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# *Modeling the aging and reliability of solder joints*

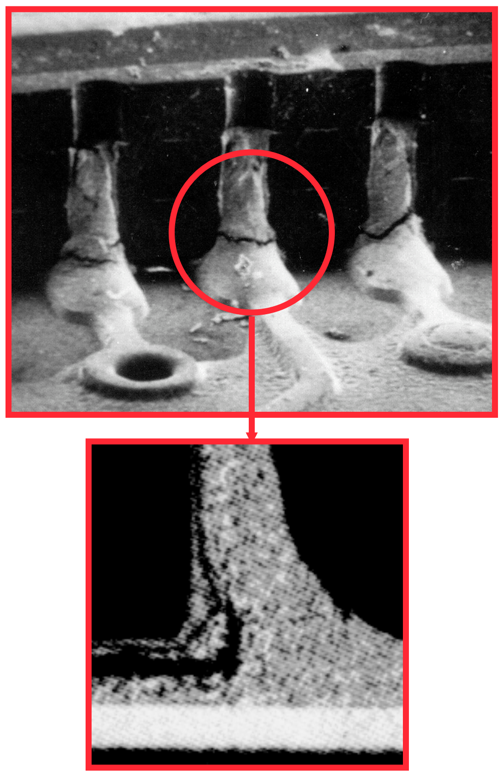
Elizabeth Holm, Michael Neilsen, and Paul Vianco
Sandia National Laboratories
Albuquerque, NM 87185 USA

# *Aging and failure of solder joints*

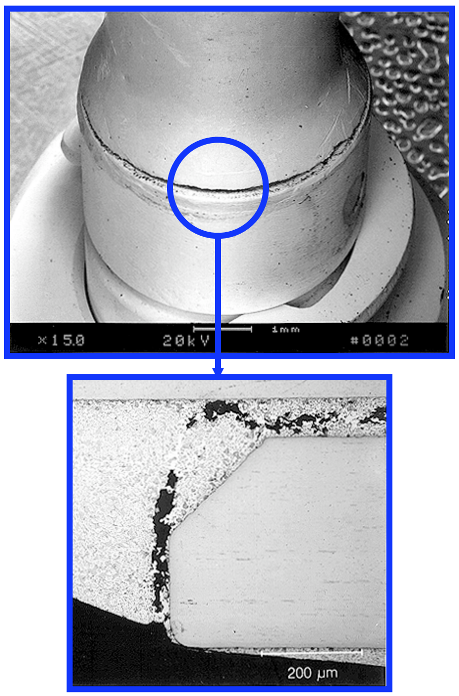
- Typical circuit boards contain thousands of solder joints.
- Solder joints function at a high homologous temperature under thermomechanical fatigue conditions.

⇒**Solder joints fail.**

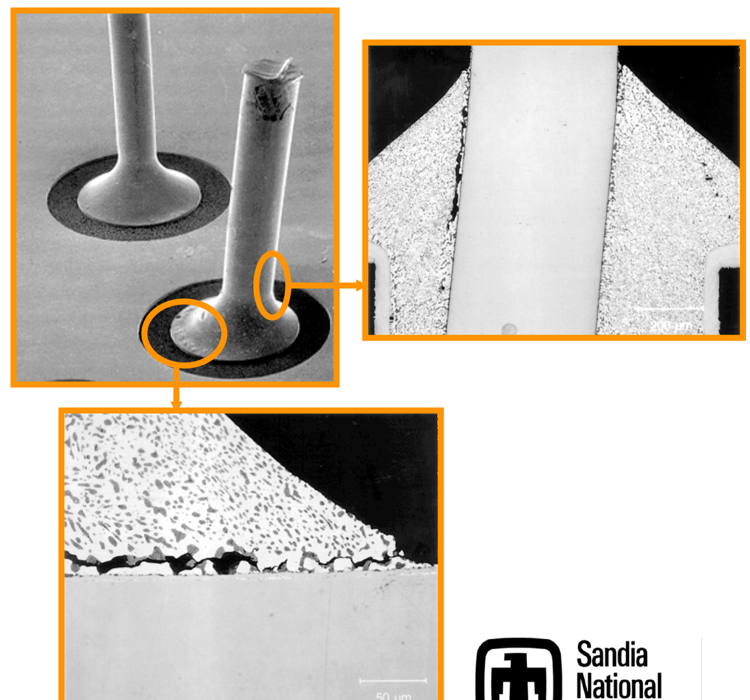
surface mount



connectors




through hole



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# *How big is the problem?*

- Studies indicate that **at least 48% of electronics failures** are likely due to solder joint failure.

- Solder joints must remain reliable beyond their initial design lifetimes

  *Military and commercial aircraft*

  *Satellites*

  *Nuclear and conventional weapons*

⇒Solder joints are a **design** problem:

*Design for reliability beyond commercial product lifetimes.*

⇒Solder joints are a **stewardship** problem:

*Predict when a component requires replacement - before it fails.*

## *Added complicatons: New solder technologies*

- Legislation and industry standard require change to lead-free solders in future circuit board assemblies.
  - These are new materials, and long-term reliability has not been fully characterized.
  - Many alloy compositions are being considered and used.
  - Surface finish effects are important in these materials.
- New package designs challenge the limits of solder reliability.
  - Higher I/O/finer pitch area-array packages
  - Package-on-package (PoP)
  - Stacked chips
  - System-in-a-package (SIP)
  - Opto-electronic devices
  - High temperature molding compounds
  - High temperature, “green” laminates

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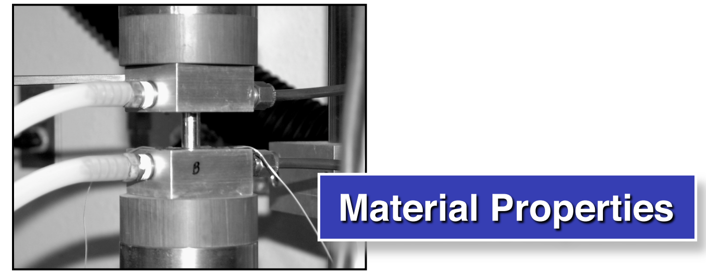
# *Integrated approach to understanding lifetime prediction and failure in solder joints*

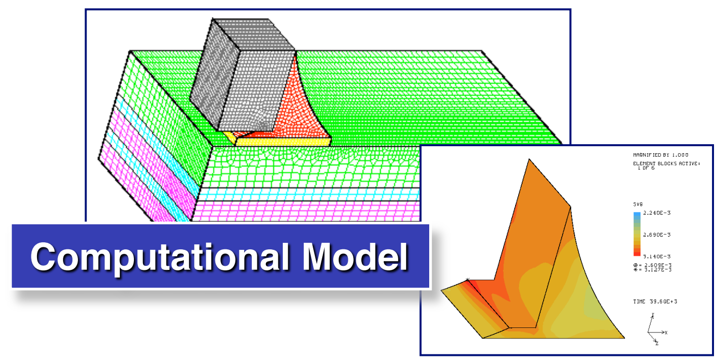
**Compile materials properties data for model input parameters.**

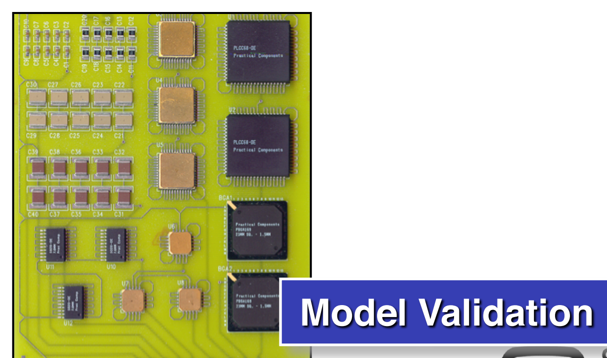
**Develop the computational model:**

- *Constitutive equation*
- *Finite element code (mesh)*
- *Optimization routines*

**Model validation using limited accelerated aging experiments.**

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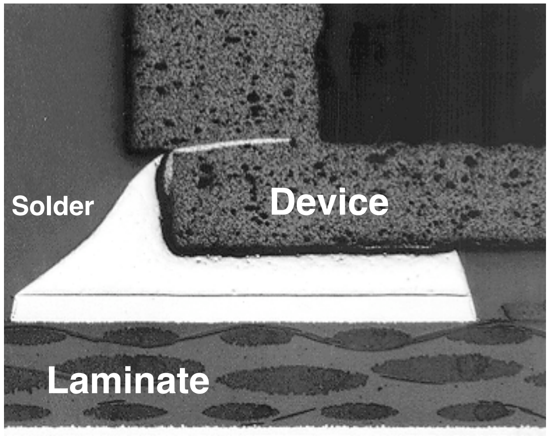
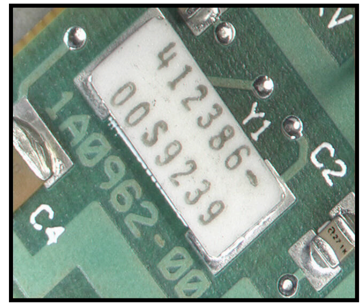
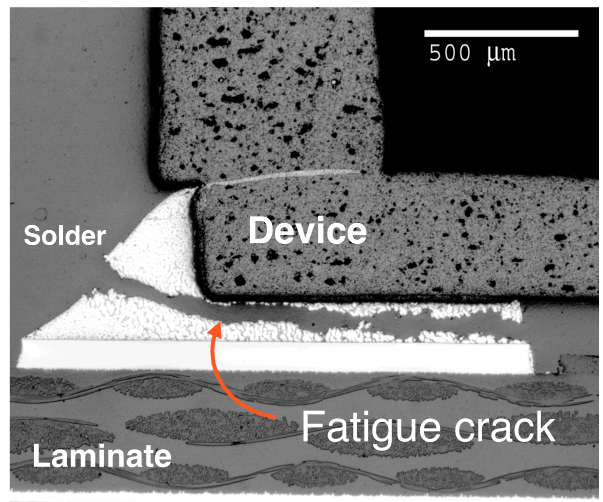
# Eutectic Pb-Sn Solders



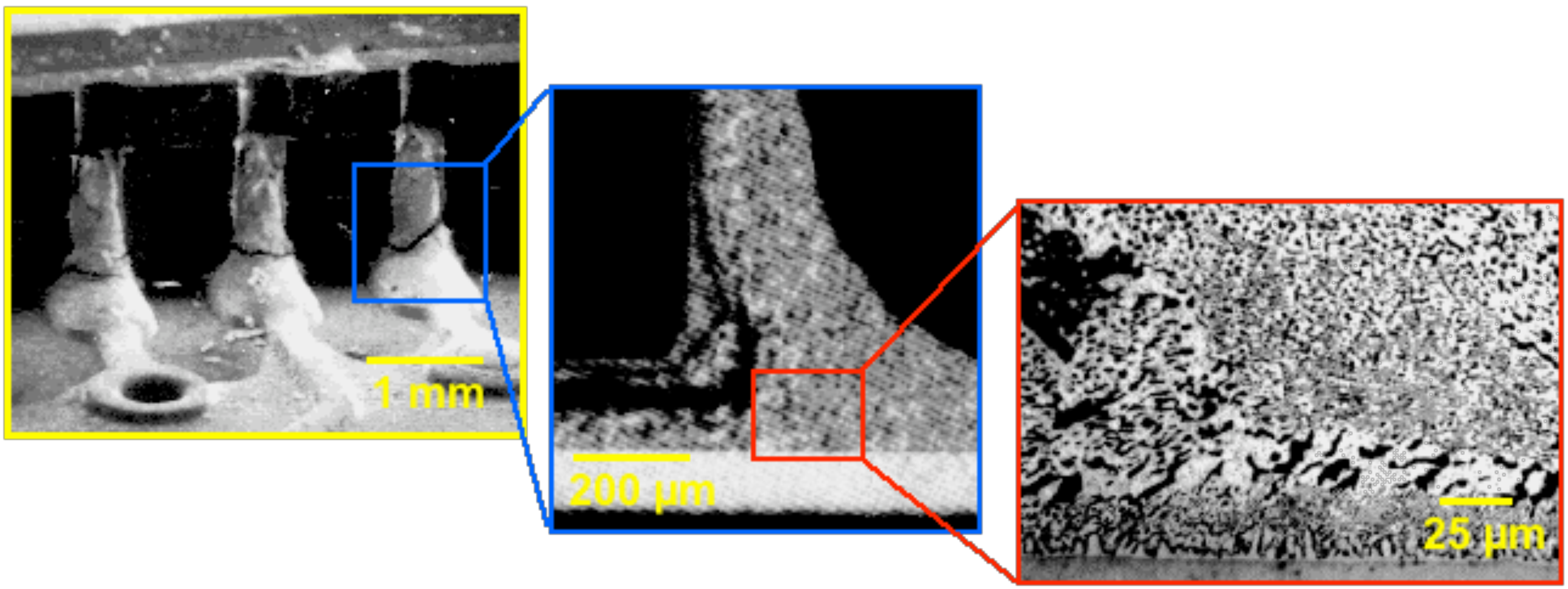




*-55°C / 125°C …*
*1000 cycles*



# *Why is microstructure important in PbSn solders?*

- The coupling between microstructure and mechanical response causes failure.

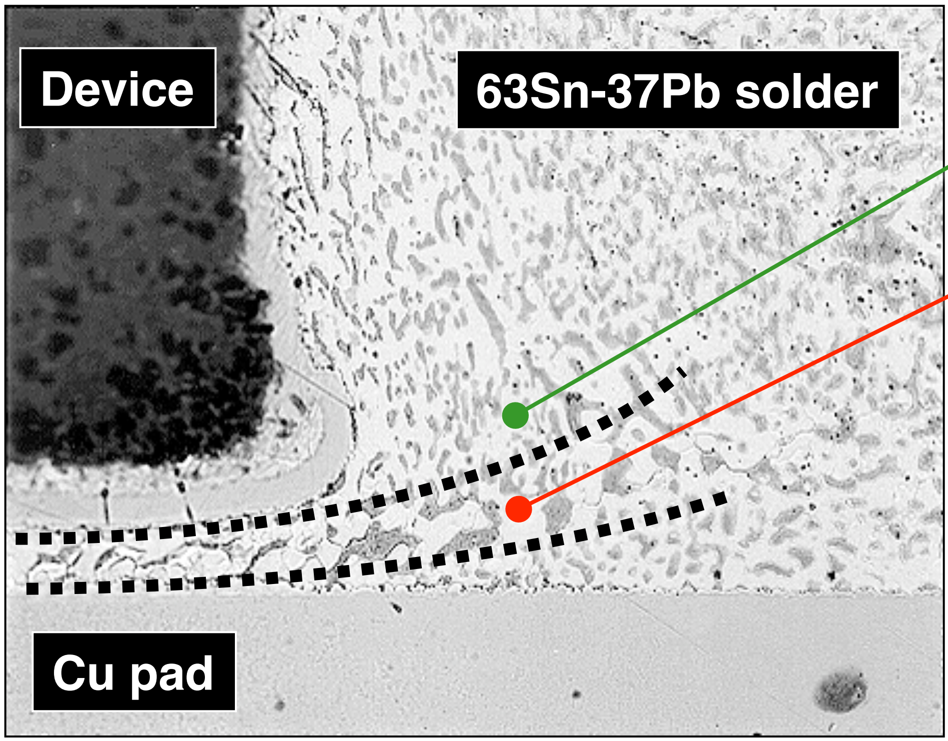



strain localization → local coarsening → further softening → failure

# *A microstructural approach to solder modeling*

•Local microstructure determines the local mechanical properties.

⇒The microstructural metric is λ, the mean Pb-rich phase particle diameter.




$[d\gamma/dt]_{fine} = f(\sigma, T, \lambda_{fine})$

$[d\gamma/dt]_{coarse} = f(\sigma, T, \lambda_{coarse})$

**The CoMPSIR© Sn-Pb solder fatigue model captures these microstructural effects to predict solder joint lifetimes.**

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# *Failure - Lifetime Prediction*

A variety of failure criteria are currently being evaluated:

| | |
|---|---|
| Failure based microstructure | Failure when $\lambda = \lambda_{critical}$ |
| Coffin-Manson | $N_f^{0.51} \Delta\gamma^P = 1.14$ (Solomon, 86) |
| Continuum damage approach | Failure when $\omega = \omega_{critical}$ |

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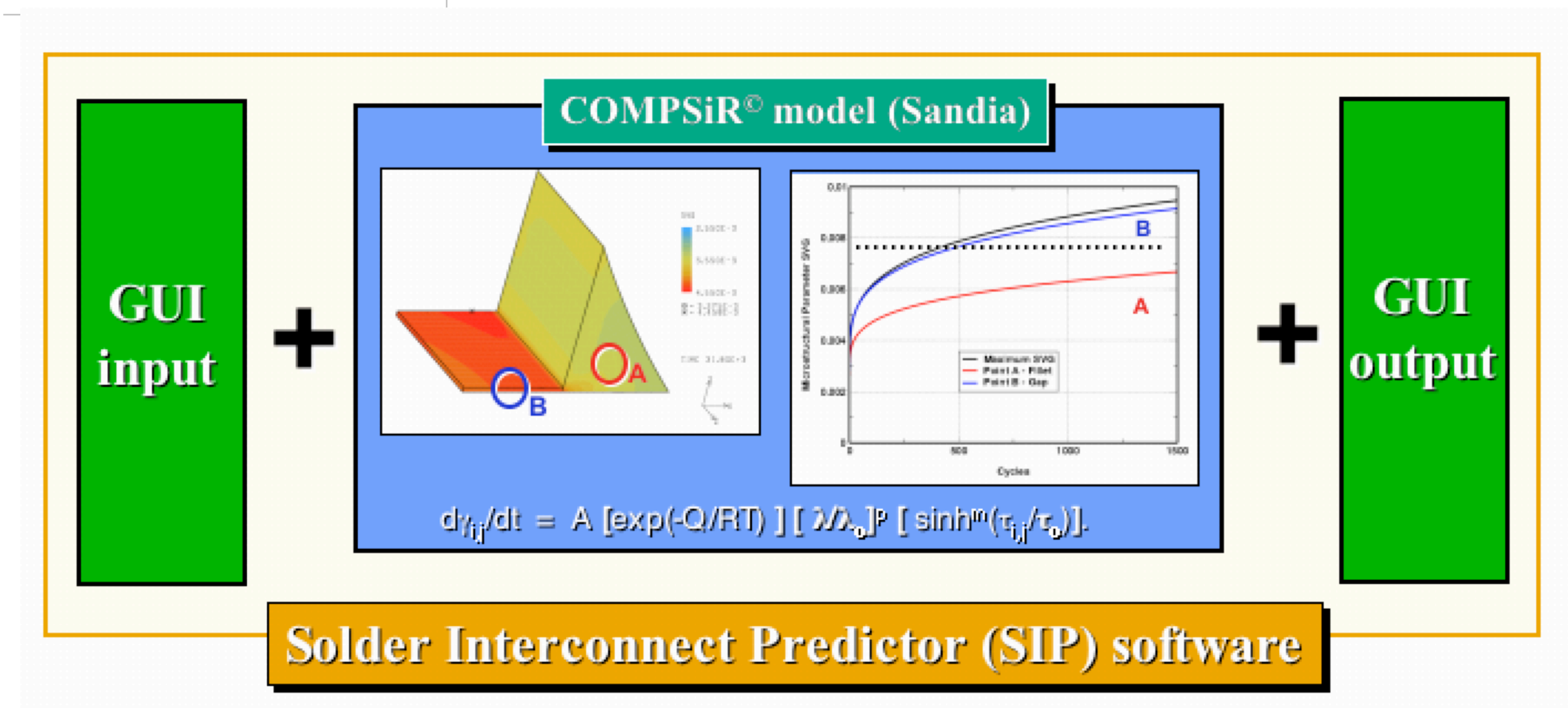
## *The solder TMF model is incorporated in a desktop design and analysis package.*




- Linux and Windows packages
- Variety of joint geometries
- Variable dimension joint shapes

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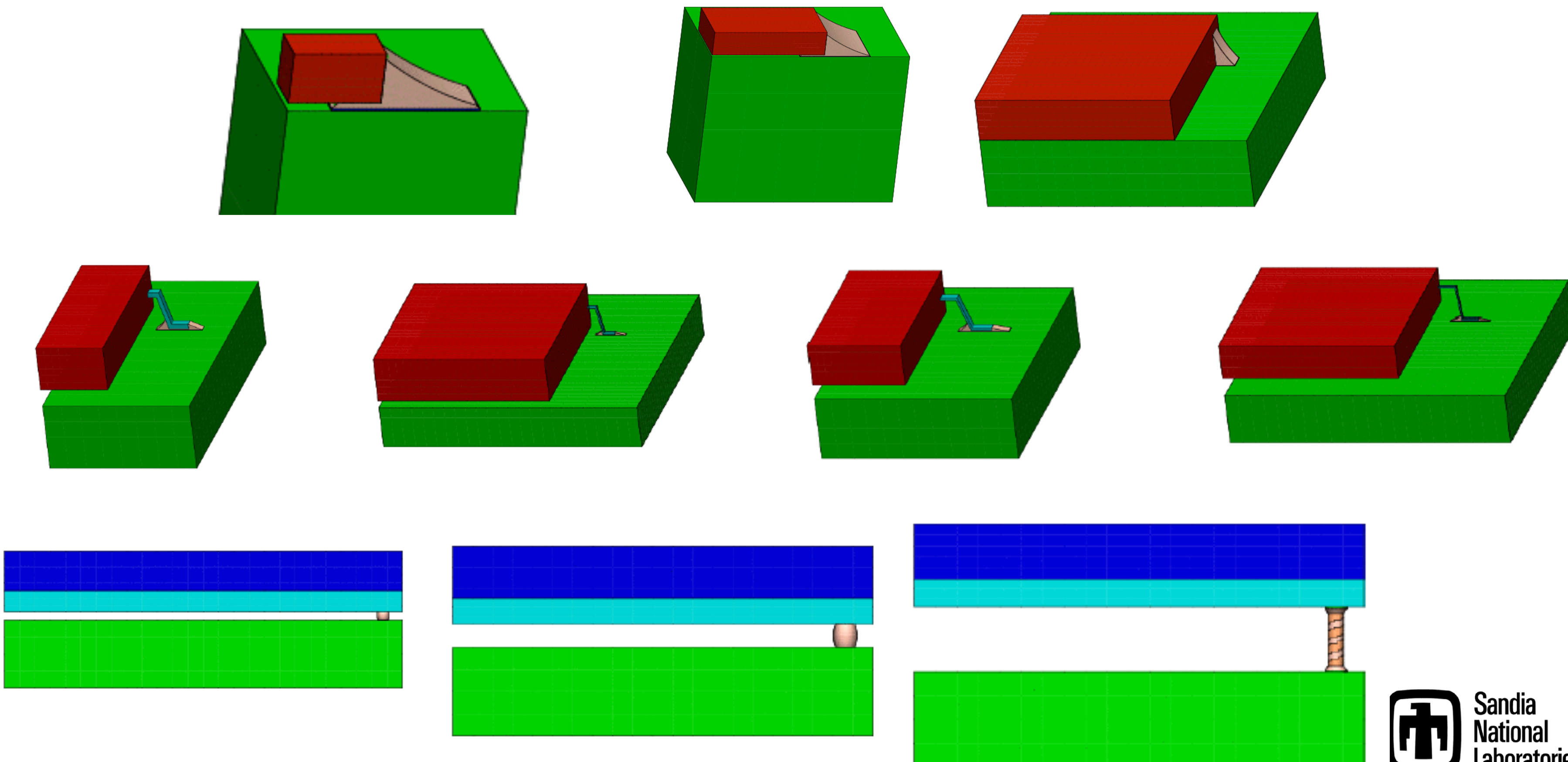
# *Is the SIP model predictive?*

- A Lockheed-Martin sponsored round robin offered the chance to **validate SIP in a blind study** against experimental data for a variety of solder joints.
- Ten solder joint geometries ranged from surface mount to FP to BGA.



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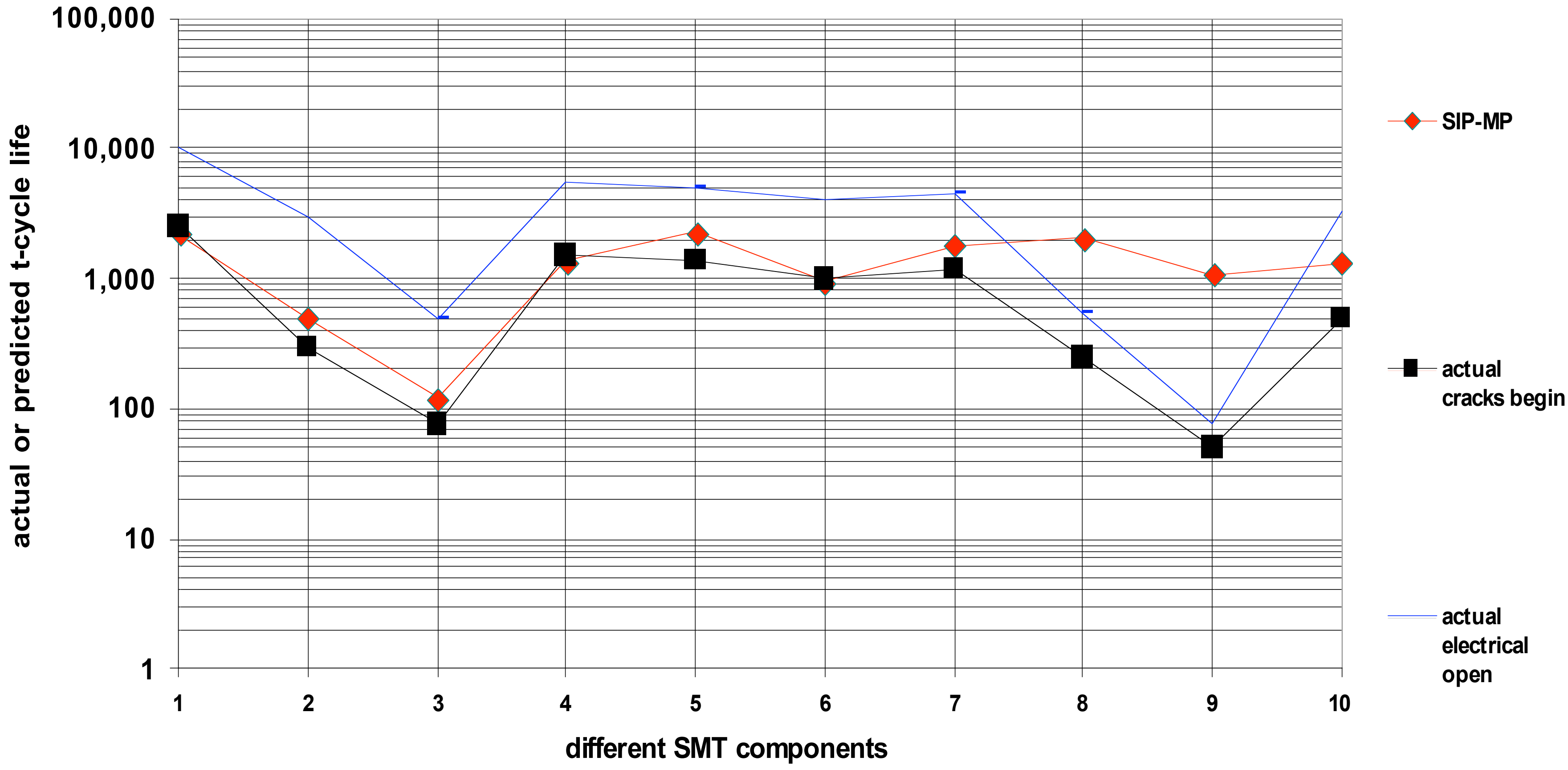
# SIP Predictions for Solder Round Robin

- Sandia-SIP (**red** line) agreed very well with experiment (**black** line) for most joint types.
- Components 8 and 9 (BGAs) demonstrated mesh refinement issues that we have addressed.



# *How can we add predictivity?*

- The Round Robin results showed that crack initiation precedes failure, often by thousands of cycles (**blue** line).

⇒***Can we models the actual failure process: cracking to open circuit?***

- – Fracture propagation is a challenge in FEM implementation, due to stress singularities and nonlinear behavior.
- – We take a smeared cracking approach – replace cracked elements with weak elastic material.
  - » When $\lambda$ gets to critical value of 6.0$\mu$m, elements become weak elastic material with $\sigma = 0.01\ \mathbf{E} : \varepsilon$ .
  - » Dramatic change in element mechanical response changes boundary value problem.
  - » No remeshing needed; no numerical difficulties from introduction of a discrete crack.

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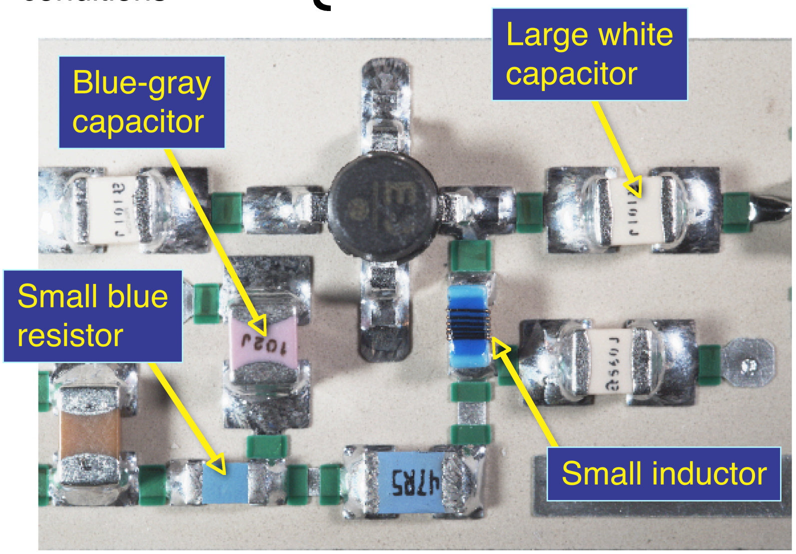
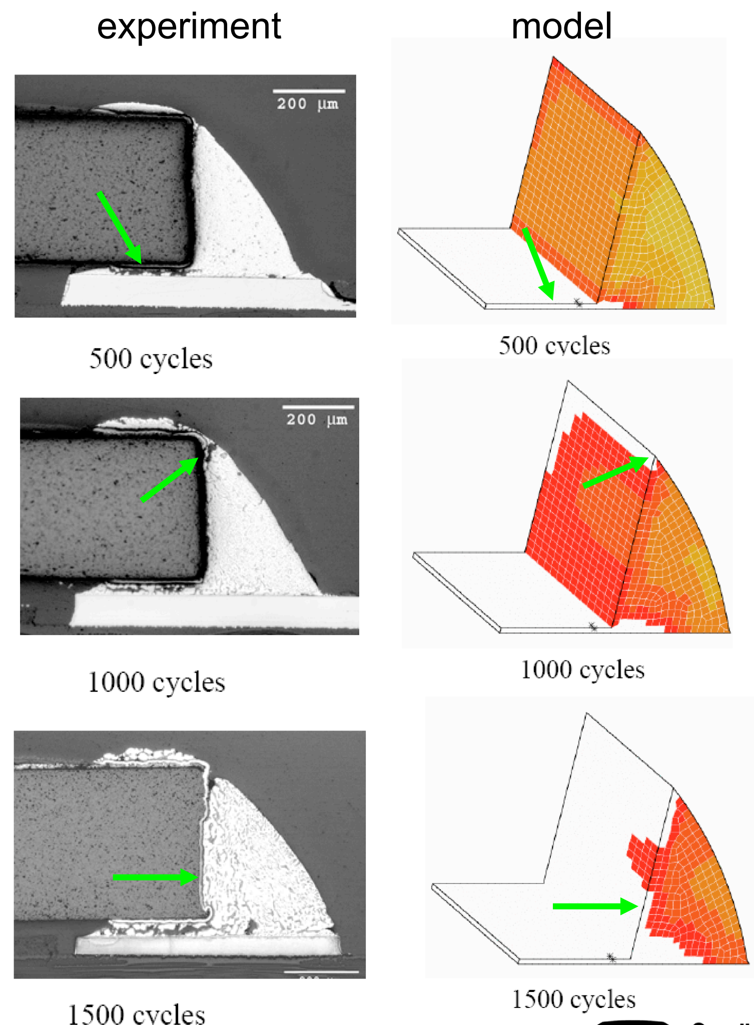
# *How well does it work?*
# *Comparisons to test vehicle experiments*

Test vehicle accelerated aging conditions: -55°C … 125°C, 20 min holds; 0, 500, 1000, and 1500 cycles




- SIP results for both crack morphology and joint lifetime agree well with experiments on a test vehicle circuit board.

Small blue resistor:




White elements are cracks.

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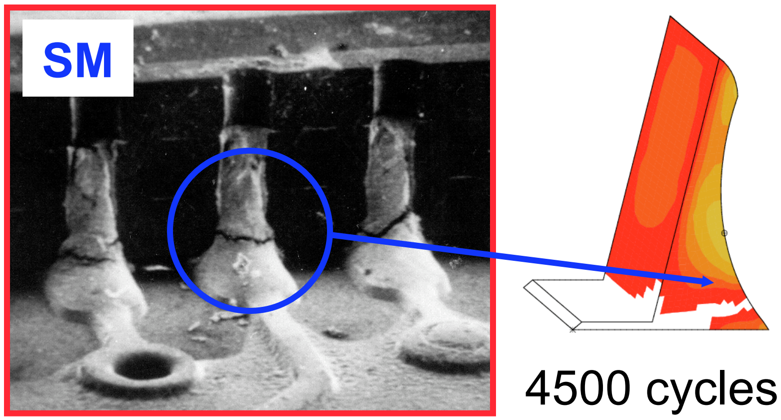
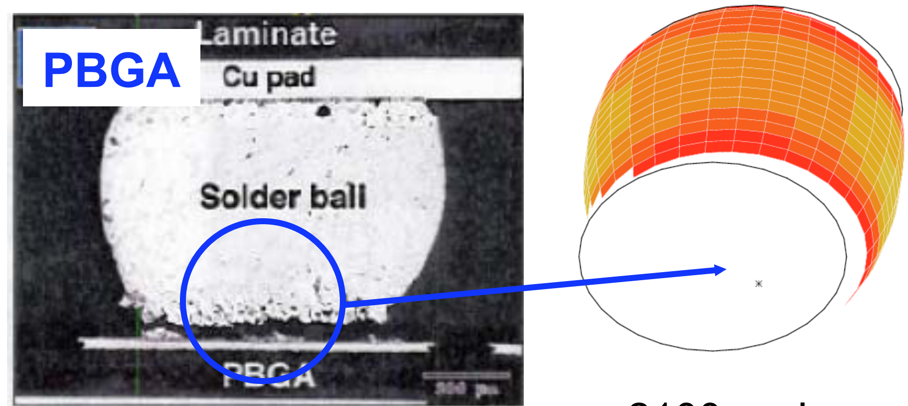
# *SIP today*

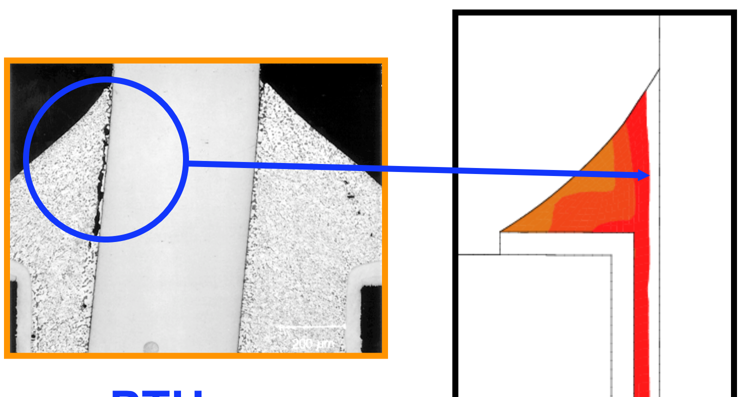
- SIP is used as a predictive design and analysis tool by Sandia, US Navy, Lockheed-Martin, and other customers.




4500 cycles



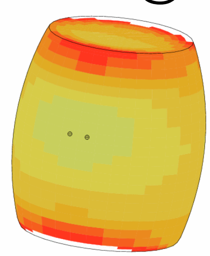

2100 cycles



PTH

2,000 cycles

Experiments indicate CBGA failure @ 200 to 300 cycles.



Cracks at 200 cycles

Electrical Open at 500 cycles

**CBGA**

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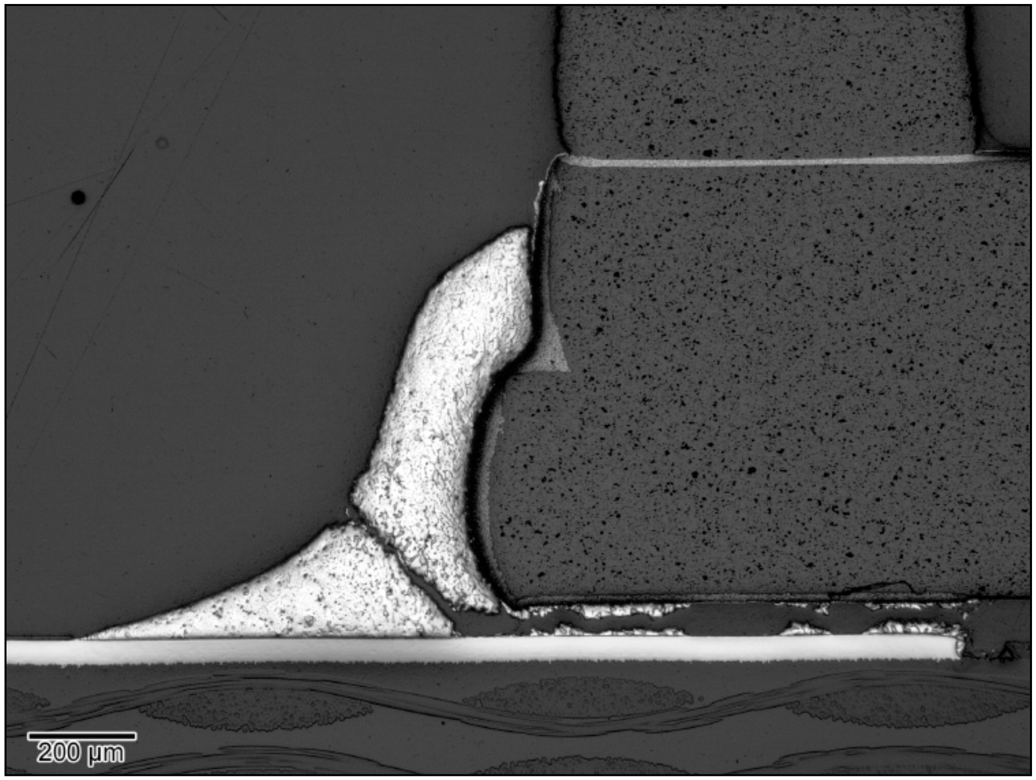
# Pb-free Solders




Pb-free LCC joint

# *Pb-free modeling approach*

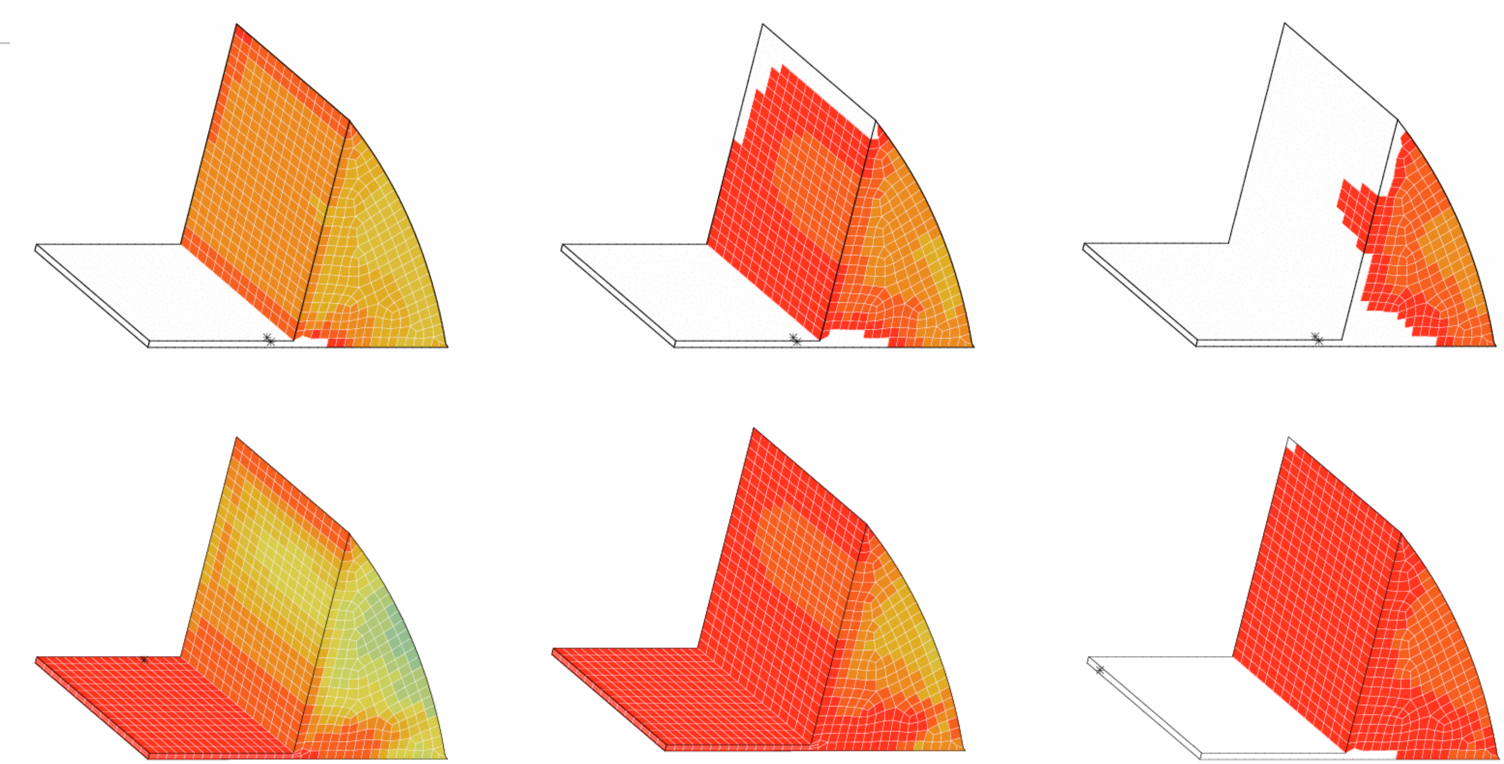
- Approach:
  - –Develop Unified Creep-Plasticity Damage (UCPD) Model for the Pb-free Solder 95.5Sn-3.9Ag-0.6Cu
  - –We use the modeling paradigm developed for Pb-Sn solder
    - »Microstructurally-based damage model
    - »Fracture when microstructural parameter exceeds critical value
  - –Implement the constitutive model in a life prediction method (Pb-free SIP)

- The model is newer, but results are promising.

# *Comparing Pb-free to Pb-Sn solders*

**Sn-Pb model**

**Pb-free model (SAC)**



500 | 1000 | 1500 cycles

⇒Pb-free SAC solder appears to have a longer lifetime than PbSn solder in the same joint configuration.

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# *Validation experiments support this generalization*

- Pb-free solder joints appear to have a better reliability than Sn-Pb solder joints.

**Sn-Pb solder**

| Cycle Target: | 5000 | 1-50 | 51-100 | 101-200 | 201-300 | 301-400 | 401-500 | 501-600 | 601-700 | 701-800 | 801-900 | 901-1000 | 1001-1100 | 1101-1200 | 1201-1300 | 1301-1400 | 1401-1500 | 1501-1600 | 1601-1700 | 1701-1800 | 1801-1900 | 1901-2000 | 2001-2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LCC1,LCC2 | 25 | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| EBGA1 | 26 | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| PLC1,PLC2 | 27 | Pass | Pass | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| CBGA2 | 28 | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| CBGA1 | 29 | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| SOT931-SOT938 | 30 | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| SOIC941-SOIC948 | 31 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| R951-R958 | 32 | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| C921-C928 | 33 | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| C911-C918 | 34 | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| R911-R918 | 35 | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| R921-R928 | 36 | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |

**Failed** **Pass**

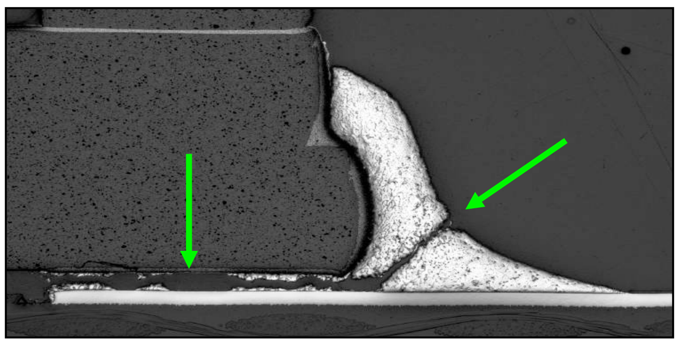
**Pb-free solder**

| Cycle Target: | 5000 | 1-50 | 51-100 | 101-200 | 201-300 | 301-400 | 401-500 | 501-600 | 601-700 | 701-800 | 801-900 | 901-1000 | 1001-1100 | 1101-1200 | 1201-1300 | 1301-1400 | 1401-1500 | 1501-1600 | 1601-1700 | 1701-1800 | 1801-1900 | 1901-2000 | 2001-2100 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LCC1,LCC2 | 85 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| EBGA1 | 86 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| PLC1,PLC2 | 87 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| CBGA2 | 88 | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| CBGA1 | 89 | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| SOT931-SOT938 | 90 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| SOIC941-SOIC948 | 91 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| R951-R958 | 92 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| C921-C928 | 93 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| C911-C918 | 94 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |
| R911-R918 | 95 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed | Failed |
| R921-R928 | 96 | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass | Pass |

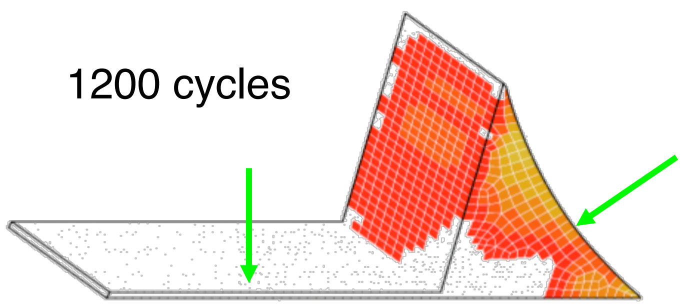
# Pb-free SIP today

- Pb-free SIP is beginning to be exercised as a predictive design and analysis tool by customers at Sandia and Lockheed-Martin.

LCC Pb-free test vehicle
900 thermal cycles



1200 cycles



# Summary

- Reliability of solder joints is an important design and stewardship issue.

- We have developed a desktop design and analysis package for solder joints, the Solder Interconnect Predictor (SIP)
  - Pb-Sn and Pb-free solders
  - Models entire lifetime to open circuit failure

- SIP uses experimental results to develop and to validate the model
  - Excellent agreement with experiment for both location and cycles to failure

- SIP is being used by customers to make engineering decisions in an ICME framework

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# Solder Constitutive Model Development

Step 1. Capture mechanical response - Elasticity, Plasticity, Creep
Effects of temperature and loading rate

Step 2. Include effects of microstructure on mechanical response
Hall-Petch effect on flow strength
Effect of coarsening on steady-state creep

Step 3. Capture evolution of microstructure - Coarsening
Temperature and mechanical loading effects
Use state variable to describe microstructure

Step 4. Failure - Lifetime prediction methodology
Failure based on state of microstructure
Coffin-Manson using plastic strain increment from fea
Continuum damage approach

# A Viscoplastic Model for Solder

Constitutive Relation
$$\dot{\sigma} = \mathbf{E} : (\mathbf{d} - \mathbf{d}^{in})$$

Inelastic Deformation Rate
$$\mathbf{d}^{in} = \frac{3}{2}\dot{\gamma}\mathbf{n} = \frac{3}{2} f \exp\left(\frac{-Q}{R\theta}\right)\left(\frac{\lambda_o}{\lambda}\right)^p \sinh^m\left(\frac{\tau}{\alpha(c+\hat{c})}\right)\mathbf{n}$$

Normalized Stress Difference Tensor
$$\mathbf{n} = \frac{\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)}{\tau}$$

von Mises Effective Stress
$$\tau = \sqrt{\frac{3}{2}\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right) : \left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)}$$

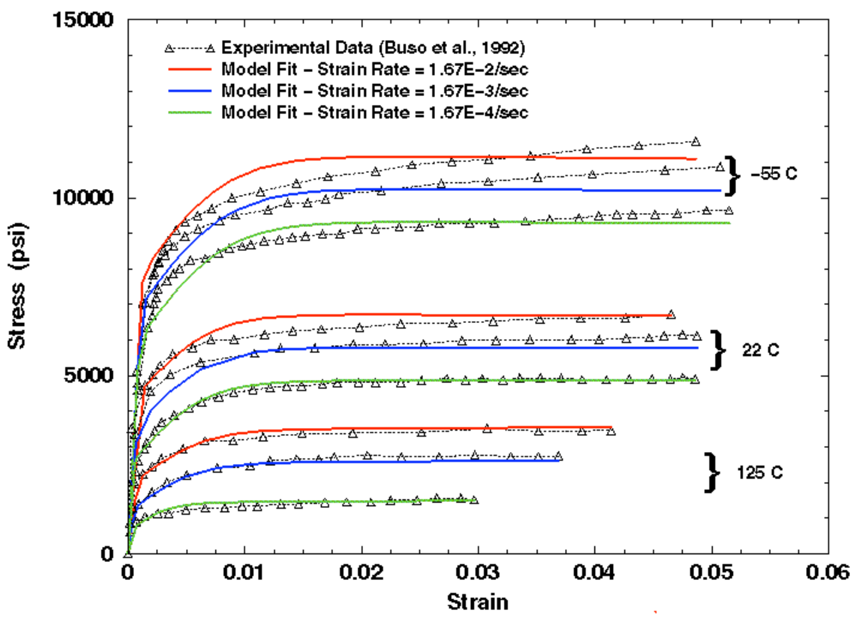
Evolution Eq. for State Variable c
$$\dot{c} = A_1\dot{\gamma} - (A_2\dot{\gamma} + A_3)(c - c_o)^2$$

Evolution Eq. for State Tensor B
$$\dot{\mathbf{B}} = A_4\mathbf{d}^{in} - (A_5\dot{\gamma} + A_6)\sqrt{\left(\frac{2}{3}\mathbf{B} : \mathbf{B}\right)}\,\mathbf{B}$$

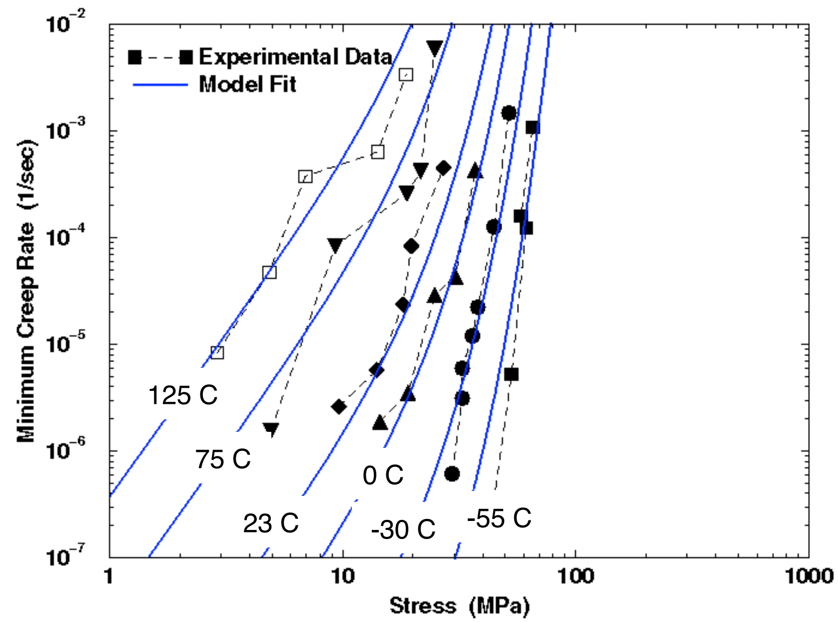
Effect of Coarsening on Strength (Hall-Petch Relationship)
$$\hat{c} = A_7\left(\frac{\lambda_o}{\lambda}\right)^{A_8} \qquad A_8 = \frac{1}{2}$$

Coarsening Rate (Pb-rich Phase Size)
$$\dot{\lambda} = \frac{(A_9 + A_{10}\dot{\gamma})}{(\lambda - \lambda_o)^{A11}}$$

# Constitutive Model vs. Experimental Data




Uniaxial Compression




Steady-State Creep

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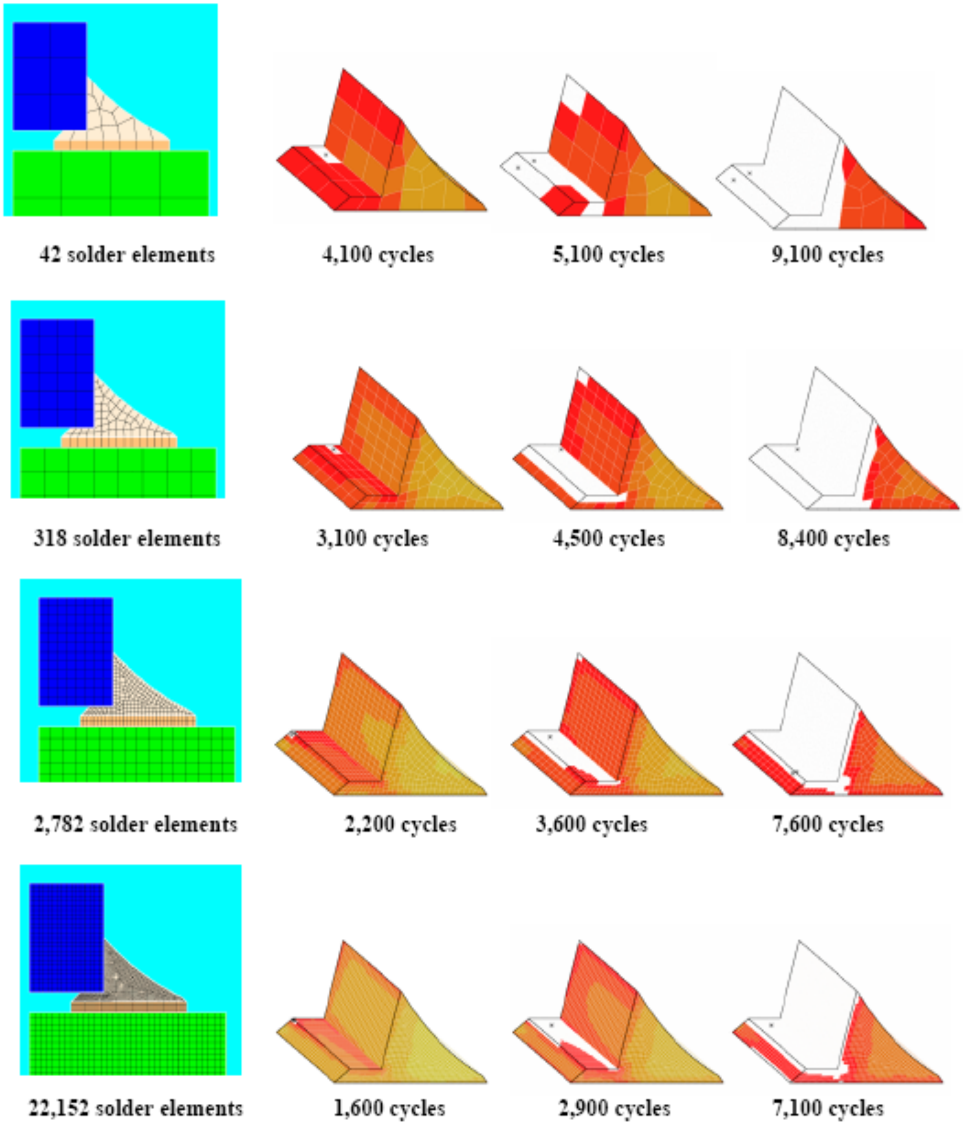
# How significant is mesh dependence?




- Mesh dependence is minimal for cracking via weak elastic elements.