°C, 3min ramp, 12min dwell

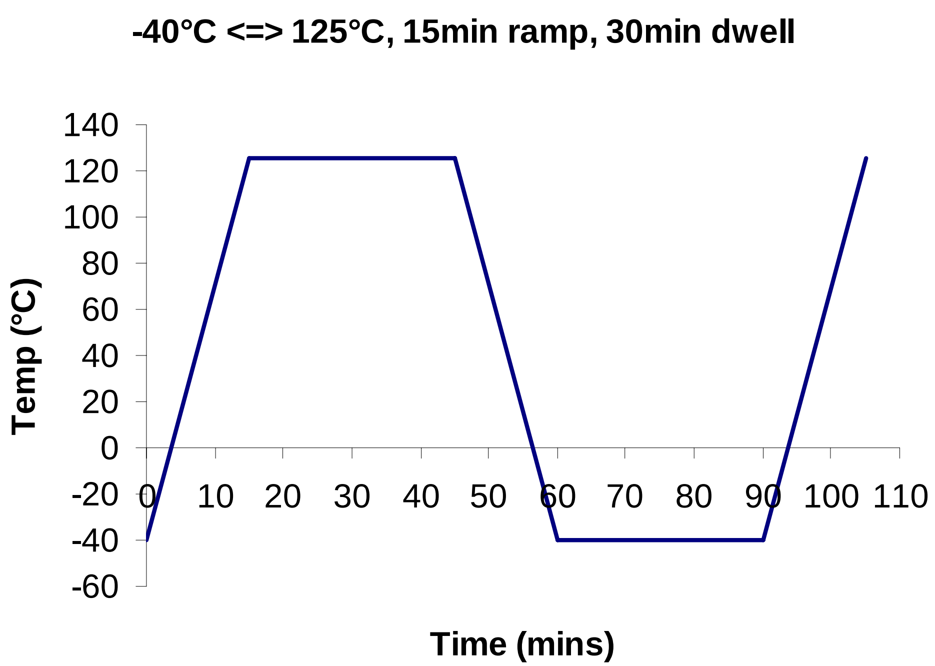
-40°C to 125°C, 15min ramp, 15min dwell

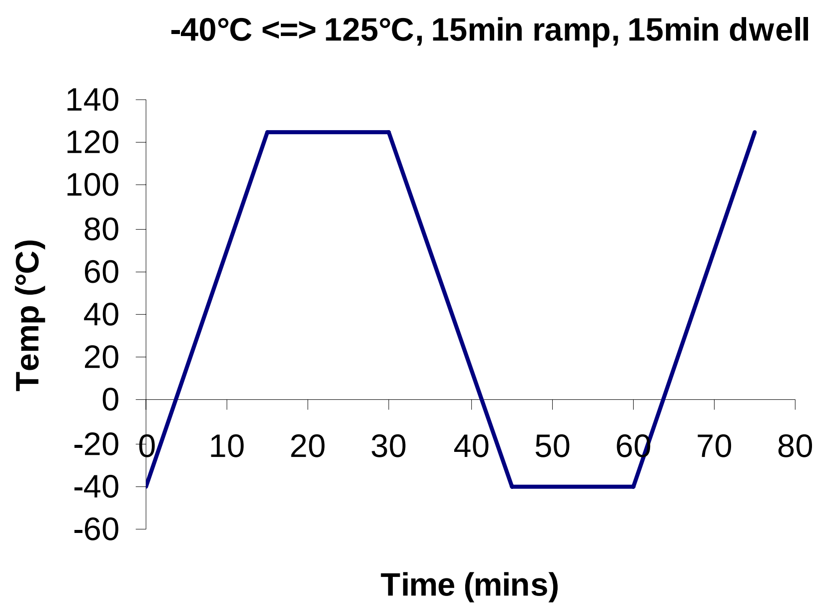
-40°C to 125°C, 15min ramp, 30min dwell

0°C to 100°C, 30min ramp, 30min dwell

-55 to 125 °C, 6 c/h, 5 min dwell







Scope of Accelerated Test Database

> *FlexBGA, PBGA*

	FlexBGA	PBGA
Package Size	7.5mm to 27mm	15mm to 27mm
Number of I/O	40 to 381	132 to 324
Die Size	3.5mm to 11.5mm	6.8mm to 10mm
Ball Diameter	0.3mm - 0.5mm	0.5mm to 0.8mm
Ball Pitch	0.5mm, 0.8mm, 1.0mm	1.0mm, 1.27mm
PCB type	4 Layer FR-4	4 Layer FR-4
PCB thickness	0.85mm, 1.6mm	1.6mm
Surface Finish	OSP, HASL, Ni/Au	OSP, HASL, Ni/Au

Scope of Accelerated Test Database
> *Flip-Chip*

	Flip-Chip
Die Size	3 mm to 12.6 mm
Ball Count	42 to 184
Ball Pitch	0.2 mm to 0.457 mm
Ball Diameter	0.04 mm to 0.195 mm
Ball Height	0.04 mm to 0.147 mm
Solder Composition	Sn63Pb37, Sn96.5Ag3.5, 95.5Sn3.5Ag1.0Cu, Sn99.3Cu0.7, Sn95.8Ag3.5Cu0.7
PCB Thickness	0.5 mm to 1 mm
T_{High}, Accelerated Test	100°C, 125°C, 150°C
T_{Low}, Accelerated Test	-55°C, -40°C, 0°C

Stepwise Regression

For each variable added, test to see if any previously selected variable may be deleted without appreciable loss of explanatory power.

$$F_\psi = a + \sum_{k \in \psi} b_k x_k$$

where a and b_k ($k \in \psi$) are estimated using method of least squares.

$$\psi \subset \{1, 2, 3........, p\}$$

Select subset, $q \le p$, candidate variables

Step	1	2	3	4	5	6	7
Constant	2494.3	1783.9	2669.1	1088.2	910.2	3080.6	4438.8
DieLengthMM	-147	-115	-87	-87	-296	-543	-665
T-Statistic	-3.24	-2.59	-2.13	-2.30	-2.23	-3.59	-4.03
P-Value	0.002	0.013	0.039	0.026	0.031	0.001	0.000
UnderfillEGpa		56	136	158	144	128	110
T-Statistic		2.53	4.42	5.37	4.77	4.46	3.67
P-Value		0.015	0.000	0.000	0.000	0.000	0.001
BallPitchMM			-6555	-8877	-8351	-7227	-6925
T-Statistic			-3.41	-4.56	-4.31	-3.93	-3.83
P-Value			0.001	0.000	0.000	0.000	0.000
BallDiaMM				22923	29754	31895	32913
T-Statistic				2.94	3.41	3.93	4.13
P-Value				0.005	0.001	0.000	0.000
UndercoverAreaSqMM					19	43	53
T-Statistic					1.63	3.16	3.63
P-Value					0.110	0.003	0.001
BallHeightMM						-19650	-18387
T-Statistic						-2.83	-2.69
P-Value						0.007	0.010
DeltaT							-6.9
T-Statistic							-1.67
P-Value							0.102
S	1055	999	900	832	817	757	742
R-Sq	18.28	28.27	43.00	52.37	55.16	62.33	64.74
R-Sq(Adj)	16.54	25.16	39.20	48.04	49.94	56.94	58.72
C-P	46.5	37.3	22.8	14.3	13.2	7.2	6.5

Multivariate Regression

Linear : $$t_{63.2\%} = a_0 + \sum_{k=1}^{n} b_k f_k$$

Log : $$t_{63.2\%} = a_0 \prod_{k=1}^{n} \left(f_k\right)^{b_k}$$

Log Multivariate Regression Models > *FlexBGA*

MULTIVARIATE REGRESSION MODEL OF FLEX-SUBSTRATE BGA THERMAL FATIGUE DATA

Predictor	Coefficient and Indices (Log A, b_n)	SE Coeff	T	p
LogConstant (or Log A)	3.8066	0.7513	5.07	0.000
LogDietoBodyRatio	-1.7395	0.1532	-11.35	0.000
LogBallCount	0.41623	0.08347	4.99	0.000
LogBallDiaMM	0.9485	0.2779	3.41	0.002
LogPCBthkMM	-0.5322	0.1105	-4.82	0.000
LogEMCFillID	0.19127	0.0434	4.41	0.000
LogMasfDefID	0.25762	0.06285	4.10	0.000
LogBoardFinishID	-0.07794	0.04044	-1.93	0.061
LogDeltaT	-0.9453	0.2789	-3.39	0.002
S = 0.0946 R-Sq = 90.20% R-Sq(adj) = 88.20%				

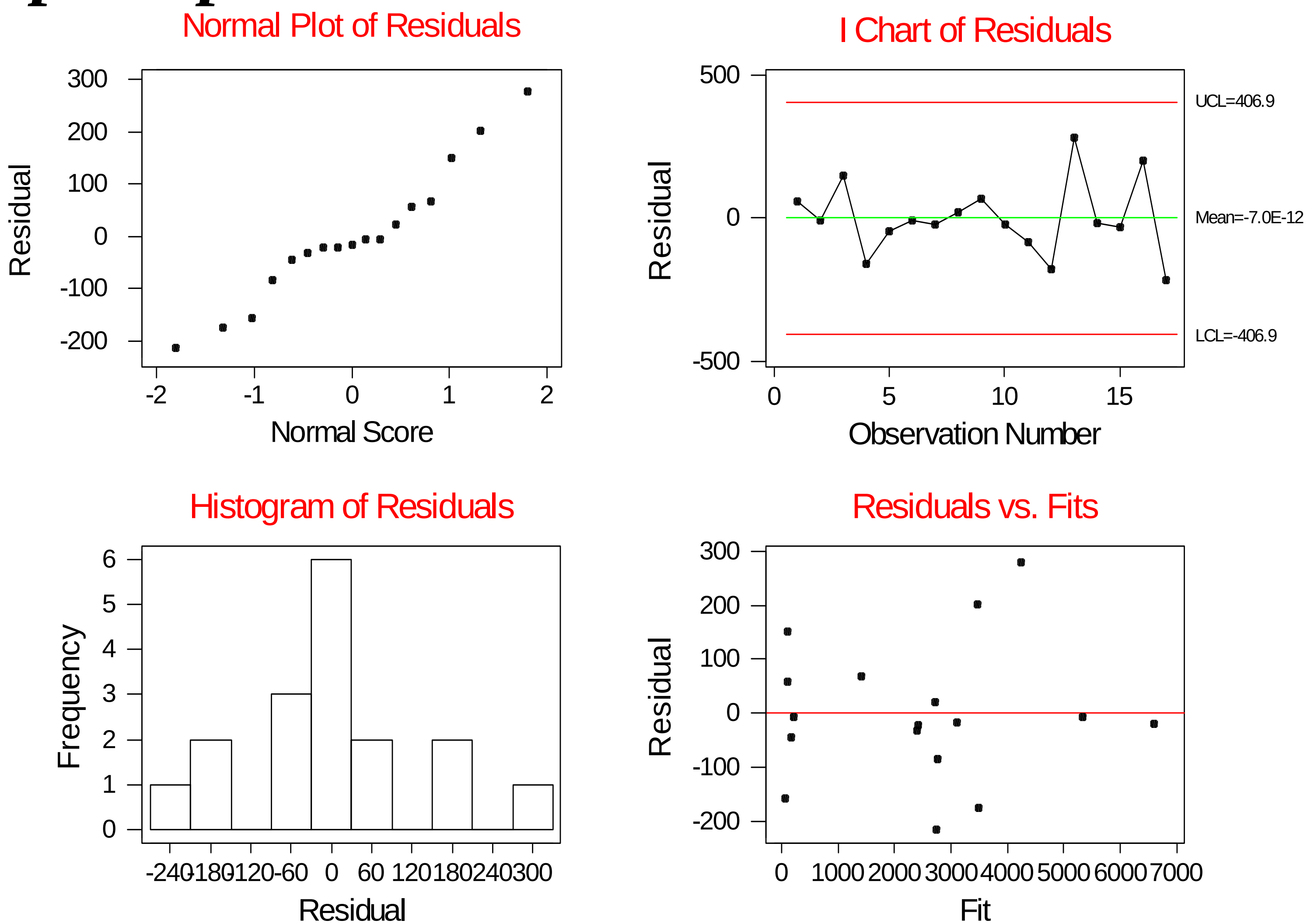
Log Multivariate Regression Models > *Flip-Chip*

Predictors (ln a_0, f_k)	Coeff (b_k)	SE Coeff	T	P-Value
Constant (ln a_0)	66.924	19.565	3.421	0.002
lnUndCovSqmm	34.088	10.841	3.144	0.004
lnUndEGpa	0.481	0.219	2.195	0.035
lnUndCTEppm	-0.292	0.102	-2.862	0.007
lnSolderEGpa	-0.665	0.283	-2.352	0.025
lnSolderDiaMM	1.805	0.867	2.082	0.045
lnDeltaTdegC	-4.813	2.342	-2.055	0.048
lnPitchMM	-0.800	0.366	-2.184	0.036
lnBallHgtMM	2.645	0.794	3.331	0.002
lnDiagLenMM	-68.216	21.645	-3.152	0.003

Linear Multivariate Regression Models
> *Flip-Chip*

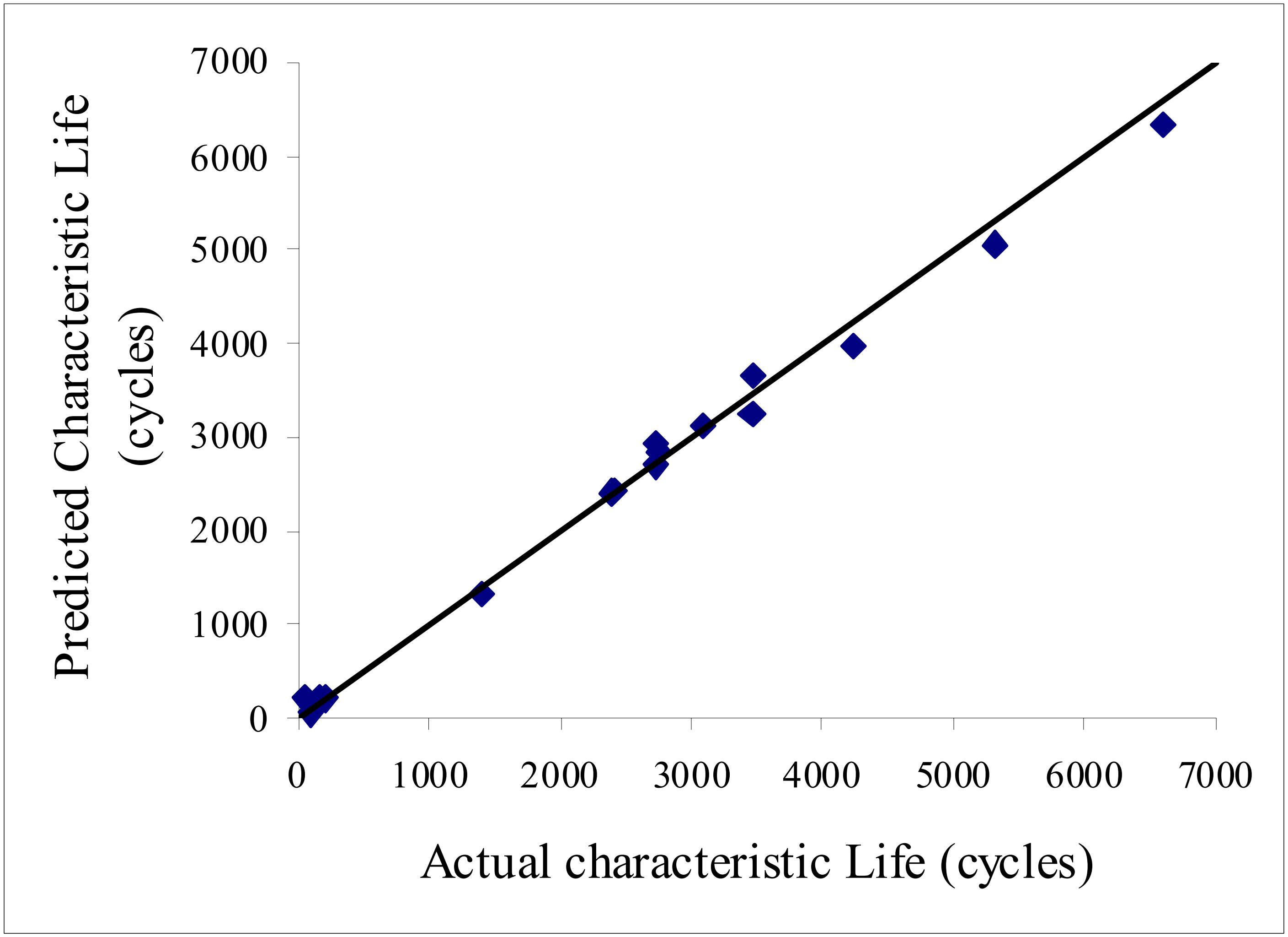
Predictors (a_0, f_k)	Coeff (b_k)	SE Coeff	T	P-Value
Constant	8334.22	1640.70	5.080	0.000
DieSizeMM	-163.12	56.43	-2.891	0.016
UnderfillID	1405.40	451.18	3.115	0.011
SolderComp	129.64	87.10	1.488	0.167
BallDiaMM	15201.29	4935.58	3.080	0.012
PadTypeID	1177.71	242.40	4.859	0.001
DeltaT	-48.05	6.12	-7.857	0.000

Residual Plots for Model Diagnostics
> Flip-Chip



Model Correlation

Actual Vs Predicted, Flip-Chip



Failure Mechanics Models

> *Flip-Chip*

Compatibility Conditions

x-displacements at the bottom of the flip-chip and top of the substrate [Suhir 1986, 1991],

$$u_1(x) = \alpha_1 \Delta t x + \lambda_1 \int_0^x F_1(\xi) d\xi - \kappa_1 \tau_1(x) - \frac{h_1}{2} \int_0^x \frac{d\xi}{\rho(\xi)}$$

$$u_2(x) = \alpha_2 \Delta t x + \lambda_2 \int_0^x F_2(\xi) d\xi - \kappa_2 \tau_2(x) - \frac{h_2}{2} \int_0^x \frac{d\xi}{\rho(\xi)}$$

$$\kappa = \kappa_1 + 2\kappa_2 + \kappa_3 \qquad k = \sqrt{\frac{\lambda}{\kappa}}$$

$$\tau(x) = \frac{\Delta\alpha \Delta t}{\sqrt{\lambda\kappa}} \frac{\sinh kx}{\cosh kl}$$

$$\lambda_i = \frac{1-\nu^2}{E_i} h_i \qquad \kappa_i = \frac{h_i}{3G_i}$$

Failure Mechanics Models

> *Flip-Chip*

Hysteresis Loop

Time-independent plasticity during temperature ramps modeled by parabolic relation [Knecht 1991]

Plastic flow equation with creep at dwell periods [Hall 1984, Wong 1991] used for hysteresis loop

$$\gamma_B - \gamma_A = \left(\frac{\tau_B}{\tau_P}\right)^2$$

where,

$$\tau_P(\text{Mpa}) = 348.79 - 2.07 \times T(°C)$$

$$\overset{\circ}{\gamma}_{creep} = A(T)\tau^3$$

Continue loop iteration untill it converges to 0.1% accuracy

Failure Mechanics Models

Life Computation (Energy-Based Models)

Modified Morrow's Model: $N_f \nu^{(h-1)} = \left[\frac{C \Delta \sigma}{\Delta W} \right]^{\left(\frac{1}{m}\right)}$

m = 0.7, C = 1.69, h = 0.9

Darveaux's Damage Relationships:

$$N_0 = K_1 (\Delta W)^{K_2}$$

$$\frac{da}{dN} = K_3 (\Delta W)^{K_4}$$

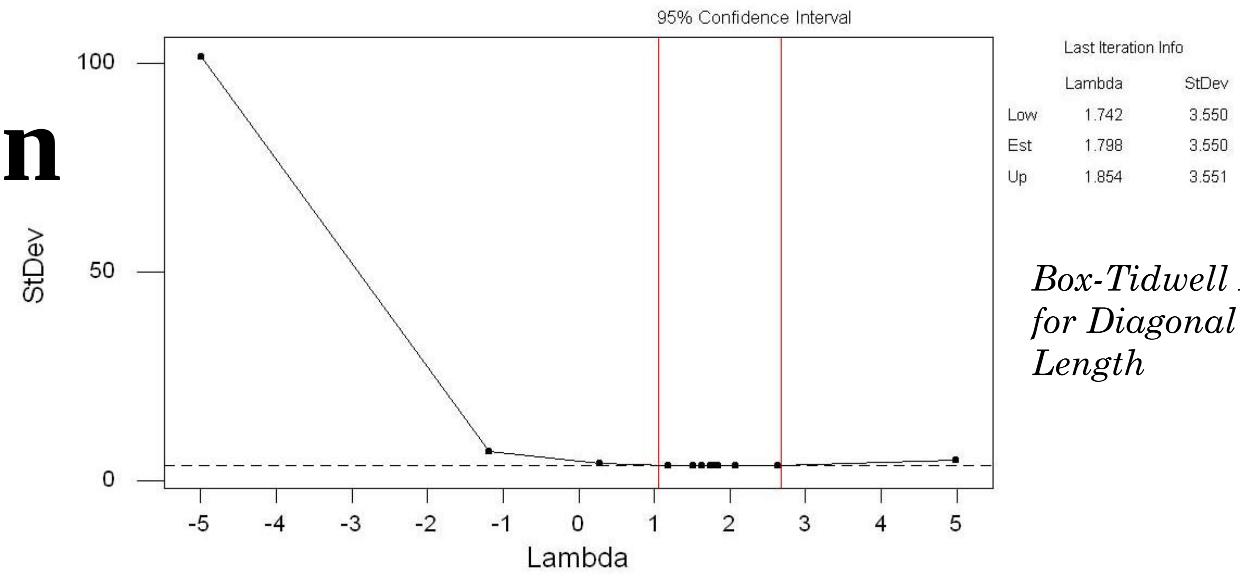
	K_1	K_2	K_3	K_4
Darveaux [1992, 1995, 2000]	48300	-1.64	3.8×10^{-7}	1.04
Lall [2003, 2004]	28769	-1.53	6×10^{-7}	0.7684

Box-Tidwell Transformation

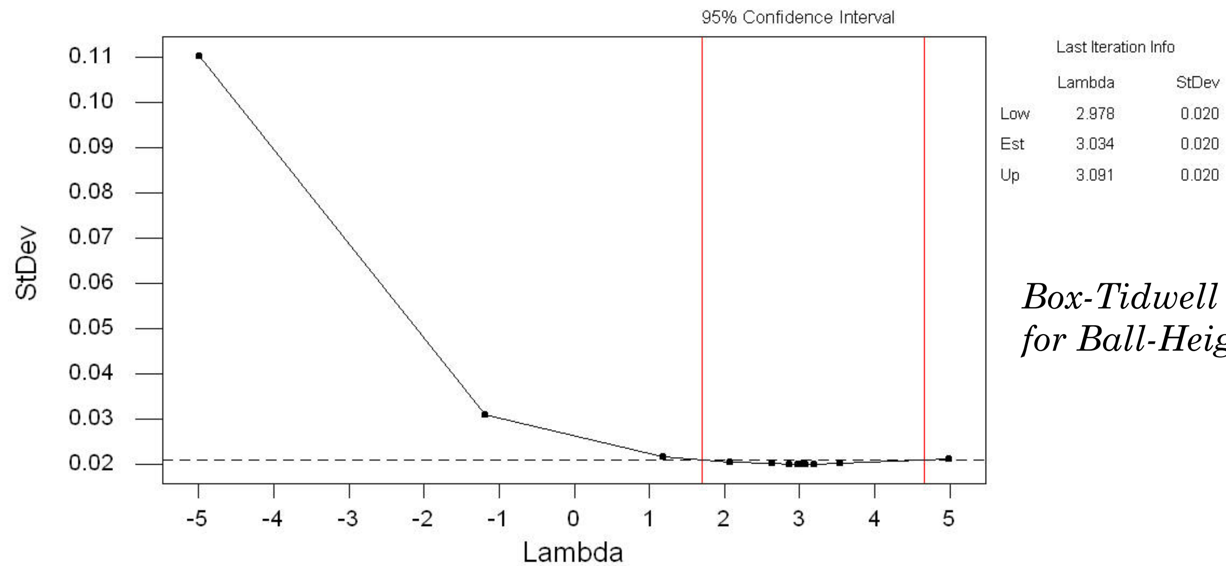
Determine the form of the transformation on regressor variables, and relation between the response and regressor variables.

$$E(t) = f(\xi, \beta_0, \beta_1) = \beta_0 + \beta_1 \xi$$

$$\xi = \begin{cases} x^{\alpha}, & \alpha \neq 0 \\ \ln x, & \alpha = 0 \end{cases}$$



Box-Tidwell Plot for Diagonal Length



Box-Tidwell Plot for Ball-Height

Model Validation
Box-Tidwell Transformation, Flip-Chip

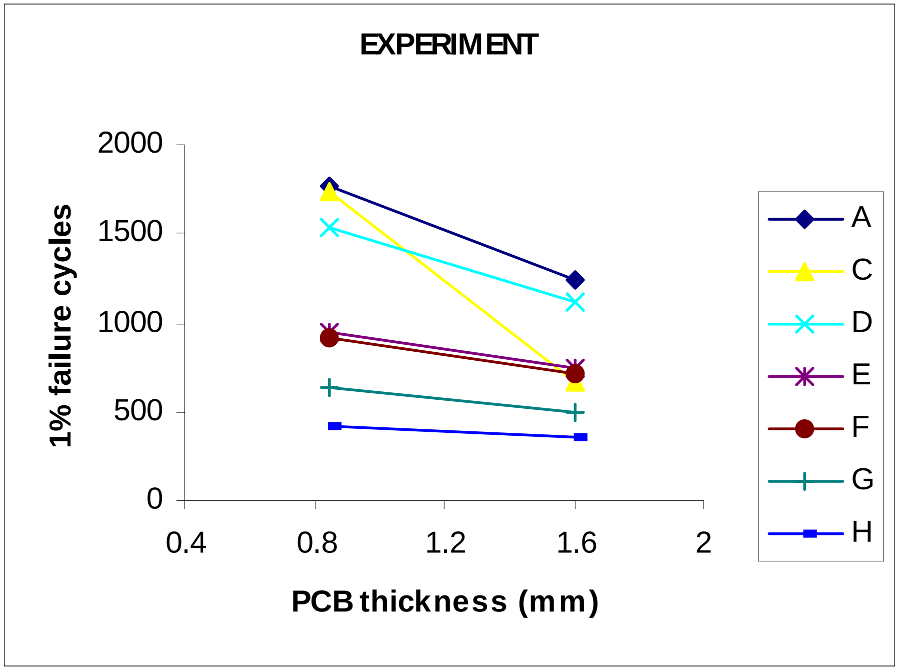
Parameter	Failure Mechanics Value	Statistical Value
Diagonal Length	2	1.798
Bell Height	2.7	3.034
Ball Diameter	4	4.89
DeltaT	2	2.7

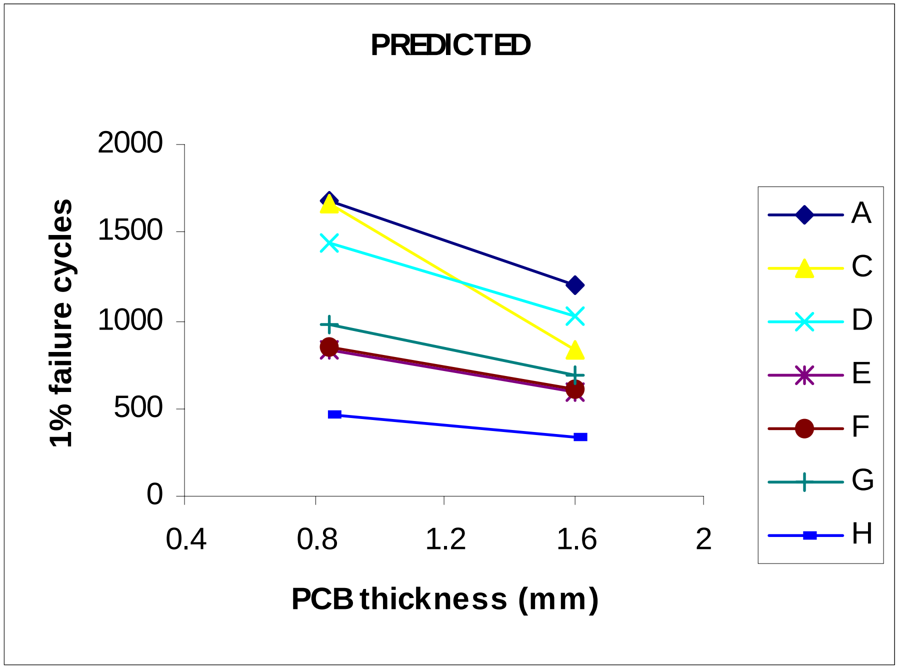
Model Validation

Parametric variation used to validate the statistical model with the experimental data:

- Die Size
- Ball count
- Underfill / Non-underfill
- Ball Diameter
- Pad configuration (SMD/NSMD)
- Thermal cycle condition (ΔT)

Effect Of PCB Thickness > FlexBGAs

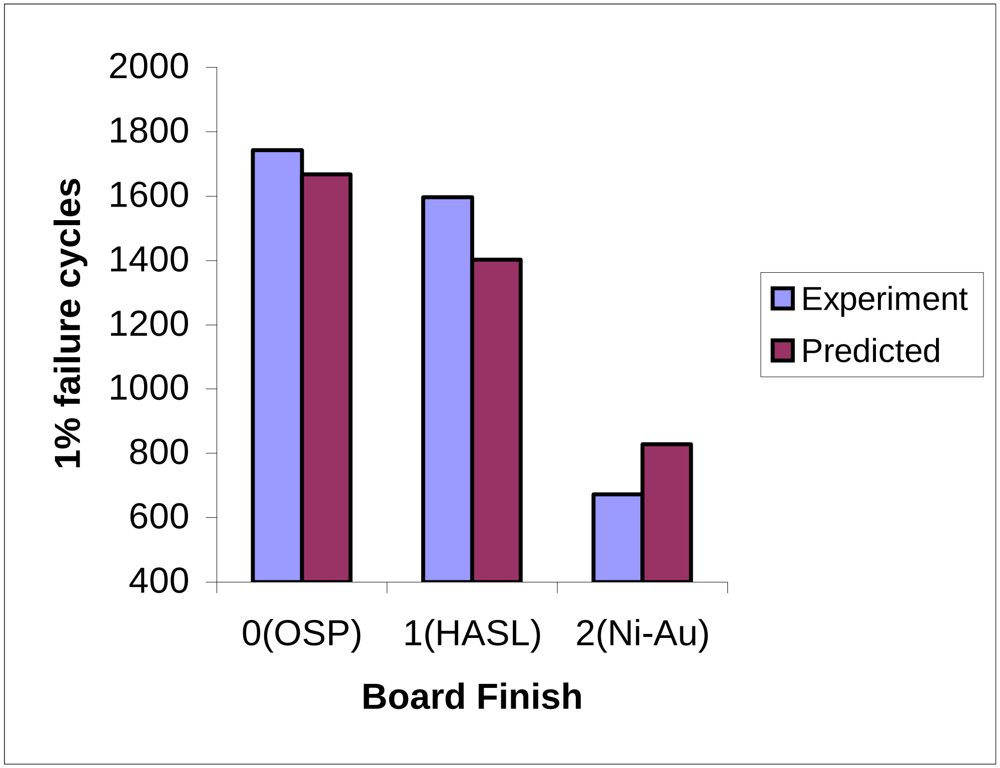




Increasing PCB thickness reduces the thermal reliability

Effect of Board Finish

> *FlexBGA*

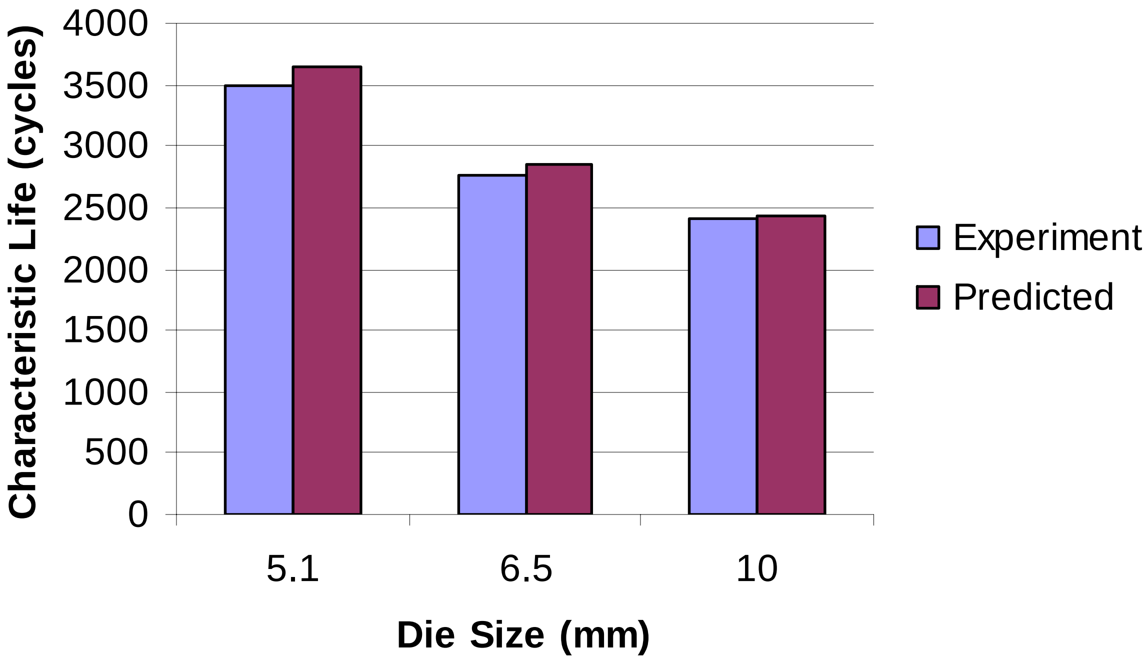


Board Finish	Experimental	Model
0 (OSP)	1743	1668
1 (HASL)	1597	1403
2 (Ni-Au)	673	828

OSP Finish gives the best thermal reliability and Ni-Au Finish is worst

Effect of Die Size

> *Flip-Chip*

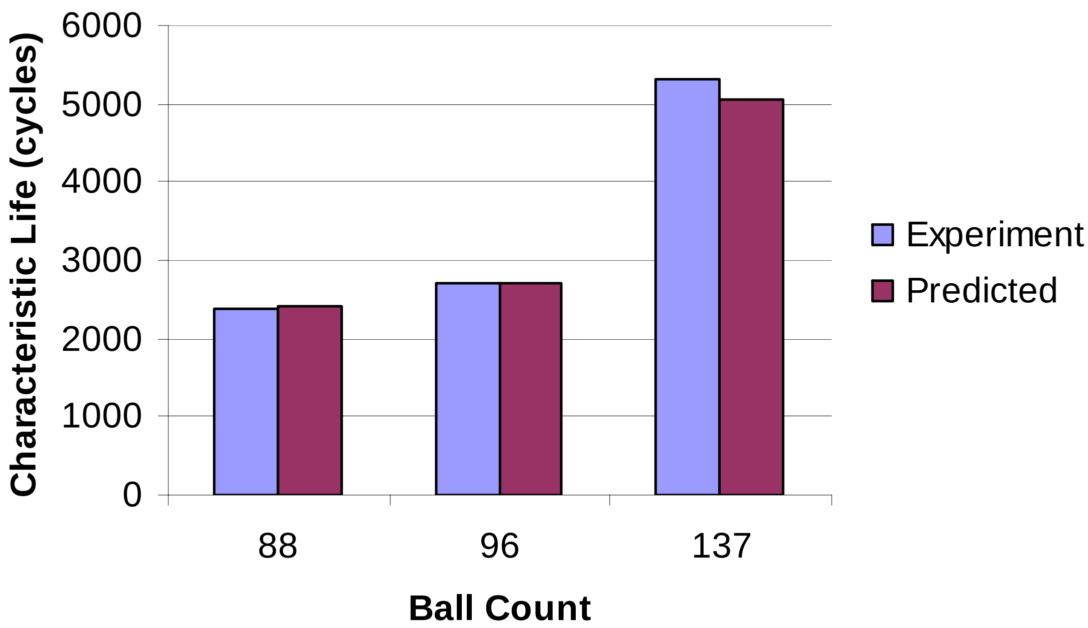


Increasing Die Size reduces the thermal reliability

Die Size (mm)	Ball Count	Pitch (mm)	Ball Dia (mm)	ATC	Characteristic Life (cycles)	
					Experiment	Model
5.1	88	0.2	0.112	-25°C to 140°C	3485	3656
6.5	96	0.25	0.098	-55°C to 140°C	2764	2843
10	184	0.2	0.126	-25°C to 140°C	2407	2426

Effect of Package I/O

> *Flip-Chip*

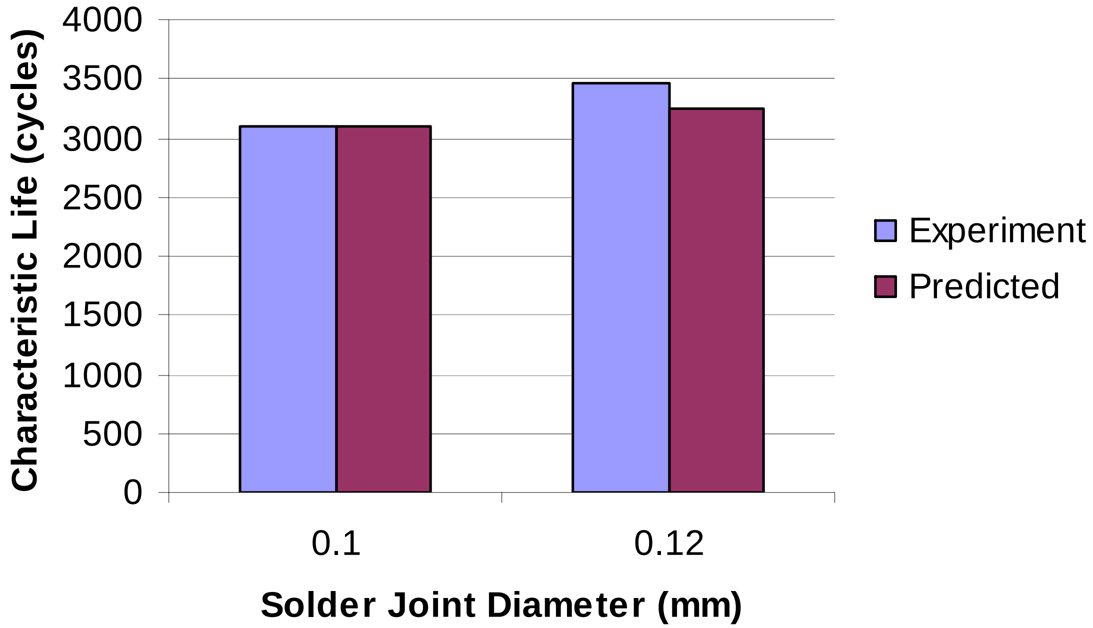


Increasing Ball Count increases the thermal reliability

Ball Count	Die Size (mm)	Pitch (mm)	Solder Composition	ATC	Characteristic Life (cycles)	
					Experiment	Model
88	5.1	0.2	Sn3.5Ag	-55°C to 140°C	2383	2410
96	12.6	0.46	Sn37Pb	-25°C to 140°C	2722	2697
137	12.6	0.2	Sn0.7Cu	0°C to 140°C	5322	5048

Effect Of Ball Diameter

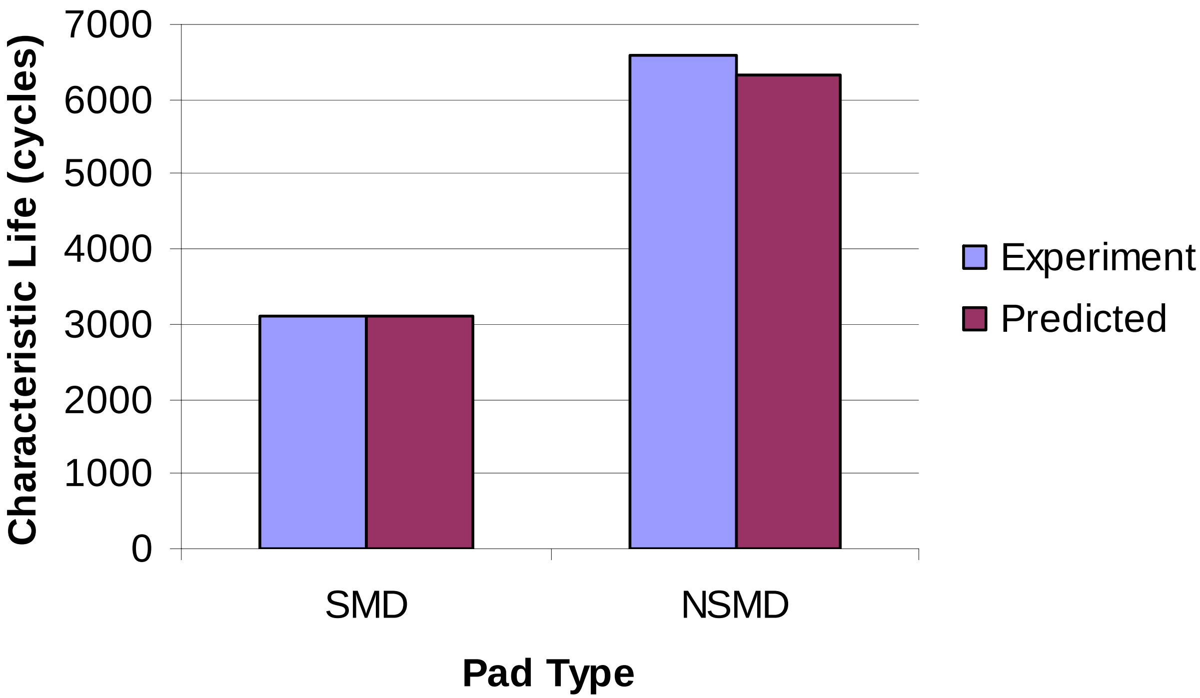
> *Flip-Chip*



Increasing Ball Diameter increases the thermal reliability

Ball Dia (mm)	Die Size (mm)	Solder Composition	ATC	Characteristic Life (cycles)	
				Experiment	Model
0.1	5.1	Sn3.5Ag	-25°C to 140°C	3092	3104
0.12	5.1	Sn3.5Ag	-25°C to 140°C	3456	3249

Effect Of Pad Configuration
> *Flip-Chip*

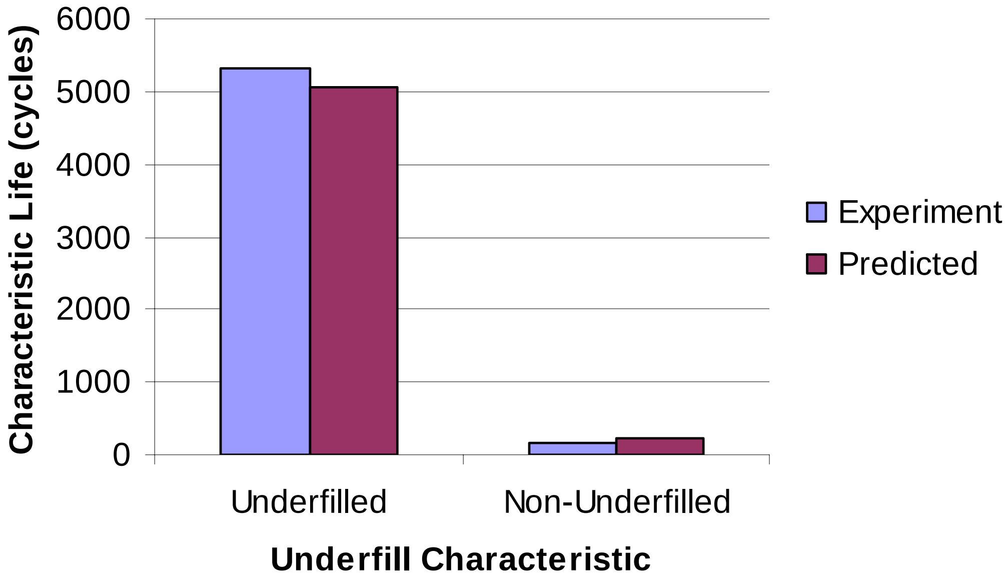


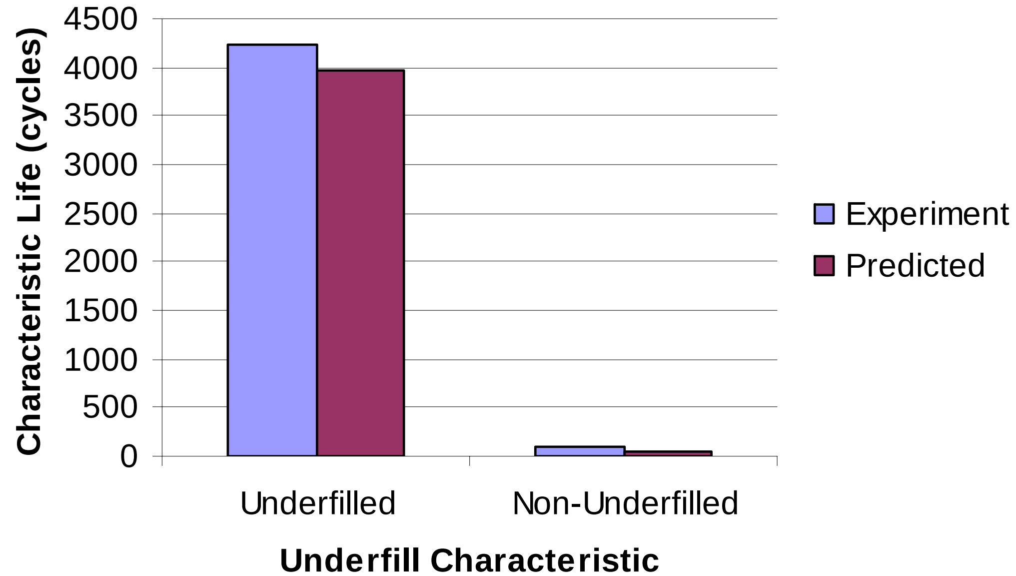
NSMD Pad configuration gives better thermal reliability than SMD Pad

Pad Type	Die Size (mm)	Solder Composition	ATC	Characteristic Life (cycles)	
				Experiment	Model
SMD	12.6	Sn0.7Cu	0°C to 100°C	5322	5048
NSMD	12.6	Sn37Pb	0°C to 100°C	6588	6328

Effect of Encapsulation

> *Flip-Chip*

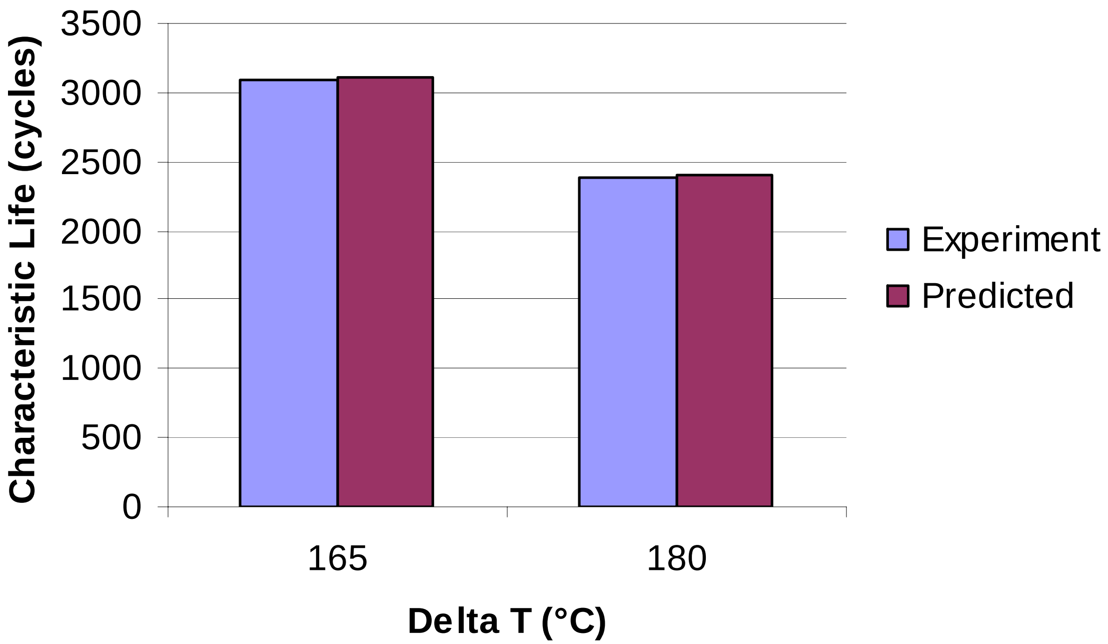




Encapsulation	Die Size (mm)	Solder Composition	ATC	Characteristic Life (cycles)	
				Experiment	Model
Underfilled	12.6	Sn0.7Cu	0°C to 110°C	5322	5048
Non-Underfill	12.6	Sn0.7Cu	-40°C to 140°C	171	213
Underfiled	5.1	Sn4Ag0.5Cu	-40°C to 140°C	4243	3958
Non-Underfill	12.6	Sn4Ag0.5Cu	-40°C to 140°C	101	41

Effect of Thermal Cycling Temperature

> *Flip-Chip*

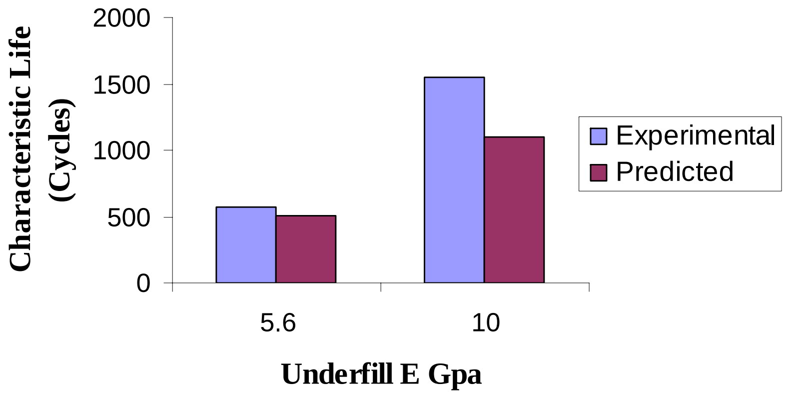


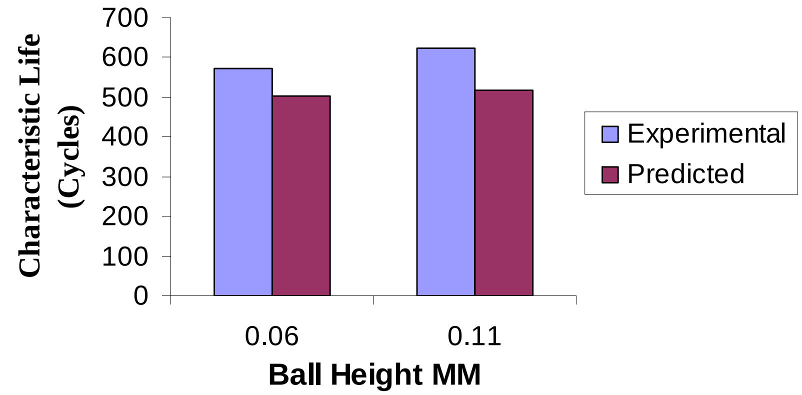
Increasing thermal cycling temperature reduces the thermal reliability

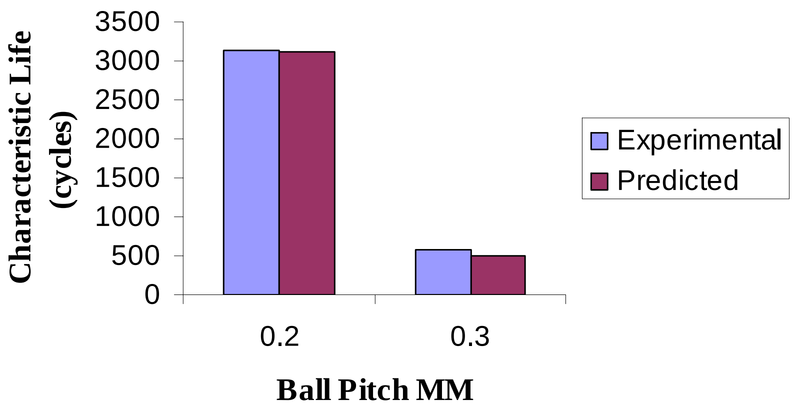
ATC	Cycle Time (mins)	Die Size (mm)	Ball Count	Ball Diameter (mm)	Characteristic Life (cycles)	
					Experiment	Model
-25°C to 140°C	60	5.1	88	0.10	3092	3104
-55°C to 125°C	17	5.1	88	0.12	2383	2410

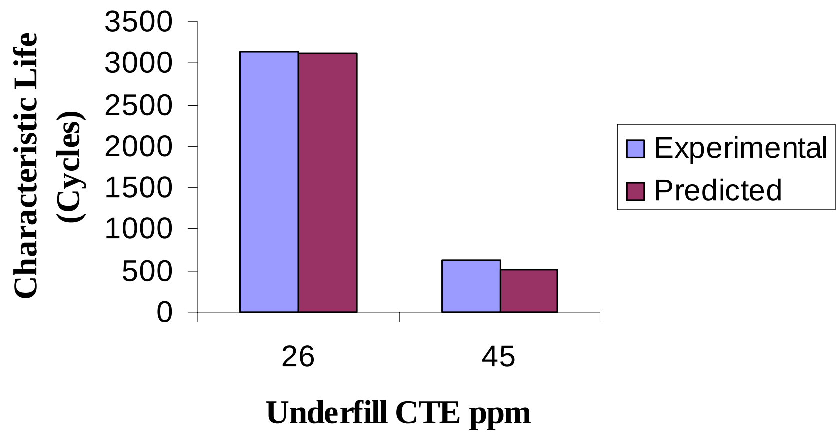
Model Validation

> *Flip-Chip*

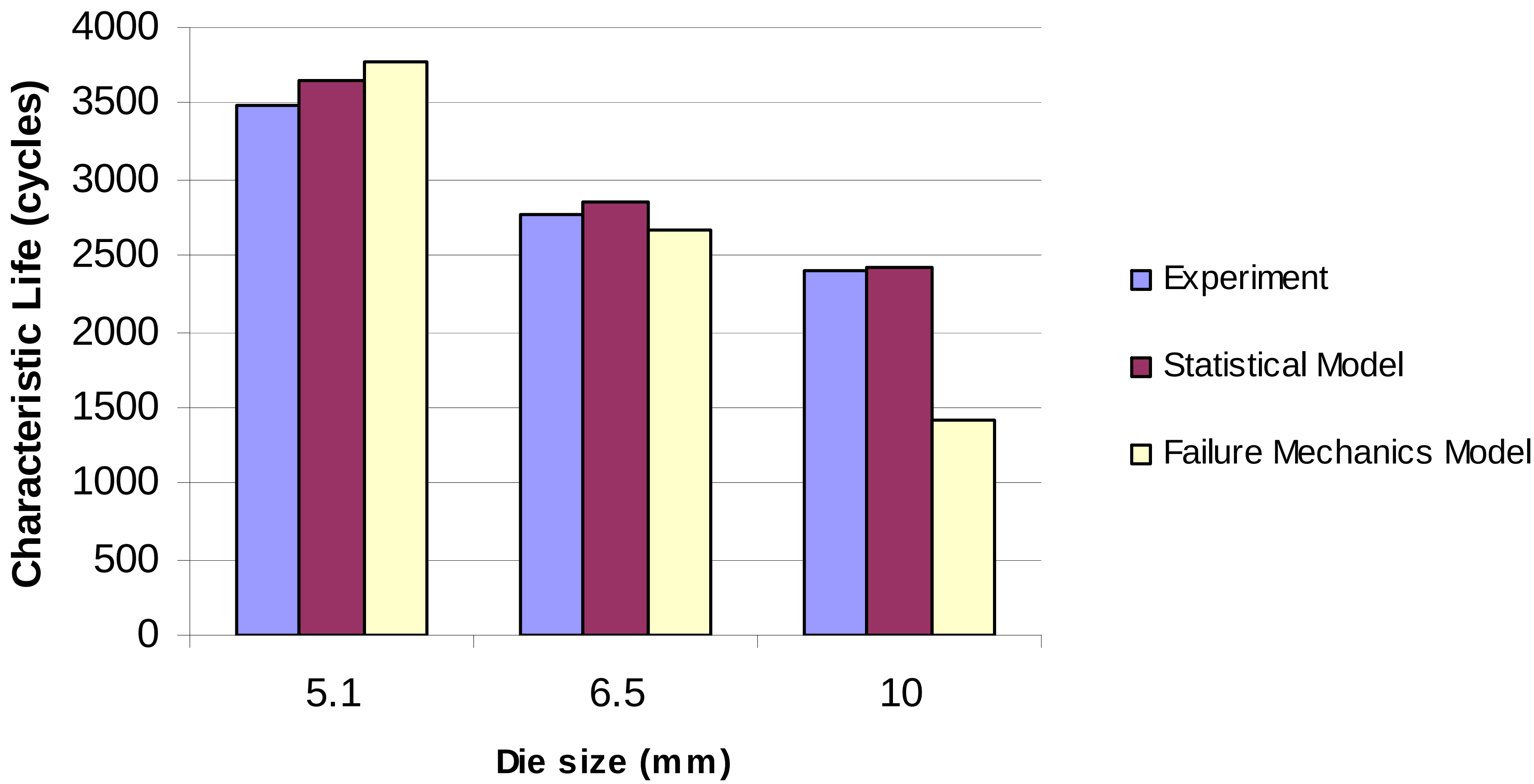






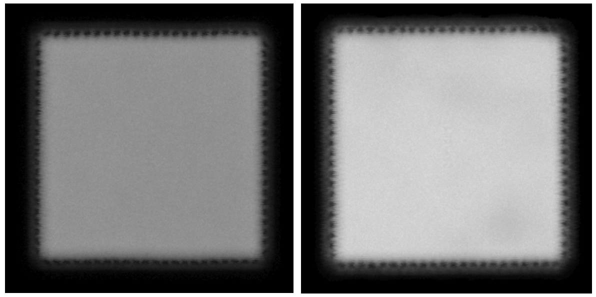


Convergence Between Model Prediction and Experimental Test Data



Nano-Underfills Reliability (CSAM)

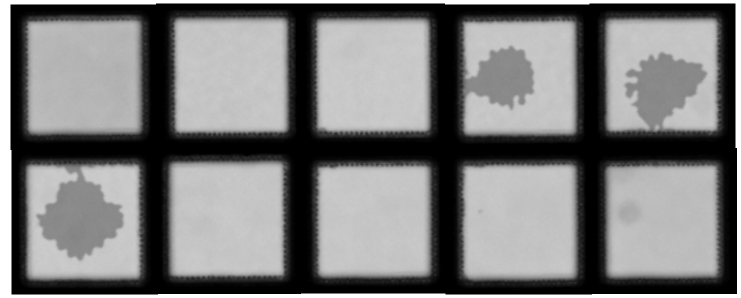
NUF-2



(a) (b)

Eutectic

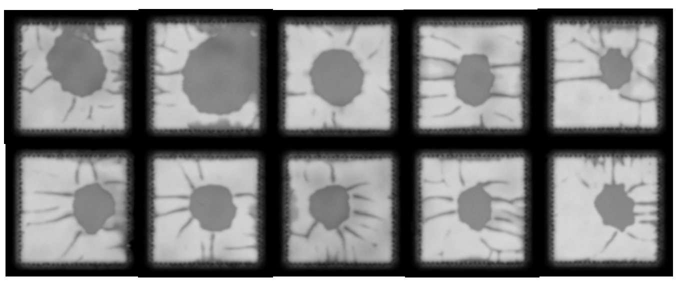
(a) As Cured, (b) After 3120 Cycles of -55°C to 125°C Thermal Shock, 100% Delamination



LF2 solder

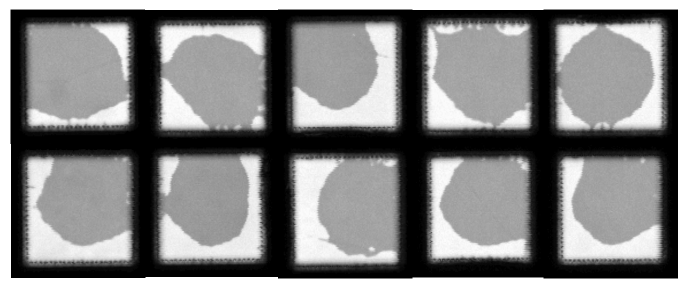
After 725 Cycles of -55°C to 150°C Thermal Shock, 70% fully Delaminated

AAB-05 or NUF-1



Eutectic

After 3120 cycles of -55°C to 125°C thermal shock

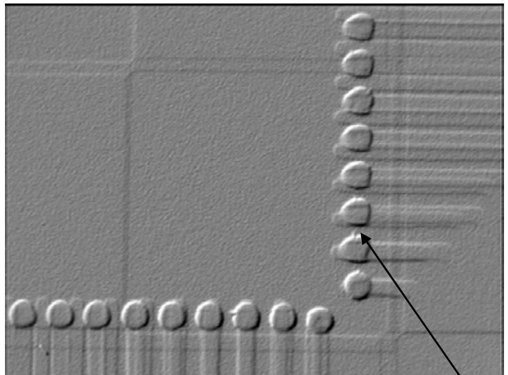


LF2 solder

After 725 cycles of -55°C to 150°C thermal shock

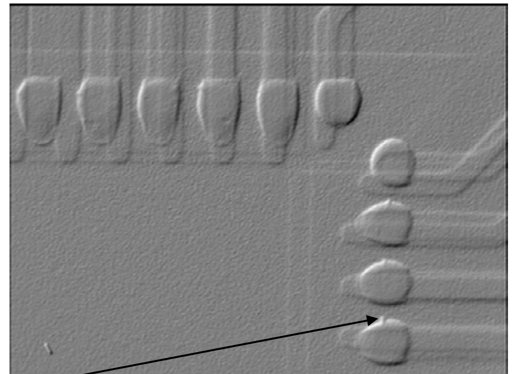
Nano-Underfills Reliability (X-ray)

NUF-2



Eutectic

After 3120 cycles of -55°C to 125°C thermal shock

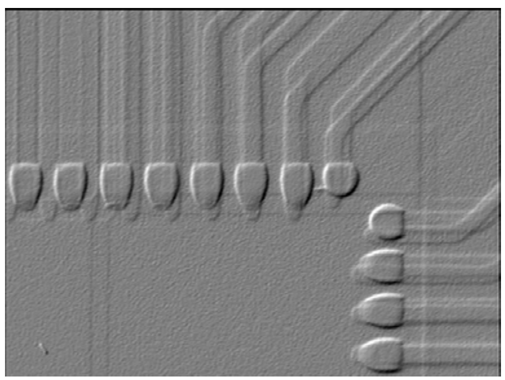


LF2 solder

After 725 cycles of -55°C to 150°C thermal shock

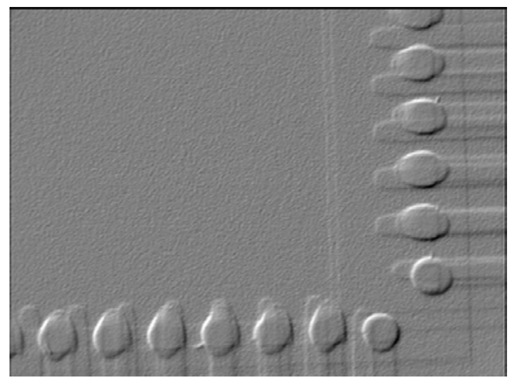
Extrusion

AAB-05 or NUF-1



Eutectic

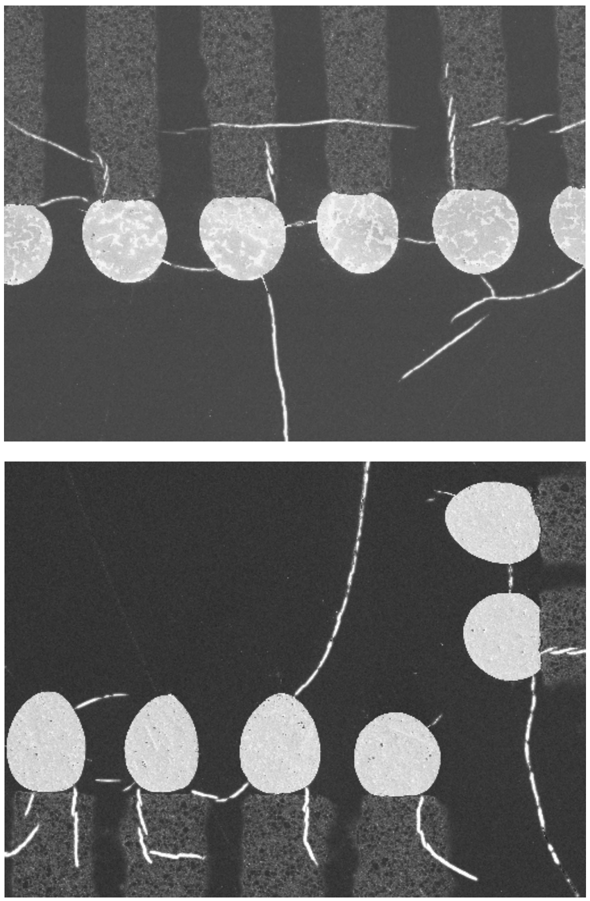
After 3120 cycles of -55°C to 125°C thermal shock



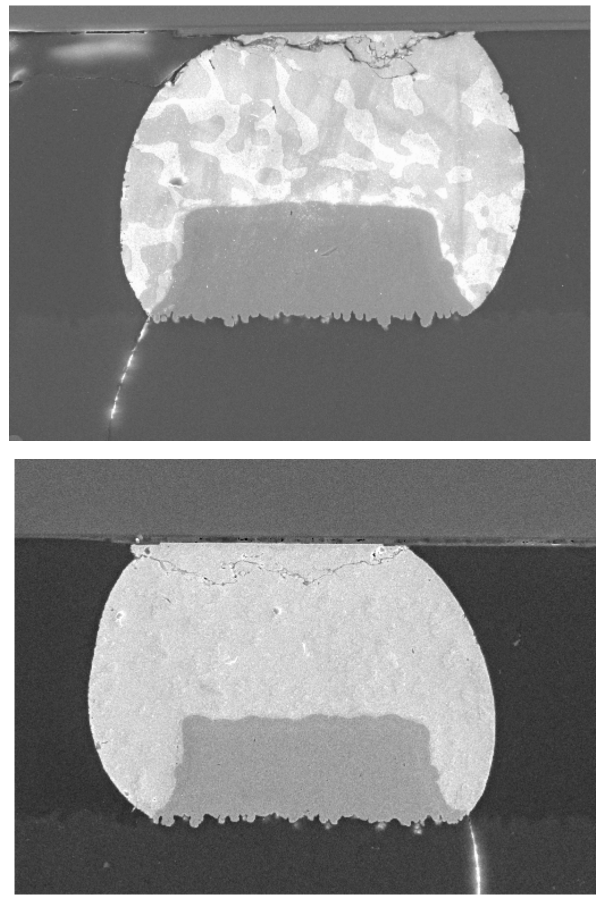
LF2 solder

After 725 cycles of -55°C to 150°C thermal shock

Nano-Underfills Reliability (AAB-05 or NUF-1)



Underfill Crack and Solder Extrusion



Underfill Delamination and Solder Fatigue

LF2 solder

After 725 cycles of -55°C to 150°C thermal shock

Summary

The sensitivities of reliability to design, material, architecture and environment parameters have been developed and validated with the experimental data.

The model predictions for various parametric variations show the similar trends in the effect on the reliability of the packages of various configurations.

The sensitivities developed in this paper can be used to analyze quantitatively the impact of various design parameters on the reliability of area array packages in harsh environments.