Overview of Reliability Models and Data Needs

Ahmer Syed
Amkor Technology

Workshop on Modeling and Data Needs for Lead-Free Solders

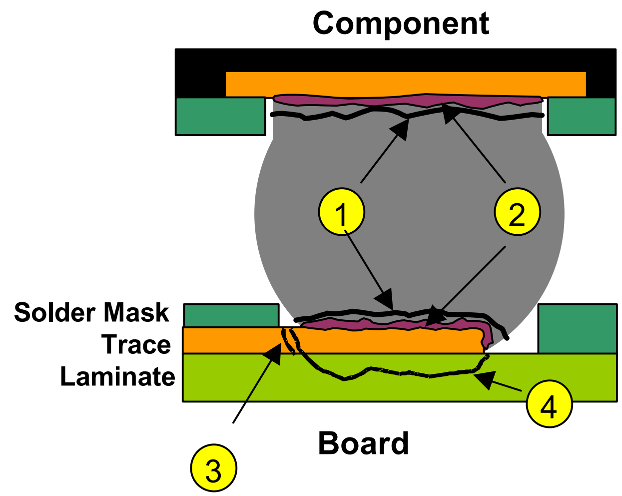
Sponsored by NEMI, NIST, NSF, and TMS

Outline

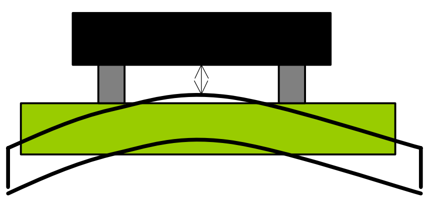
- **Failure Mechanisms Related to Solder Joint**
- **Life Prediction Model Requirements**
- **Lessons Learned from Sn/Pb**
  - Life Prediction Models
  - Material Behavior
  - Stress Analysis Approach
  - Test Data
- **Data Needs for Pb Free Solder**

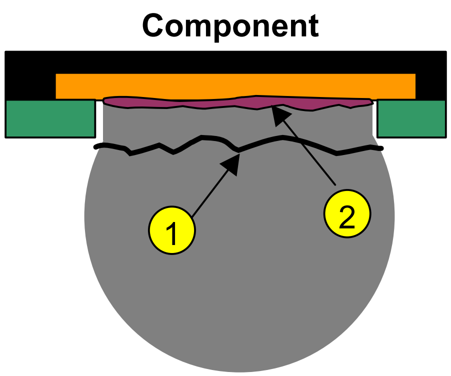
Failure Modes & Mechanisms Related to Solder Joint

- **Failure Modes**
  - Failure in Bulk Solder (1)
  - Failure at Intermetallic Layer (2)
  - Trace Failures (3)
  - PCB Failures (4)



- **Failure Mechanisms**
  - Temperature Related: T, dT/dt, ΔT
  - Displacement Related: ΔD
  - Acceleration: G, Grms



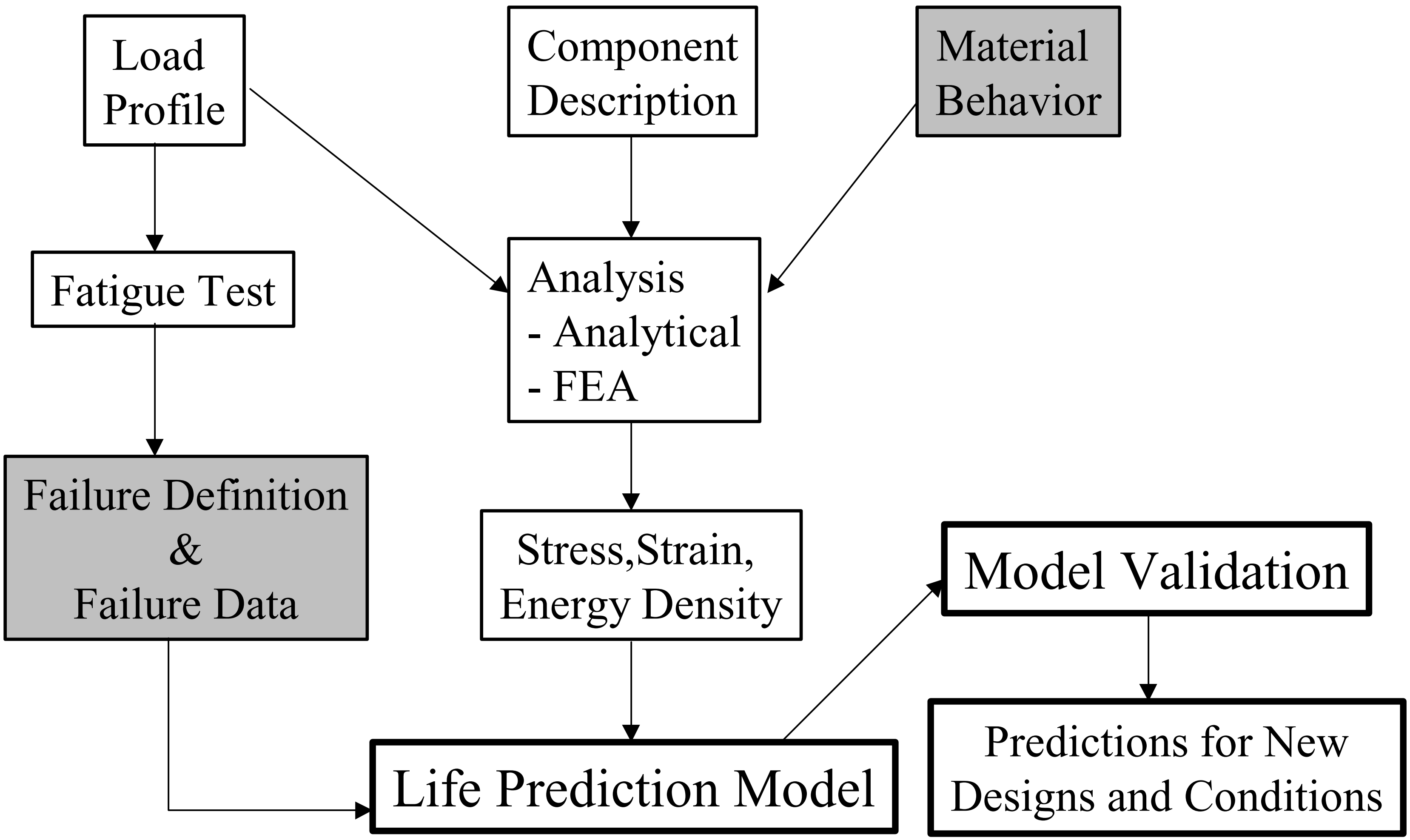


Causes of Failures

- **Thermal/Power Cycling**
  - CTE Mismatch, ΔT, dT/dt, Tmax, Tmin, Time @ Tmax and Tmin
    - Failure in Bulk Solder - Creep-Fatigue
    - Failure at Intermetallic - Overstress
- **PCB Bend, Cyclic Bend, Vibration**
  - Relative Displacement Between Package & Board
    - Failure in Bulk Solder - Fatigue, Creep Rupture
    - Failure at Intermetallic Layers - Overstress
    - Trace & PCB Failures - Solder Alloy/Intermetallic Strength
- **Shock & Drop**
  - High Gs, Large Displacements
    - Failure at Intermetallic Layers - Overstress
    - Trace & PCB Failure - Solder Alloy/Intermetallic Strength
- **Ball Shear**
  - Intermetallic or Bulk Solder

How Well Can We Predict?

Life Prediction Model Requirements/Steps



Sn/Pb Solder Fatigue Life Prediction Models

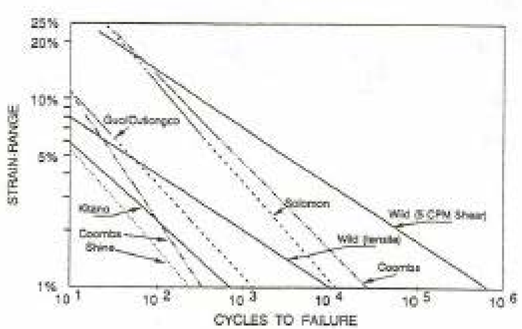
- **Early Attempts (mid to late 80s)**
  - Traditional Coffin-Manson Eqn

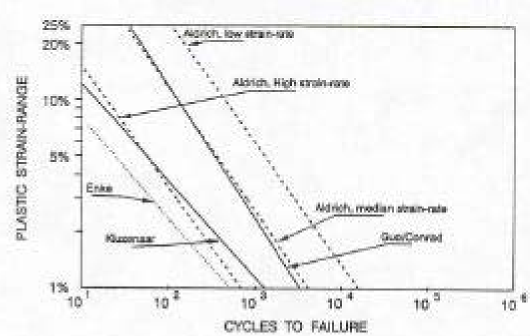
$$\Delta\varepsilon_p = C N_f^{-k}$$

  - Isothermal Mechanical Fatigue
  - Plastic Strain Range Controlled Tests
    - Temperature Modification
    - Frequency Modification
  - Very Little Data on Real Solder Joints

Wen & Ross, ASME EEP-9

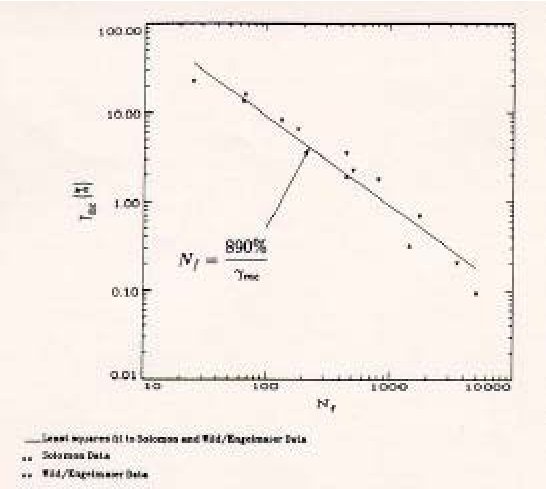
Investigator	C	k	Remarks
Coomb	0.52	0.68	Torsion
	1.18	0.46	Lap Shear
Wild	0.16	0.30	Tensile Joint
	0.6	0.39	1/15 CPM Shear Joint
	0.565	0.30	5 CPM Shear Joint
Shine	0.19	0.53	1 Hz, Tensile
Kitano	0.1538	0.415	0.5Hz
	0.24	0.41	
Enke	0.26	0.52	
Gua/Cutionco	0.34	0.49	
Solomon	1.32	0.52	
Guo/Conrad	3.00	0.70	Tensile
Kluizenaer	0.39	0.51	Tensile
Aldrich	1.3	0.637	strain rate 0.1/sec
	4.72	0.653	4 x 10-4/sec
	10.12	0.643	1 x 10-5/sec

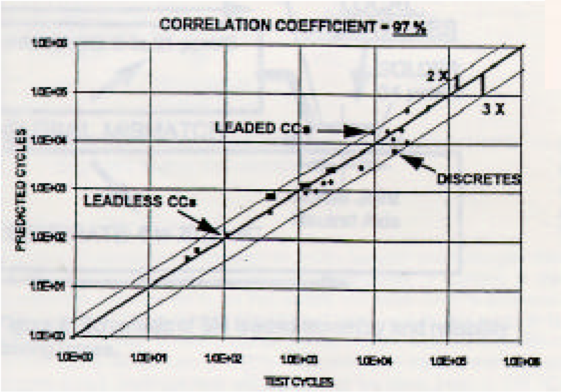




Sn/Pb Solder Fatigue Life Prediction Models

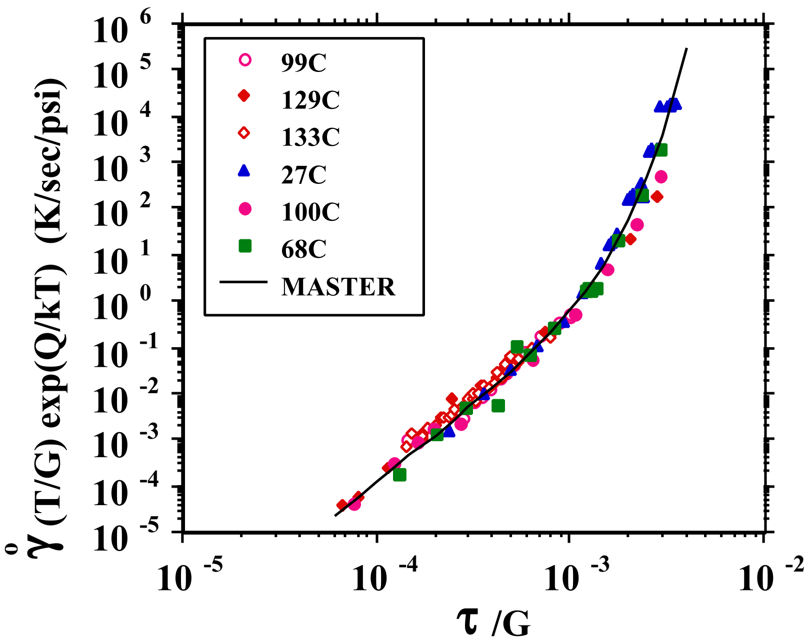
- **Models Incorporating Time & Temperature Dependent Behavior of Solder (Mostly Analytical Treatment)**
  - Damage Integral Method **(Subrahmanyan et al, CHMT 1989)**
    - Stress Based
  - Energy Partitioning Approach **(Dasgupta et al, ASME, EEP, 1993)**
    - Elastic + Plastic + Creep
  - Fracture Mechanics Based **(Pao, CHMT 1992)**
  - Matrix Creep Model **(Shine & Fox, ASTM STP 942)**
    - Isothermal Test Data
    - Calculated Creep Strain
  - CSMR Model **(Clech et al, 43rd ECTC)**
    - Analytical Model
    - Inelastic Strain Energy

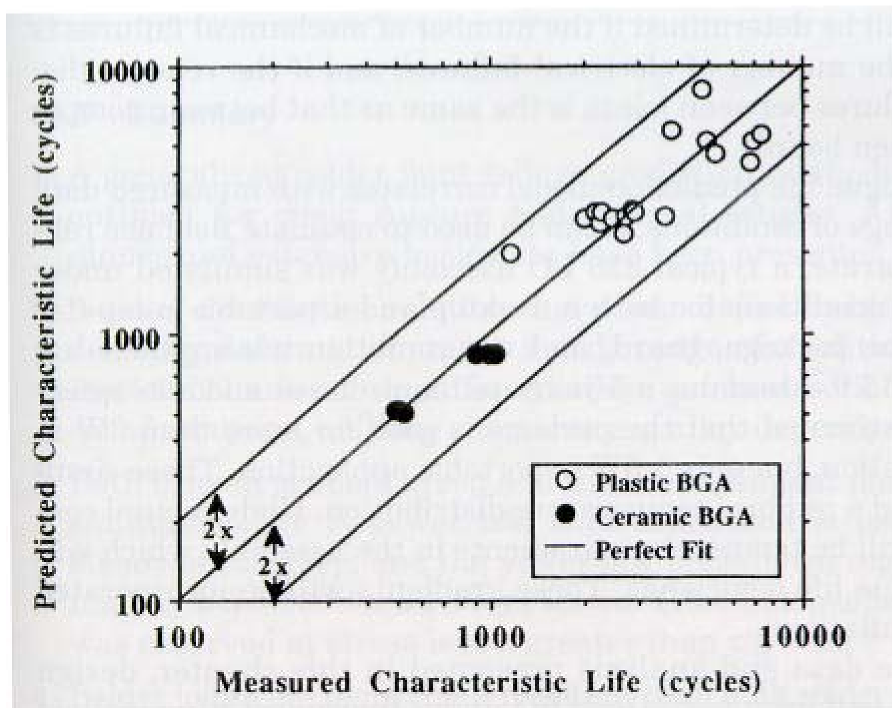




Sn/Pb Solder Fatigue Life Prediction Models

- **Energy Density Based** (Darveaux et al, Ball Grid Array Technology, Ed. J. Lau)
  - Crack Initiation & Growth
  - Inelastic Constitutive Eqn
  - Finite Element Analysis

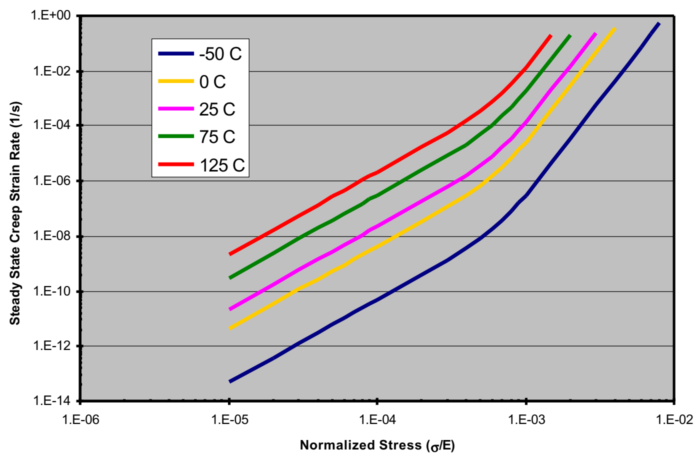


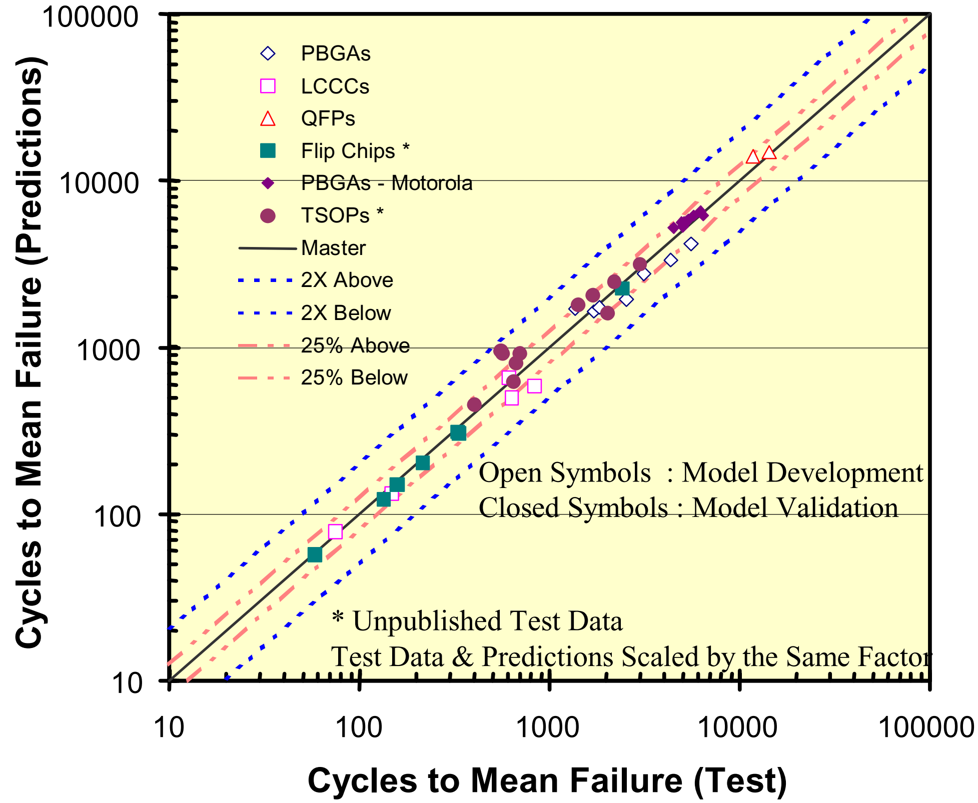


Sn/Pb Solder Fatigue Life Prediction Models

- **Partitioned Creep Strain Based (Syed, 1996 SEM)**
  - Wong et al Constitutive Eqn (CHMT, 1989)
    - two mechanisms
  - Finite Element Analysis

$$N_f = (0.02x\mathrm{E}_{GBS} + 0.063x\mathrm{E}_{MC})^{-1}$$

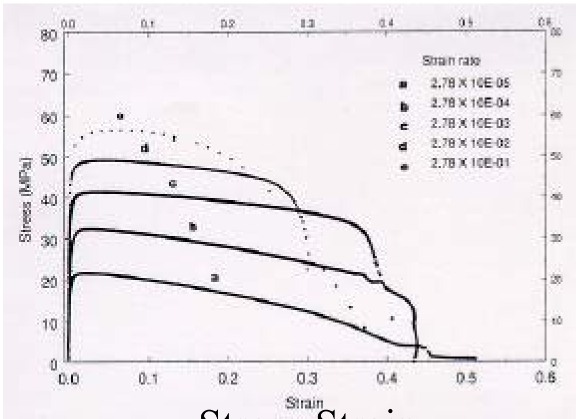




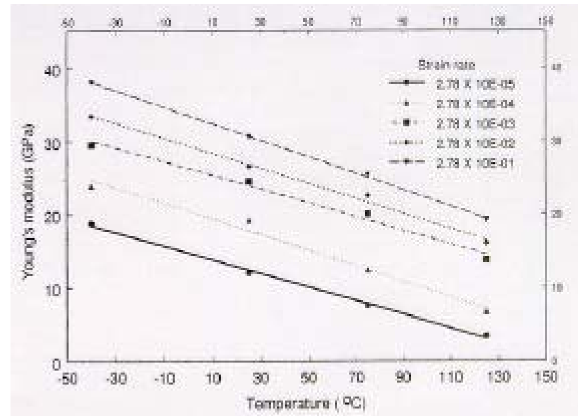
Amkor Technology

Material Property Characterization

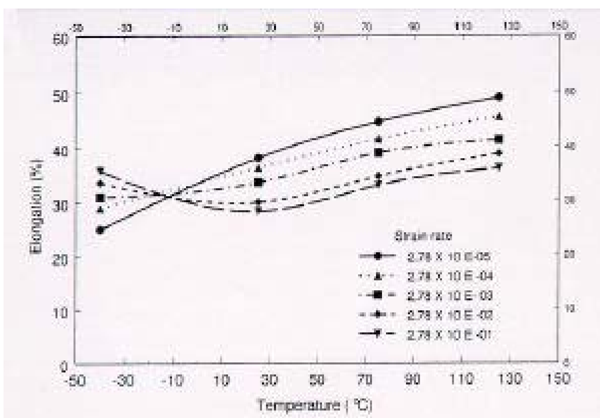
- **Stress-Strain** **(Shi et al, JEP, 1999)**



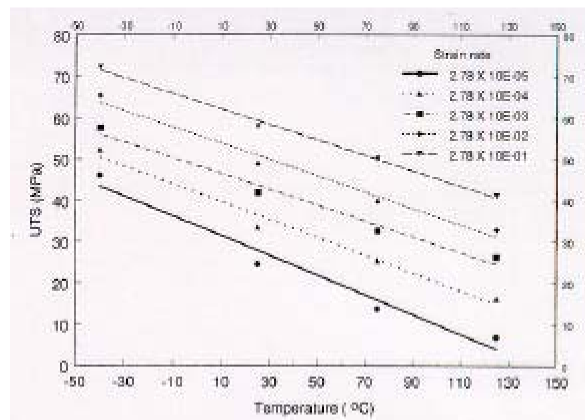
Stress-Strain



Modulus



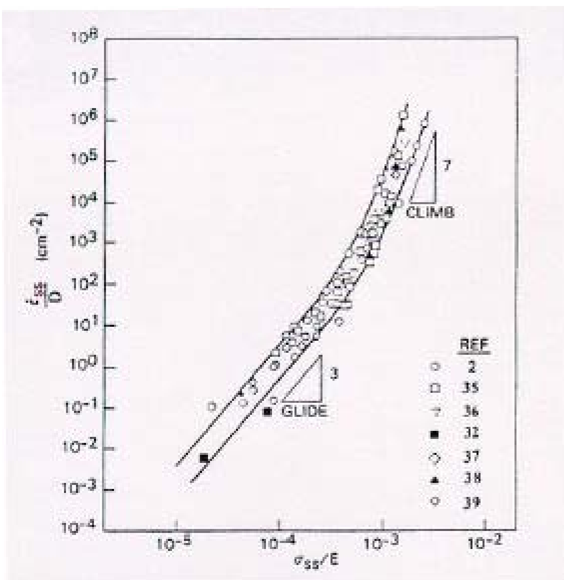
Ductility



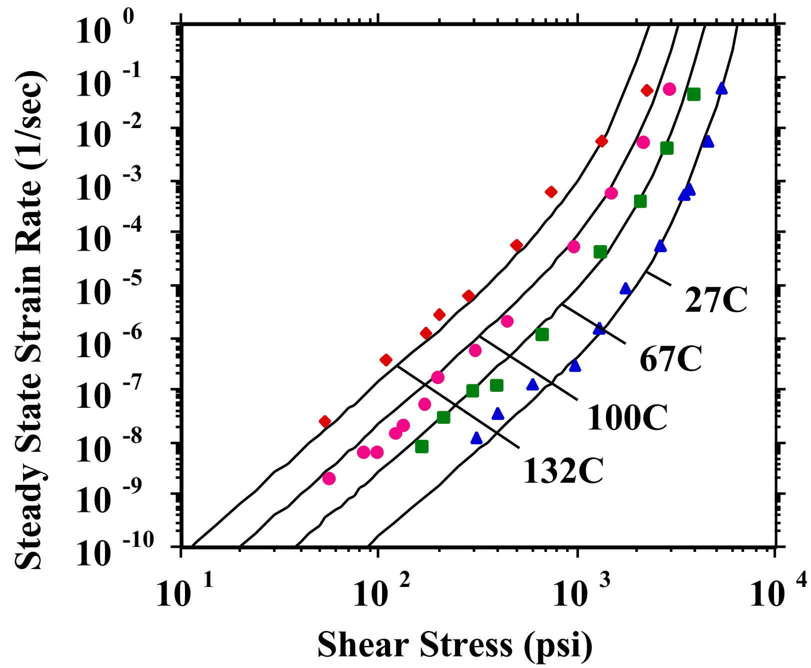
Strength

Material Property Characterization

- **Creep Behavior**
  - Aldrich & Avery, Kashyap & Murty, Grivas, Mohamed & Langdon, Lam et al, Arrowood and Mukherjee, and others
  - Hall, Solomon, Wilcox, Wong, Shine & Fox, Darveaux, Busso, Hong, and others



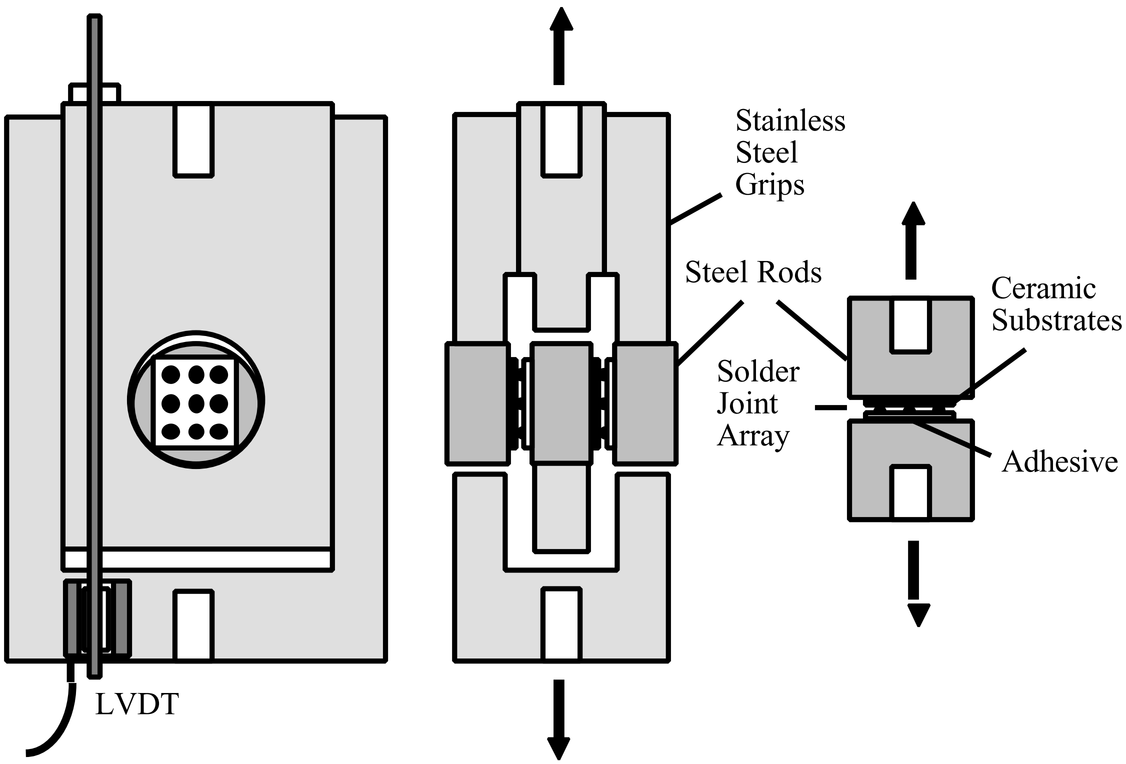
Bulk Solder (Wong et al Model)



Real Joints (Darveaux)

Material Property Characterization

- **Mechanical Test Fixture for Creep Test of Real Joints**
  - **(Darveaux et al, Ball Grid Array Technology, Ed. J. Lau)**

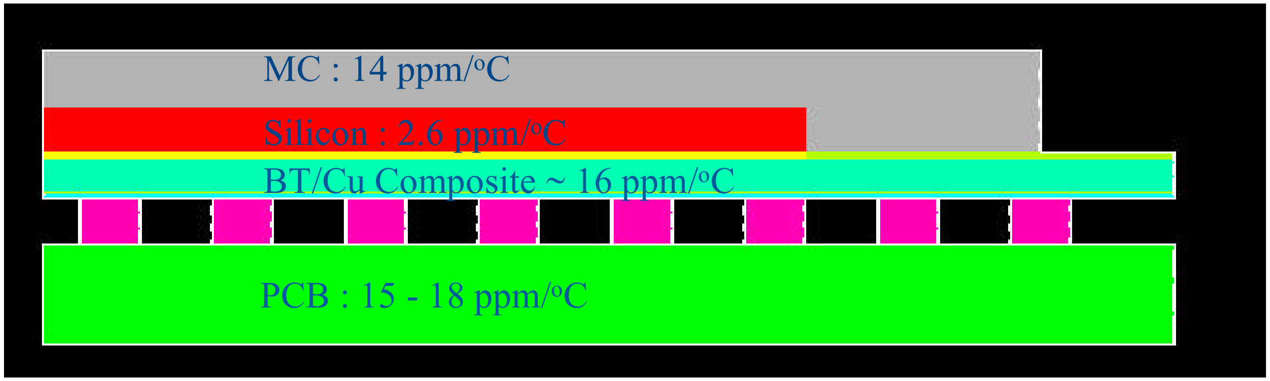


Double Lap Shear Fixture

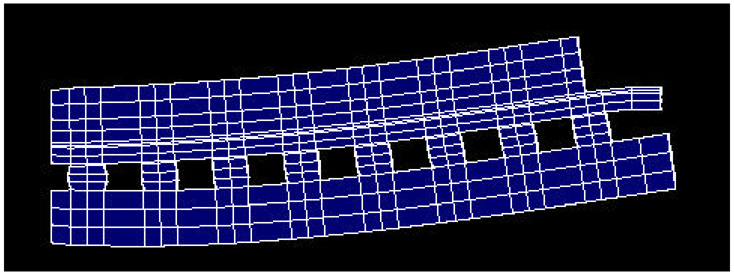
Tensile Fixture

Stress Analysis

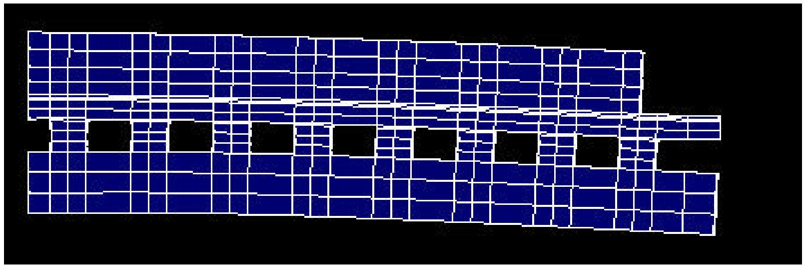
- **Analytical Models**
  - CTE Mismatch
  - Pure Shear



- **Finite Element**



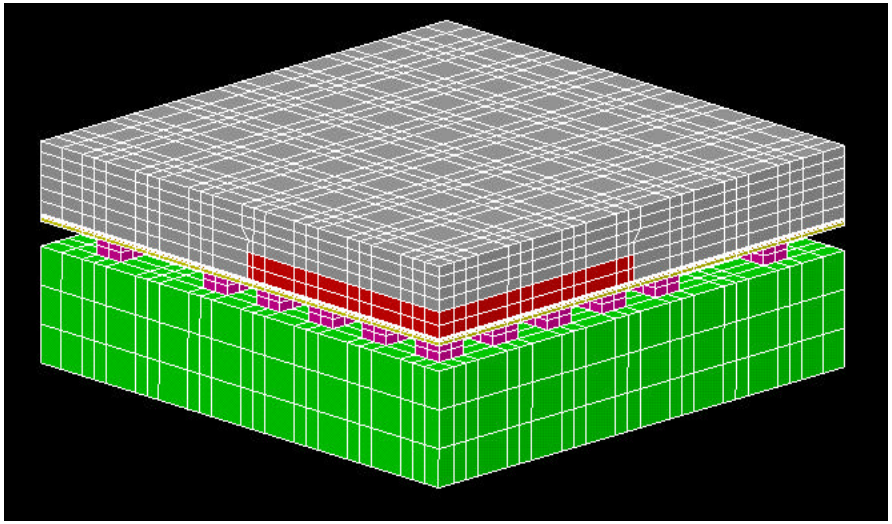
25 to 125°C

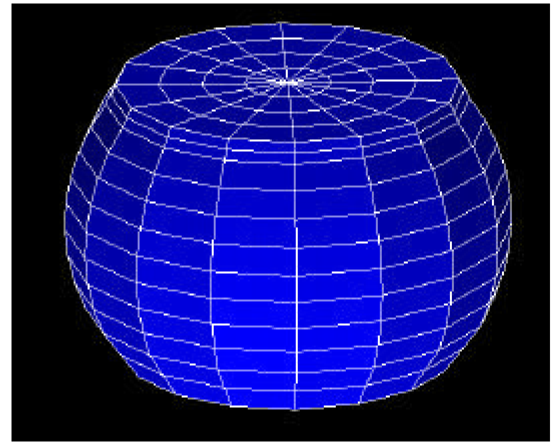


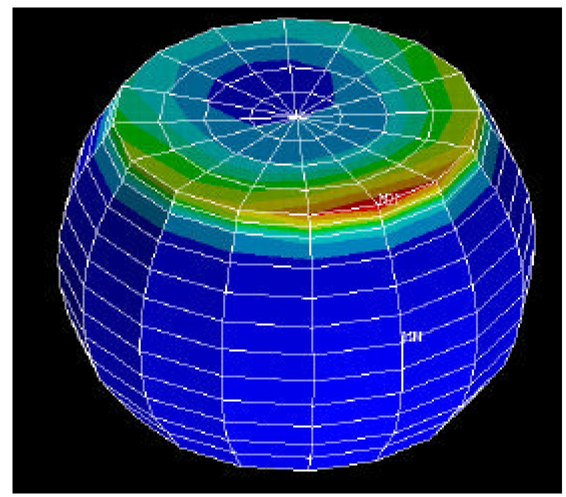
25 to -40°C

Finite Element Modeling

- **3-Dimensional Models**



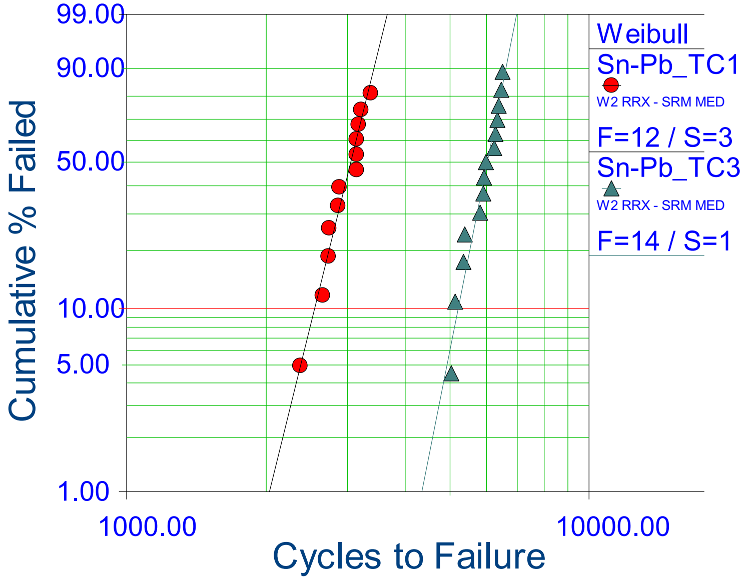




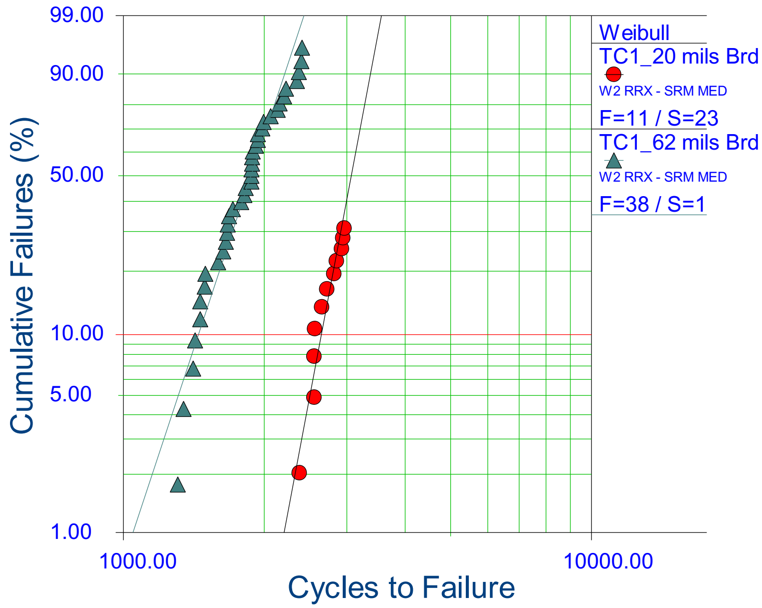
- **Inelastic Constitutive Models**
- **Accurate Loading Conditions**
- **Multiple Responses**
  - Stress, Strain, Energy Density

Failure Data

- **Failure Definition - Electrical Open**
- **Thermal Cycle Fatigue Test Data**
  - Different Cycling Conditions
  - Test Board Variables
  - Component Design Variables



β1=10.40, η1=3164.00, ρ=0.98
β2=12.95, η2=6194.94, ρ=0.97

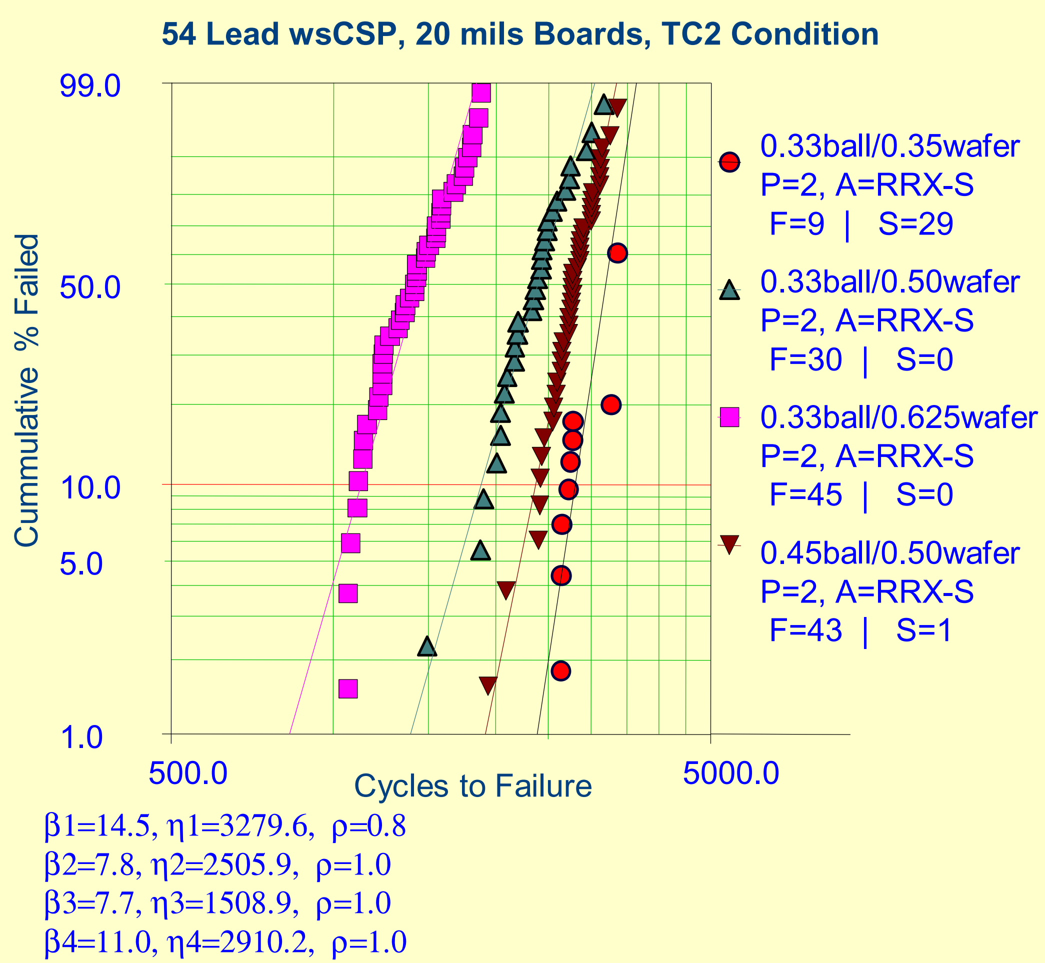


β1=12.80, η1=3161.34, ρ=0.96
β2=7.30, η2=1968.64, ρ=0.97

Solder Joint Reliability

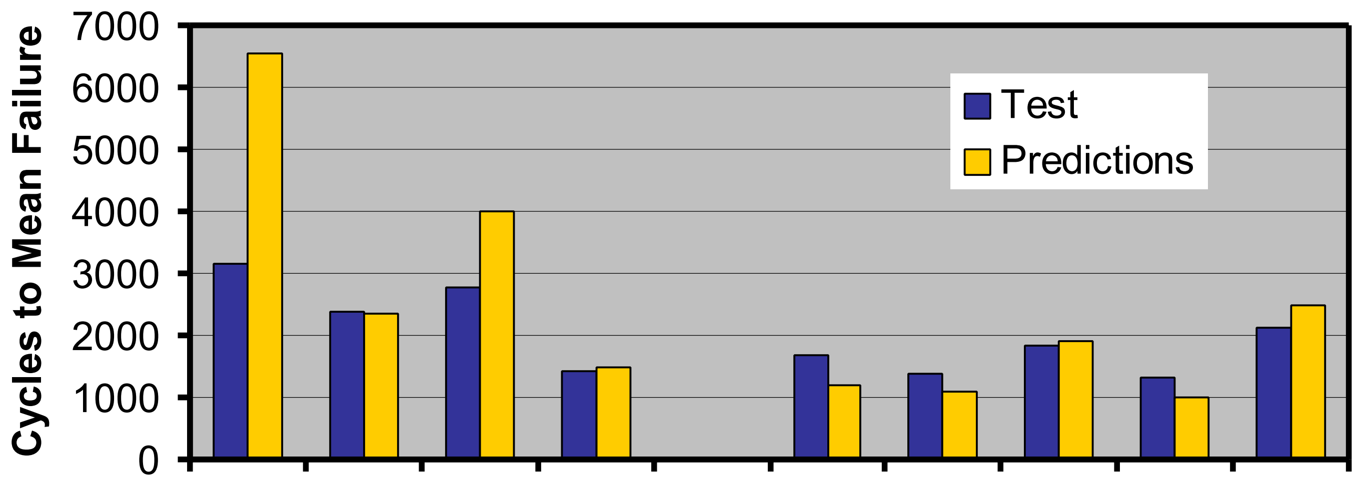
Temperature Cycle Test Data

- **wsCSP**
  - 54 Lead Center Pad, 9x11 mm
  - Wafer Thickness
    - 45% and 60% Reduction in Life with Wafer Thickness of 0.5 and 0.625 mm
  - Ball Size
    - Mounted Height < 1mm for 0.33mm Balls
    - 30% Improvement in Fatigue Life with 0.45mm Solder Balls



Life Prediction Model Correlation

for wsCSP

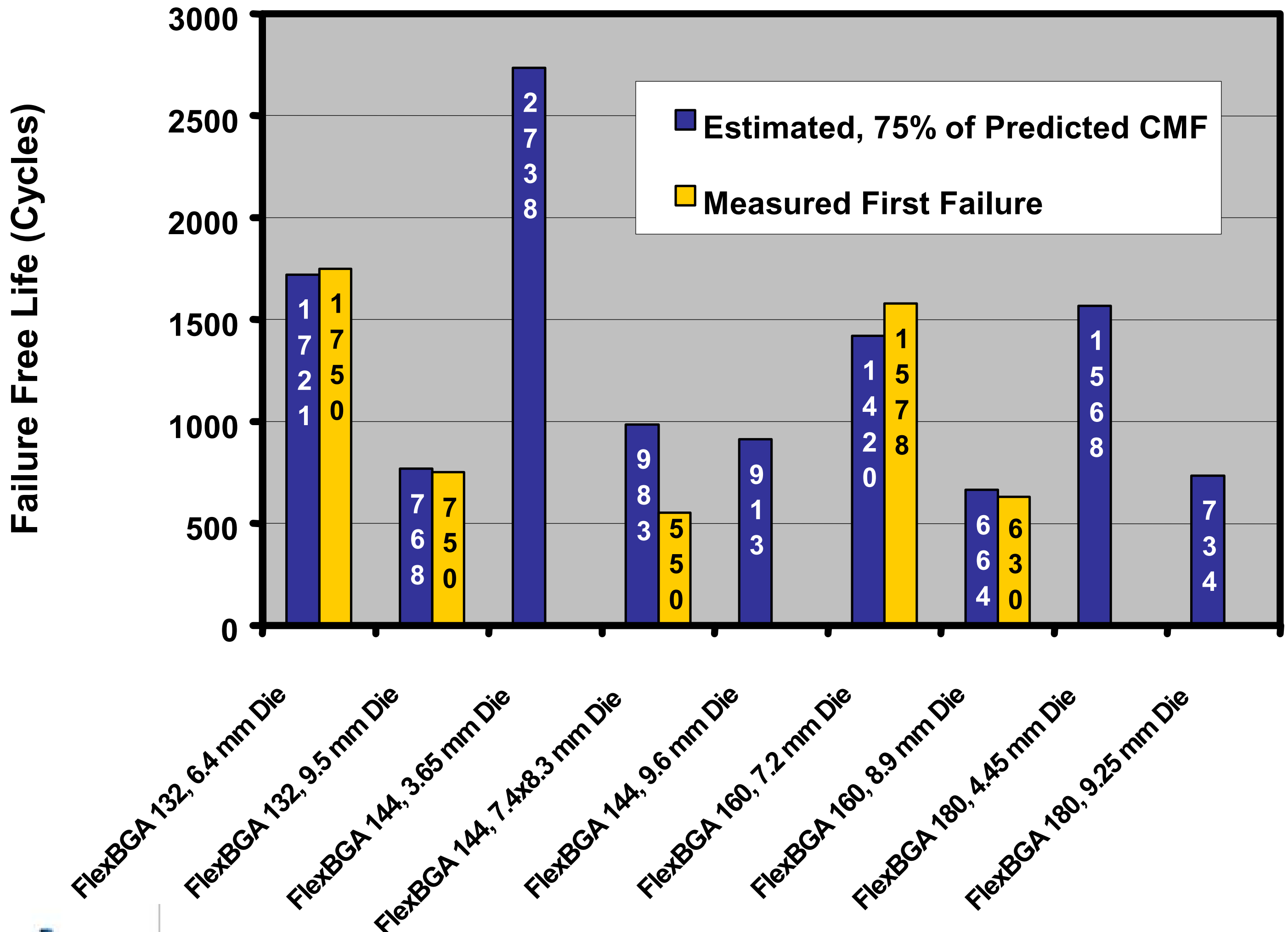


Ball Size (mm)	0.33	0.33	0.45	0.33		0.33	0.33	0.45	0.33	0.33
Wafer Thk. (mm)	0.35	0.50	0.50	0.625		0.35	0.50	0.50	0.625	0.50
PCB Thickness (mm)	0.50	0.50	0.50	0.50		1.60	1.60	1.60	1.60	0.50
Temp Cycle	TC2	TC2	TC2	TC2		TC2	TC2	TC2	TC2	TC1

- **Predictions within 25% Except for 2 Cases**
- **Same Trend Predicted as Observed from Tests**

Solder Joint Reliability Prediction

Prediction Vs. Measured



Amkor Technology

Solder Joint Reliability Prediction

Field Conditions

Application : Cell Phone

Assumed Worst Case Field Conditions

Sales Person; May - October : Arizona, November - April : Alaska

Arizona Cycling : +20 to +55 C, 6 Cycles/Day, 1000 Cycles in 6 Months

Alaska Cycling : -20 to +20 C, 6 Cycles/Day, 1000 Cycles in 6 Months

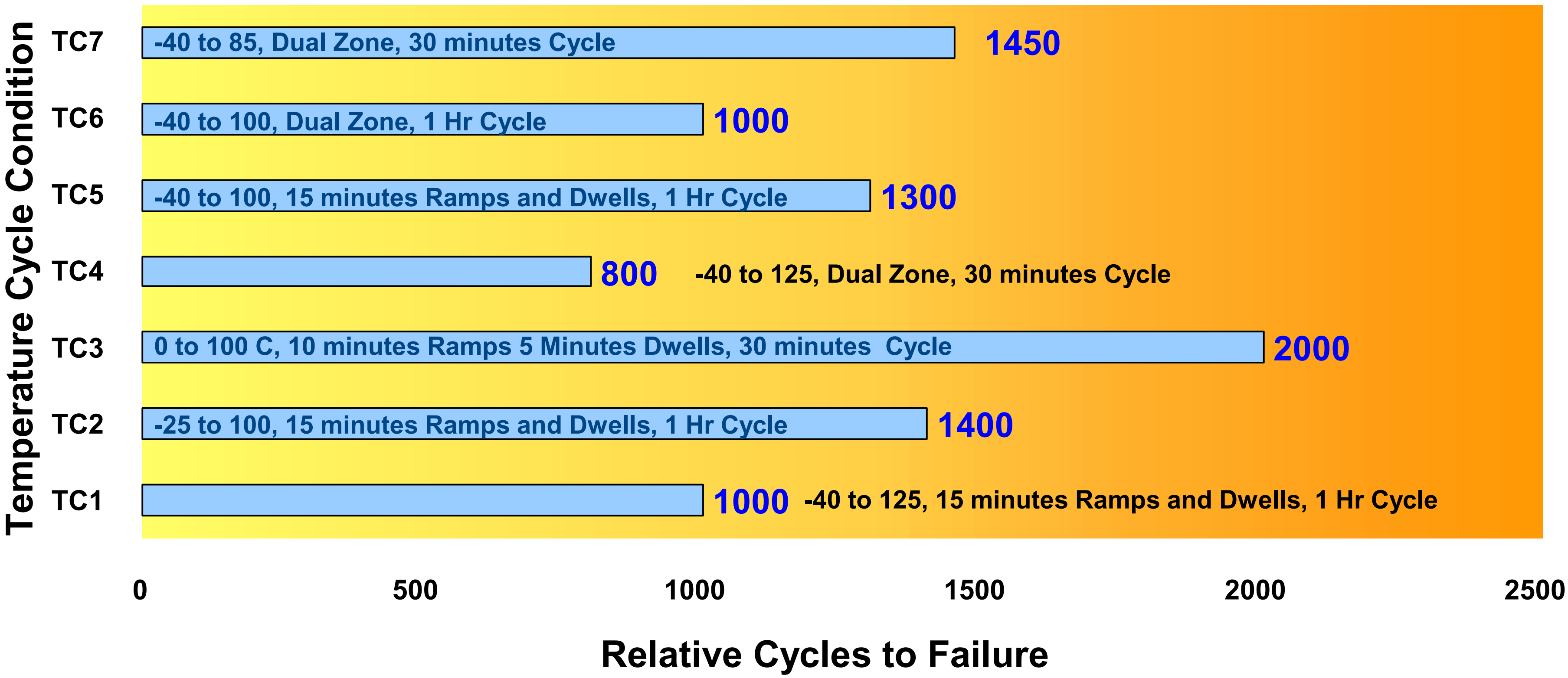
Required Life/Year : 2000 + 20% = 2400 Cycles

Condition	Realistic Reliability Requirements			Specified Reliability Requirements
	Chamber Zones	1 Year Life	5 Years Life	
0 to 100 C	Single	180	900	1500 Cycles
-25 to 100 C	Single	125	625	700 Cycles
-40 to 100 C	Single	120	600	800 Cycles
-40 to 125 C	Single	90	450	500 Cycles
-40 to +85 C	Dual	130	650	300 - 500 Cycles
-40 to 100 C	Dual	90	450	800 Cycles
-40 to 125 C	Dual	70	350	500 Cycles
-55 to 125 C	Dual	60	300	300 Cycles

Realistic Realistic - Excessive Excessive

Solder Joint Reliability Prediction

Test Condition Comparison

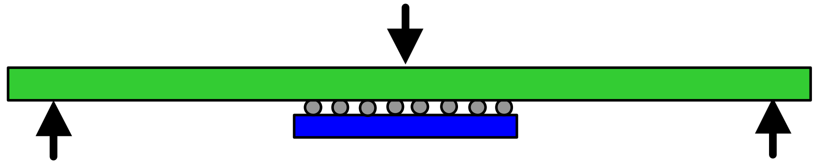


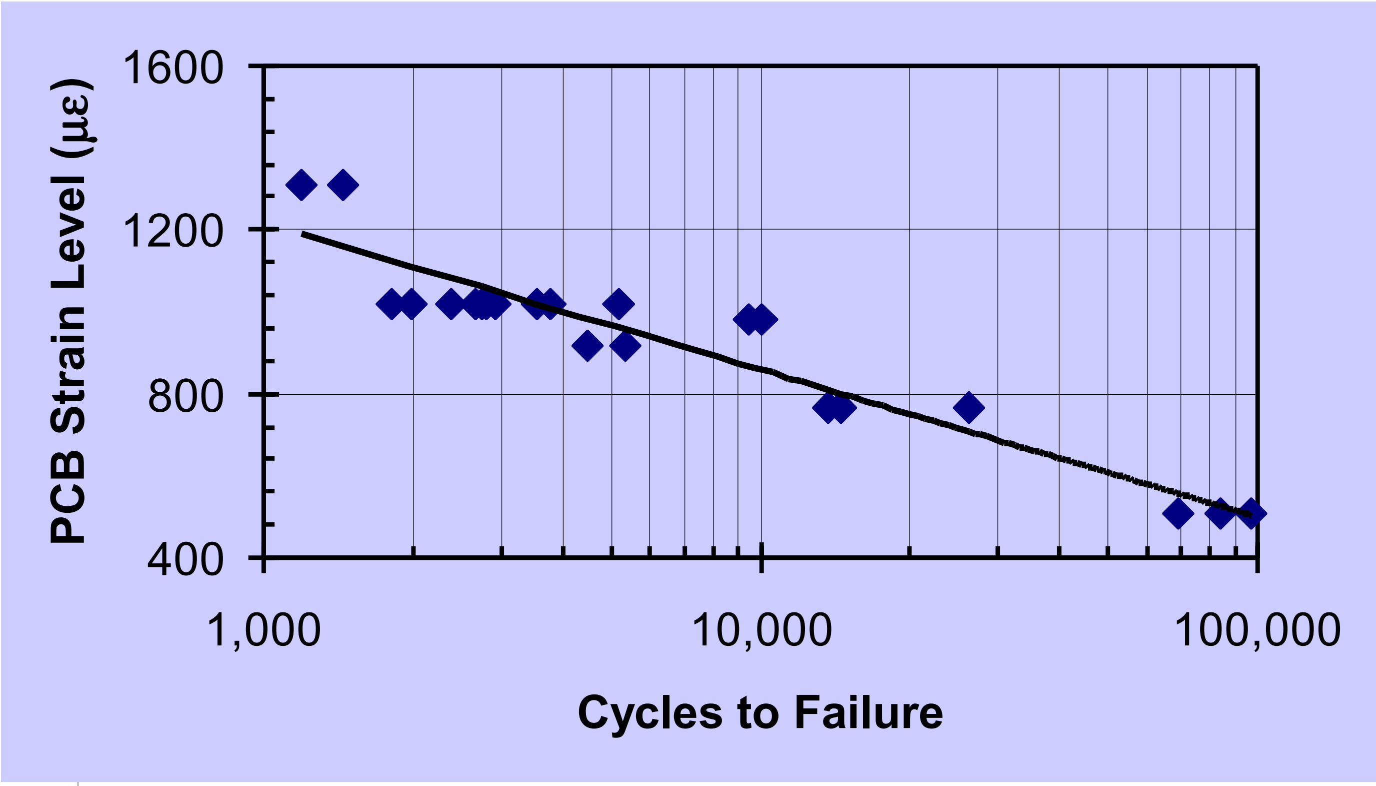
Single Zone : Slow Ramps

Dual Zone : Fast Ramps (2-3 Sec Transfer), Steady State at Board Level within 2-3 minutes

Cyclic 3-Point Bending

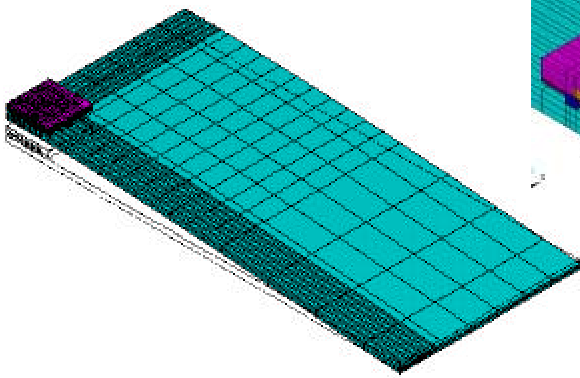
- **PCB Strain vs. Life**
  - 12mm-132 lead fleXBGAs
  - 0.85mm thick Board (h)
  - Measured Strain Level

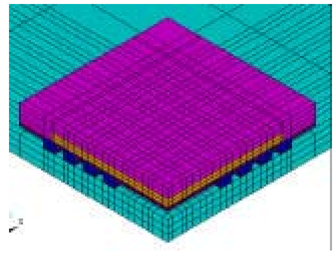


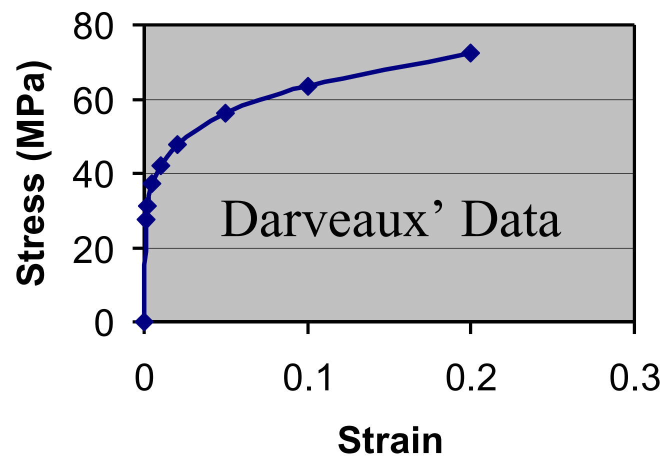


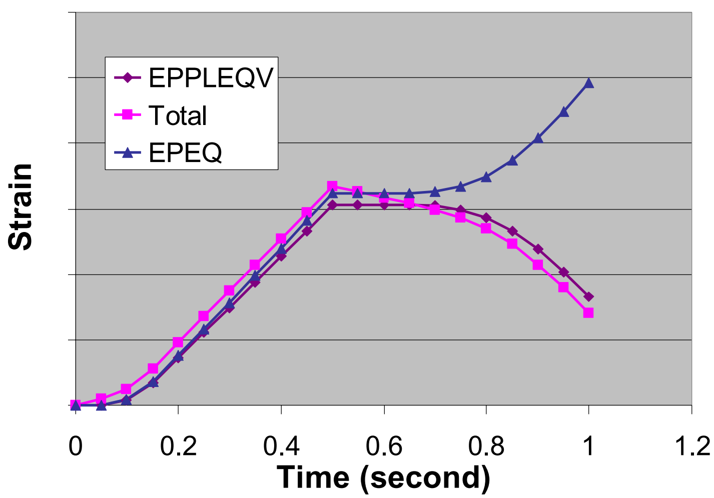
3-Point Bend Cycle Simulation

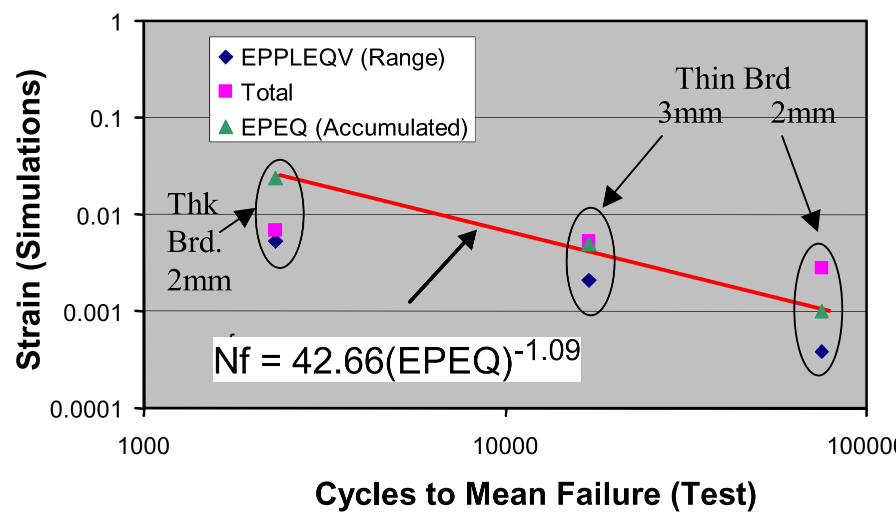
- **Bend Cycle Fatigue**



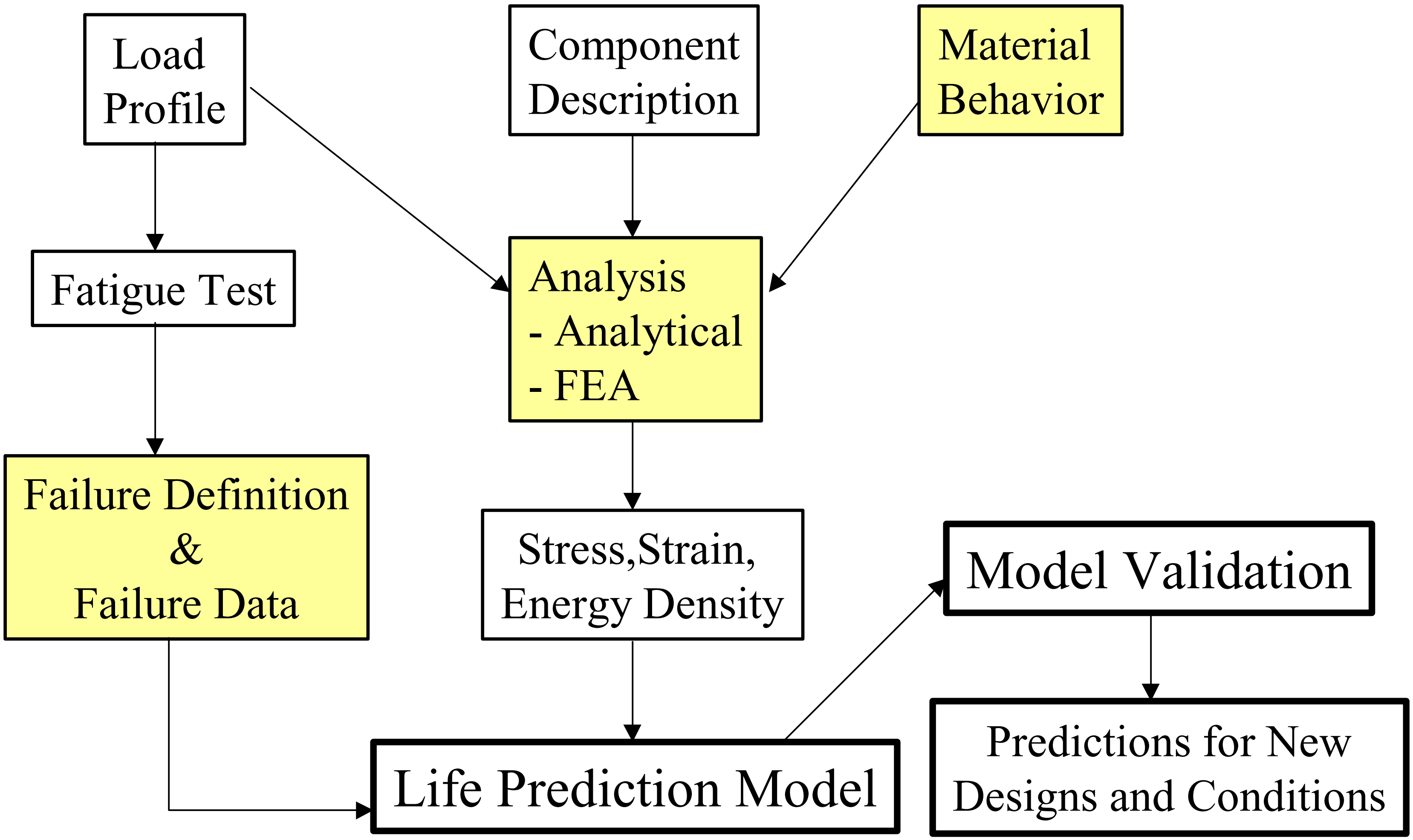








What is Needed for Pb Free Solder

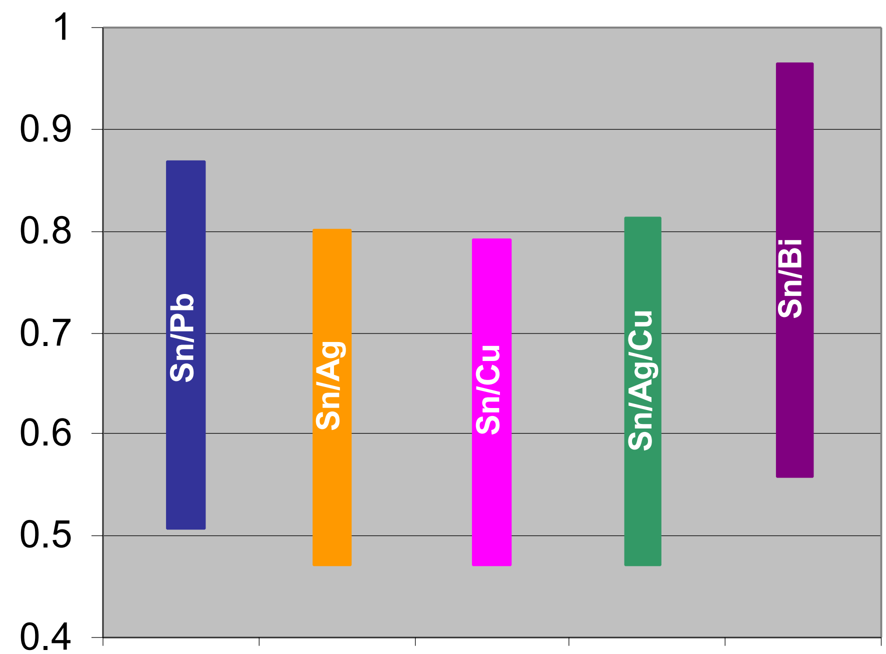


What is Needed for Pb Free Solder

Material Behavior

- **Material Charaterization**
  - Stress-Strain Behavior
    - strain rates dependent, and
    - temperature dependent
  - Ductility & Strength
  - Temperature Dependent Modulus
  - Temperature Dependent Inelastic Behavior
    - Creep & Stress Relaxation
    - Stress to Rupture

Pb Free Alloys In Consideration Have Homologous Temperature of ~ 0.5 at -40^{o}C

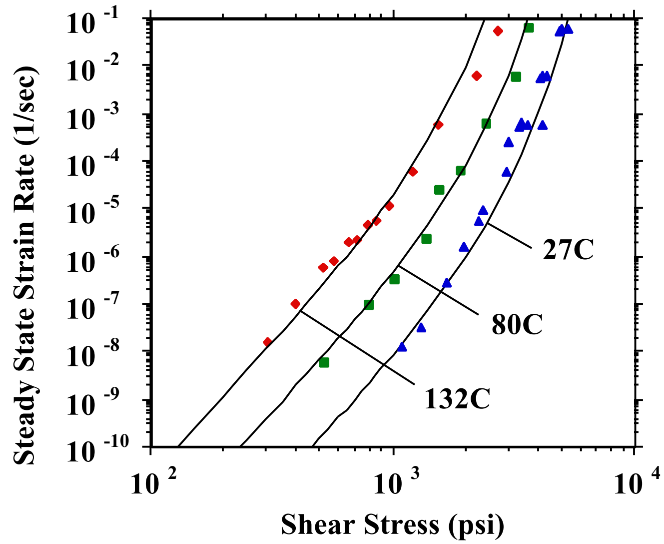


-40 to 125^{o}C Cycle Range

What is Needed for Pb Free Solder

Material Behavior

- **Of all Pb free Alloys, Sn/Ag has been Characterized the most**
  - Not as much as Sn/Pb
- **Very Little data on other alloys**
  - Recent data on Strength and Ductility on Sn/Ag, Sn/Cu, Sn/Ag/Bi,Sn/Ag/Cu by Xiao et al (J. of Electronic Materials, 2000)
  - Time &Temperature dependent material behavior is of most Importance.

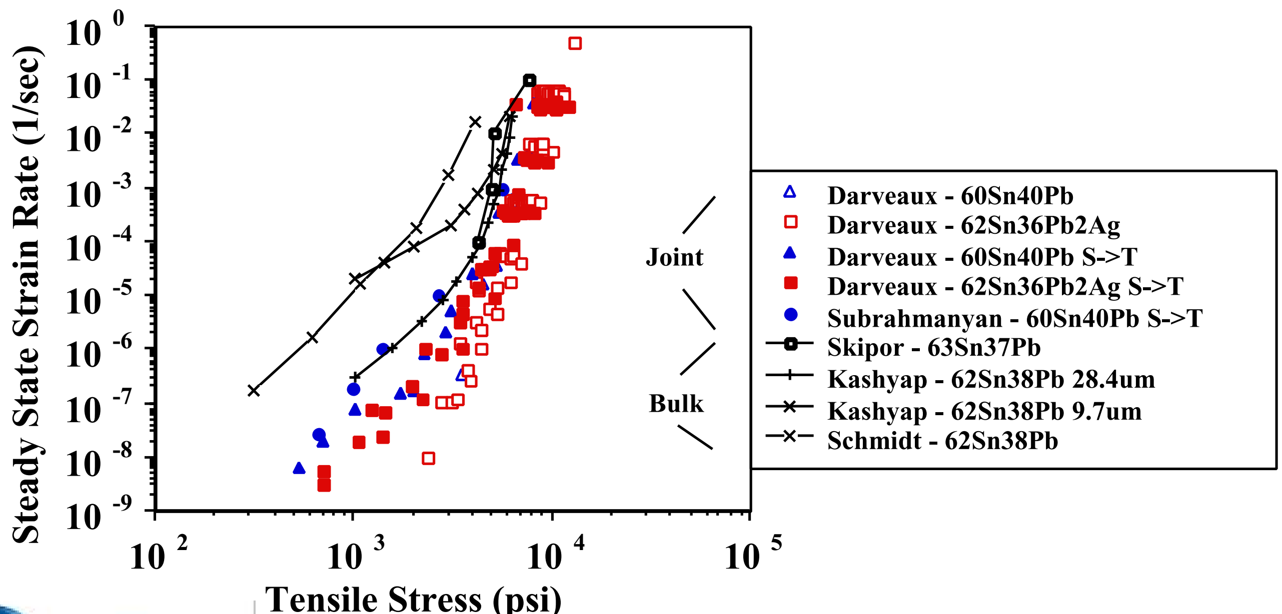


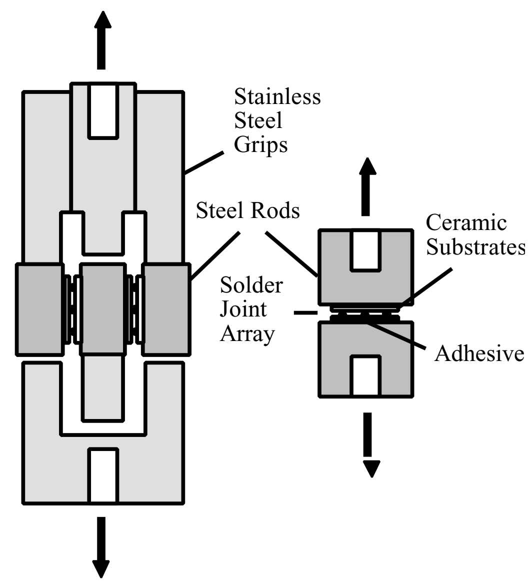
Steady State Creep Data
on Sn/Ag by Darveaux et al
(Ball Grid Array Technology, Ed. J. Lau)

What is Needed for Pb Free Solder

Material Behavior

- **Bulk versus Joint Behavior**
  - Data from bulk solder samples might not be directly applicable to solder joints
    - Constraining effect of the solder / substrate interfaces,
    - Precipitation strengthening from dispersed intermetallics, and
    - Difference in grain structure, grain size, or grain / specimen size ratio.
  - Data from Real Solder Joint Samples is Preferred





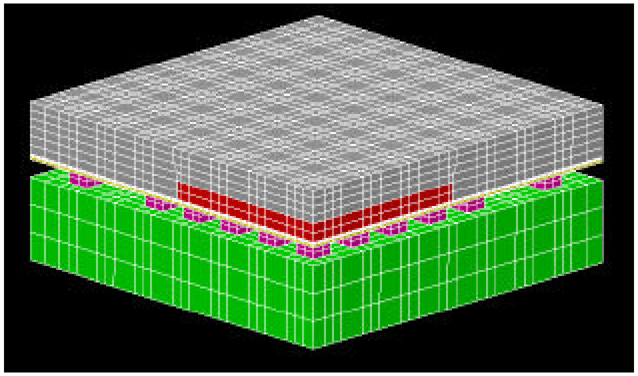
ture

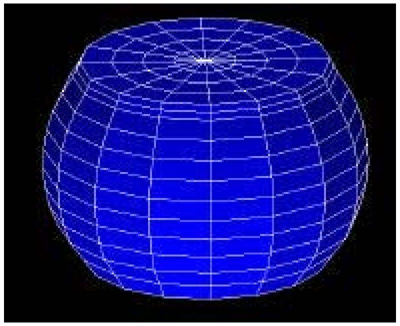
Tensile Fixture

What is Needed for Pb Free Solder

Analysis
- Analytical
- FEA

- **Analysis Tools and Methodologies are in Place**





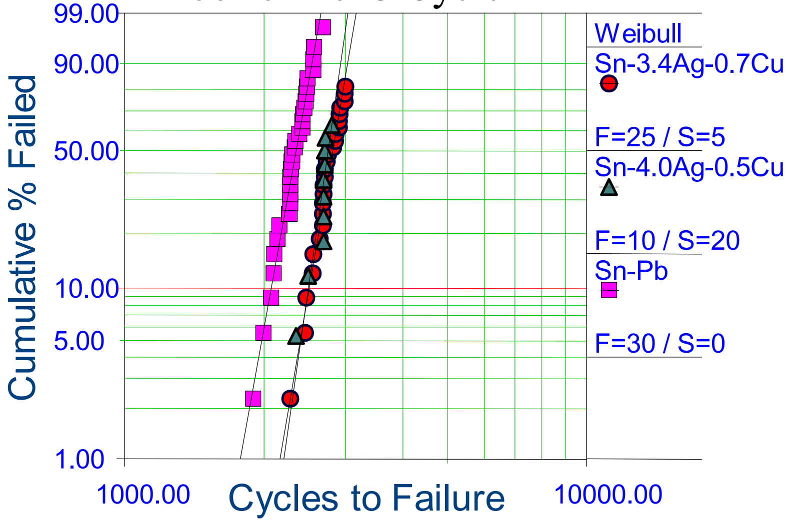
- **Constitutive Equations Need to be developed**
  - Consideration must be given on how to implement a particular constitutive Equation in FEA Software packages.
    - Provide guidelines or User subroutines

What is Needed for Pb Free Solder

Failure Data

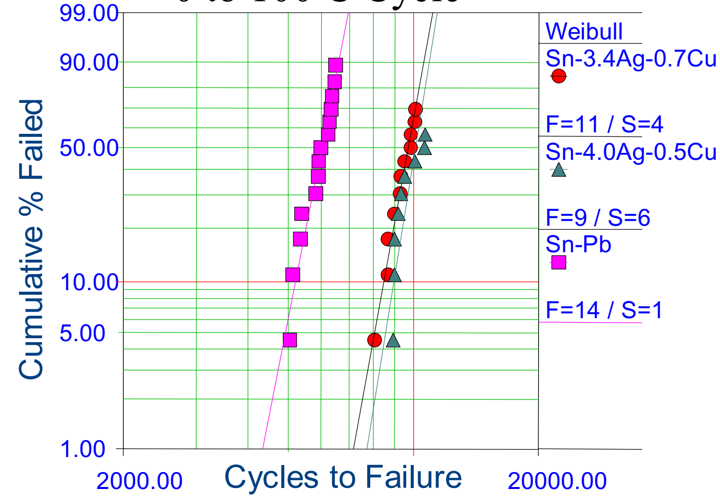
- **Sn/Pb vs. Sn/Ag/Cu (*fle*XBGA Package)**

-55 to 125 C Cycle



$\beta 1=16.07$, $\eta 1=2886.19$, $\rho=0.98$
$\beta 2=19.28$, $\eta 2=2809.33$, $\rho=0.91$
$\beta 3=15.16$, $\eta 3=2409.32$, $\rho=0.99$

0 to 100 C Cycle



$\beta 1=13.95$, $\eta 1=9983.61$, $\rho=0.99$
$\beta 2=15.70$, $\eta 2=10368.55$, $\rho=0.84$
$\beta 3=12.95$, $\eta 3=6194.94$, $\rho=0.97$

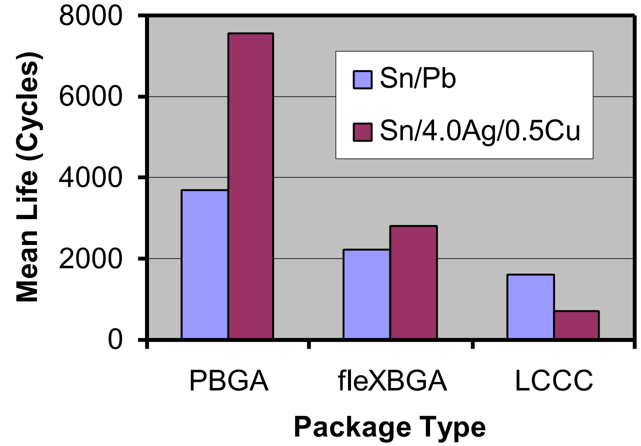
- **No Difference in two Sn/Ag/Cu Compositions**
  - Sn/Ag/Cu Better than Sn/Pb
    - 25% for -55 to 125°C Cycle
    - 80% for 0 to 100°C Cycle

What is Needed for Pb Free Solder

Effect of Package Type

Failure Data

- **PBGA**
  – **2X Higher Life for Sn/4.0Ag/0.5Cu (A14) Compared to Sn/Pb**
- **fleXBGAs**
  – **25% Higher Life for A14**
- **20 Lead LCCCs**
  – NCMS TMF Test
    - -55<>125°C, 70 minute Cycle
  – **2X Reduction in Life for A14!**



- **Performance is Highly Dependent on Package Type**
  – Solder Deformation Behavior is a Strong Function of Stress, Strain Rate, and Temperature
- **Sn/Ag/Cu More Creep Resistant at Low Stresses, Less Creep Resistant at High Stresses!**
- **Will a Ceramic Component Soldered with Sn/Ag/Cu Perform worse than Sn/Pb in Actual Field Conditions?**

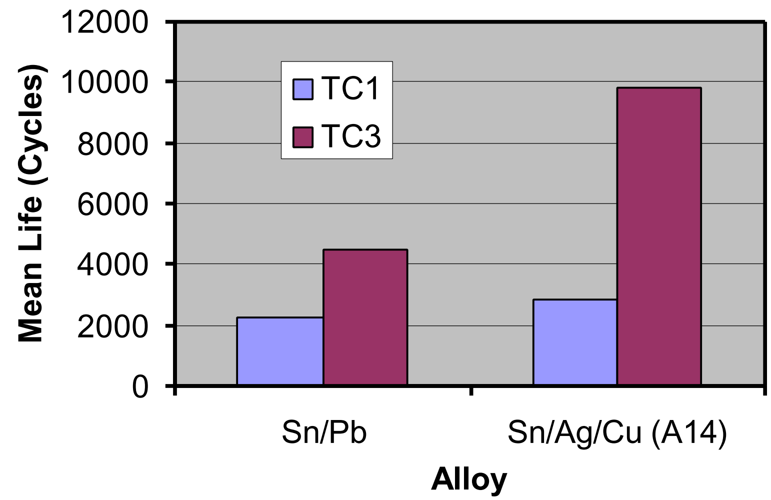
Amkor Technology

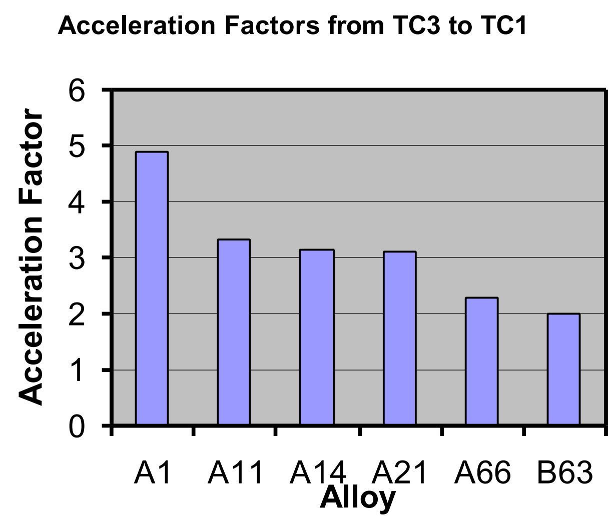
What is Needed for Pb Free Solder

Effect of Test Conditions

Failure Data

- **Acceleration Factors Depend on Accelerated Test Condition & Alloy**
  - Different for each Alloy
  - -40<>125C → 0<>100 C
    - **Sn/Pb: 2X Higher Life**
    - **Sn/Ag/Cu: 3.5X Higher Life**
- **Field Conditions Much More Benign than Accelerated Test Conditions**
- **A Package-Alloy Combination Performing Worse in Accelerated Test Condition May Actual Perform Same or Better in Field Conditions**
- **Performance Comparison from Only One Accelerated Test Maybe Misleading**
  - At Least two test conditions should be used





Life Prediction for Pb Free Solder

- **Materials need to be characterized for time and temperature dependent behavior**
  - Creep deformation will still play a dominant role for temperature cycle failures
  - Time independent plasticity more relevant for vibration and other high cycle fatigue simulation
  - Data from realistic joint samples is more useful
- **Temperature cycle data on real components is needed**
  - Isothermal fatigue data is not useful for life prediction model development
  - Publish as much as you can, don't normalize
  - Use multiple cycling conditions & components
- **Modeling Techniques Exist**
  - Easy implementation of Constitutive Equation in FEA software is the key
    - Guidelines or user subroutines should be provided for complex stress-strain behavior