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TurboSiP© Software Workshop

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Albuquerque, NM

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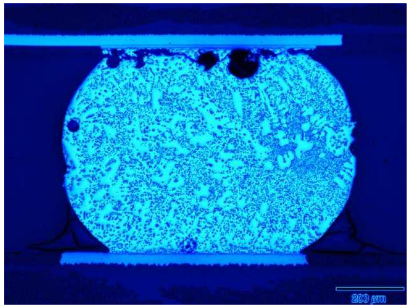
Outline

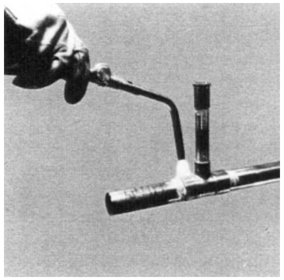
- Brief Perspective on Solder Joint Fatigue
- Background - Sandia Solder Joint Fatigue Models
- TurboSiP© Software
- Future Directions for Sandia Modeling Efforts
- Critical Perspective on Reliability
- Hands-on Use of the TurboSiP© Software

M. Neilsen

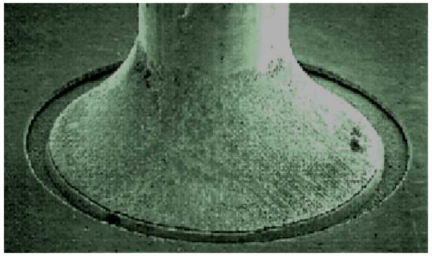


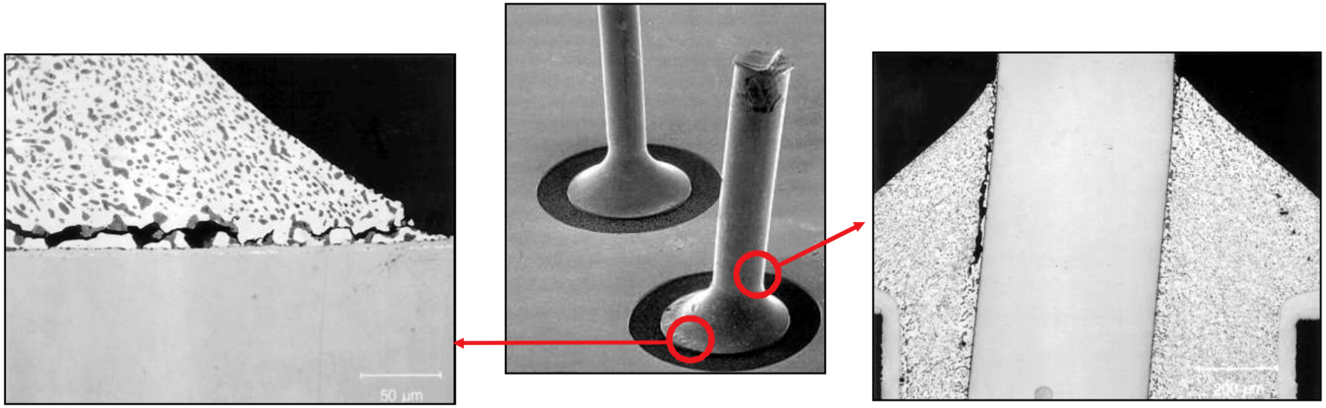
Solder Joint Fatigue

- **Fatigue is not a dominant failure mode in structural solder joints (e.g., piping, sheet metal, etc.)**



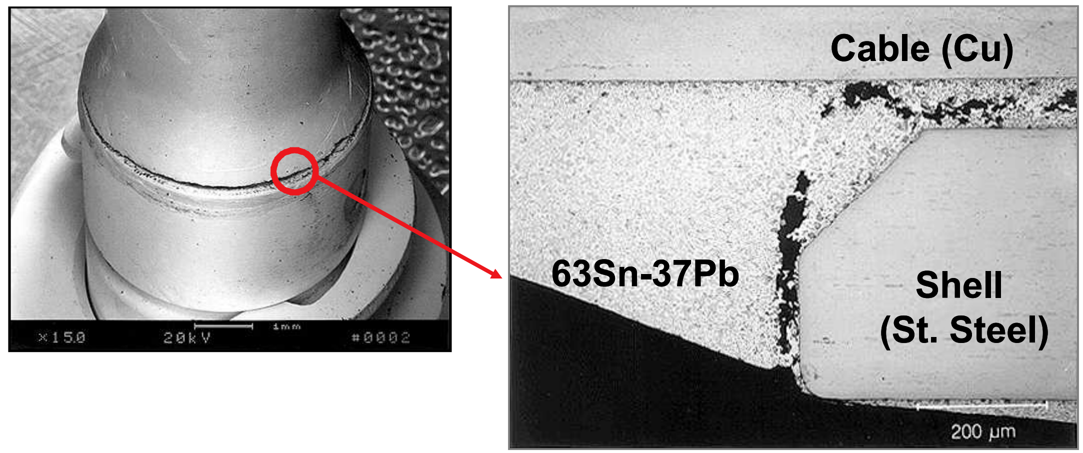
- **Fatigue is also not a dominant failure mode in through-hole, printed circuit board electronics.**
  - **The solder joints were simply too robust (over-designed) for this application.**
  - **But, it can occur ...**



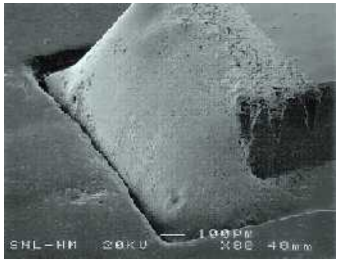


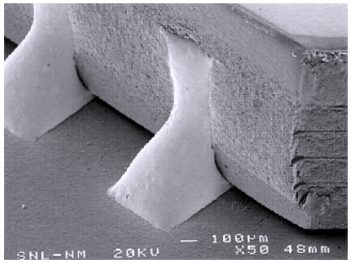
Solder Joint Fatigue

- Fatigue can occur in other electronic components, particularly those placed in vibration environments.



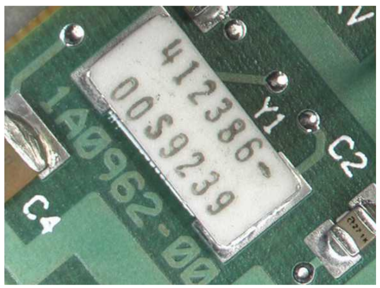
- Fatigue of solder joints “hit the spot light” with the widespread use of surface mount technology during the early 1980’s, and through to today.
    - Reduced margin in their role as mechanical fasteners.

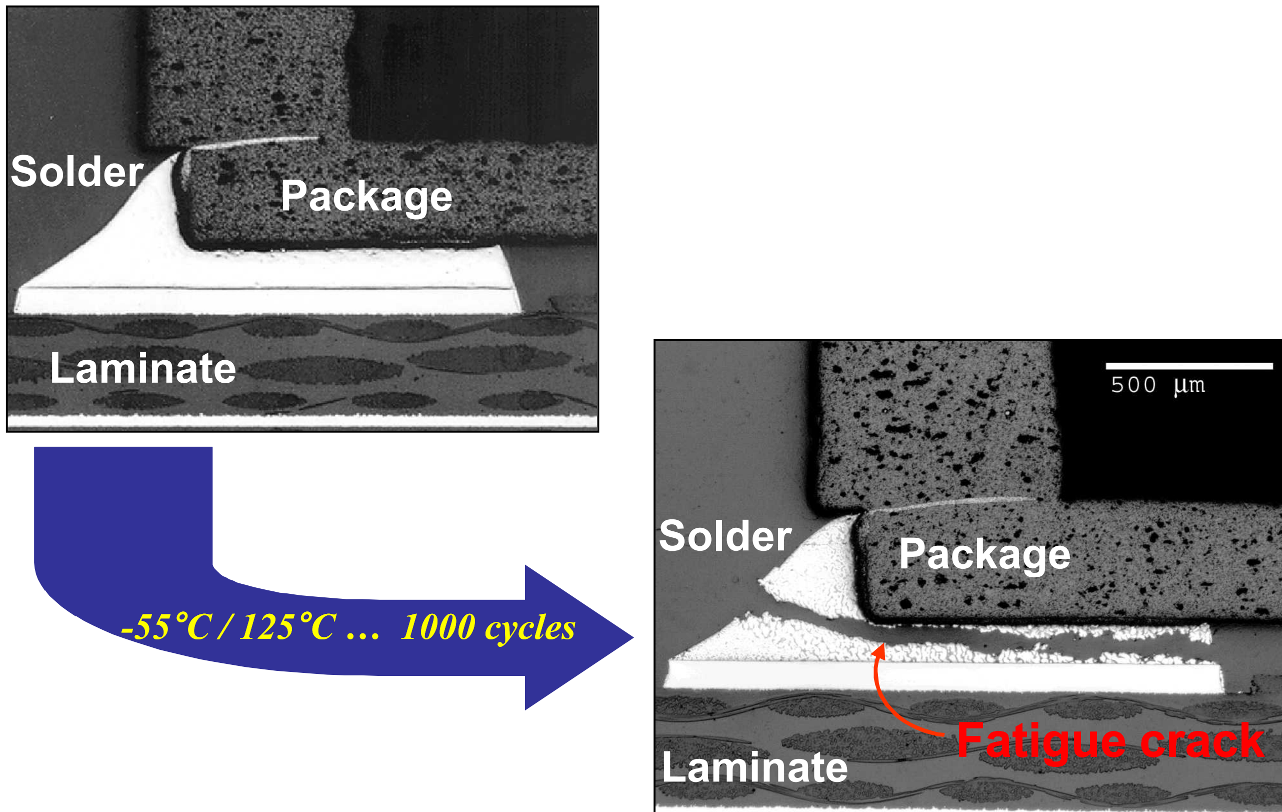




Solder Joint Fatigue

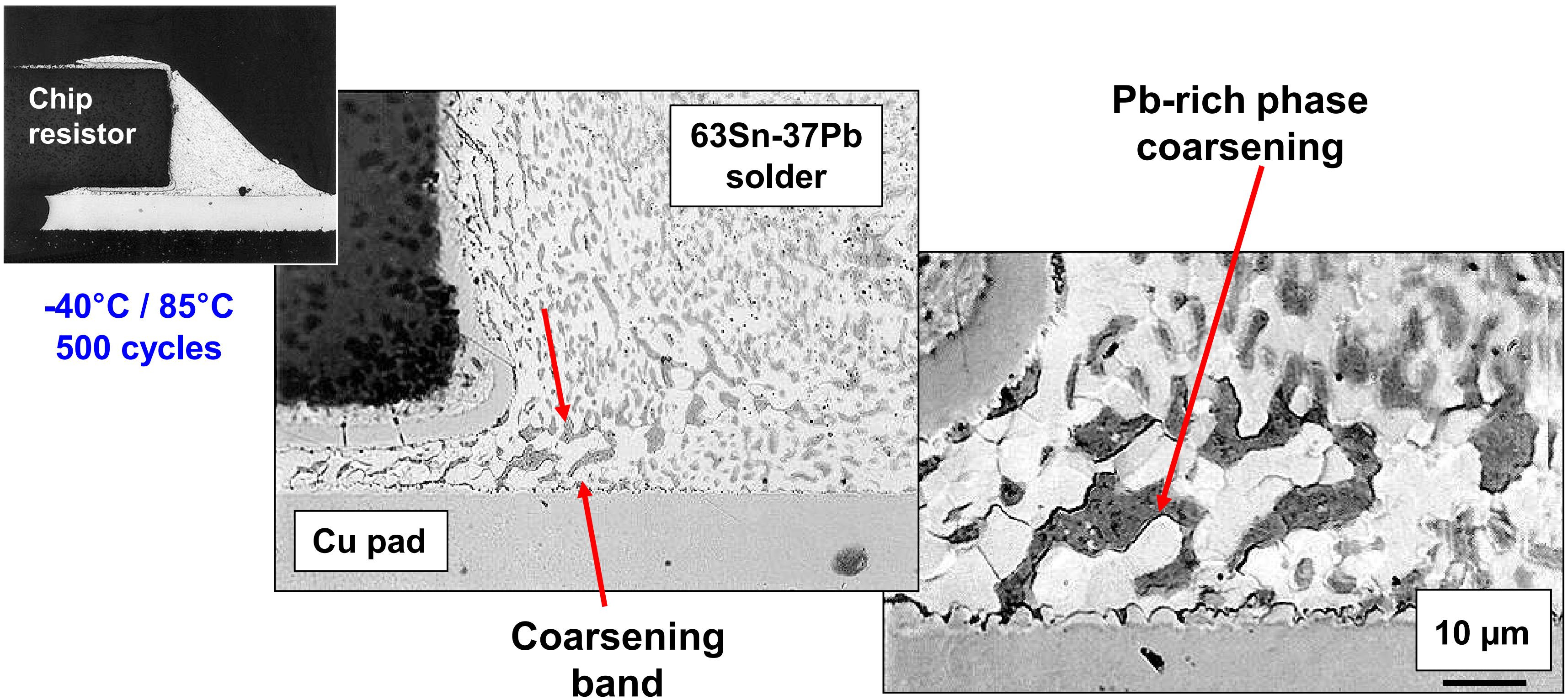
- The **thermal mechanical fatigue (TMF)** failure of a eutectic Sn-Pb solder joint is illustrated here for a ceramic package (resonator).





Solder Joint Fatigue

- It was recognized, early on, that the TMF of eutectic Sn-Pb solder began with a coarsening of the microstructure.

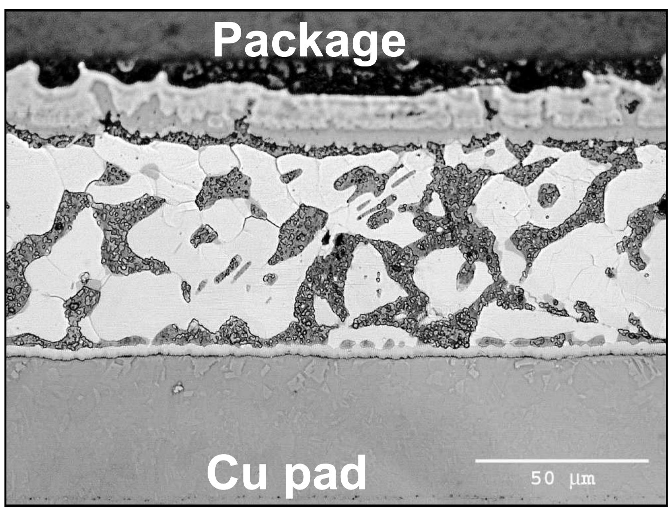


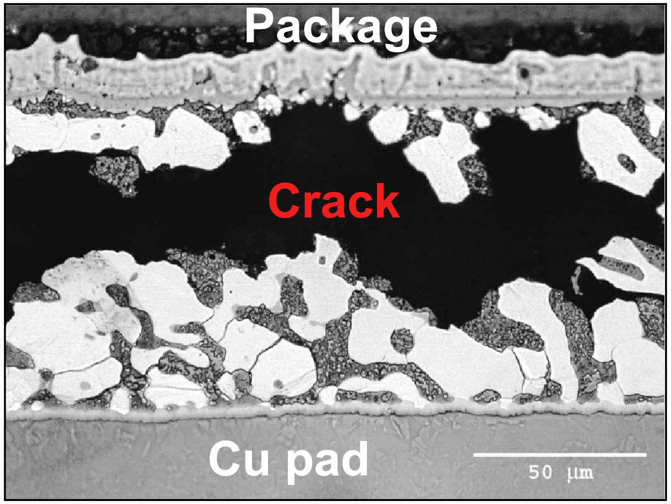
-40°C / 85°C
500 cycles

- The microstructural coarsening originates as a consequence of the mechanism of dynamic recrystallizaton (DRX).

Solder Joint Fatigue

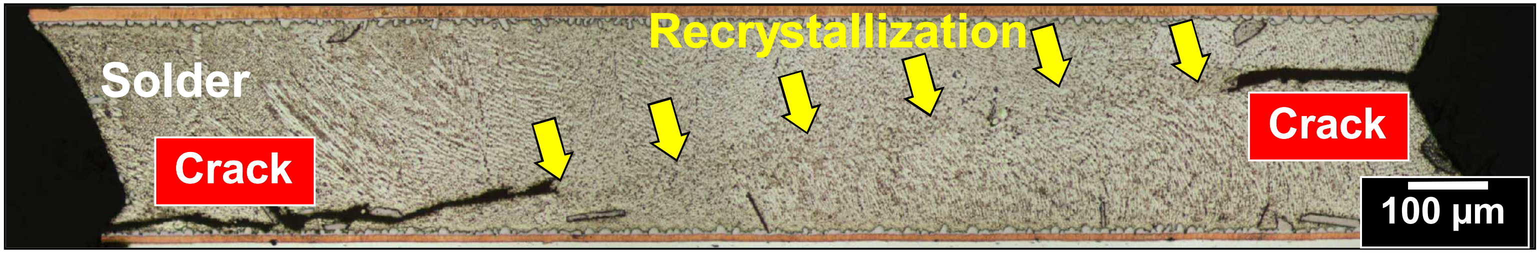
- The microstructural coarsening is followed by the initiation and propagation of a fatigue crack through the solder joint.



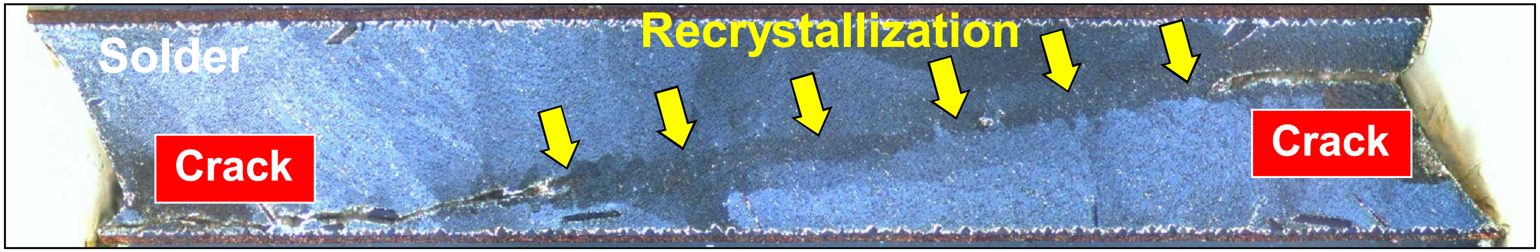


Solder Joint Fatigue

- **At first glance, the TMF deformation of Sn-Ag-Cu solder interconnections appears to differ from that of Sn-Pb joints.**
- ***Such is not the case; it is all dynamic recrystallization (DRX).***



Bright-field

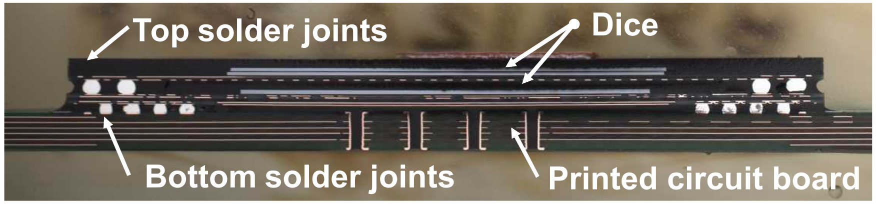


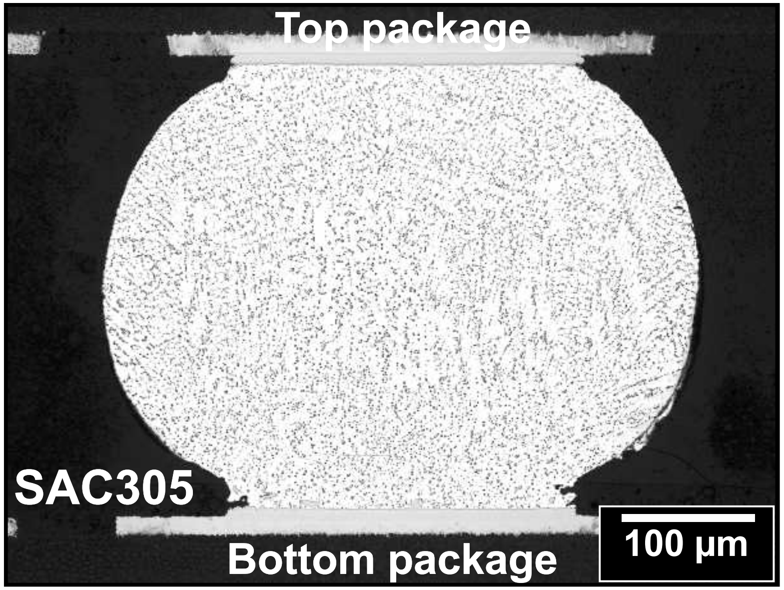
Polarized light

25°C … $\Delta\varepsilon_{corrected}$ = 1.1% … 750 cycles

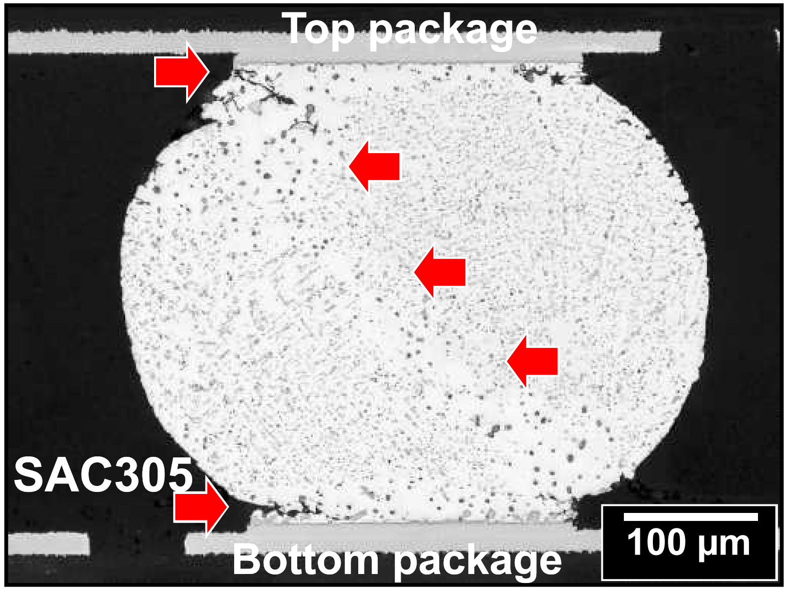
Solder Joint Fatigue

- DRX is evident in the Sn-Ag-Cu microstructure by **coarsening of the Ag_3Sn particles** preceding a crack. The effect is less dramatic than Pb-rich phase coarsening in Sn-Pb solder.





500 cycles

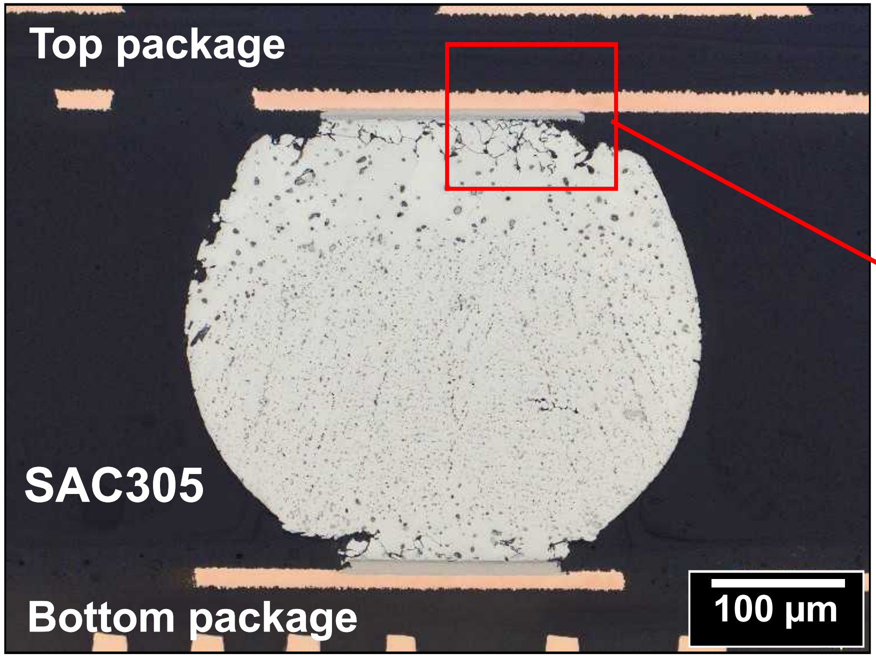


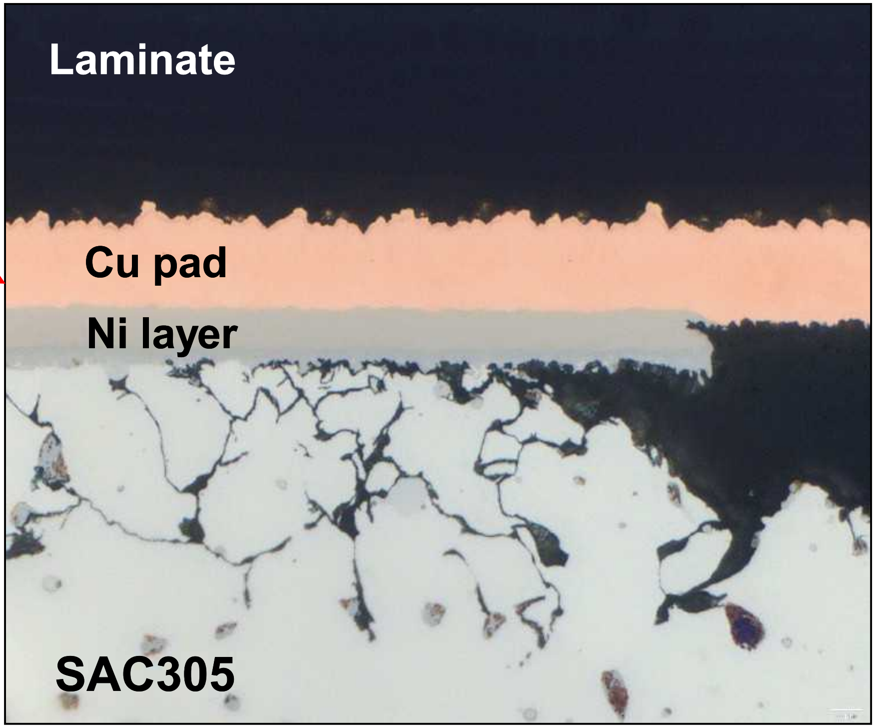
5000 cycles

Underfill, both gaps; Sn-Pb/SAC305 bottom joints

Solder Joint Fatigue

- **Crack initiation and propagation in Sn-Ag-Cu solder takes place at the grain boundaries created within the DRX regions.**
  - **This crack morphology is like that in eutectic Sn-Pb solder, except in the latter case, the cracks also propagate along phase boundaries.**

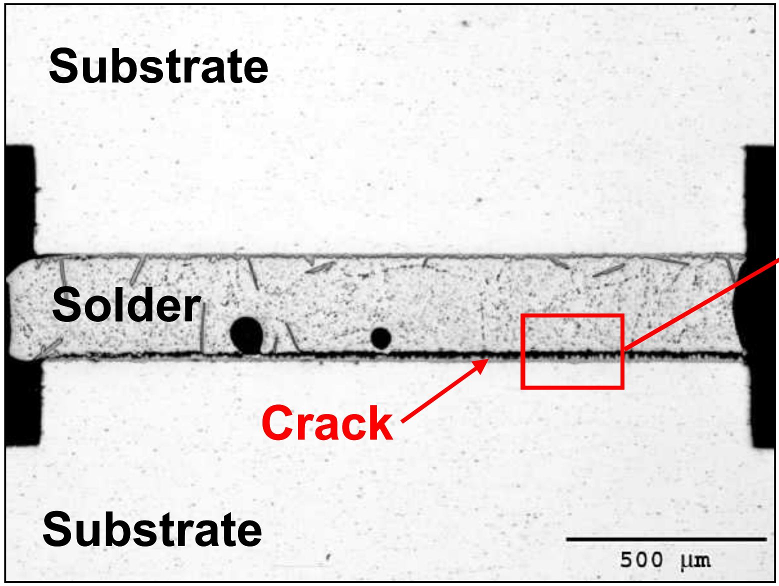


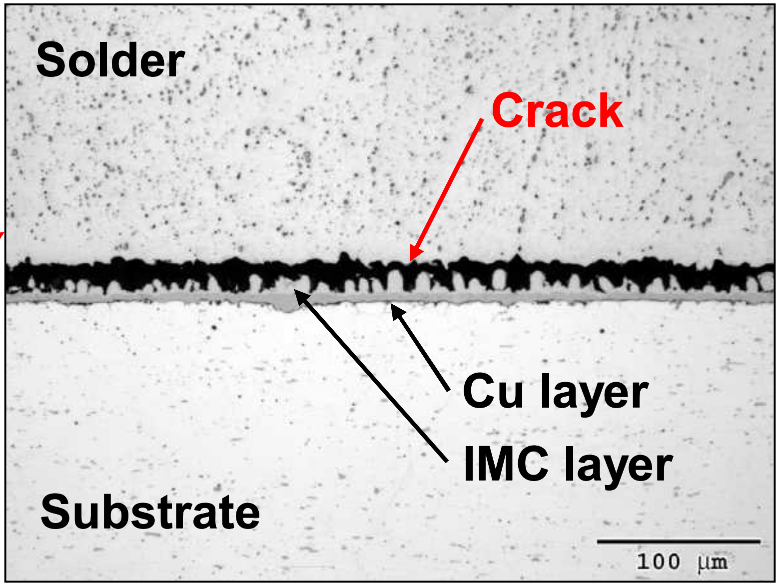


Underfill, both gaps; Sn-Pb/SAC305 bottom joints; 7500 cycles

Solder Joint Fatigue

- At large strains, the DRX zone sets up at the immediate solder/substrate interface, resulting in an **"unzipping" failure mode** that does not significantly damage the IMC layer.

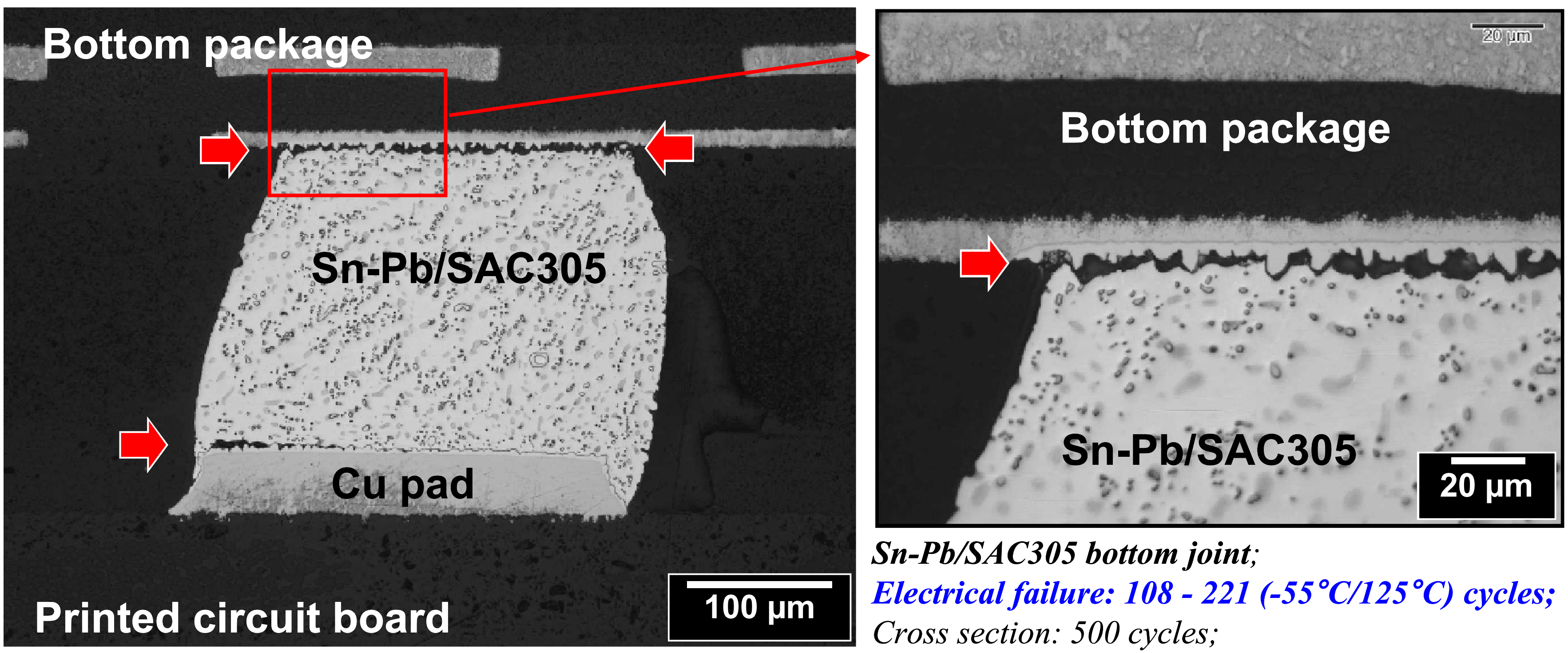




160°C … $\Delta\varepsilon_{corrected}$ = 8.8% … 12 cycles (50% L.D.)

Solder Joint Fatigue

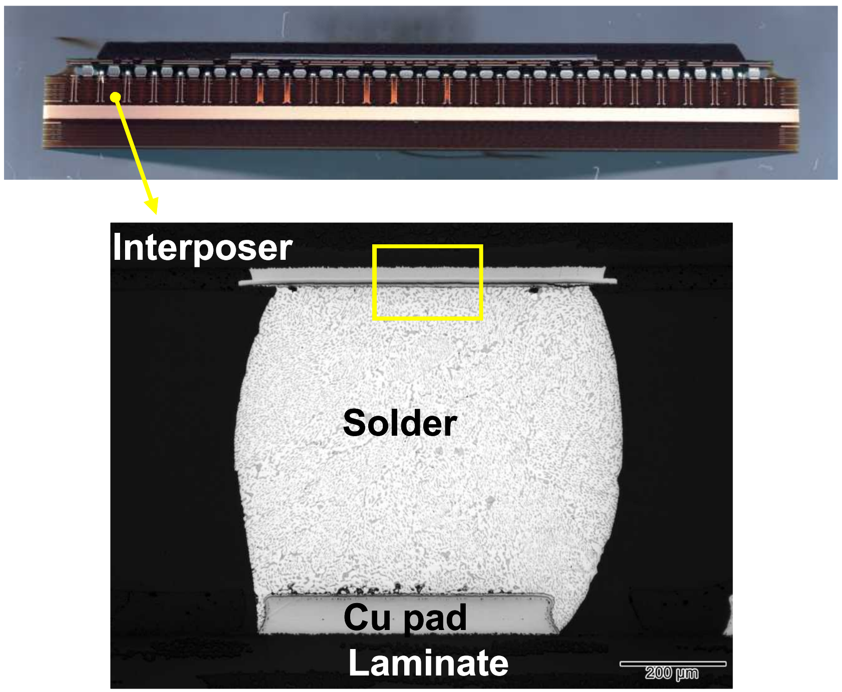
- **A similar failure phenomenon was observed for package-on-package solder joints that failed after relatively few cycles.**
  - **In this case, the large fatigue strain was generated by the introduction of an underfill material around the joints.**

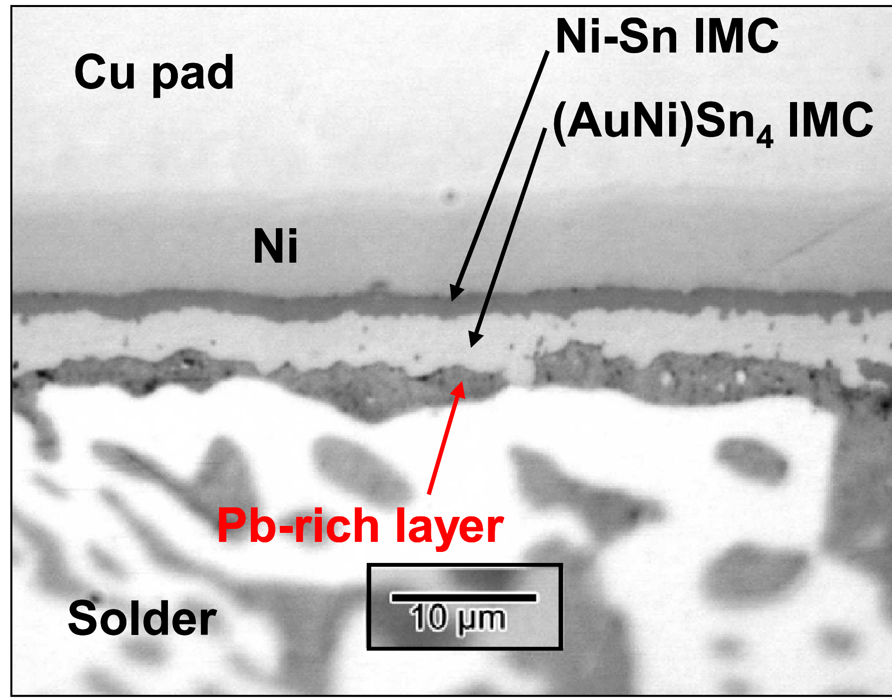


Sn-Pb/SAC305 bottom joint;
Electrical failure: 108 - 221 (-55°C/125°C) cycles;
Cross section: 500 cycles;

Solder Joint Fatigue

- **Solder fatigue can be accelerated by ancillary phenomena**:
- **Example: Gold, which had diffused into the solder (ball), diffused back to the interface, accelerating growth of the $(AuNi)Sn_4$ layer.**



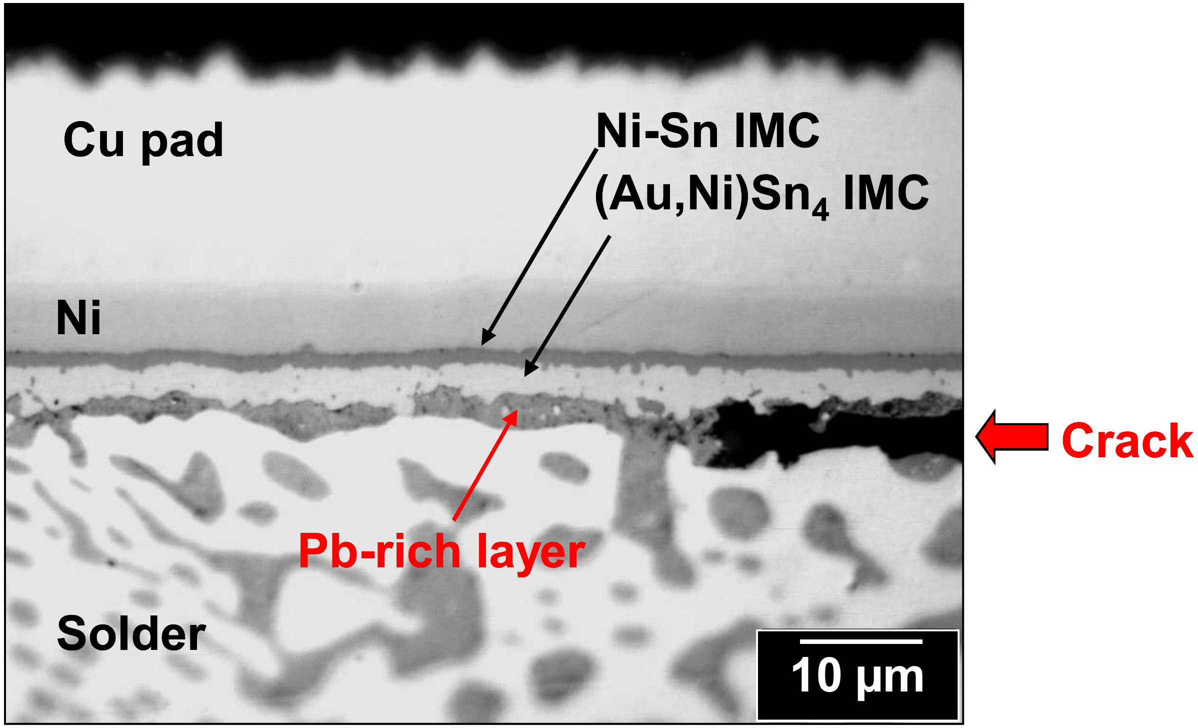


But … it's not just an embrittlement problem:

- **The $(AuNi)Sn_4$ IMC layer causes formation of a Pb-rich layer.**

Solder Joint Fatigue

- The **Pb-rich layer** is the favored path of **fatigue cracks**.

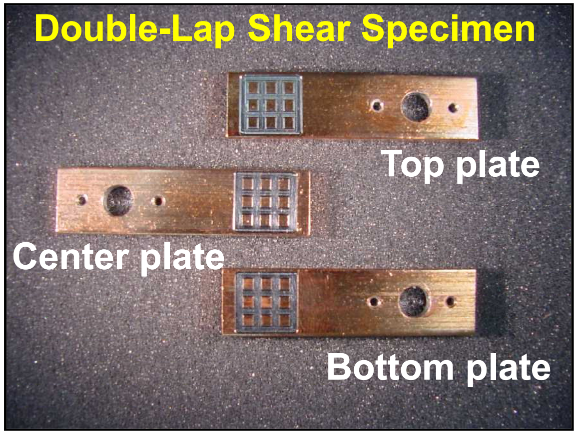


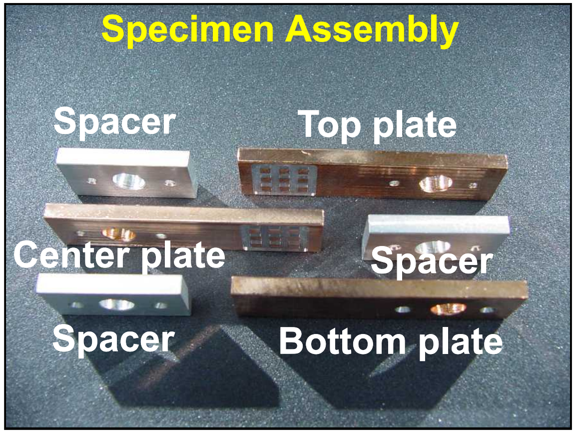
- The result is an acceleration of the **wear-out mechanism**.

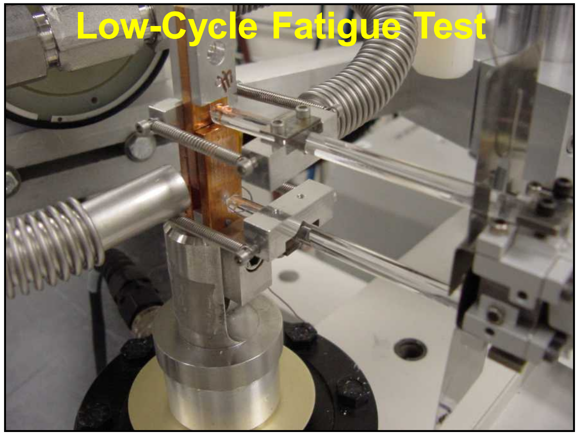
Solder Joint Fatigue

- It was clear that there needed to be a means to **predict TMF failures of electronic solder joints** in order to predict the long-term reliability of consumer and high-reliability electronics.
- This predictive capability was critical to enabling the use of surface mount technology in electronics assemblies.
- There were two approaches used in the 1980s through 1990s to develop the reliability database:

Isothermal fatigue testing



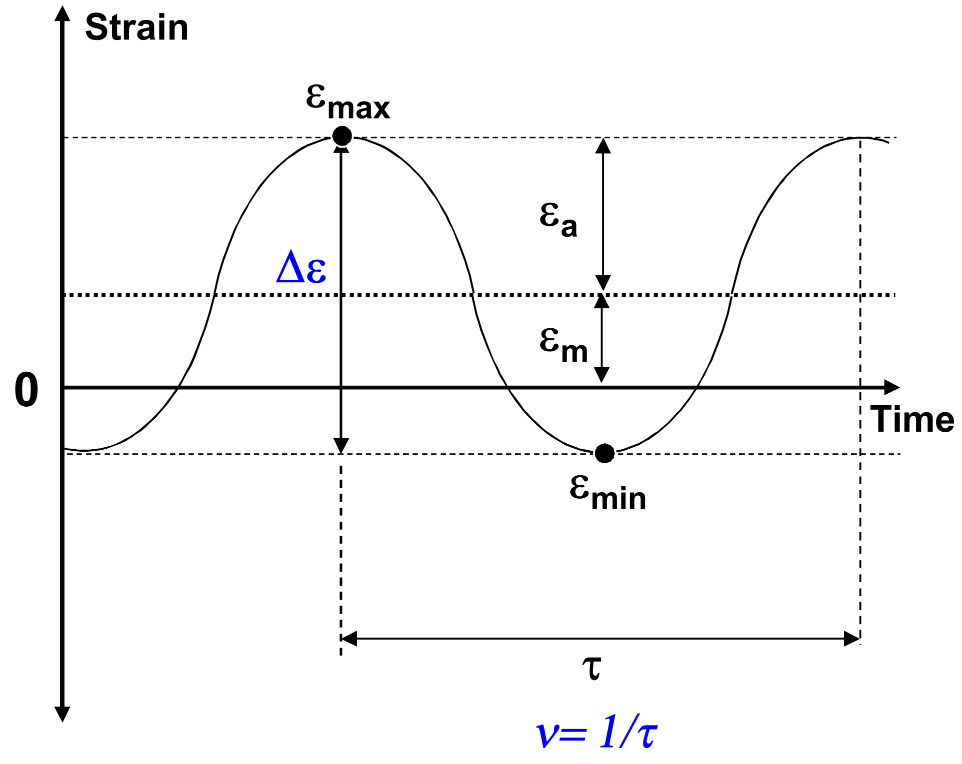




Solder Joint Fatigue

Isothermal fatigue testing

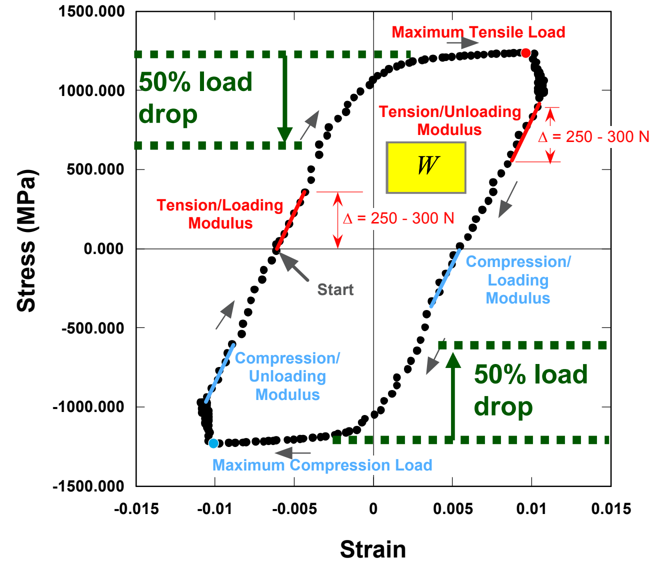
- **The key parameters that define isothermal fatigue deformation are:**
  - **strain range, $\Delta\varepsilon$,**
  - **frequency, $\nu = 1/\tau$.**
- **The total strain range, $\Delta\varepsilon$, is broken down into the elastic strain range, $\Delta\varepsilon_e$, and the inelastic strain range, $\Delta\varepsilon_p$, or *plastic strain range*.**



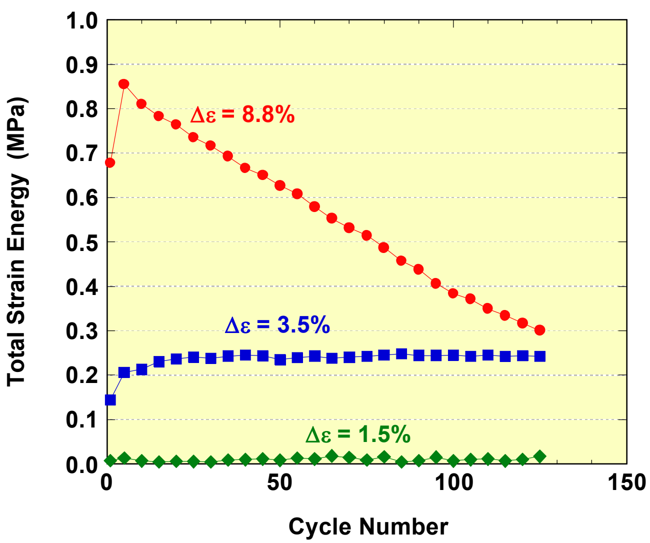
Solder Joint Fatigue

Isothermal fatigue testing

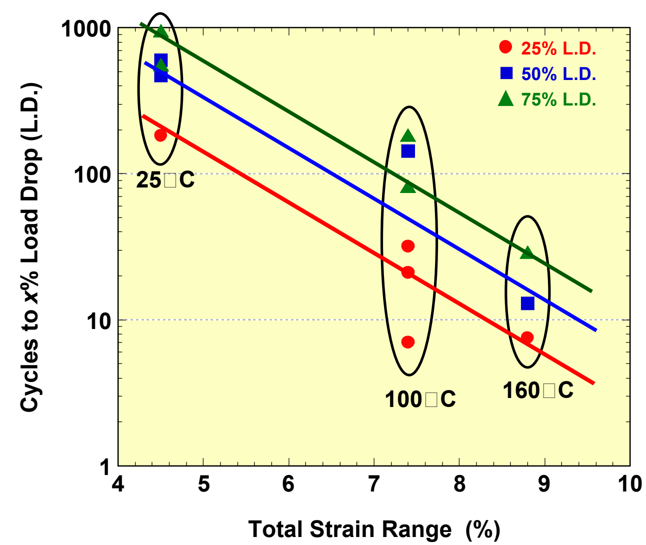
- Hystereses loops were obtained from the tests.



- Samples were tested to specific **cycle counts** or **load drop values**.



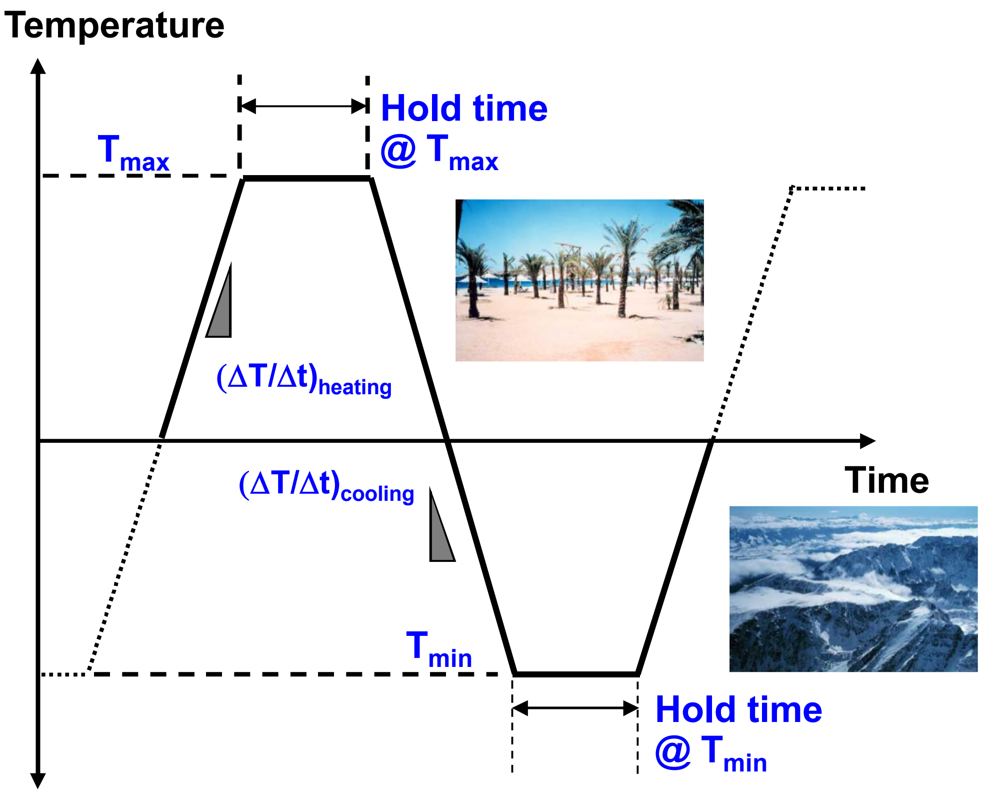
Failure, $N_{f, \%LD}$: The cycles to failure for a % load drop (LD) as a function of the strain range.



Solder Joint Fatigue

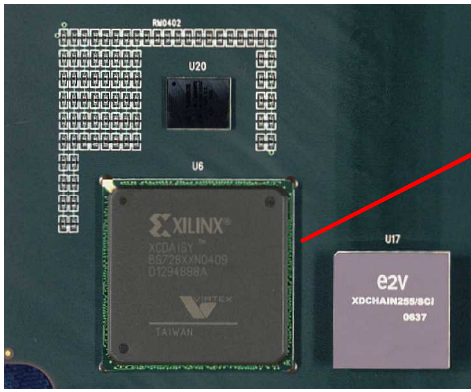
Temperature cycling

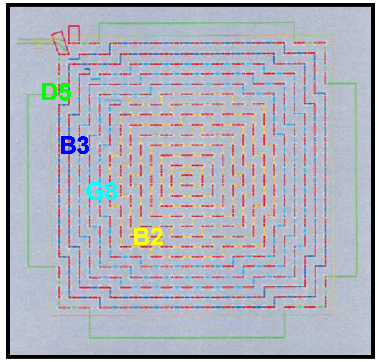
- **Temperature cycling combined the effects of:**
  - **Fatigue strain** *(CTE mismatch)*
  - **Temperature conditions**
- **The key parameters that define temperature cycling deformation are:**
  - **Temperature limits:** T_{max}, T_{min}
  - **Hold times**
  - **Ramp rates:** $\Delta T/\Delta t$

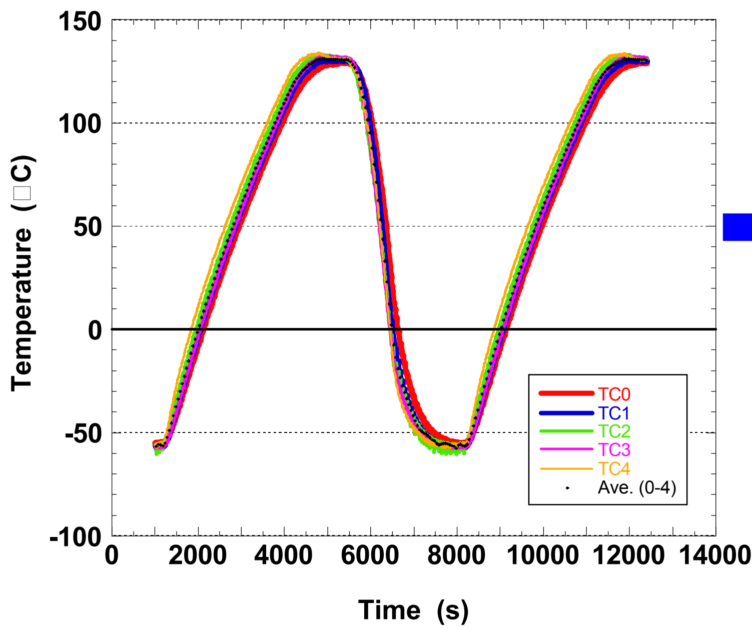


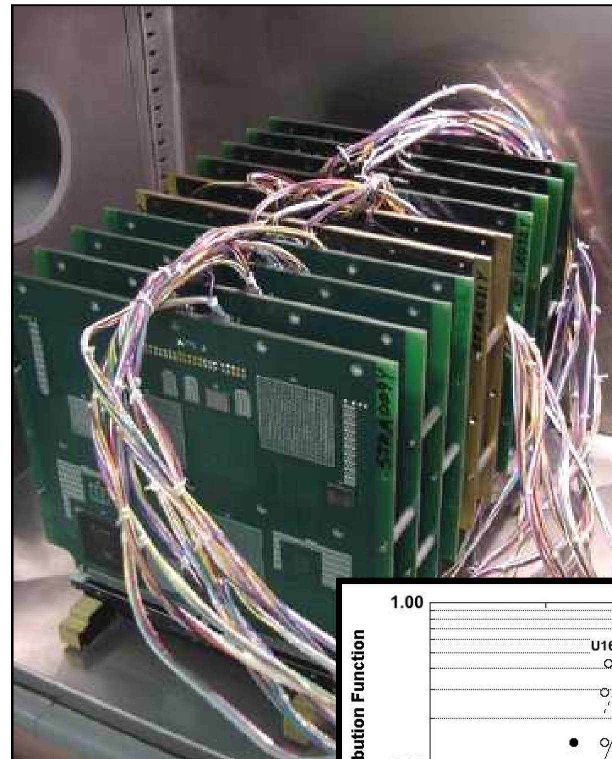
Solder Joint Fatigue

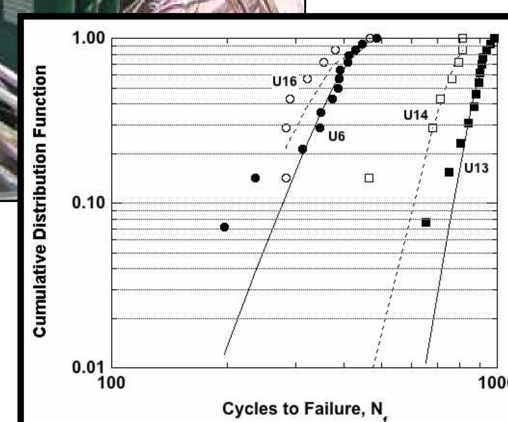
Temperature cycling











Solder Joint Fatigue

Temperature cycling

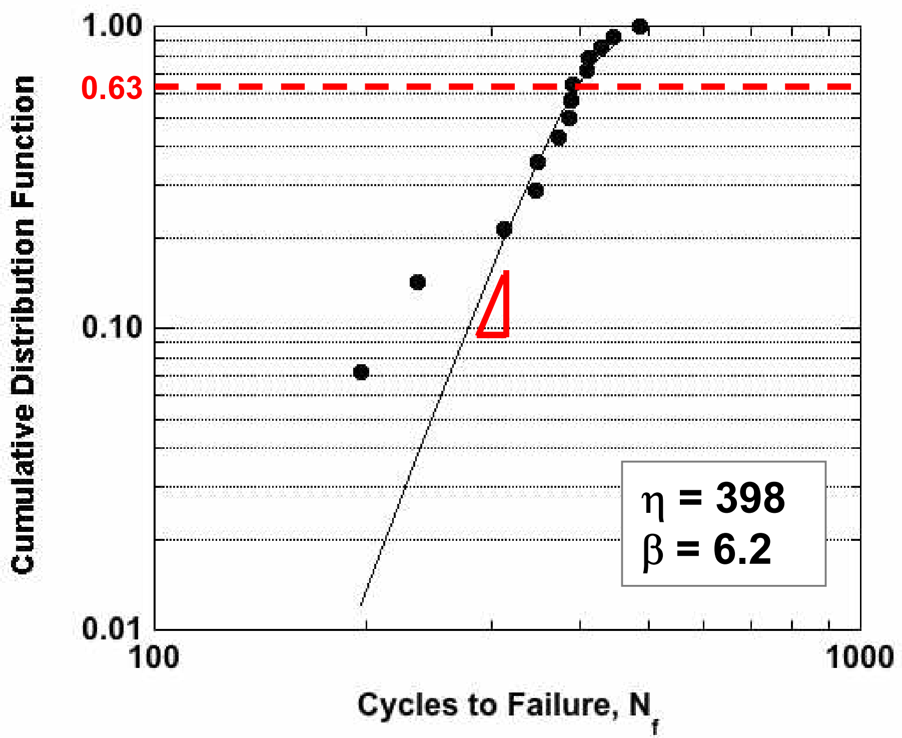
- **Cumulative failure data are generally represented by one of two cumulative distribution function (CDF) approaches:**
  - **Two-parameter Weibull**

$$CDF(N_f) = 1 - \exp[-(N_f/\eta)^{\beta}]$$

where:

η **is the characteristic life,** *or N_f at CDF = 0.632*

β **is the slope**



- **η provides a metric that benchmarks the cycles to failure**
- **β measures the spread (width) of the distribution ≈ *uncertainty***

Solder Joint Fatigue

Temperature cycling

- **Log-normal distribution**

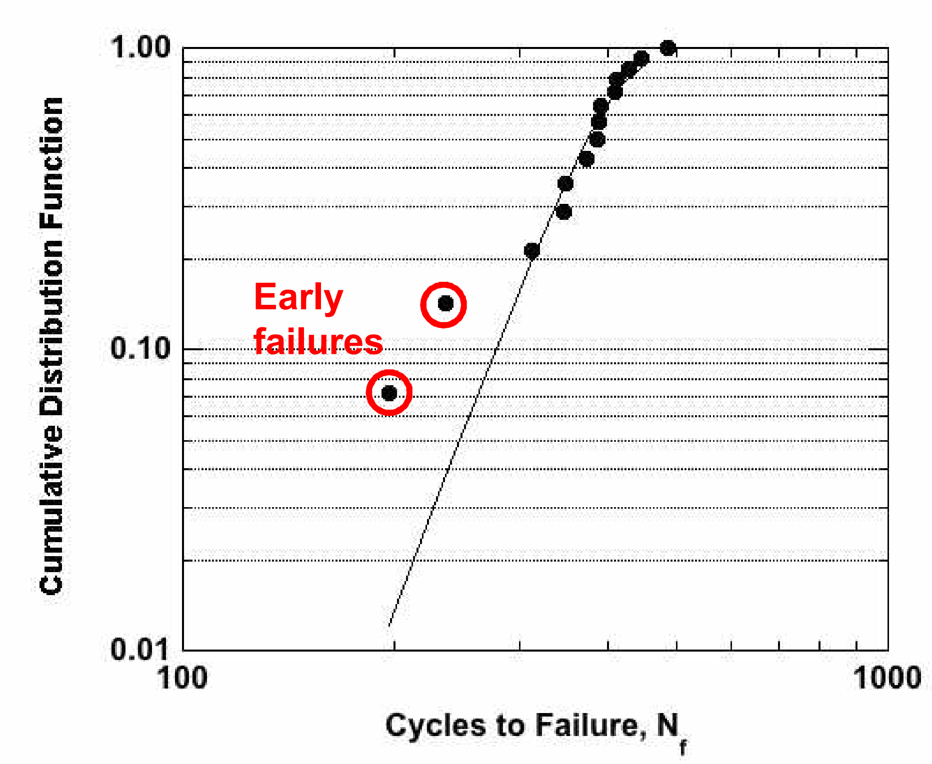
CDF (N_f) =

$$\frac{1}{2}\mathrm{erfc}\left\{-\left[(\ln N_f - \mu)/(\sigma\sqrt{2}\right]\right\}$$

μ is the mean life,

σ is the standard deviation

The parameters, μ and σ have the same qualitative meaning as do η and β used in the Weibull distribution.

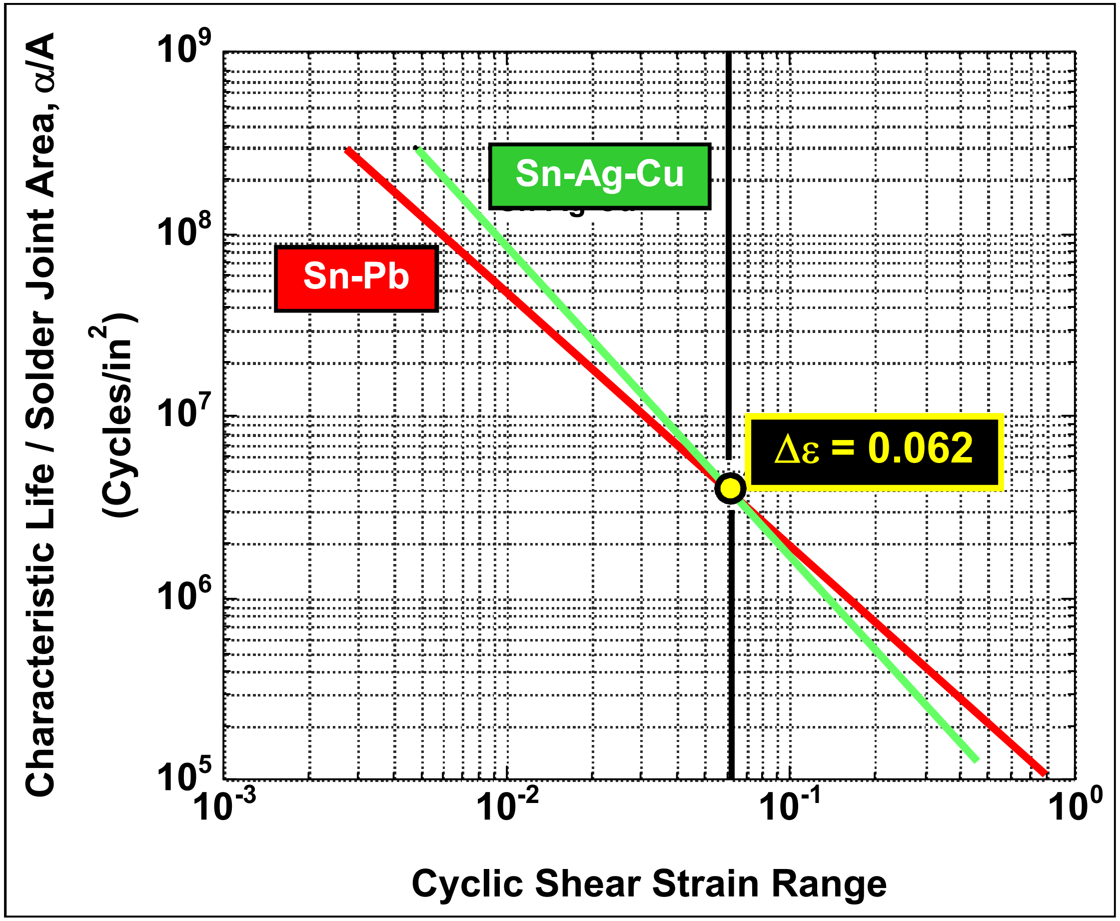


- **An important consideration with either CDF is the occurrence of early failures, which can indicate infant mortality or latent failures.**

Solder Joint Fatigue

Temperature cycling

The "crossover" effect explained the discrepancy between the TMF lifetimes of Sn-Pb solder joints and Sn-Ag-Cu interconnections.



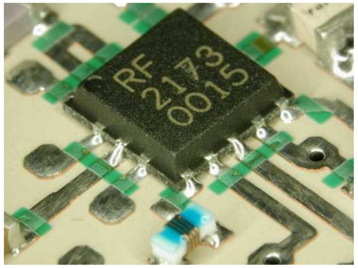
The "crossover" effect REVERSES between the Sn-Pb and Sn-Cu solders.

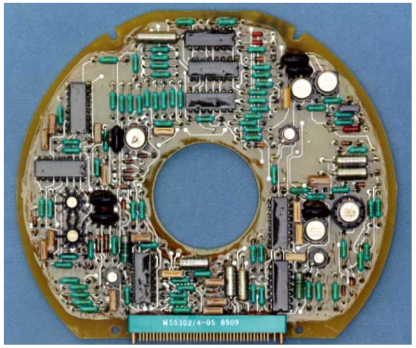
$\Delta\varepsilon = 0.028$

J.-P. Clech, Proc. IPC Expo (2004)

Solder Joint Fatigue

Solder joint reliability analysis truly stands at a cross-roads ...

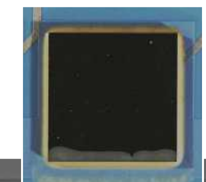


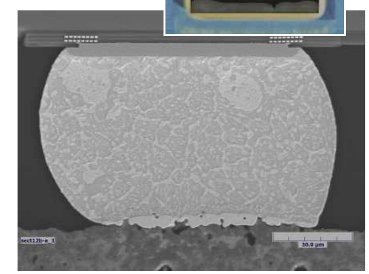


Solder Joint Fatigue

- **Two trends warrant an alternative approach for analyzing solder joint reliability to replace either strictly isothermal fatigue testing or an entirely empirical temperature cycling program.** ***Reasons …***

1. New package designs and materials

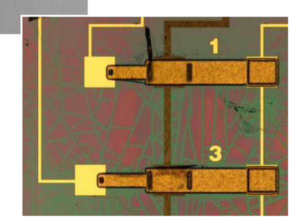




- **Higher I/O and finer pitch area-array packages**
- **Package-on-package (PoP)**
- **Stacked chips**
- **System-in-a-package (SIP)**
- **Opto-electronic devices**
- **High temperature molding compounds**
- **High temperature, "green" laminates**

2. Pb-free solder technology

- **Growing number of alloy compositions**
- **Mixed solder joint compositions**
- **Alternative surface finish effects**



Solder Joint Fatigue

- **The consequence of these trends is that the development of reliability databases, using “business-as-usual” testing methods is fast becoming an intractable means to this goal.**

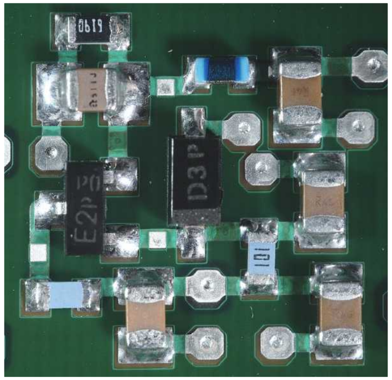
“… do the math …” →

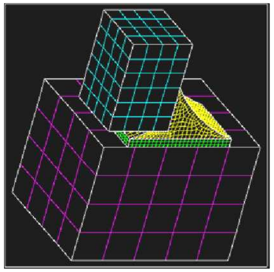
	Material sets - Packages - Laminates	
X	**Solder alloys** - Sn-Pb - Pb-free	
X	**Environments** - Accelerated aging - Service lifetimes	
=	**Resources ???**	

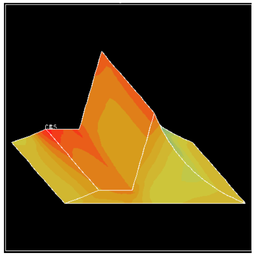
- **At the same time, programs are requiring detailed, quantitative reliability predictions for costlier ground, flight, and space systems; … *and providing that data in an increasingly cost-and schedule-conscious procurement cycle.***

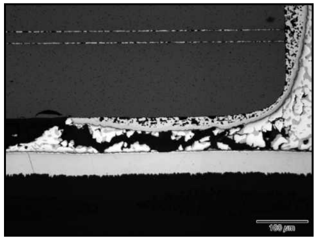
Sandia Solder Joint Fatigue Models

- Develop a **computational modeling methodology** that provides a **timely, cost-effective determination of solder joint reliability** for components, sub-systems, and systems that will meet program and mission requirements.







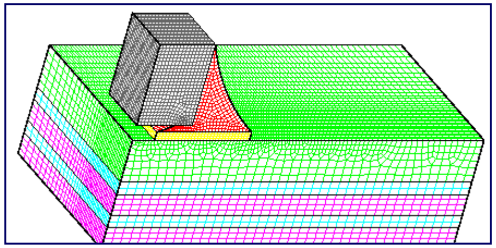


- This methodology must transcend all past, current, and future solder, package, and substrate materials technologies as well as variations of test and service environments.

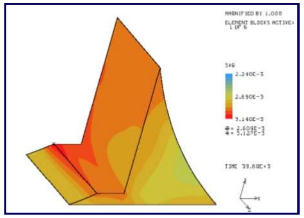
Sandia Solder Joint Fatigue Models

- **Other attributes of a computational modeling capability:**
  - **Solder composition effects, including contamination, can be addressed at the material properties measurement stage.**
  - **The deterministic calculation eliminates the expressed need for an acceleration factor to correlate testing to field-use conditions.**

    The inaccuracy of the acceleration factor is amplified with increased number of cycles.



  - **The "dwell-time" issue is avoided because the constitutive equation calculates the deformation, *explicitly*.**



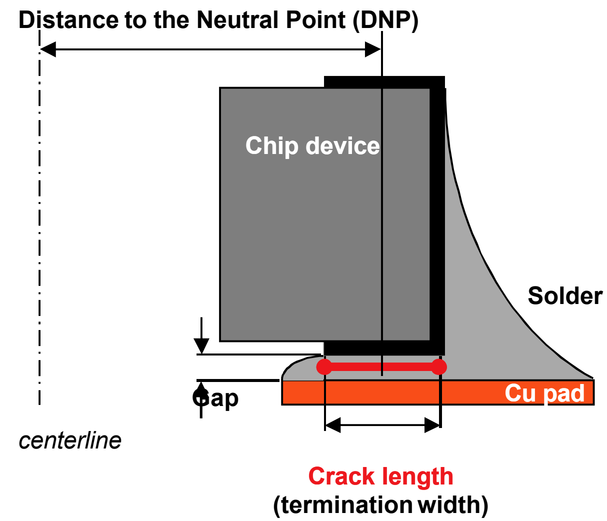
  - **Computational modeling approach allows for quantifying margins and uncertainty (QMU) that is based upon specific workmanship and environment details.**

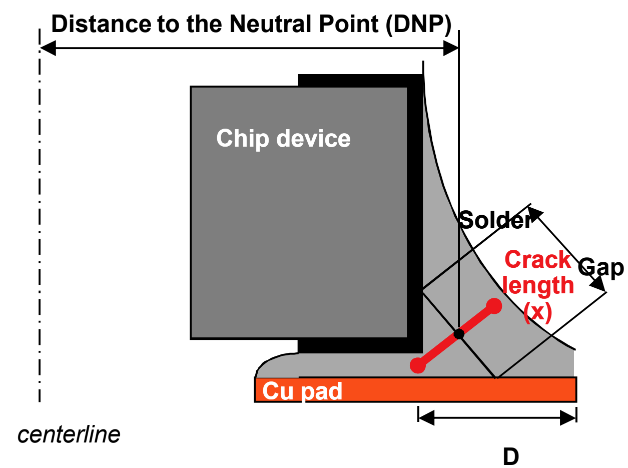
Sandia Solder Joint Fatigue Models

- There are commercial software packages:

Solder Reliability Solutions©
ESP, Inc.
(1990)

- **Strain energy approach**
  $N_f(\Delta W^{\alpha}) = D$
- **Library of components, material properties, and thermal histories**
- **Limited user input**
- **Statistical prediction**

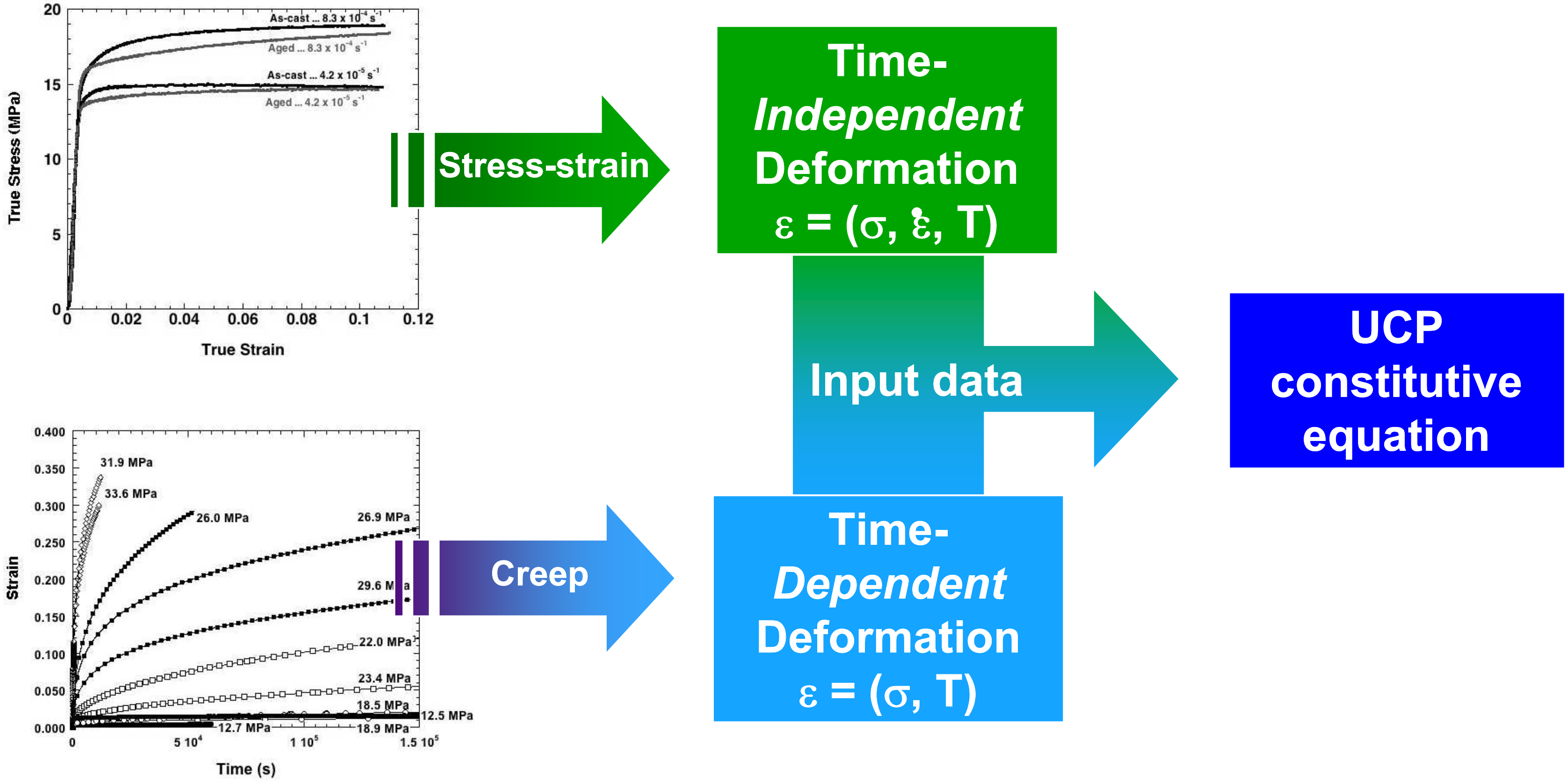




The inability of the software to incorporate an accurate description of the joint led to overly conservative predictions for even the simplest of joint geometries.

Sandia Solder Joint Fatigue Models

- **Develop a computational model that meets these objectives.**
- **Fatigue (including TMF) has two deformation process:**
    - **Time-independent deformation**
    - **Time-dependent deformation**



Sandia Solder Joint Fatigue Models

- **The next step is to transform the deformation behaviors of the solder into a mathematical construct:**

The Unified Creep-Plasticity (UCP) constitutive equation* is the mathematical function that describes both time-dependent and time-independent deformation in the solder.

$$d\gamma_{\square\square}/dt = f\,(\tau_{\square\square}, T, A_{i}$$

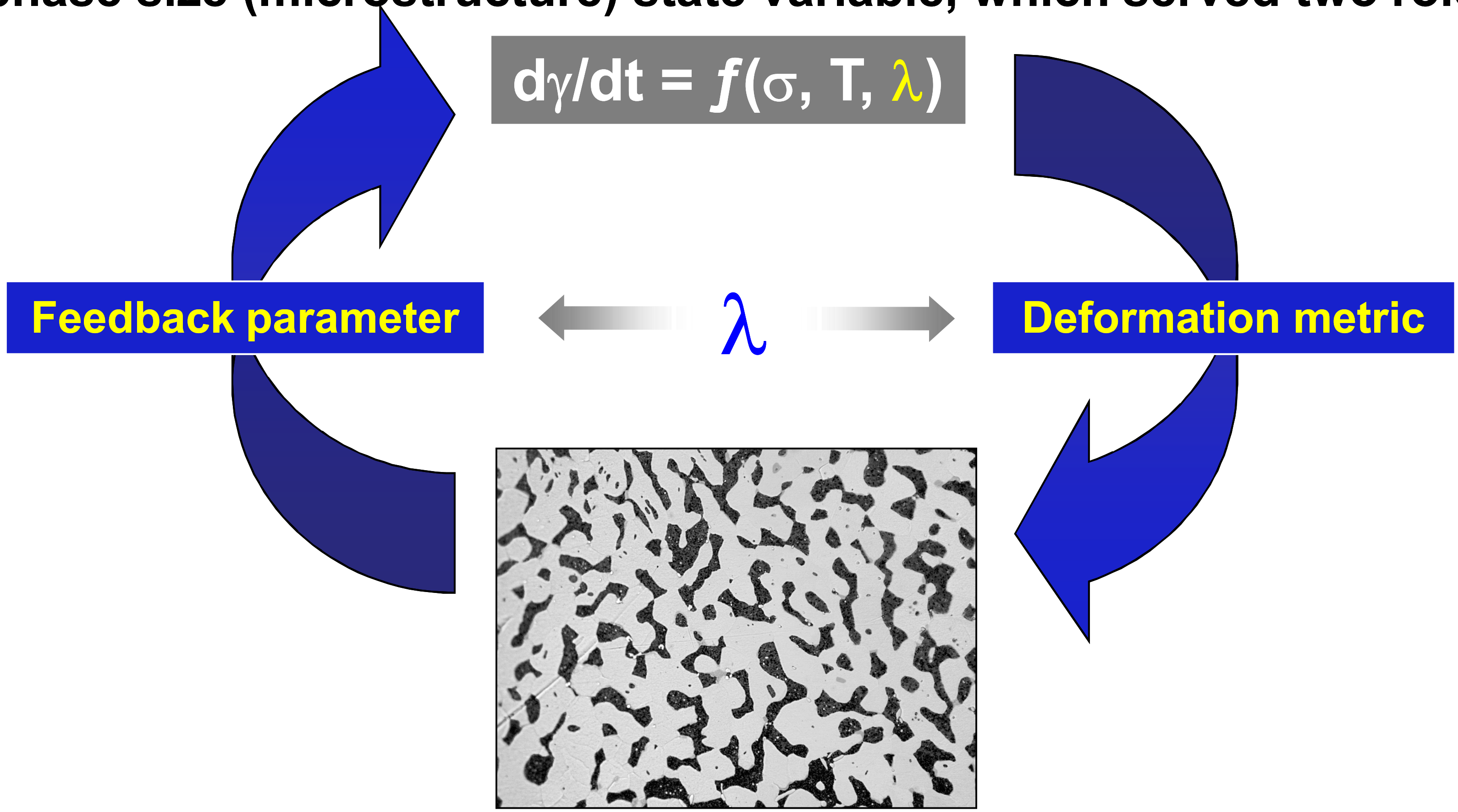
- Strain rate matrix, ……….$d\gamma_{\square\square}/dt$
- Stress matrix, ….. $\tau_{\square\square}$
- Material properties ….. A_{ij}
- Temperature, ………. T

---

*M. Neilsen, S. Burchett, C. Stone, and J. Stephens, *Sandia Report* SAND96-0984 (1996).

Sandia Solder Joint Fatigue Models

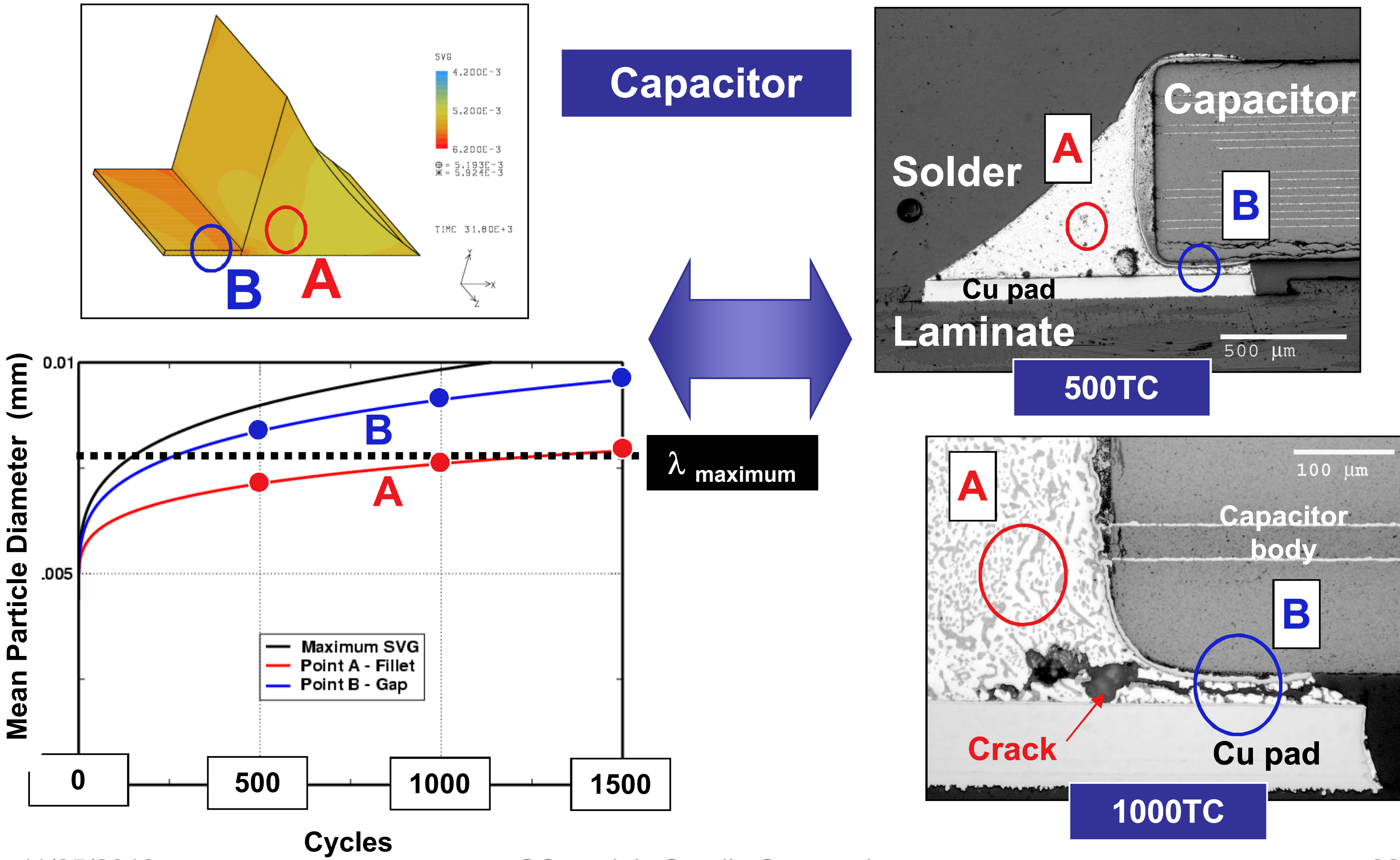
- **The initial version of the UCP equation included λ, the Pb-rich phase size (microstructure) state variable, which served two roles:**



$$\lambda = \lambda_o + \left\{\left[4.10\times10^{-5}\, e^{-11023/T} + 15.6\times10^{-8}\, e^{-3123/T}\, d\gamma/dt\right]t\right\}^{0.256}$$

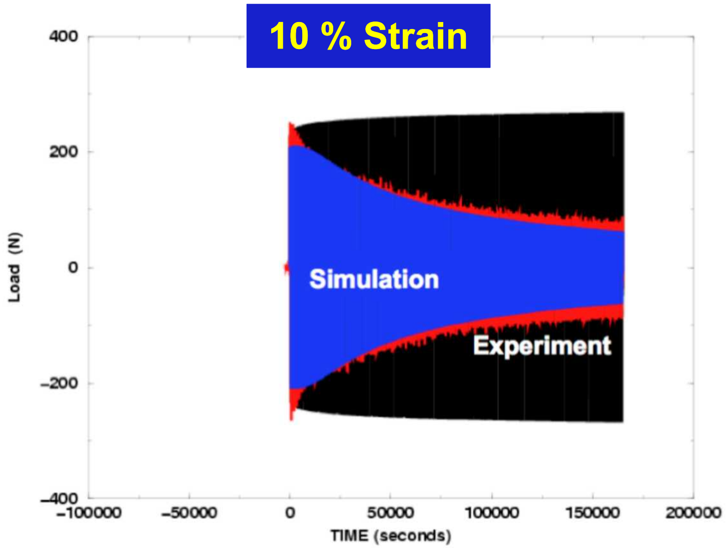
Sandia Solder Joint Fatigue Models

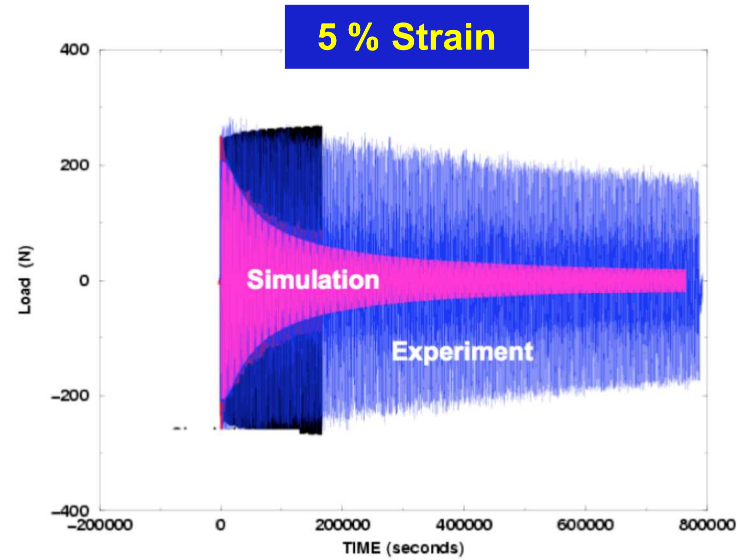
- Early validation tests produced favorable comparisons between Pb-rich phase coarsening and crack initiation (at $\lambda_{maximum}$).



Sandia Solder Joint Fatigue Models

- Validation data indicated that at small strains (< 10%), the model predicted fewer cycles-to-failure than observed, experimentally.
- This trend was confirmed by comparing model predictions against double-lap shear, isothermal fatigue experimental data.





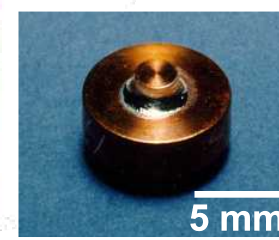
Experiments and simulation match very well at 10% strain, but not so well at reduced strain (e.g., 5%).

Sandia Solder Joint Fatigue Models

- Validation data indicated that at small strains (< 10%), the model predicted fewer cycles-to-failure than observed, experimentally.
- The microstructural (coarsening) parameter was replaced with a damage parameter, D_{ω}, that includes strain *and* strain rate effects.

$$d\gamma_{\square\square}/dt = f\,(\tau_{\square\square}, T, A_{ij}, D_{\omega}$$

- Strain rate matrix, ….$d\gamma_{\square\square}/dt$
- Stress matrix, ….. $\tau_{\square\square}$
- Material properties ….. A_{ij}
- Temperature, ………. T
- **Damage metric, ….. $D_{\omega} = f(\gamma_{\square\square}, d\gamma_{\square\square}/dt)$**

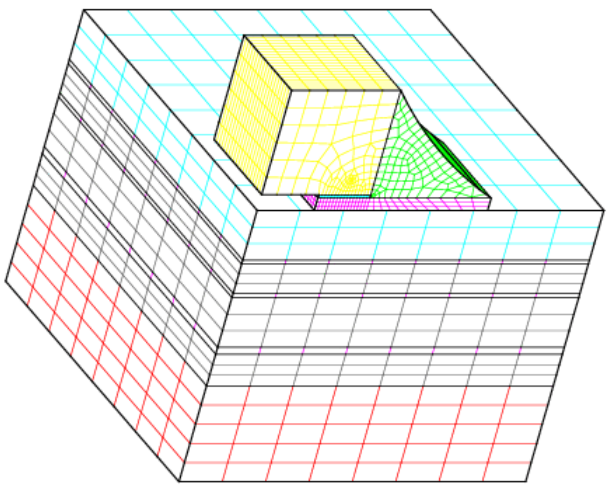


- Ring-and-plug isothermal fatigue tests are being used to validate this new constitutive modeling method.

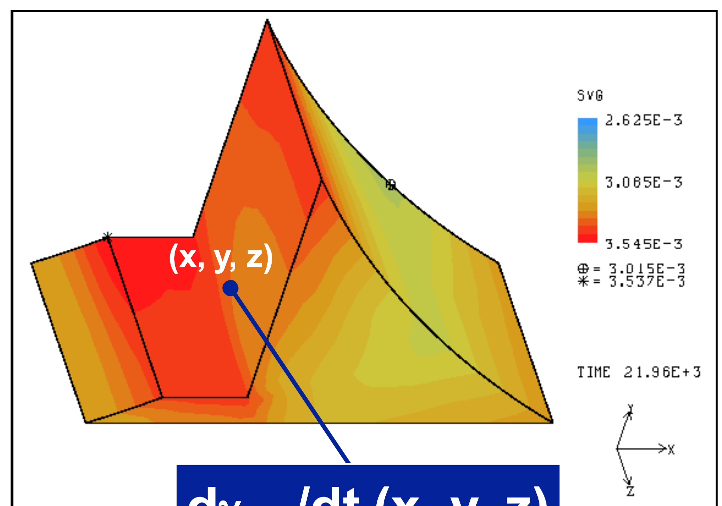
Sandia Solder Joint Fatigue Models

- The finite element mesh maps the stress field imposed on the material (x, y, z coordinate), and then maps the strain rate and damage that are generated at (x, y, z).

$d\gamma_{\square.\square}/dt = f\,(\tau_{\square.\square}, T, A_{ij}, D_{\omega})$



Finite element mesh

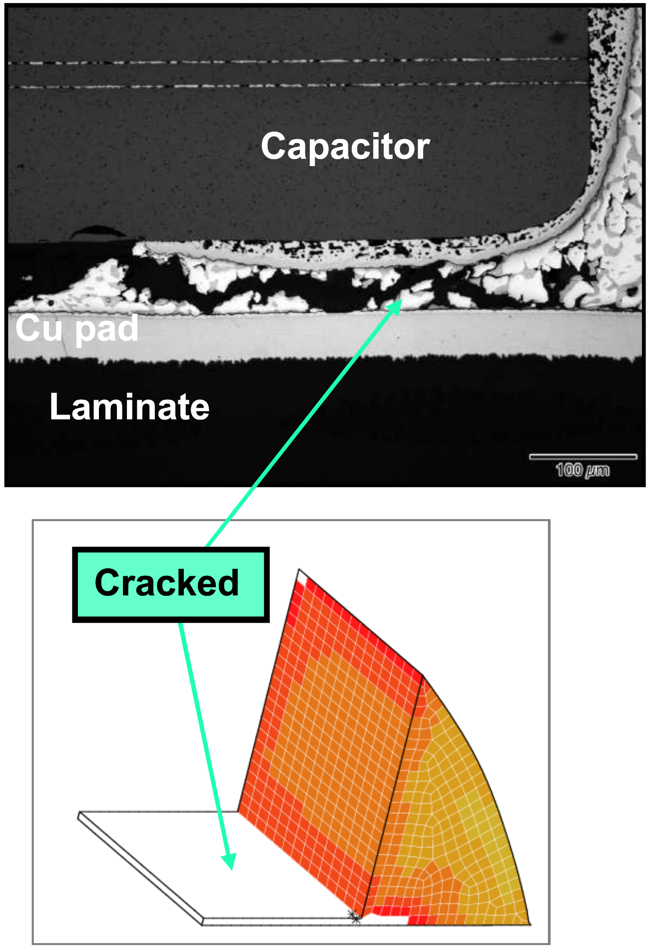


Sandia Solder Joint Fatigue Models

- The next step in the constitutive model development was to be able to predict the propagation of fatigue cracks in the joint.

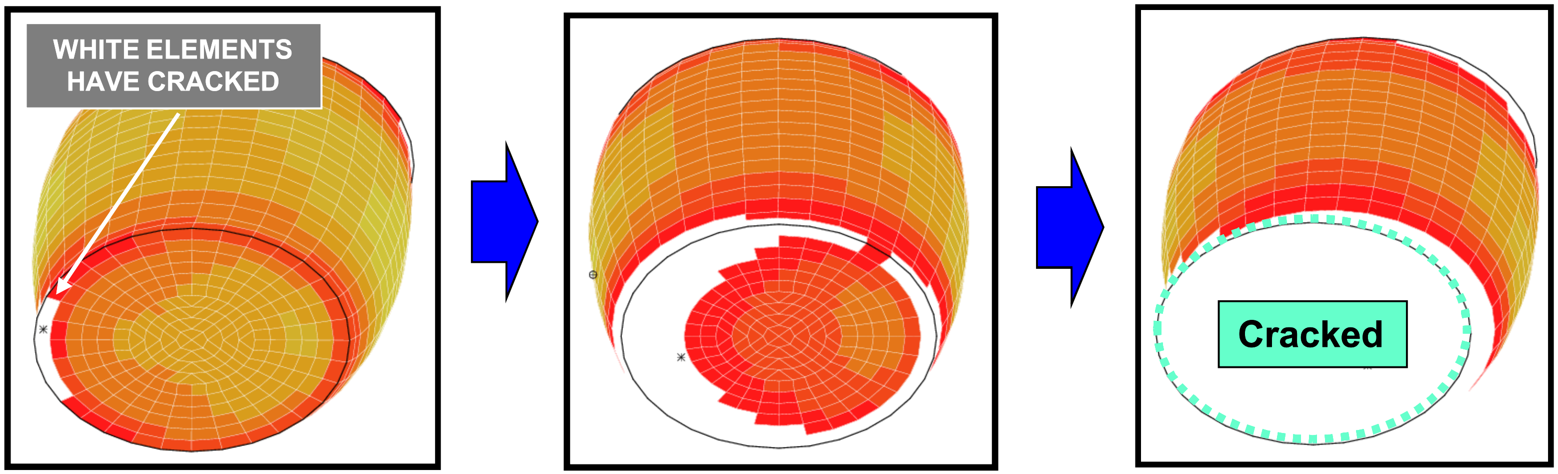
- ***Material science part:***
  The underlying hypothesis was that, when the strength of an element had reduced to less than 1% (0.01) of the elastic modulus, the element was no longer capable of bearing a load.

- ***Numerical code part:***
  The non-load bearing (failed) elements have to drop out *without* the need to remesh the joint.



Sandia Solder Joint Fatigue Models

- Validation is performed by comparing model predictions against experimental data. The empirical data include:
  - Metallographic cross sections
  - Cumulative failure data (event detection)



Crack start: 900 cycles | Crack grows: 1800 cycles | Electrical open: 2100 cycles

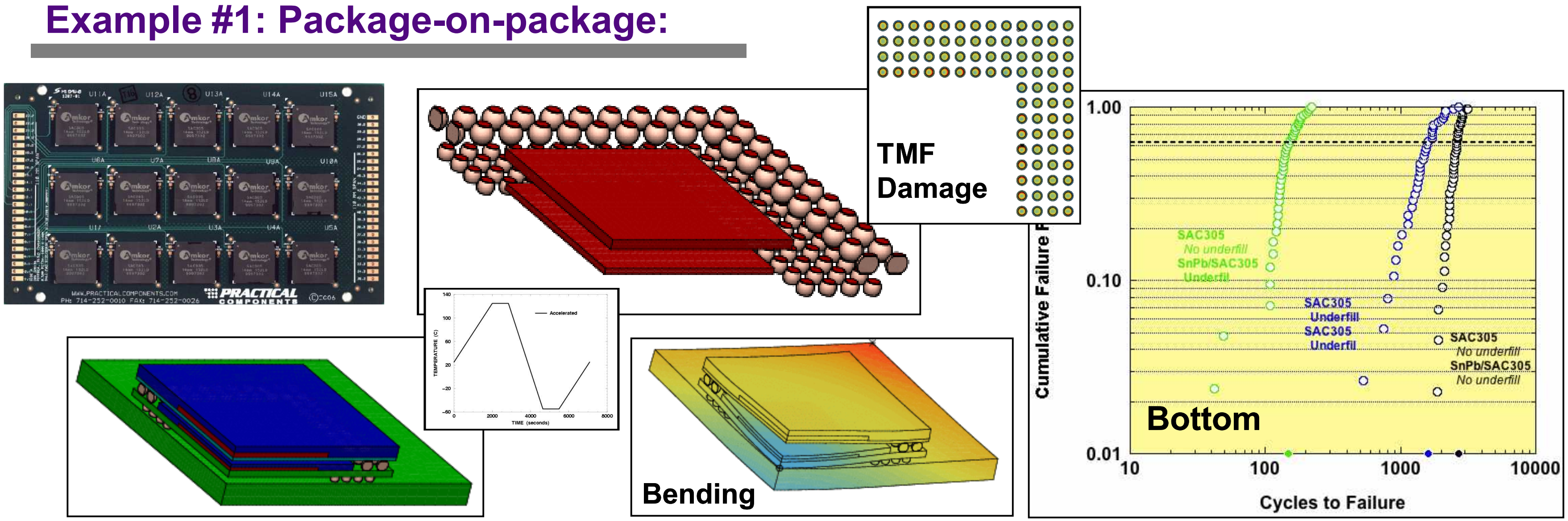
- Thus far, crack location and initiation are right-on-target.
- The validation task is currently highlighting crack propagation.

Sandia Solder Joint Fatigue Models

- **Continue the efforts to validate the fatigue models:**
  - **JGPP project: Phase I and Phase II**
  - **Enhanced Surveillance Campaign (SNL/DoE)**
  - **Satellite program data within SNL**

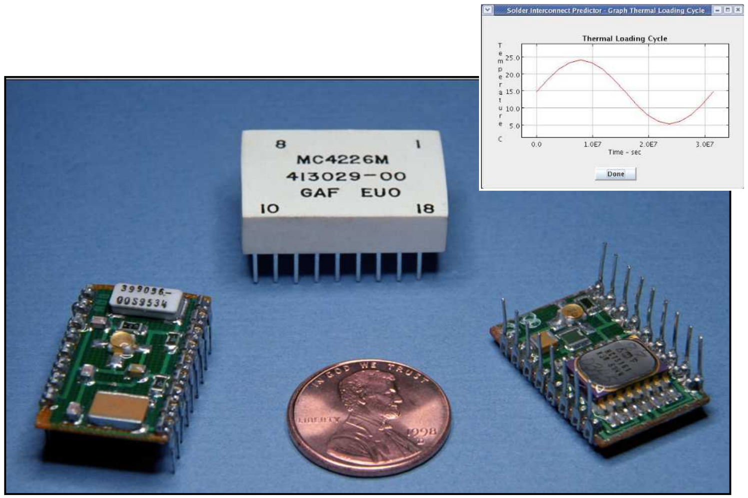
- **The solder fatigue models are being applied to multiple applications to confirm code stability and prediction fidelity.**

Example #1: Package-on-package:

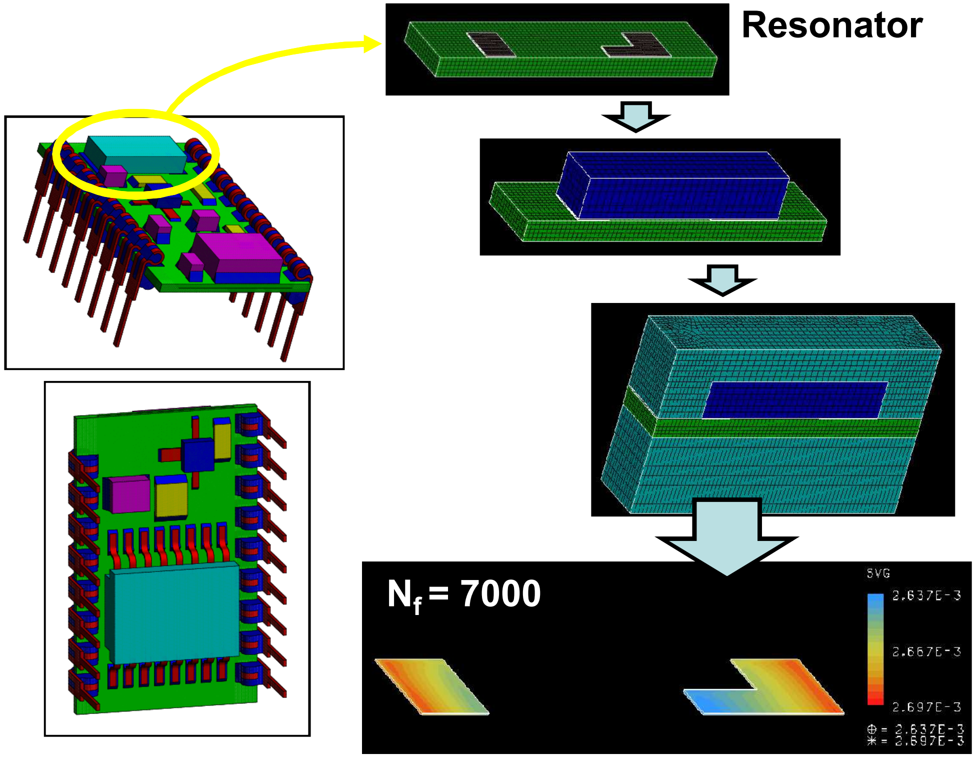


Sandia Solder Joint Fatigue Models

Example #2: Encapsulated SMT PWA:



Many Sandia PWAs are encapsulated for shock resistance or to provide high-voltage electrical isolation.



- Incorporation of shock (overload) and vibration (high-cycle fatigue) prediction capabilities into the software package.

Constitutive equations have been determined for shock applications.

Sandia Solder Joint Fatigue Models

- **This methodology guides the computational modeling approach.**

Material Properties
- *Stress-strain test*
- *Creep tests*
- *Thermal expansion*

Validation Testing
- *Test vehicles*
- *Accelerated aging*
- *Failure mode analysis*

Computational Model
- *Platform independent*
- *User friendly (GUIs, fast)*
- *WEB-based*

Screening Assessments
Computational or empirical

Predict Solder Joint Fatigue
Crack Initiation and Propagation

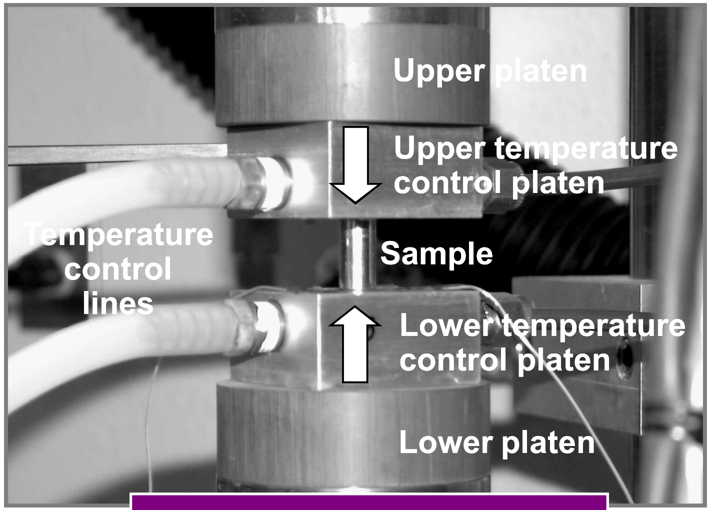
Sandia Solder Joint Fatigue Models

- **Materials properties measurements:**
  - **Stress-strain tests:**

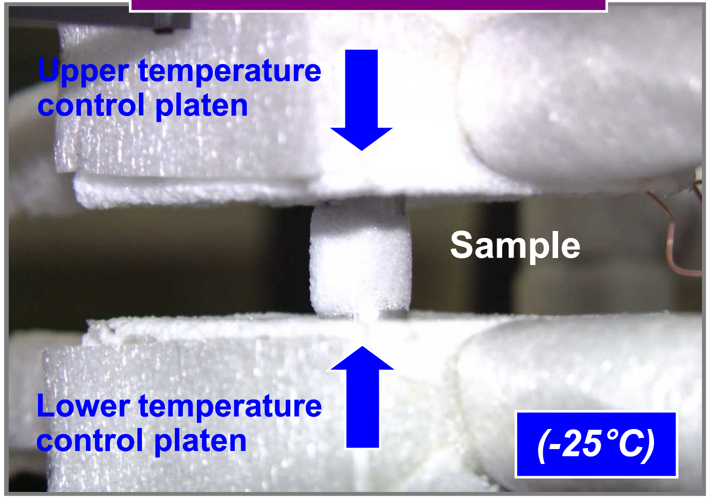
    Yield strength, effective elastic modulus, and stress-strain curves
  - **Creep tests:**

    Steady-state creep rate, apparent activation energy, and strain-time curves.
  - **Static modulus (acoustic technique)**
  - **Thermal expansion coefficient**
  - **Different test temperatures:**

    -25°C, 25°C, 75°C, 100°C, 125°C
  - **Isothermal fatigue testing (shear):**
    - **Test temperatures: -25°C - 160°C**
    - **Strain range (0.01 - 0.10)**

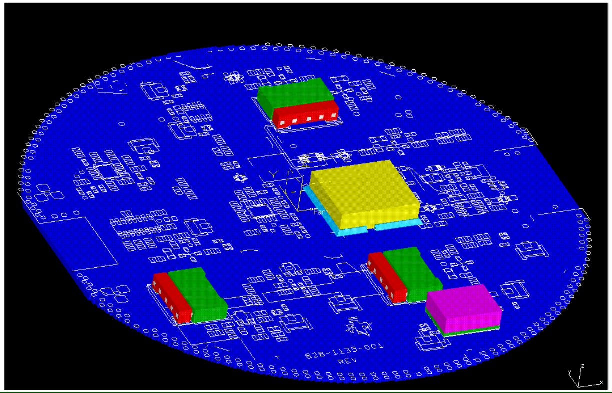


Compression Testing

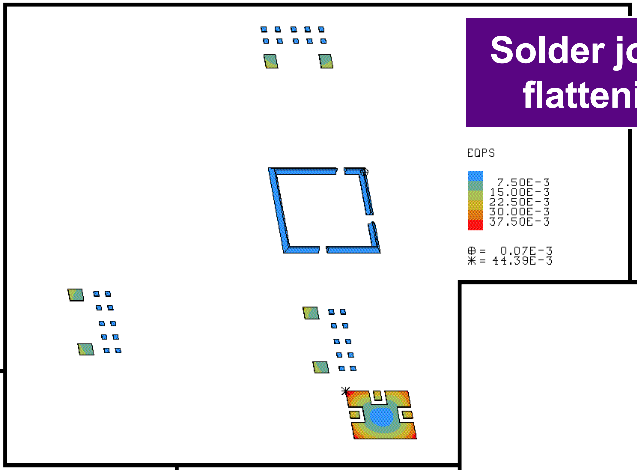


Sandia Solder Joint Fatigue Models

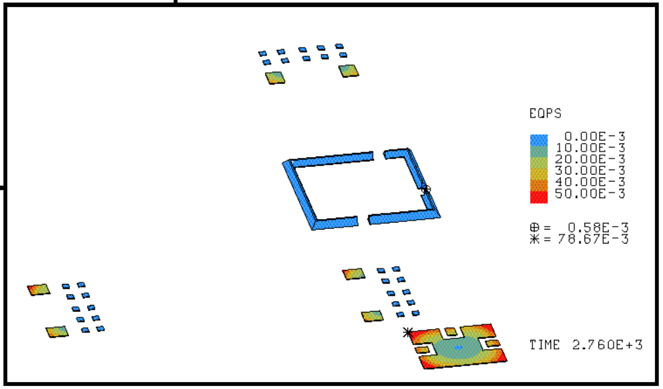
- **Screening assessments** using mechanical finite element analysis identify solder joints that are most susceptible to fatigue damage.



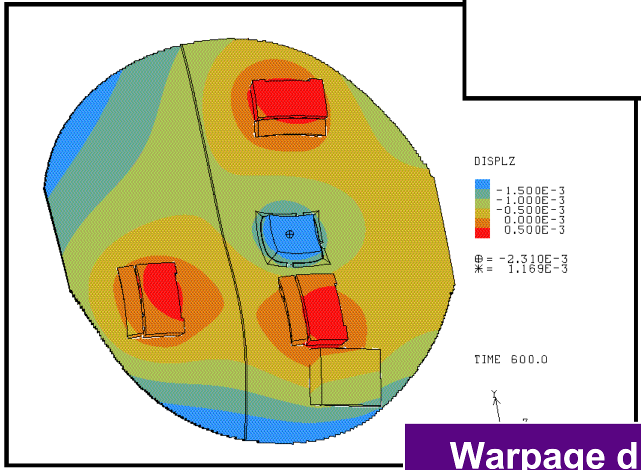
Printed wiring assembly (PWA)



Solder joint strain due to flattening of the PWA



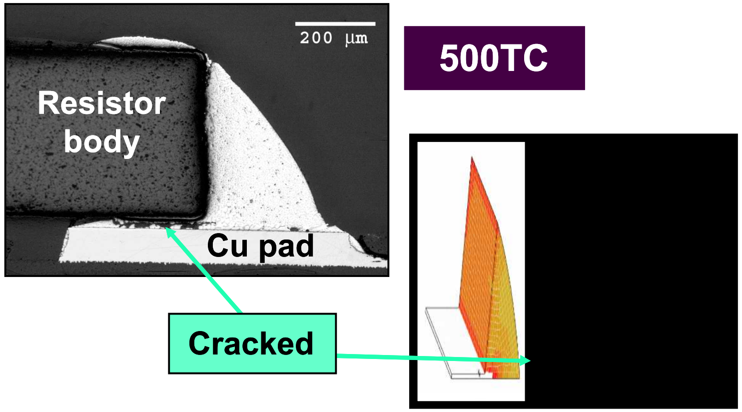
Solder joint strain due to flattening & thermal cycling

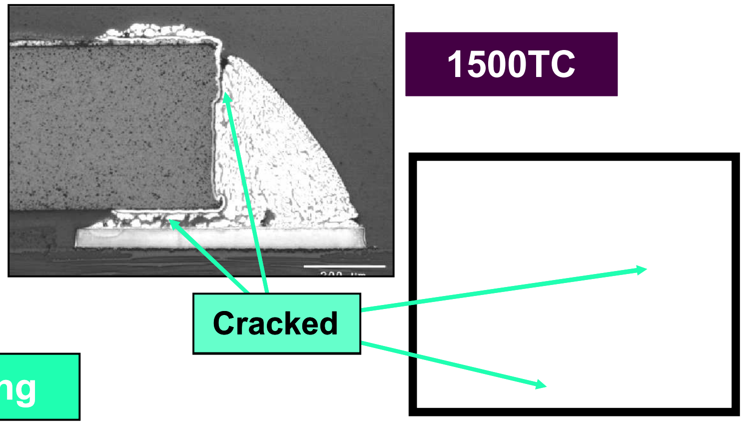


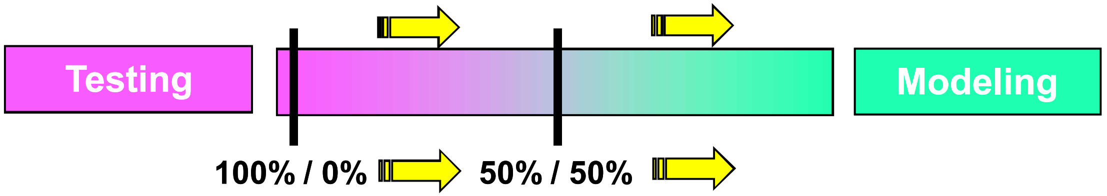
Warpage due to reflow

Sandia Solder Joint Fatigue Models

- The **validation testing** is considerably scaled-back effort when compared to a fully-empirical, reliability assessment.
  - The validation effort would utilize a small number of test vehicles - *far fewer than the number needed for statistical significance* - to confirm model predictions and the activity of the expected failure mode(s).
  - It is anticipated that, as the model gets continually exercised, there will be an increased confidence in its predictions to the point that **validation testing can be minimized or, even eliminated**.

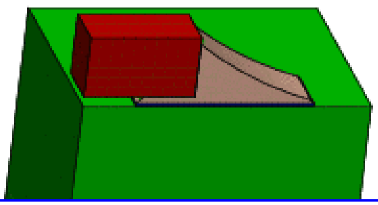






Sandia Solder Joint Fatigue Models

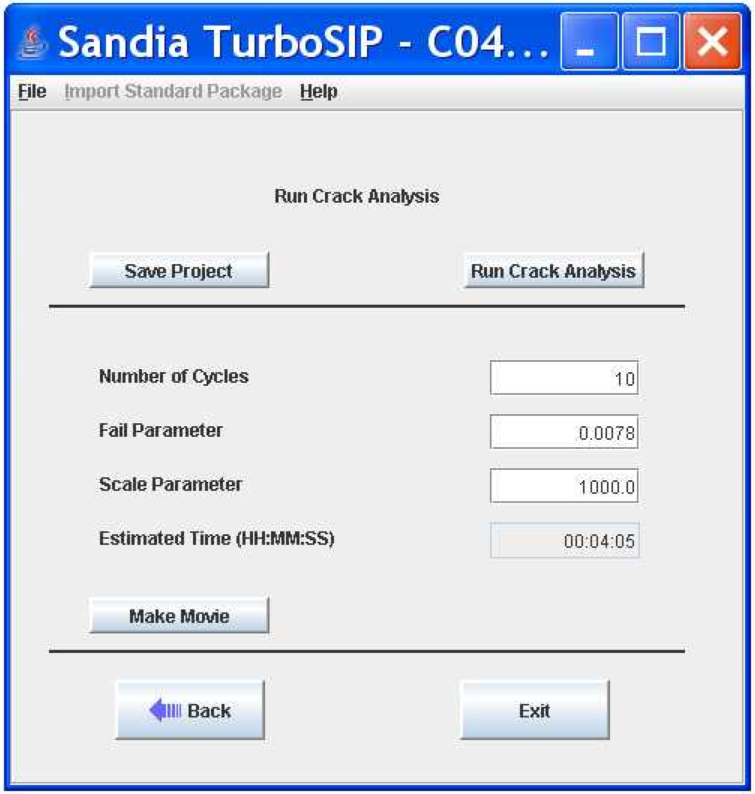
- A brief history is provided of the Sandia models-to-software trek:
  - **Comprehensive Solder Interconnect Reliability (CompSIR®) model (1999):**
    This is the underlying code that has the unified creep-plasticity (UCP) constitutive model, finite element mesh generation tools, and analysis routines. It is still used on the SNL parallel-processor machines.
  - **Solder Interconnect Predictor (SIP®) software (2002):**
    First software package developed in a collaboration with LMCO (Shared Vision) and a contract with Strikewire Technologies, LLC. Used a Coffin-Manson analysis routine to calculate cycles-to-failure. Further refinement of the software occurred under LMCO/DTO (ONR) and contracts with Kansas State U.)
  - **Solder Interconnect Predictor - Lite (SIP - Lite) software (2003):**
    This software use a closed-form solution and Coffin-Manson analysis as a "quick-and-dirty" predictor of solder fatigue failures for relatively simple cases.



$$N_{Coffin-Manson} = \left(\frac{1.31636}{\Delta EQPS}\right)^{1.96078}$$

Sandia Solder Joint Fatigue Models

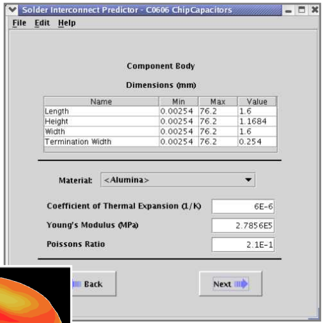
- **Turbo-Solder Interconnect Predictor (TurboSIP®) software (2009):** **Solder fatigue deformation, crack initiation, and crack growth to determine cycles-to-failure for Sn-Pb or Pb-free solder joints (SNL: ASC, ESC, MOU; LMCO/DTO with ONR; Kansas State U.).**
  - **Windows XP, MAC OS versions (10.4 and 10.5), and LINUX with respective installation packages.**

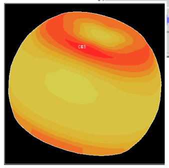


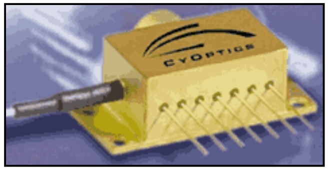
- **Recent modifications:**
  - **Introduced new damage state variable into the TurboSiP© code**
  - **User-prescribed displacement history to accompany the user-prescribed, temperature history to incorporate the ring-and-plug test sample into the library.**

TurboSiP© Software

- **The underlying premises of the TurboSiP© software :**
  - **"User-friendly" so as to be accessible to design and process engineers with a personal computer or work station.**
  - **Quick turn-around analysis (less than 15 minutes).**
  - **Software could be executed on multiple platform types (PC, MAC, Linux, etc.)**
  - **Sufficiently flexible to include past, current, and future materials and designs of printed circuit boards and packages.**
  - **Adaptable to Sn-Pb, Pb-free, low-temperature and *future* high-temperature solder alloys as well as their respective test and service environments.**



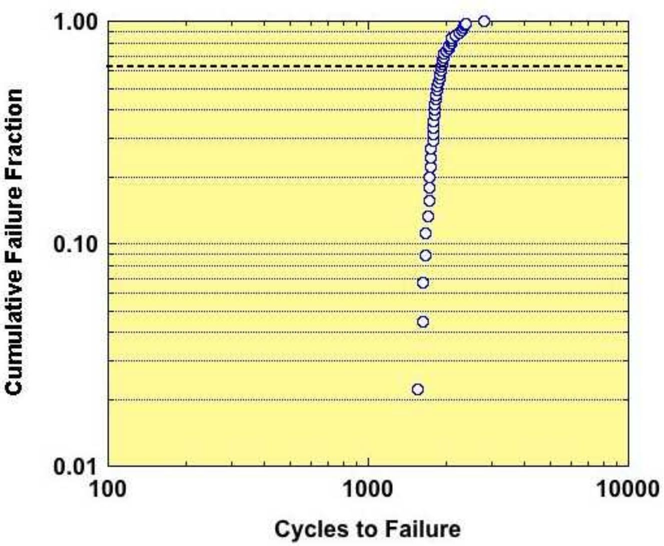




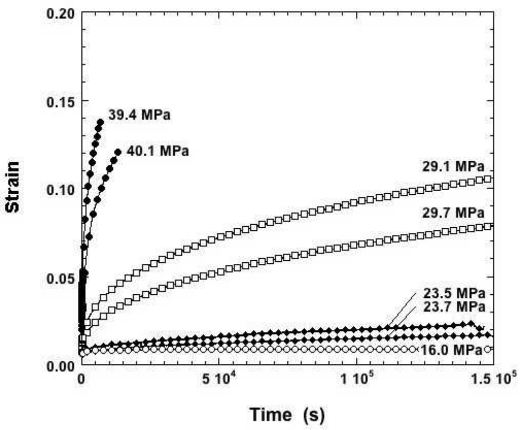
TurboSiP© Software

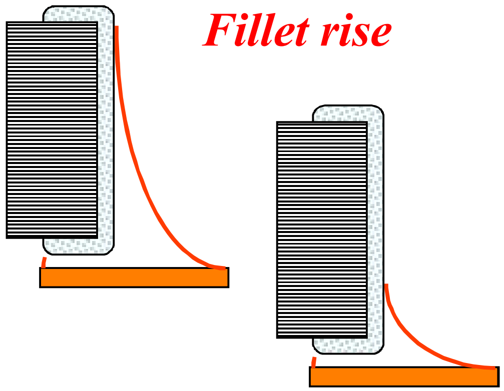
- The nature of the software output is a **deterministic prediction** of the number of cycles for crack initiation and growth to failure.

  "But … reliability data is typically presented in a statistical format having means, confidence intervals, and probability distribution functions."



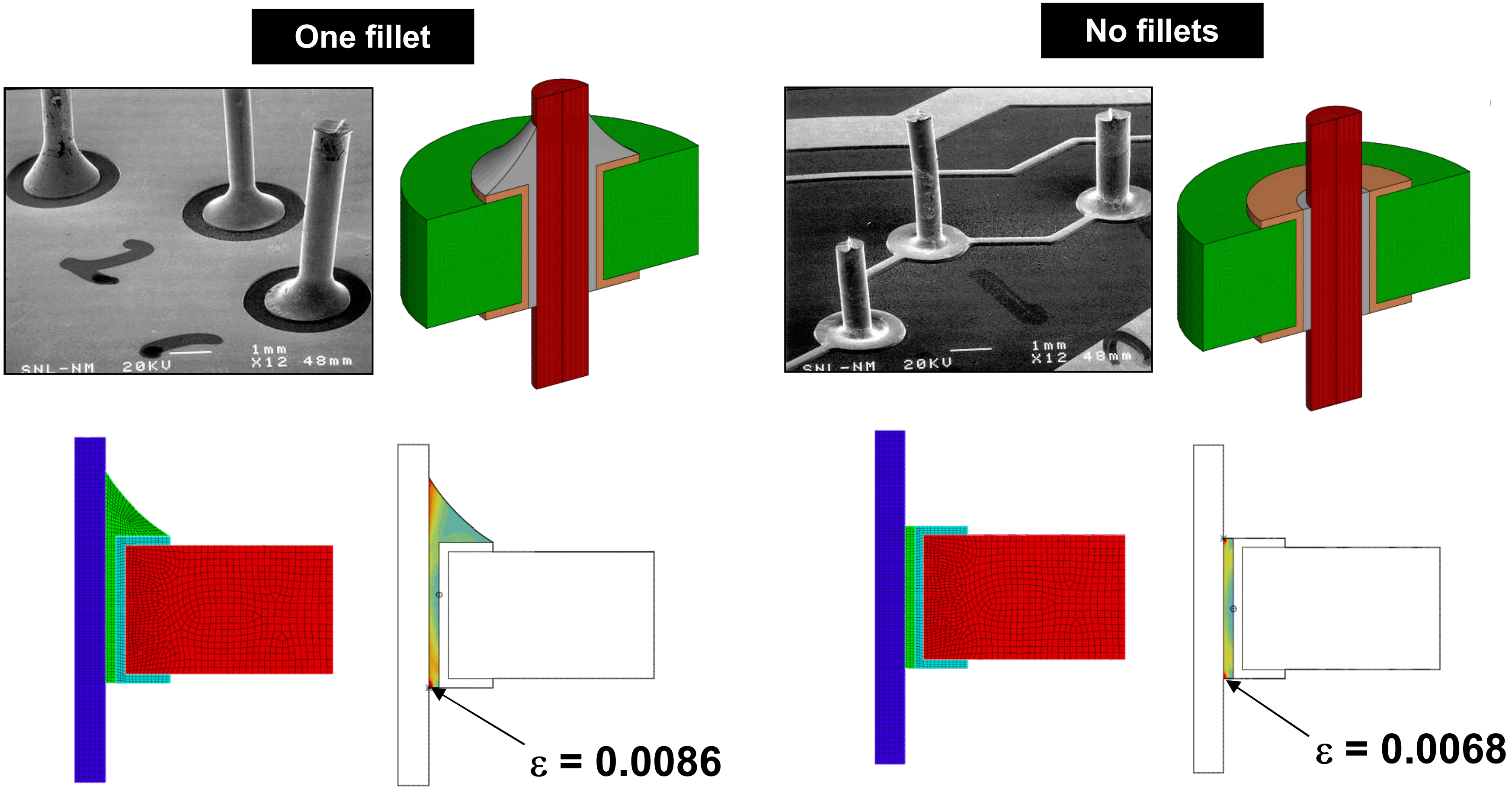
- Computational modeling approach allows for quantifying margins and uncertainty (QMU) in a deterministic manner by identifying, explicitly, variations of materials properties and/or workmanship.





TurboSiP© Software

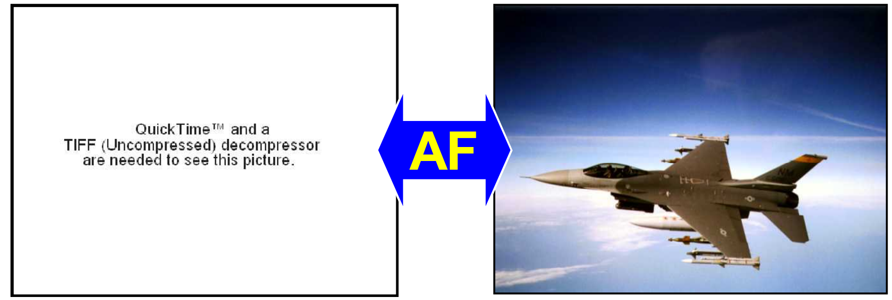
- Inconsistent solder joint geometries caused by poor solderability have a greater risk for infant mortality failures or the occurrence of accelerated wear-out failures.



TurboSiP© Software

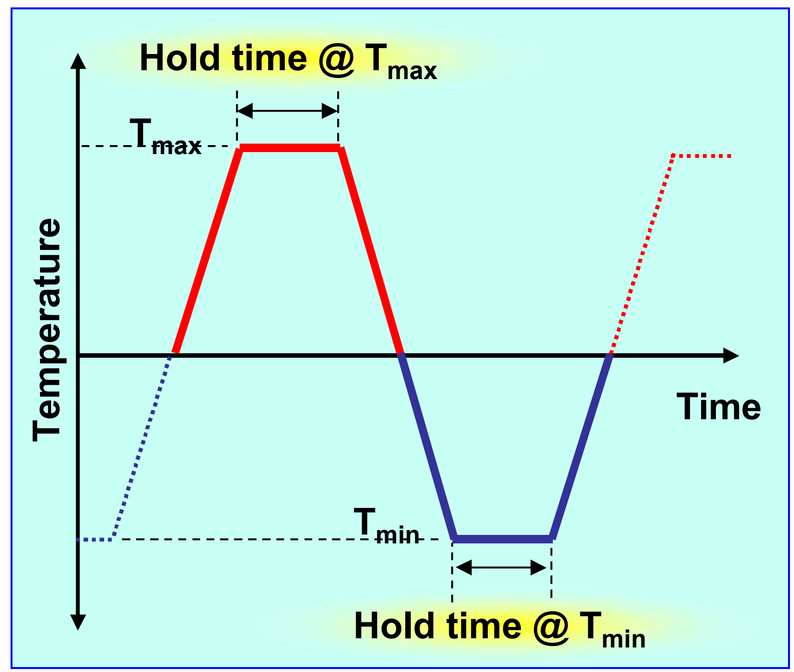
- **The deterministic calculation eliminates the expressed need for acceleration factors (AF) to correlate test conditions with service environments.**

  The inaccuracy of the acceleration factor is amplified with increased number of cycles.



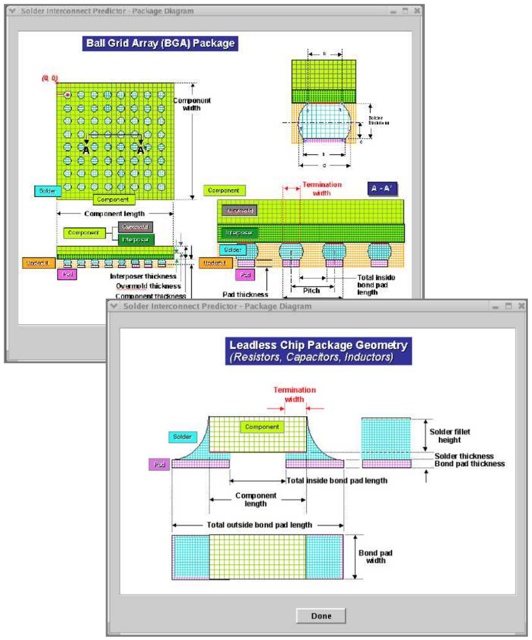
Testing *Service*

- **The controversial “dwell-time” issue brought about by Pb-free solders, and additional testing requirements, are avoided because the constitutive equation calculates the deformation, *explicitly*, based on creep and plastic flow.**



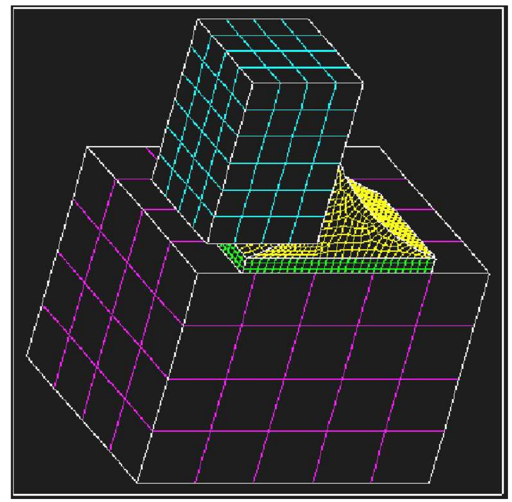
TurboSiP© Software

- There are four basis steps to the software:



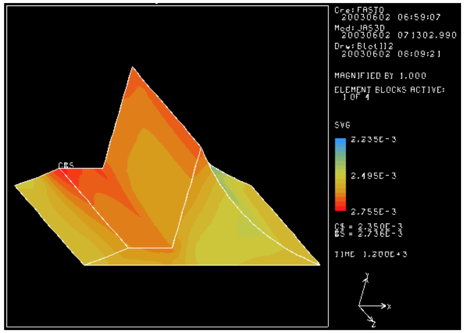
1. Data input:

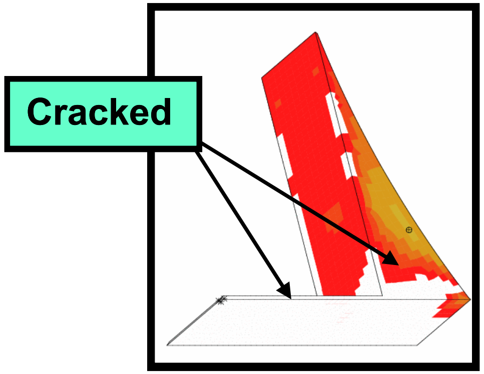
- Part Geometries
- Material Models (Sn-Pb or Sn-Ag-Cu)
- Materials Properties
- Temperature Cycle



2. Mesh Generation

3. Code Execution



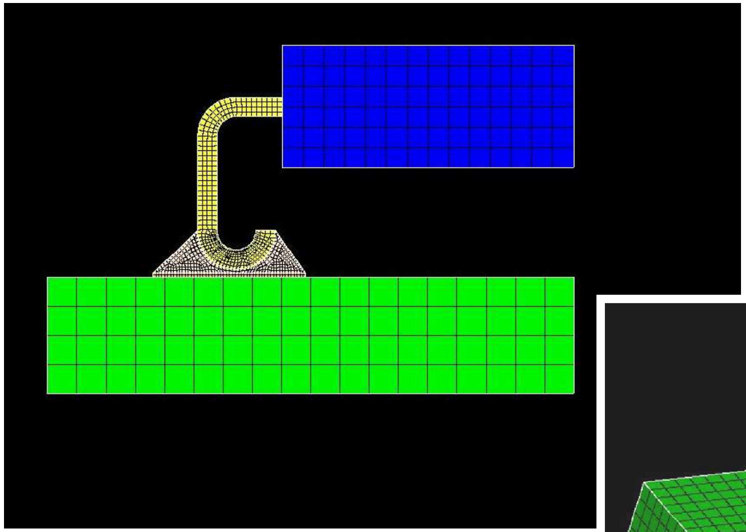


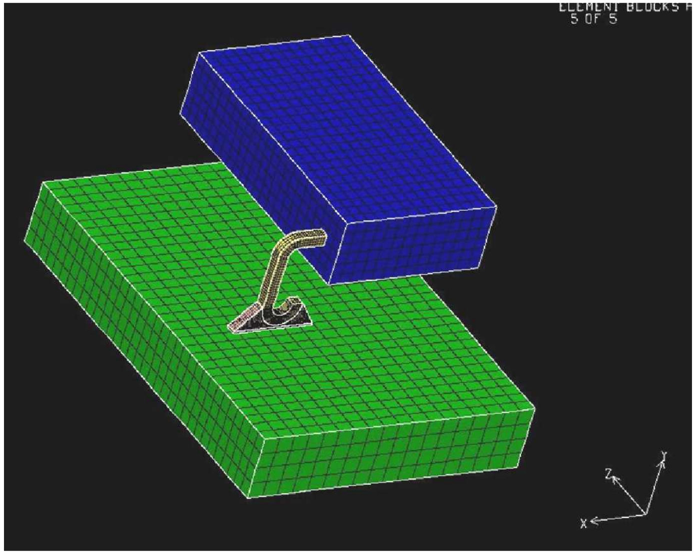
4. Post-Processing

•Fatigue deformation
•Crack propagation

TurboSiP© Software

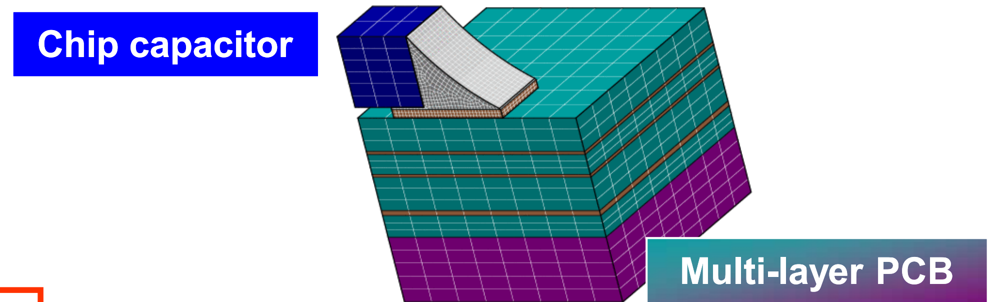
- Features have been added to facilitate the analysis: user can rotate the mesh and output graphics for better visualization of the model and results.



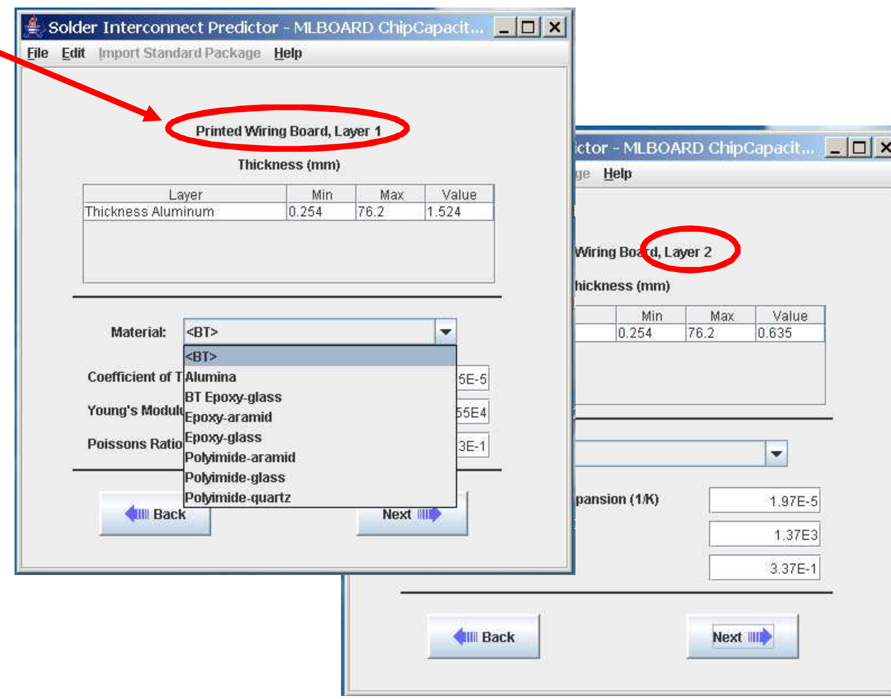


TurboSiP© Software

- Can readily add capabilities to address advanced packaging and substrate designs and materials:



- **Developed general capability for multi-layer boards (user can input properties / thickness for each layer)**



- Significantly sped up SVG analysis step by replacing numerical integration over thousands of cycles with numerical integration over 1 cycle and clever use of results

- Added new components and printed circuit board materials and validated them with experiments.

TurboSiP© Software

- The TurboSiP© software is managed in the following manner:
  - **TurboSiP© v0.1 software:**
    - SNL/DoE copyright 1188.0
    - Licensable, externally
    - There is no LMC proprietary information or 2° use of that proprietary information.
    - Government use notice (GUN) has been issued to US Army, Redstone Arsenal, AL and Picatinny Arsenal, NJ.
  - **TurboSiP© v0.1 software (LMC restricted):**
    - There is LMC proprietary information, or the 2° application of it.
    - Licensed to LMC; dissemination through the EPI Center.
    - Export control and encryption.
    - This version of the software is not copy-righted.

TurboSiP© Software

- **How will SNL and LMCO manage the software *in the future*?**

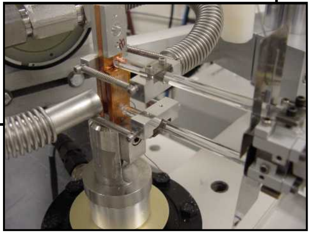
  - **Constitutive model**
  - **Validation exercises**

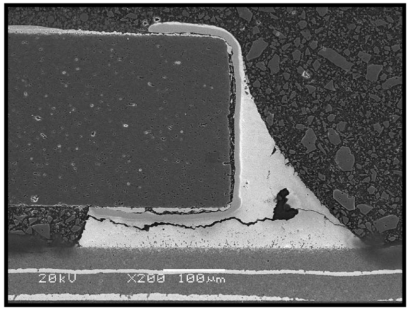
  } **Sandia / LMCO**

$$\dot{e}^p_{11} = f_0 \exp(-Q/RT)\sinh^p\left(\frac{|\sigma_{11}-B_{11}|}{\alpha D}\right)\mathrm{sgn}(\sigma_{11}-B_{11})$$

$$\dot{D} = \frac{A_1|\dot{e}^p_{11}|}{(D-D_0)^{A_3}} - A_2(D-D_0)^2$$

$$\dot{B}_{11} = \frac{A_4\dot{e}^p_{11}}{|B_{11}|^{A_6}} - A_5 B_{11}|B_{11}|$$





  - **Software debugging**
  - **Software upgrades**

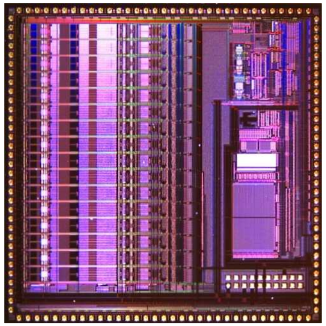
  } **Outside software company ???**

Future Directions for Sandia Modeling Efforts

- Continue model validation

- New solder alloys … *and some old ones*.
- New packaging configurations and materials

- New printed circuit board materials
- Test and service environments:
  - Vibration
  - Mechanical shock
  - Combined conditions



- Solder joint size effects (IRAD collaboration between LM/MFC, Ocala and Sandia)

Future Directions for Sandia Modeling Efforts

- **New solder alloys**
  - **Compression testing to develop the constitutive model for the software.**
    - **Stress-strain tests**
    - **Creep tests**
    - **Thermal expansion**

  - **Completed:**

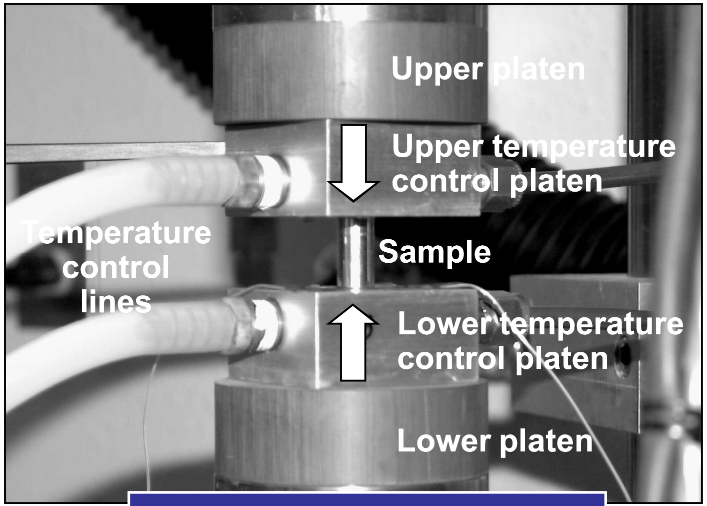
63Sn-37Pb	SAC432*
SAC396	97In-3Ag*
SAC397*	52In-42Sn*

* Not yet in the software library

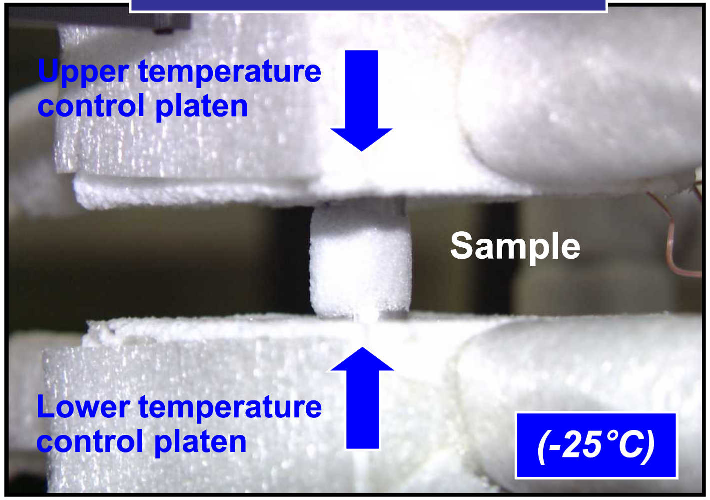
  - **Currently being measured*:**

SAC105	80Au-20Sn
SAC396 + x wt% Pb	100In

* Stress-strain tests completed.

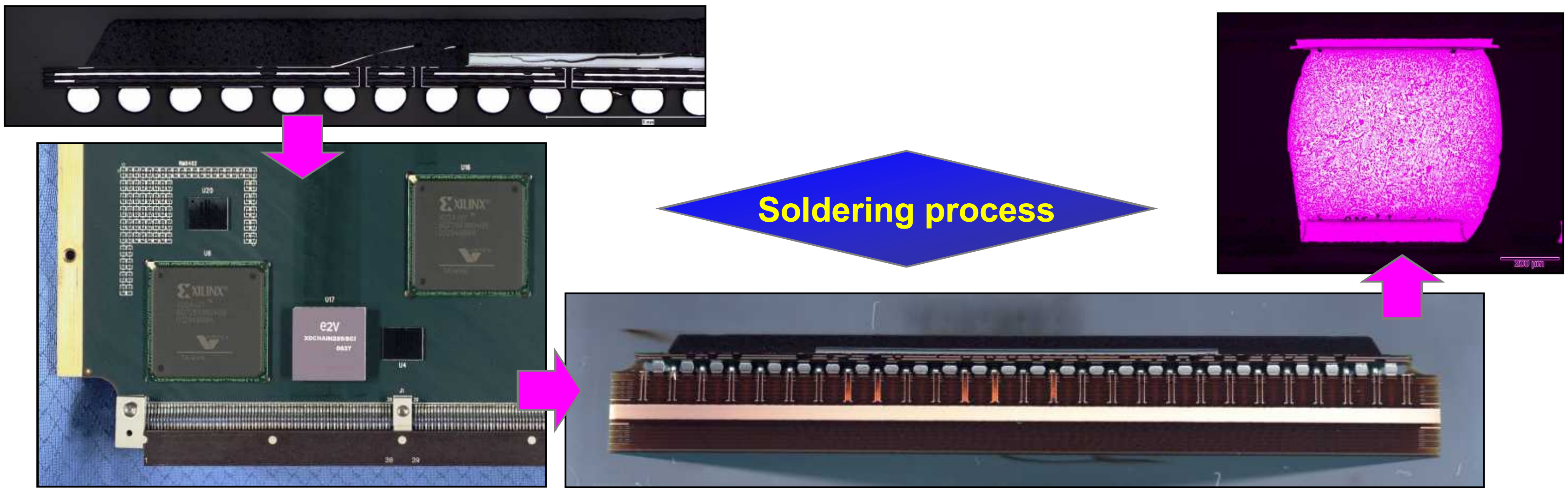


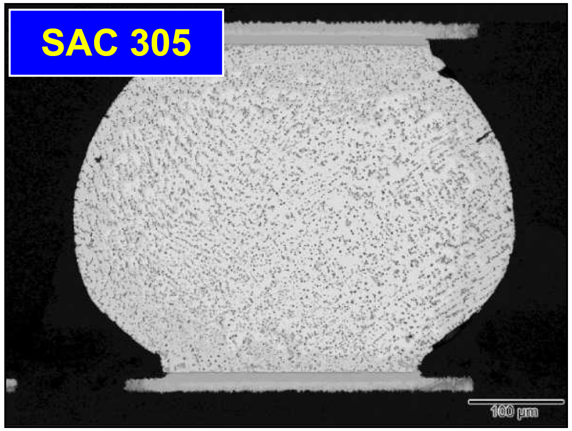
Compression Testing

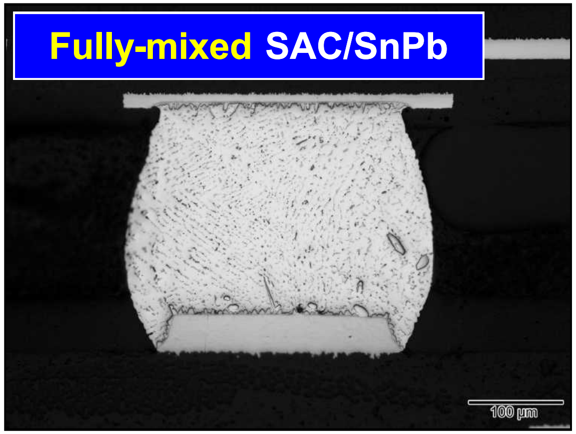


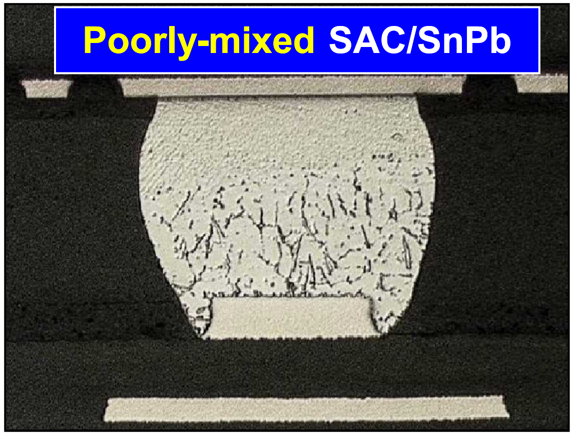
Future Directions for Sandia Modeling Efforts

- **Mixed solder joints:** Sn-Ag-Cu balls/columns and Sn-Pb paste.



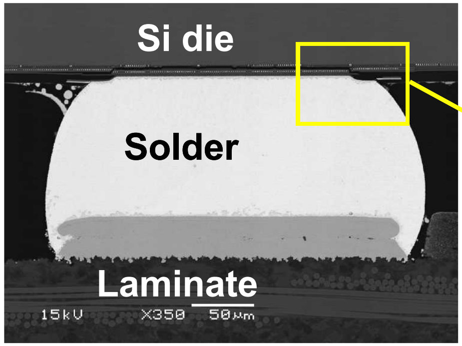




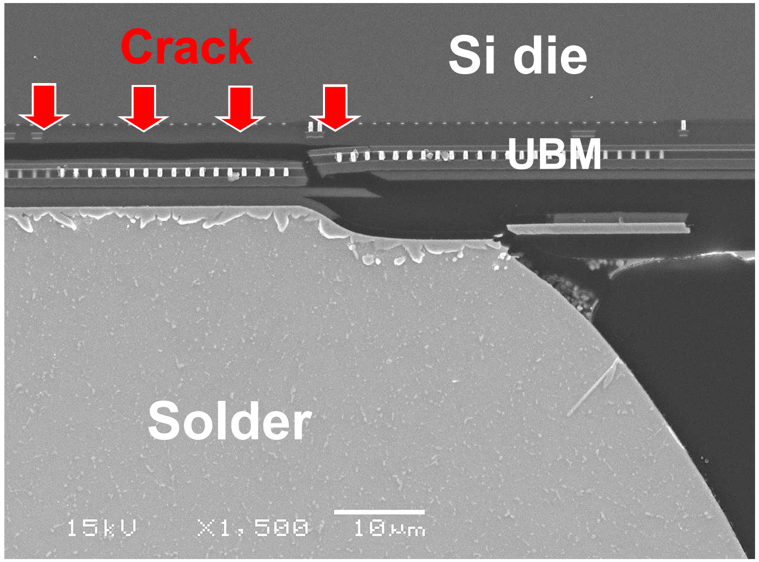


Future Directions for Sandia Modeling Efforts

- **Mechanical shock and vibration:**
  - **Unlike consumer products, shock and vibration requirements did not change significantly in the high-reliability electronics sector.**
  - ***What did change was an increased complexity of the electronics that required new materials and smaller interconnections.***



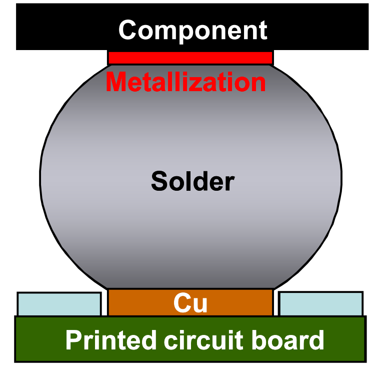
Underbump metallurgy (UBM) damage to a chip-scale package



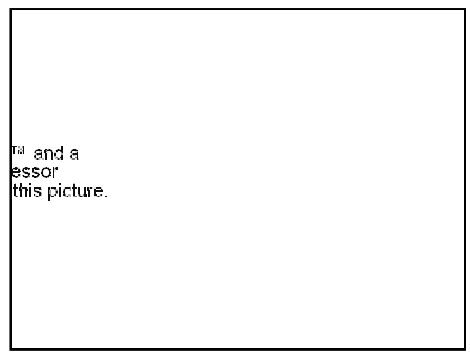
- **Alternative failure modes have appeared in solder joints.**

Future Directions for Sandia Modeling Efforts

- **Pb-free solders have high elastic moduli and high yield strengths that are pushing the applied and residual stresses into the component or PCB structures (e.g., pad cratering).**
- **Board flexure is often a cause for high-cycle fatigue (vibration) or shock failures.**

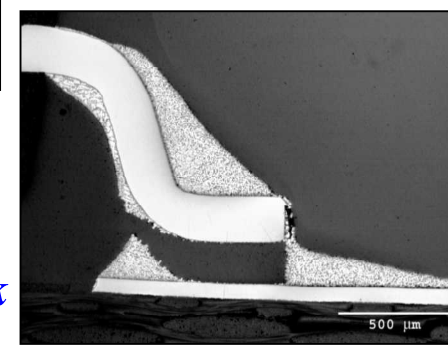


The "whole" solder joint.



Vibration

Shock

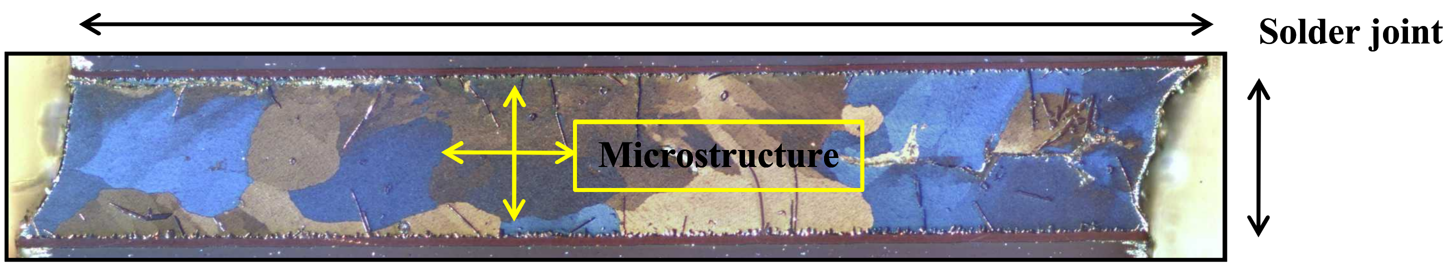


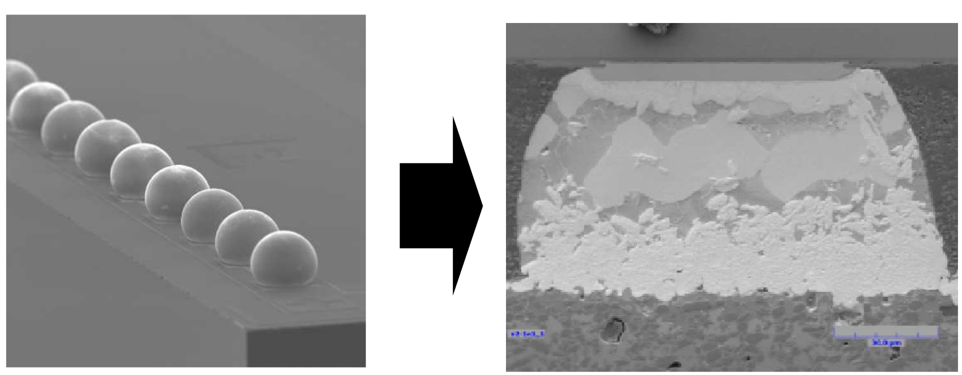
Future Directions for Sandia Modeling Efforts

- A collaboration between LM MFC, Ocala (L. Woody) and Sandia has undertaken an IRAD project to examine the reliability of ***small solder joints***.

Small solder joints ≡ **interconnections having a size that is commensurate with the scale of the microstructural phases.**

Sn-Ag-Cu solder joint

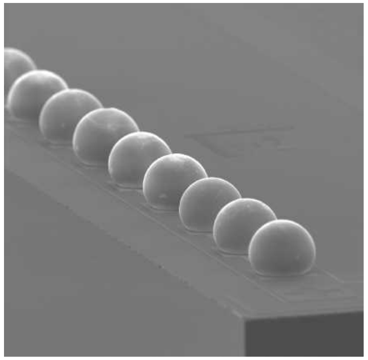


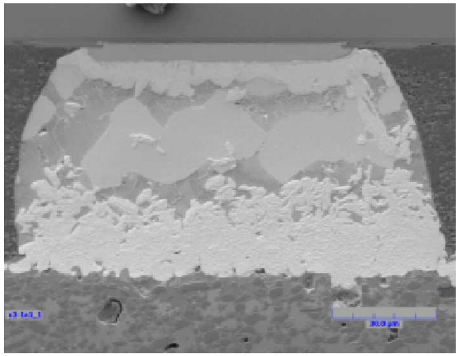


Future Directions for Sandia Modeling Efforts

- The specific objective is to determine if there is a **size scale at which, the continuum mechanics assumption breaks down**.

- If such a cut-off exists, then …
  - What is the **size parameter** that identifies that point?
  - What is the **constitutive model** that describes the deformation of the solder at those smaller scales?

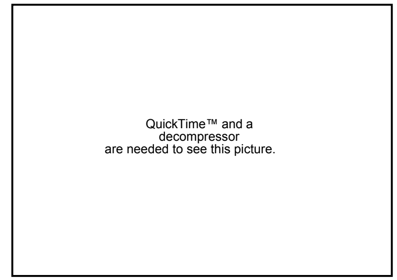




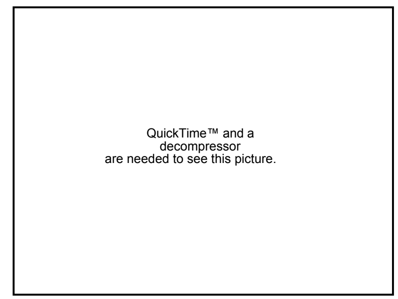
Future Directions for Sandia Modeling Efforts

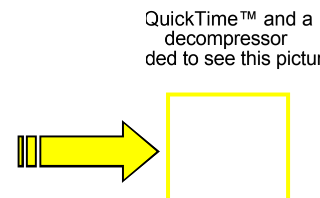
- **The IRAD project takes a two-pronged approach at this problem.**

1. **Measure the time-dependent, time-independent, and isothermal fatigue properties of small solder joints.**

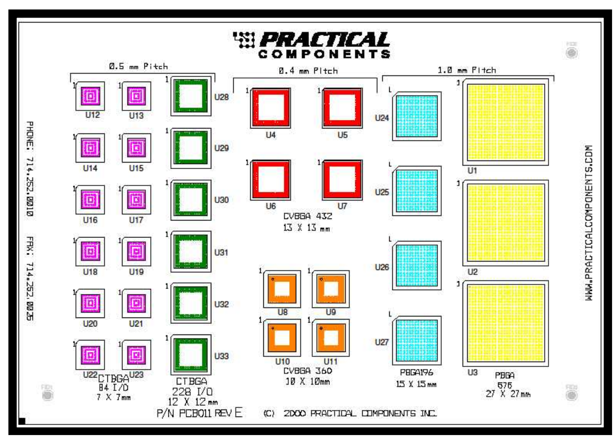


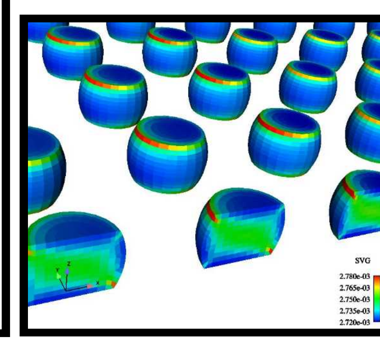
The constitutive properties of the solder (bulk) will be inferred from the behavior of the joints.





2. **Validate the solder joint fatigue model using printed wiring assembly test vehicles having components with the smallest solder joints.**





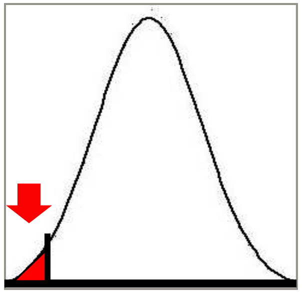
Critical Perspective on Reliability

Final word …

Critical Perspective on Reliability

The "1% Problem"

- **System-level failures are on the increase in the A&D industry with the further miniaturization of the electronic interconnections and increased use of commercial off-the-shelf (COTS) parts.**



"1%" Problem

Commercial products cannot be blamed entirely for the "1%" defect issue; we may have already been headed down this road even with MIL-grade components, due to greater system complexity and increased functionality requirements.

- **Irrespective of the solder technology, the A&D industry must develop a plan to address the "1% problem" in order to prevent significant cost overruns and schedule delays to current and future programs.**
- **The supply chain *cannot* be expected to undertake a comprehensive reliability analysis of all hardware, even with their price premiums.**

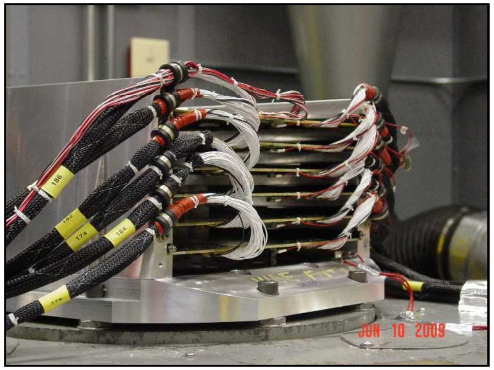
Critical Perspective on Reliability

- **Approach to address the "1% problem":**

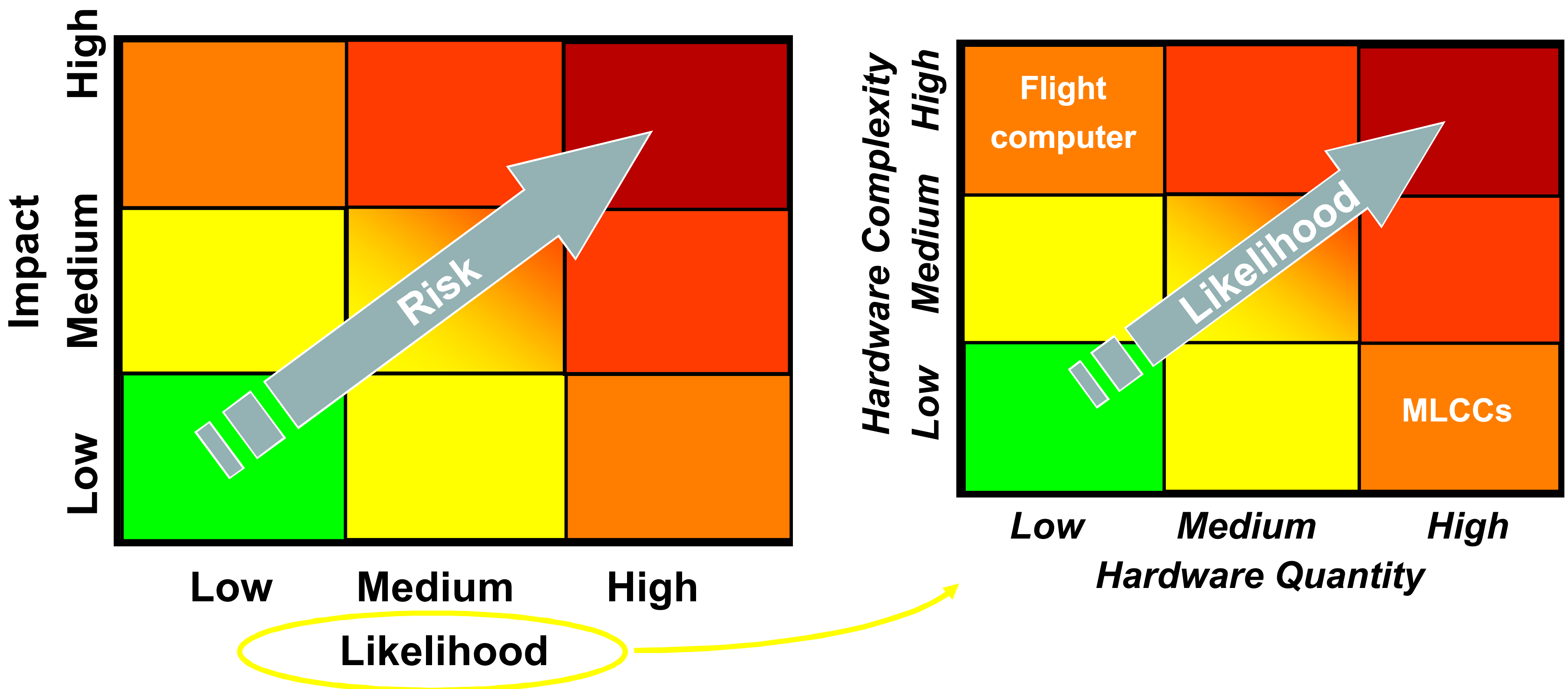
1. **Bring together materials, processing, and reliability SMEs to focus on solder interconnection technologies in complex hardware.**
   - ***Optical elements, mechanical structures, and electronic components.***
   - ***No component or sub-system is beyond scrutiny, any longer!***

2. **Develop test and modeling methodologies to fully understand these low defect rate phenomena, which must include failure mode analyses, QMU, and the necessary statistical assessments.**
   - ***Characterization test vehicles***
   - ***Accelerated aging environments (HALT, HAST, ESS, etc.)***

3. **Establish the risk to system-level reliability caused by low failure-rate defects.**
   - ***Determine materials reliability at the component level; estimate reliability at the component level.***
   - ***Failure mode effects analysis (FMEA) to track the risks and reliability through the system level.***



Critical Perspective on Reliability



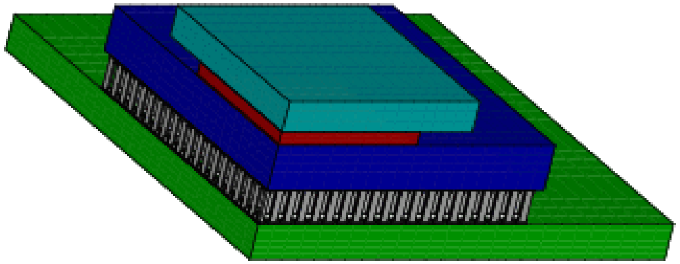
Often, the A&D Industry Misses the "Likelihood Diagram"!

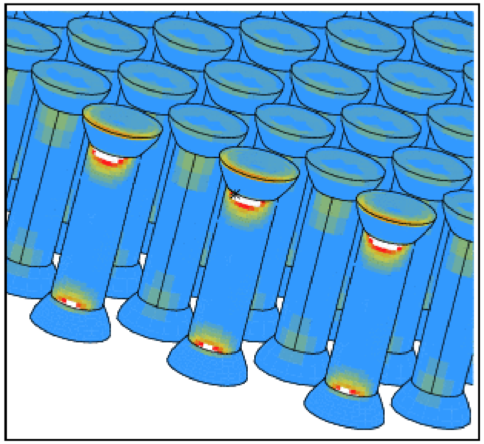
A simple component of "mature technology", but one that is highly pervasive within a sub-system or system, can impact system reliability, significantly, by shear numbers, alone.

Critical Perspective on Reliability

- A particular challenge that is associated with the testing option of high-valued hardware is the scarcity of test assets.

- It is difficult to develop an adequate statistical framework from empirical data when the sample size (N) is very small.

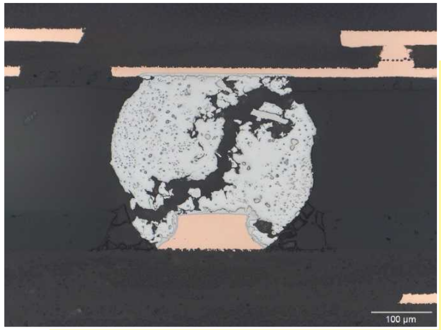




- It is under these circumstances that the computational modeling approach will add important value to the reliability analysis.

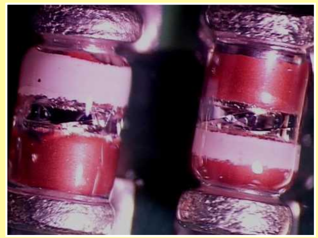
- Additional resources to address this issue:
  - Materials science and physics-of-failure.
  - Small population statistical analysis techniques

Critical Perspective on Reliability

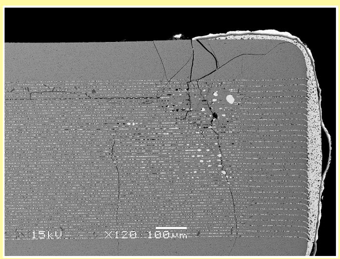


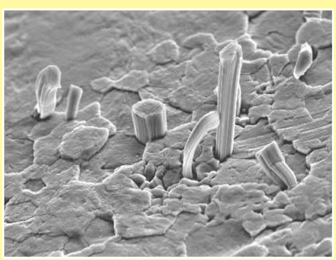
Solder joints

Cracked diodes



Shorted MLCCs





Sn whiskers

Solder joints

The A&D industry has had tremendous successes. But …

New technologies will present new hardware challenges …

There are lessons-learned …

The A&D industry must use new approaches to quantify the reliability of new technologies for future products …

Then, the A&D industry *will* continue on a road to success …

Critical Perspective on Reliability

- **The failure to pay *due diligence* to these concerns can lead to the need to repair and rework fielded systems, resulting in cost overruns and schedule delays that will far outweigh any investment made at a program's front-end, which could have prevented those defects.**
- **Washington D.C. funding sources are becoming increasingly *unsympathetic* to excessive cost overruns and schedule delays, a fact that can affect the continued support of existing programs, and the ability of organizations to win future contracts.**