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Computational Models: A Critical Enabler of Advanced Electronic Packaging for Use in High-Reliability Applications

Paul T. Vianco

Sandia National Laboratories
Albuquerque, NM 87185
ptvianc@sandia.gov

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Introduction

- **The development and operational sustainment of down hole renewable (geothermal) and non-renewable (fossil fuel) energy resources will be challenged by increasingly higher costs factors:**
  - **Site preparation ($B)**
  - **Loss of site operations ($M/day)**
  - **Liability – environmental restoration ($B)**

Courtesy of Dept. of Energy

Courtesy of Dept. of Energy

Courtesy of NASA

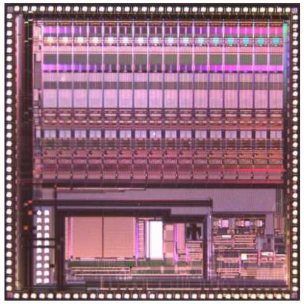
Introduction

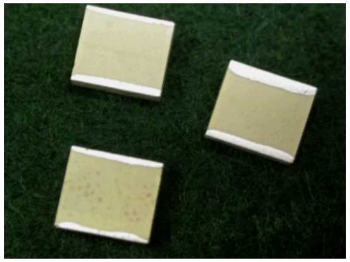
- Placing sensor electronics down-hole can significantly improve the efficiency and reliability of well exploration and production.
- Oil, gas, and geothermal wells present some of the harshest service conditions for electrical equipment.
  - **Temperatures:** 300°C continuous; 350°C peak
  - **Pressures:** 15,000 to 30,000 psi
  - **Vibration:** PDS (g^2/Hz), 0.01 – 0.1 (0.6 – 3 kHz)
  - **Corrosion:** H_2S, H_2, brine, superheated steam.

Courtesy of Sandia National Labs.

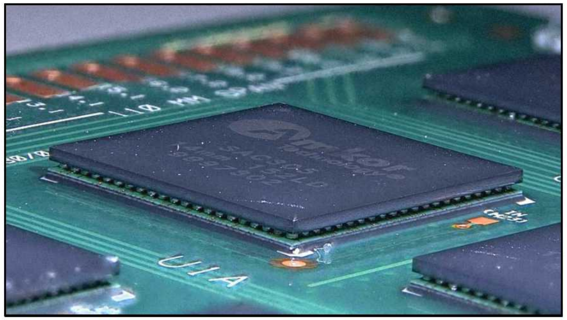
Introduction

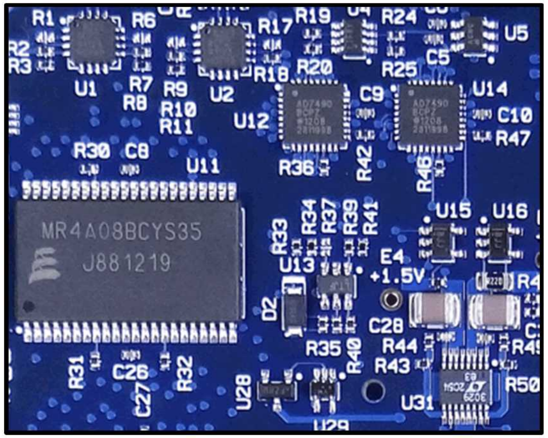
- **Significant advances have been made in the development of electronic components, including those for use in high-temperature environments.**
  - **The increased functionality of new products can enhance the information flow from the hole to the field engineer.**

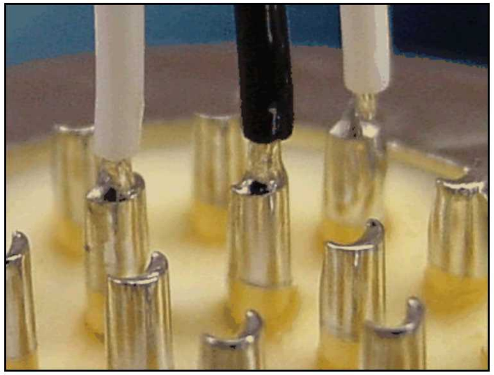




- **However, the benefits to cost and production schedules can only be realized when electronic packaging technology keeps pace.**







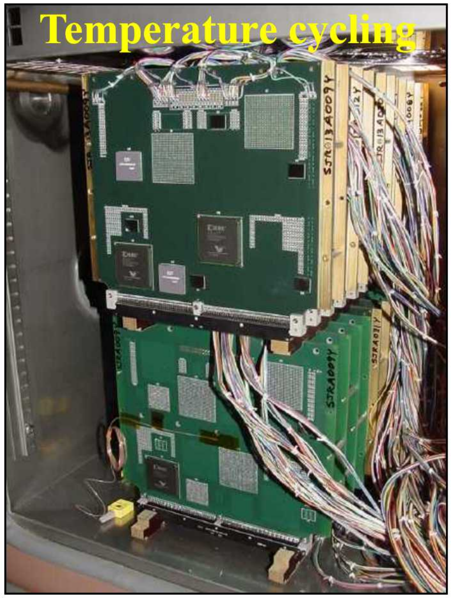
Introduction

- **Objective within the high-temperature electronics industry:**

… introduce advanced electronics into field operations as quickly as possible.

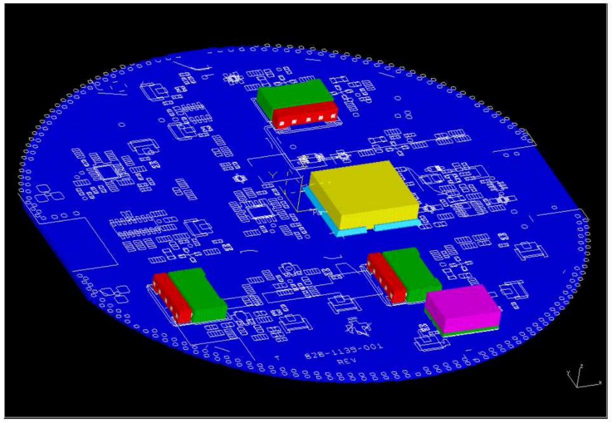
- **A cornerstone of this goal is to assure that electronic packaging meets the reliability requirements of downhole service.**

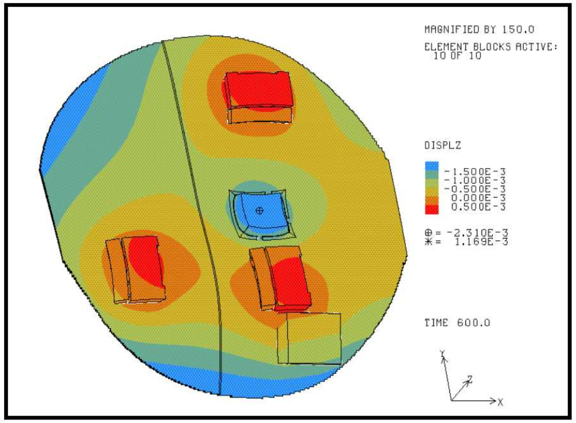
- **However, the collection of reliability data using empirical methodologies is fast becoming an unattractive approach in today's marketplace.**
  - **There are simply too many materials choices, packaging configurations, as well as service environments to be addressed by test programs in a cost-effective manner.**



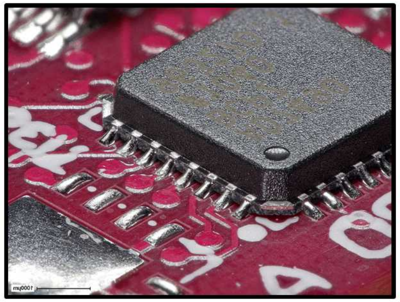
Introduction

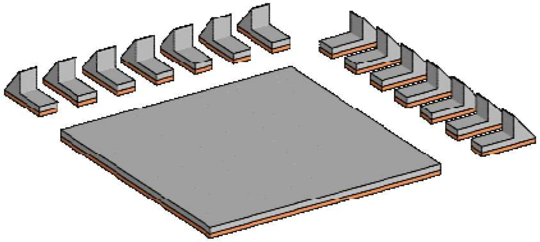
- **Computational modeling** provides the only viable alternative to empirical testing, which will enable the use of advanced electronic products in downhole applications.

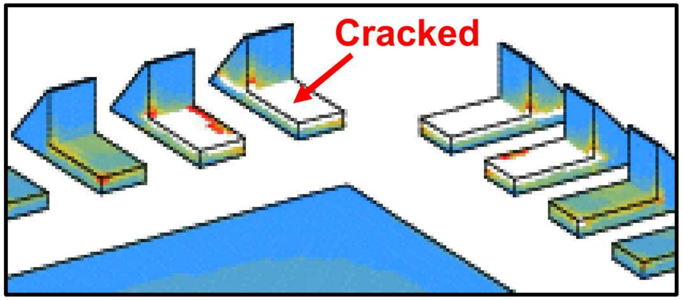




- This presentation focuses on the ***computational modeling tools*** developed by Sandia to predict **the reliability of solder joints**.

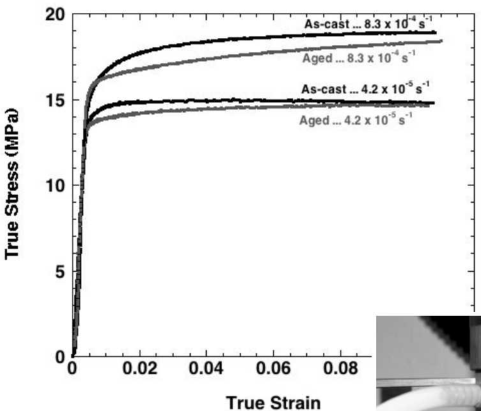


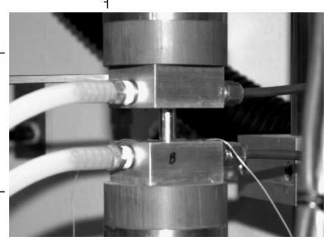


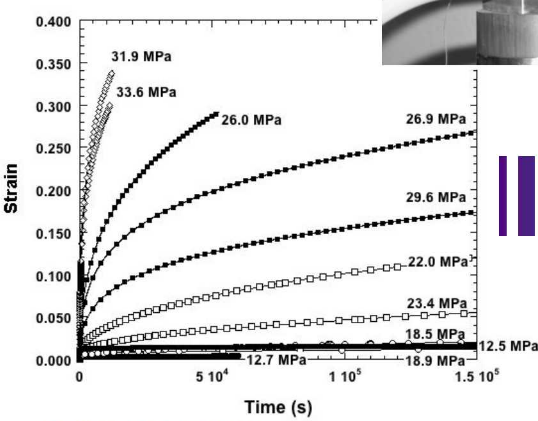


Computational Modeling Methodology

- **The computational modeling approach is based upon the unified creep-plasticity (UCP) equation for each solder alloy.**
  - **Compression testing is used to determine the time-independent and time-dependent mechanical properties of the solder alloy.**







Stress-strain → Time-Independent Deformation $\varepsilon = (\sigma, \varepsilon, T)$

Creep → Time-Dependent Deformation $\varepsilon = (\sigma, T)$

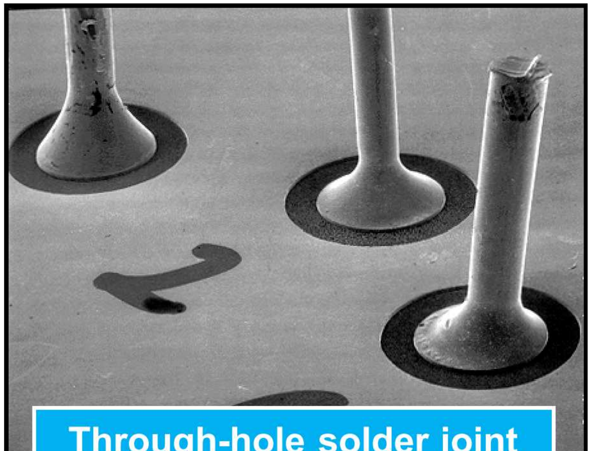
→ UCP constitutive equation

$d\gamma/dt = f(\sigma, T, E)$

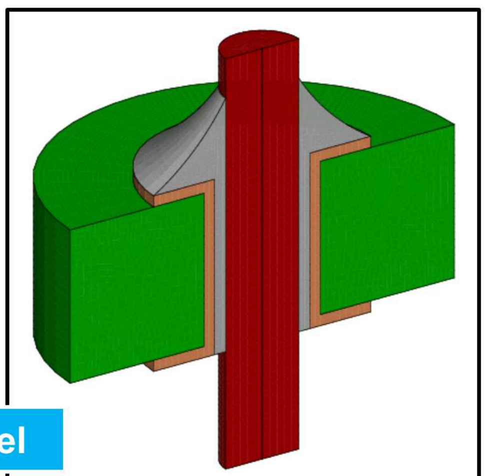
- **σ, stress matrix**
- **T, temperature**
- **Elastic and physical properties**

Computational Modeling Methodology

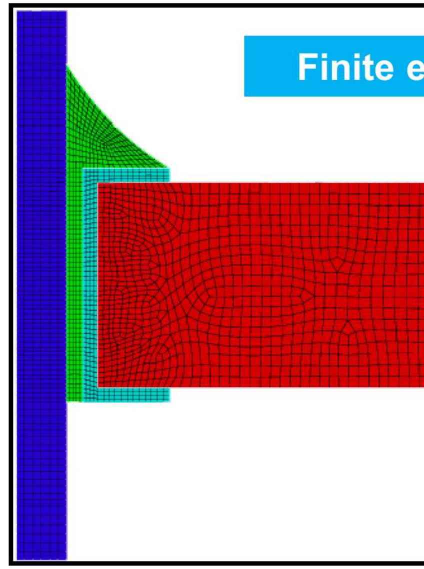
- The UCP equation is then applied to the solder joint geometry through the construction of the appropriate finite element model.



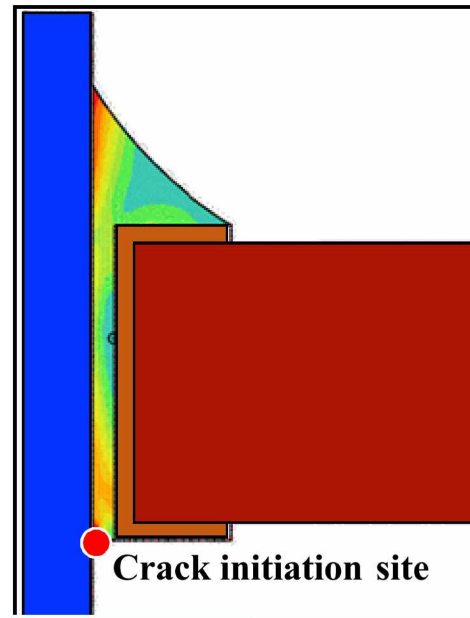
Through-hole solder joint



Solid model



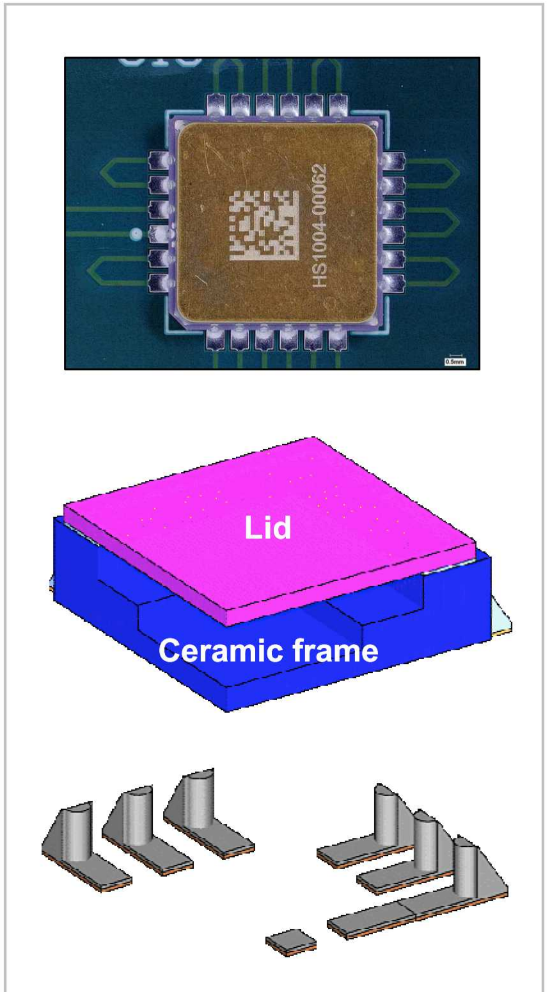
Finite element mesh

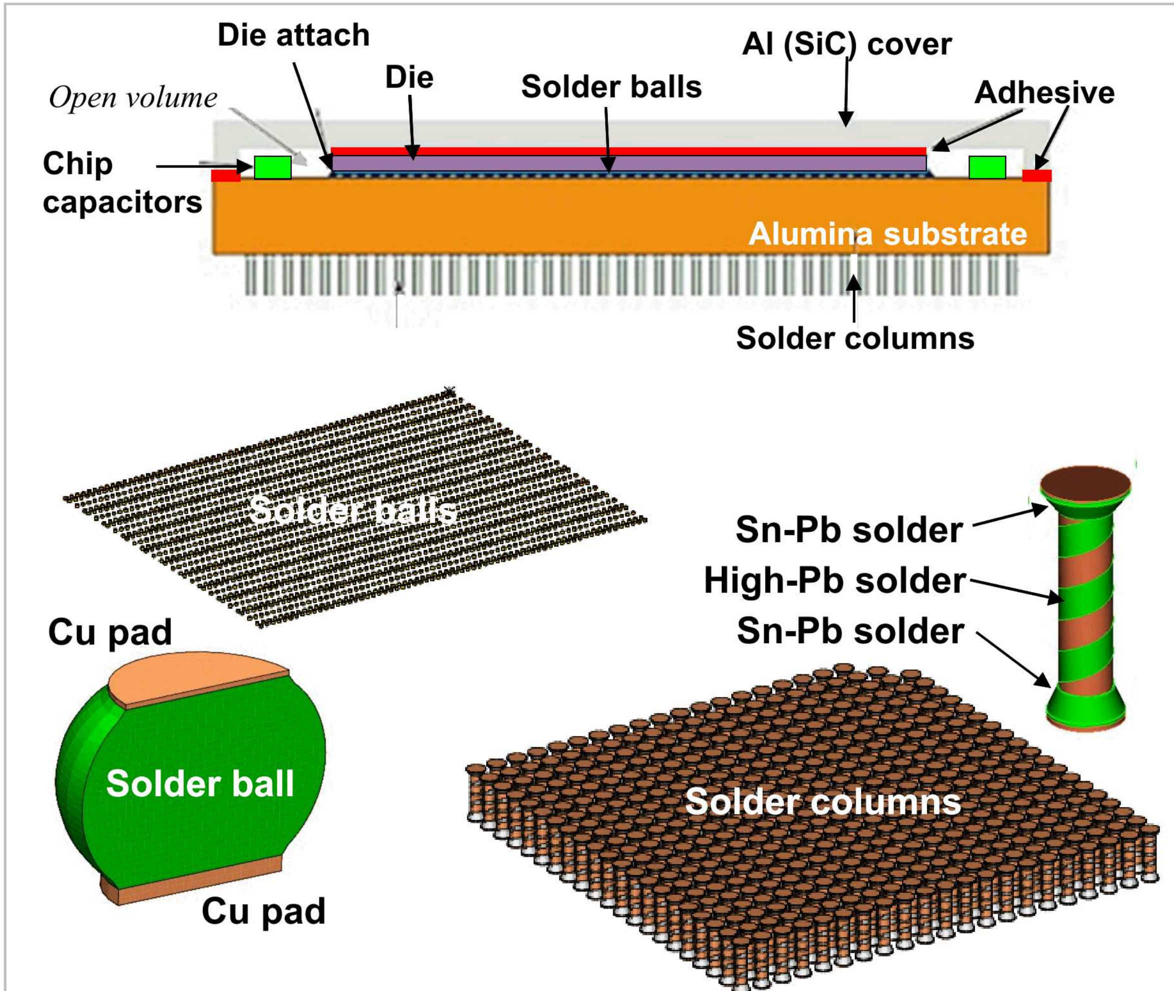


Predicted fatigue strain

Computational Modeling Methodology

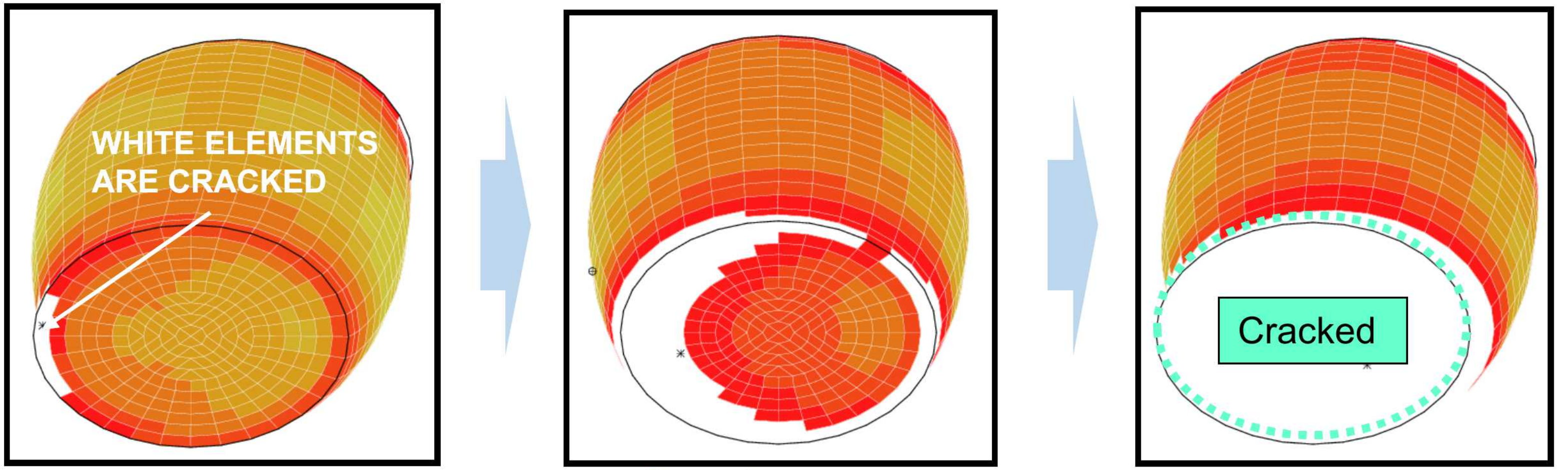
- The finite element model can be as simple, or as complex, as is required to accurately predict the fatigue stresses and strains.





Computational Modeling Methodology

- The solder fatigue model now has the capacity to predict crack propagation in the solder joint.

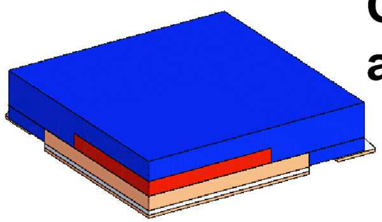


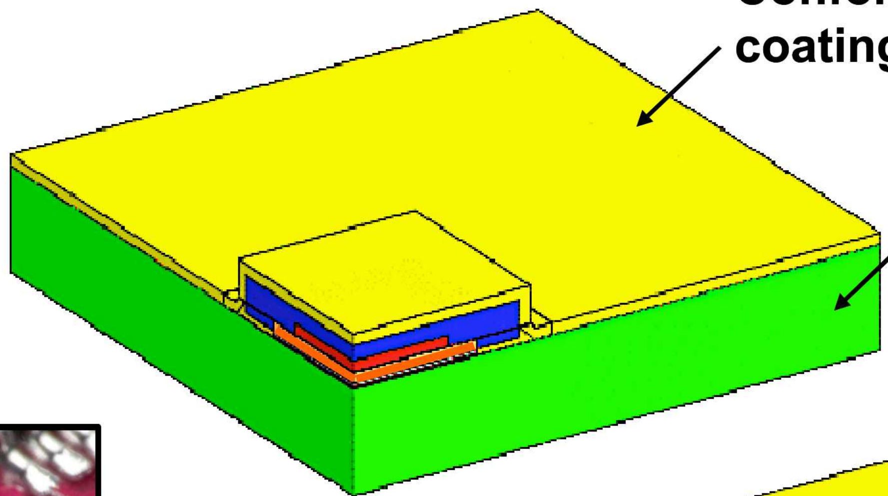
Crack start: 900 cycles | **Crack grows:** 1800 cycles | **Electrical open:** 2100 cycles

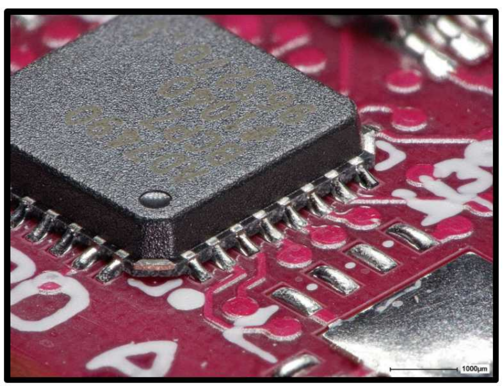
- The advantages of the crack growth model are:
  - Document the path taken by crack propagation.
  - Determine load-bearing capacitor of partially cracked joints.
- Crack growth predictions are validated by empirical data.

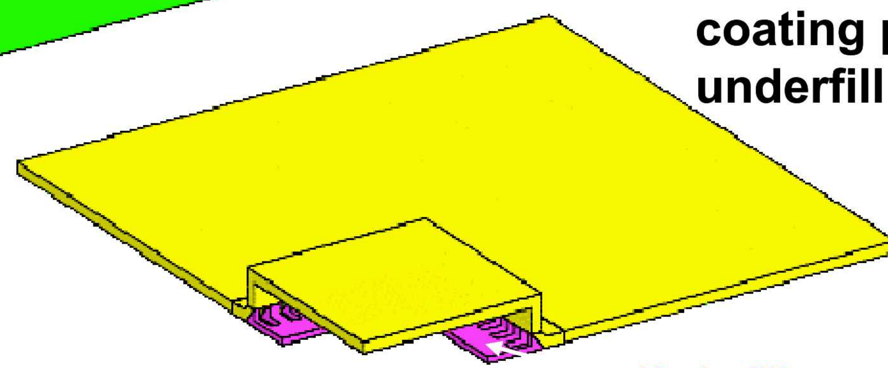
Computational Modeling Methodology

- **Conformal coatings**, **underfills**, and **component staking** can have a significant effect on solder joint fatigue lifetimes.



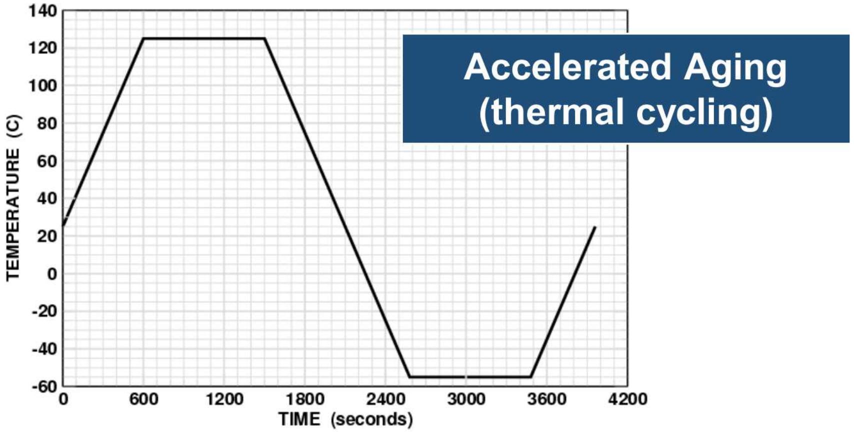


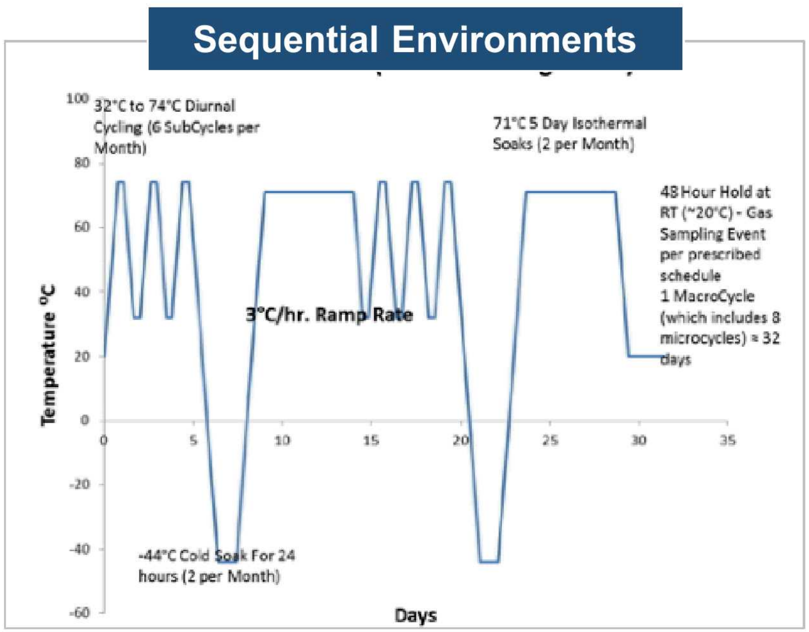


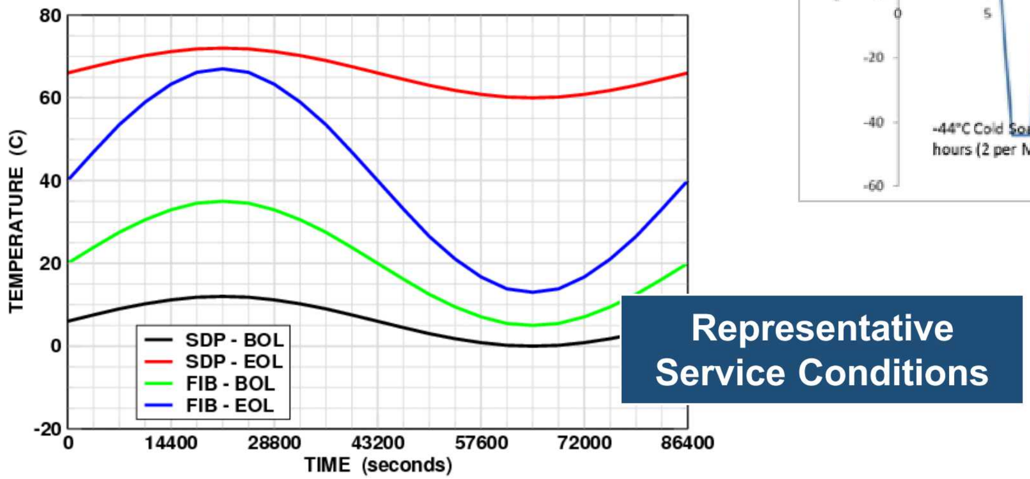


Computational Modeling Methodology

- **Computational modeling can be used to predict solder joint fatigue for accelerated aging tests, actual service environments, as well as to address sequences of multiple environments.**

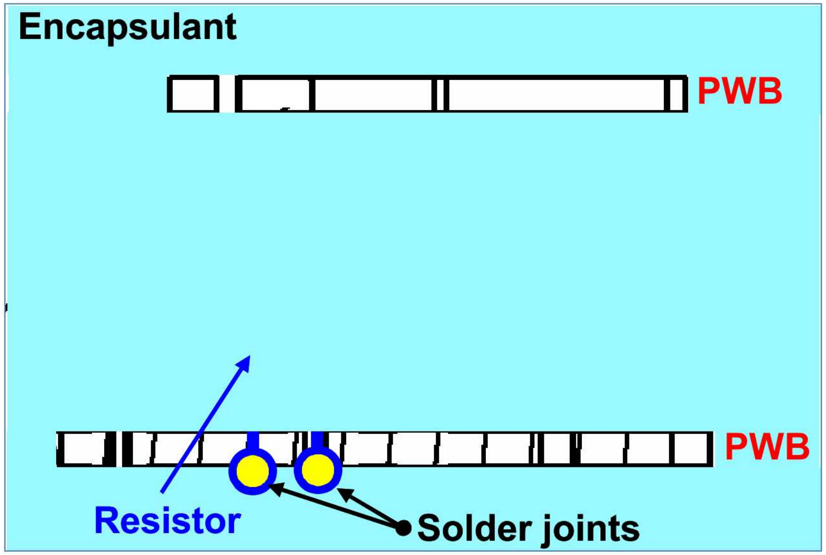






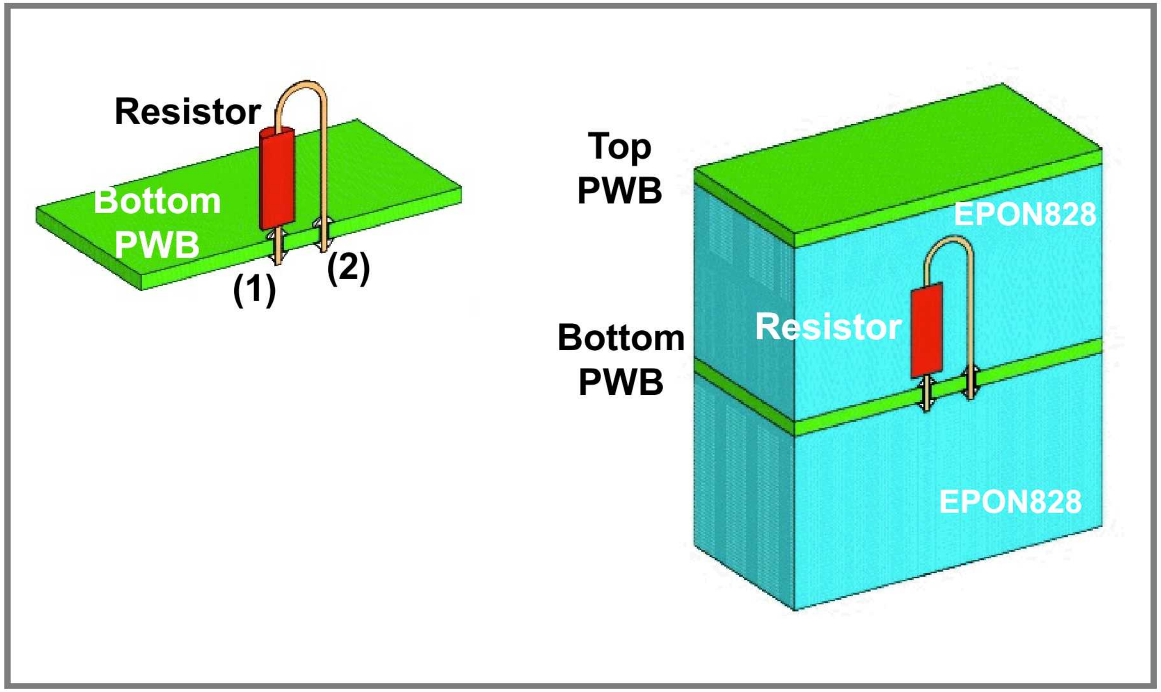
Case Study A: Encapsulation Effects

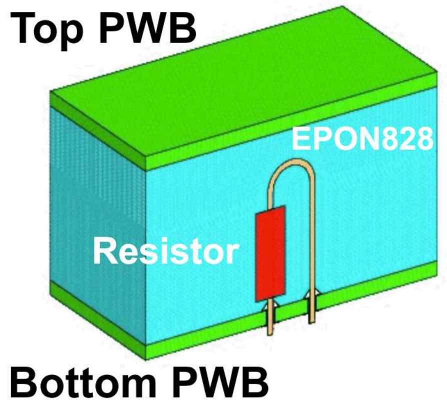
- **Encapsulation is used to reduce the degradation to solder joints caused by shock and vibration environments.**
- **Encapsulants affect solder joint fatigue under temperature cycles.**
- **Solder joint workmanship is a compounding factor in reliability.**
- **Less-than-complete hole fill can occur on an encapsulated, through-hole assembly.**



Case Study A: Encapsulation Effects

- A finite element model was built-up of the solder joint geometry.

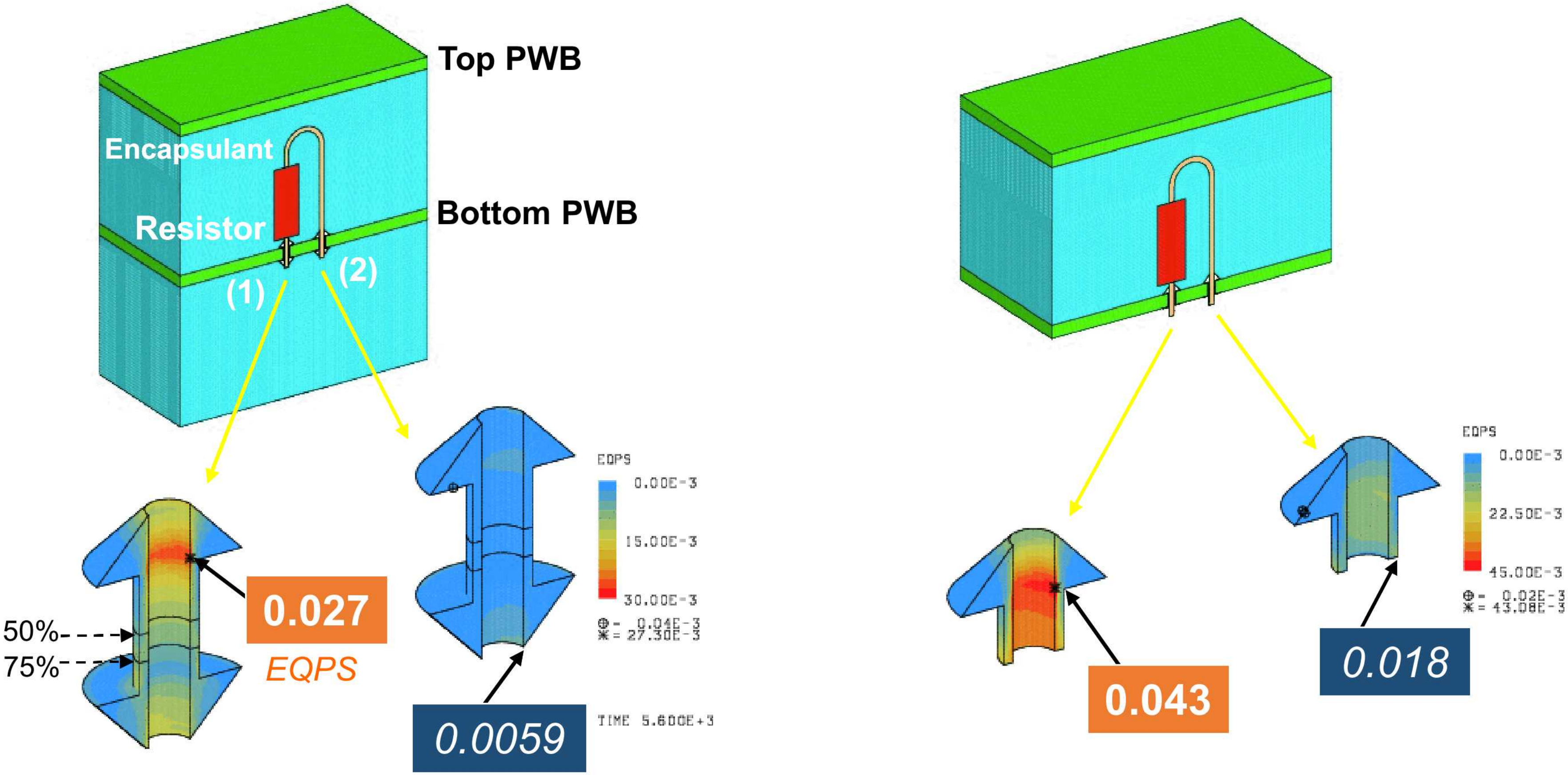




- A special case was evaluated whereby the **encapsulant was absent** from under the bottom PWB – e.g., instance of a void.

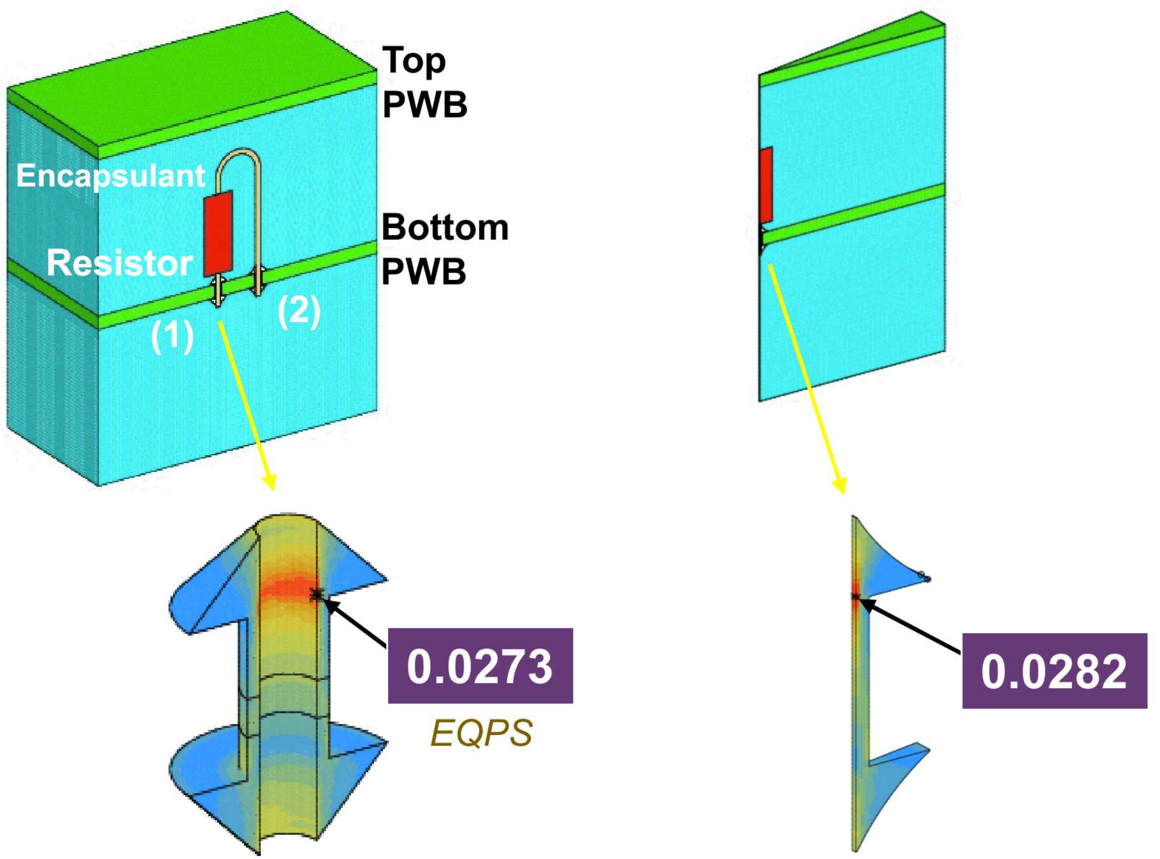
Case Study A: Encapsulation Effects

- Scoping analyses determined that solder joint (1) experience four-times the equivalent plastic strain (EQPS) than solder joint (2) for both limiting cases. *The analysis was focused on solder joint (1).*



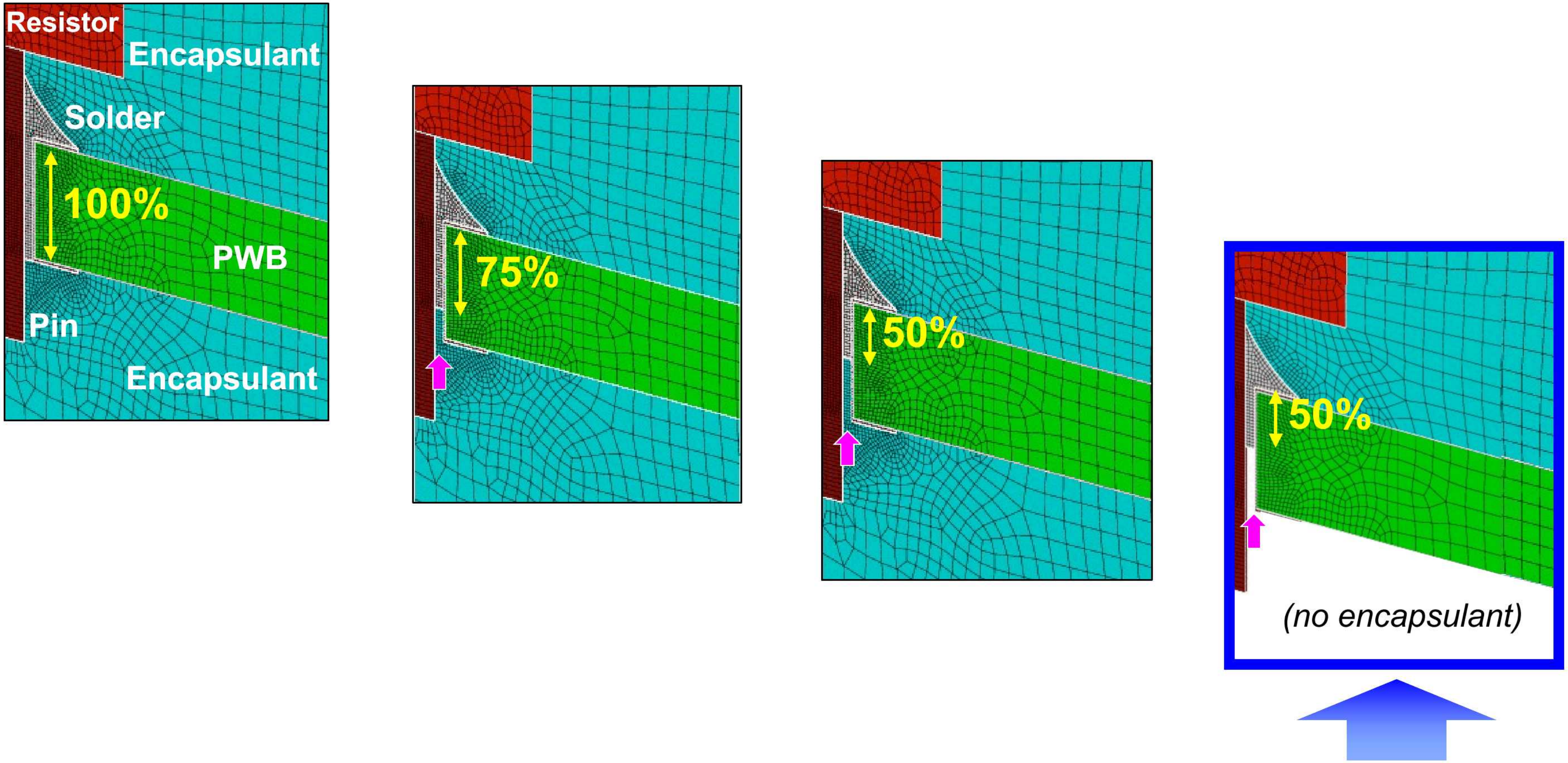
Case Study A: Encapsulation Effects

- Cylindrical symmetry of the single joint allowed for reducing the finite element model down to a "10 deg pie slice" configuration.



Case Study A: Encapsulation Effects

- The four finite element configurations are shown below:

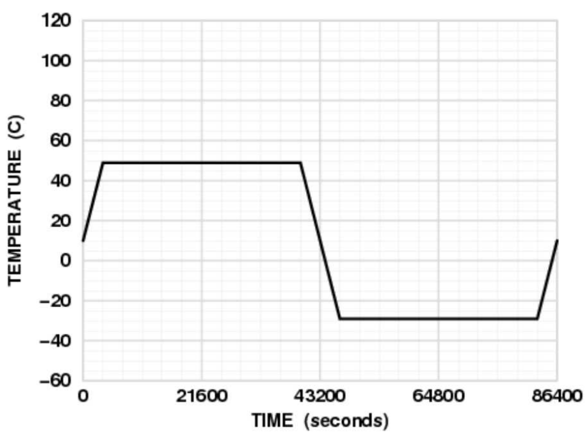


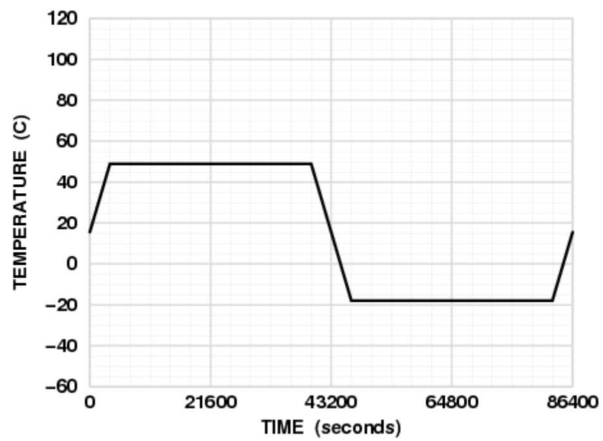
- **The worst-case had 50% hole fill as well as asymmetric stress due to encapsulant missing from underneath the bottom PWB.**

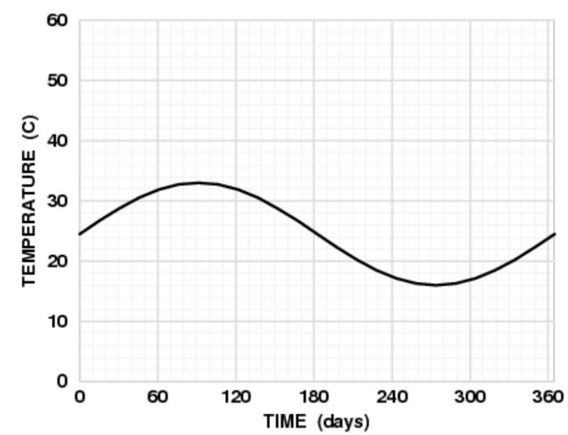
Case Study A: Encapsulation Effects

- The **service environment** was comprised of two transportation segments #1 and #2, and the (final) use segment:

Transport – #1	Transport – #2	Use
-29°C/49°C; 15 cycles; 24 hour period	-18°C/49°C; 15 cycles; 24 hour period	16°C/33°C; 60 cycles 1 year period







Percentage of Total Fatigue Life Used-up =

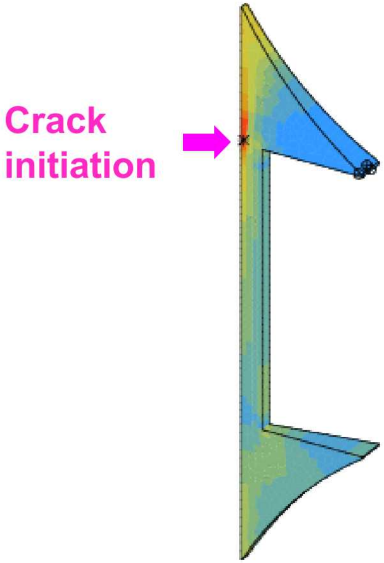
$$\left[(N_{\#1}/ N_{f,\#1}) + (N_{\#2}/ N_{f,\#2}) + (N_{Use} / N_{f,use}) \right] \times 100$$

The "f" refers to the failure criterion.

Case Study A: Encapsulation Effects

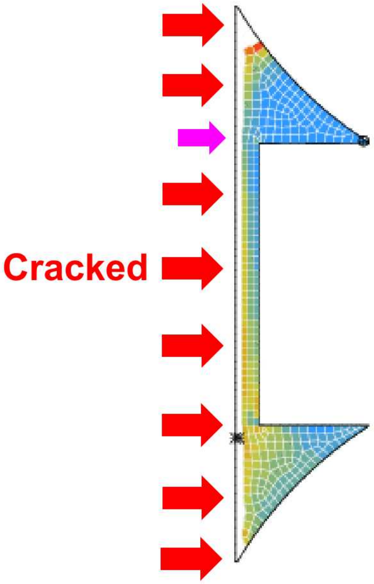
- The two failure criteria, crack initiation and 100% crack (electrical open) are exemplified by the *use segment: 16C/33C; 1 year cycle:*

Cycles to crack initiation



140,000 cycles

Cycles to 100% crack



390,000 cycles

Case Study A: Encapsulation Effects

- **The percent of TMF life used up by the Service Conditions**

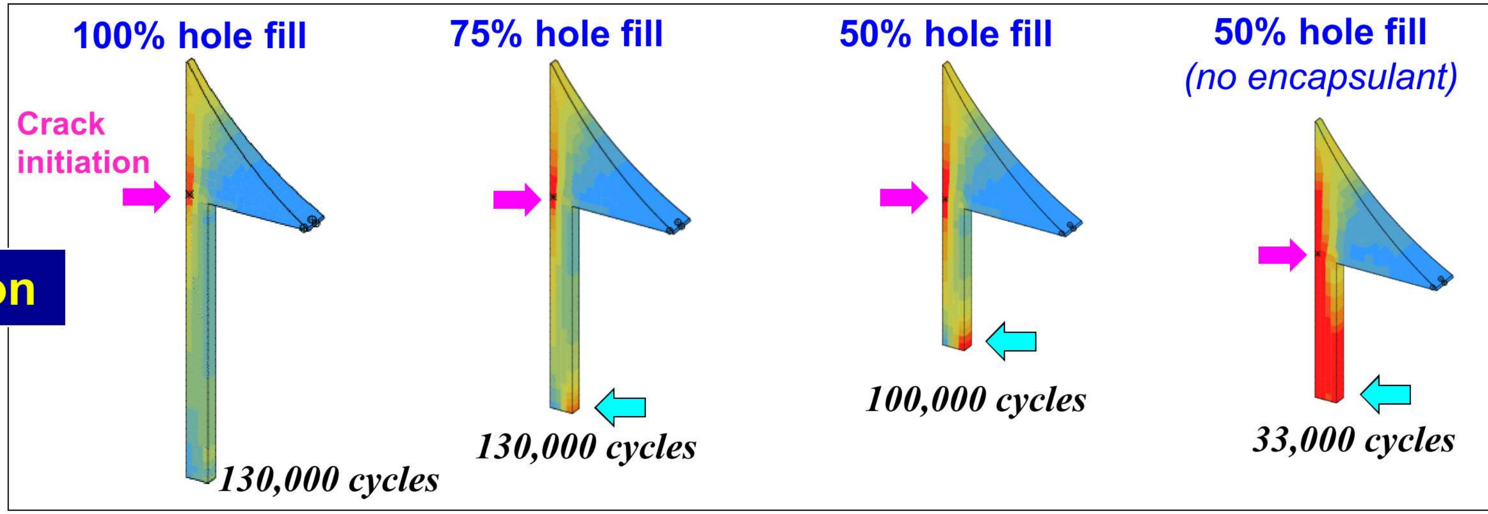
Service = Transp. #1 + Transp. #2 + Use

Through-Hole Configuration	Percent of Life Used to Crack Initiation (%)	Percent of Life Used to Complete Crack (%)
Full fillet, both sides	*0.66*	*0.18*
100% hole-fill	**0.65**	**0.20**
75% hole-fill	**0.73**	**0.28**
50% hole-fill	**0.94**	**0.33**
50% hole-fill; *No bottom encapsulant*	**3.9**	**1.7**

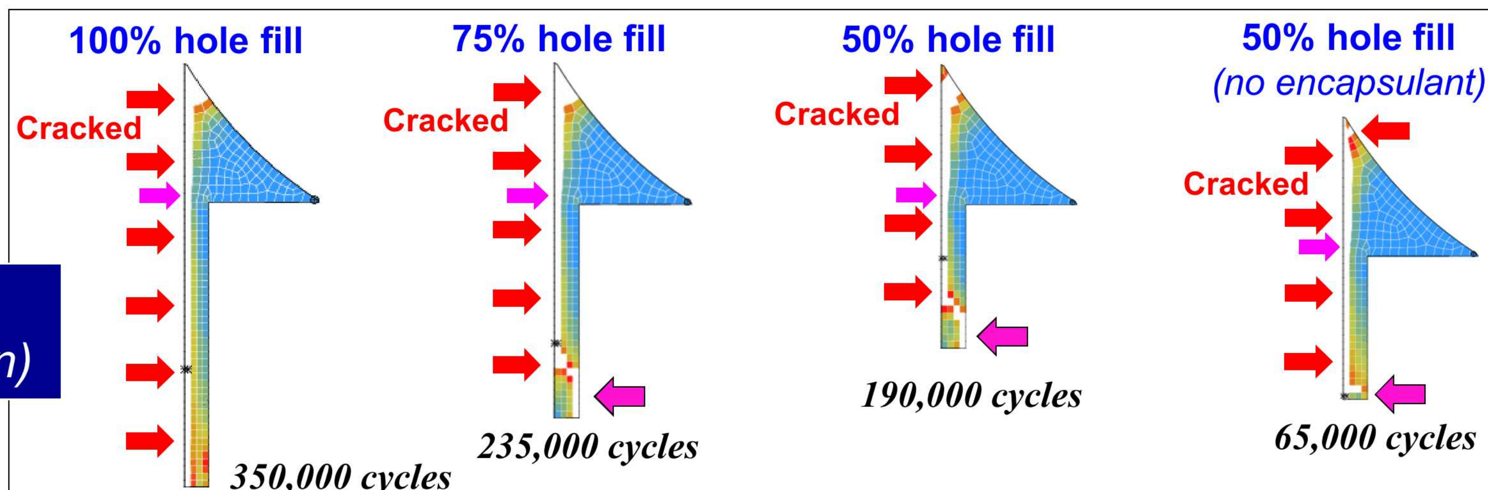
Case Study A: Encapsulation Effects

- The model predictions are shown of **TMF deformation** and **crack propagation** for the *use segment: 16C/33C; 1 year cycle*.

Crack initiation



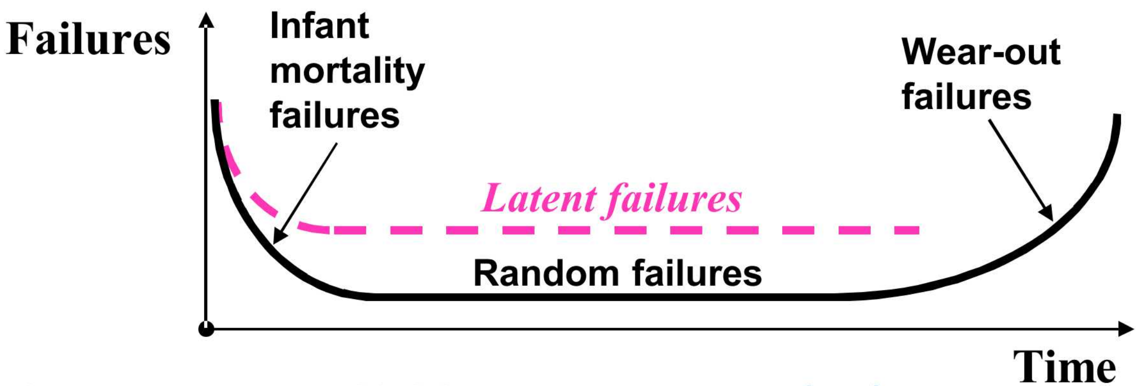
100% crack
(Electrical open)



Case Study A: Encapsulation Effects

- The computational model can be used to determine the impact of acceptance test and effectiveness of qualification test variables.
- Destructive tests, or D-tests, assess the long-term reliability by accelerating solder joint fatigue onto the wear-out failure regime.

  - **Acceptance test: -32°C/60°C; 2 cycles; 4 hour holds; 12°C/min max.**
    - *Goal: Identify defects responsible for **infant mortality failures***
  - **D-test: -32°C/60°C; 26 cycles; 4 hour holds; 12°C/min max.**
    - *Goal: Identify defects responsible for **latent failures***



Case Study A: Encapsulation Effects

- **The D-test is too benign to represent the long-term reliability of the assembly if the assumed failure mode is solder joint TMF.**

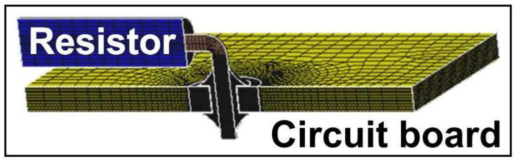
Acceptance test + D-test

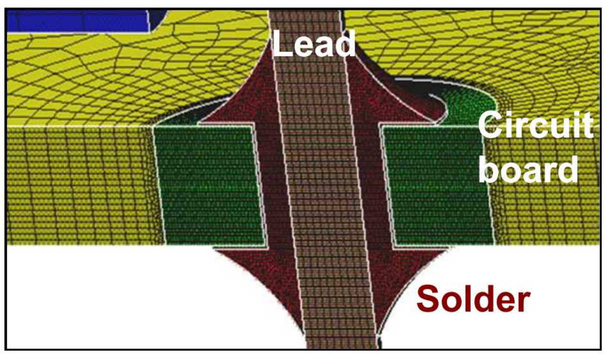
Through-Hole Configuration	Percent of Life Used to Crack Initiation (%)	Percent of Life Used to Complete Crack (%)
Full fillet, both sides	*2.5*	*0.61*
100% hole-fill	**2.2**	**0.55**
75% hole-fill	**2.8**	**0.75**
50% hole-fill	**2.9**	**0.78**
50% hole-fill; *No bottom encapsulant*	**11**	**3.7**

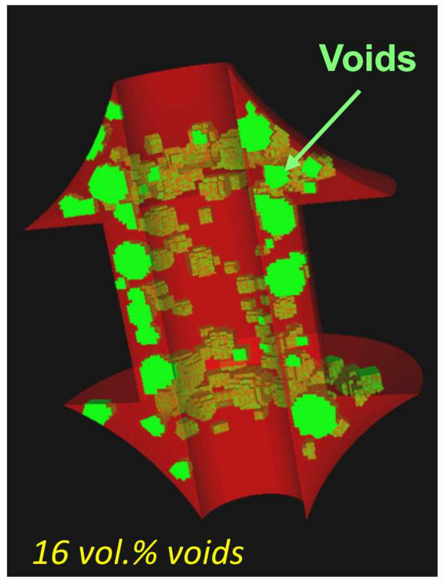
Case Study B: Effects of Manufacturing Defects

- **Computational modeling predicts the effects of manufacturing defects on long-term reliability – *in this example, voids*.**

Finite element mesh

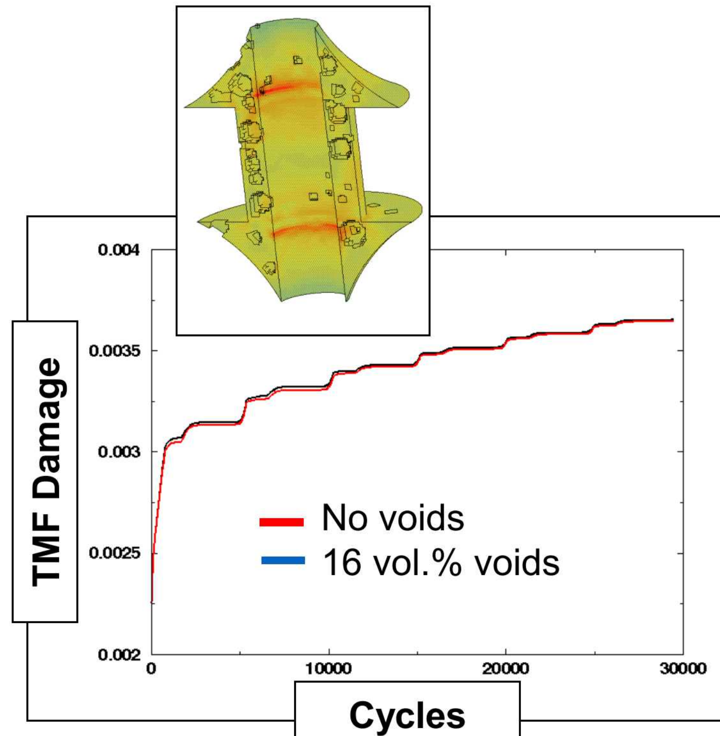






Void sizes and distribution replicated observations of an actual solder joint.

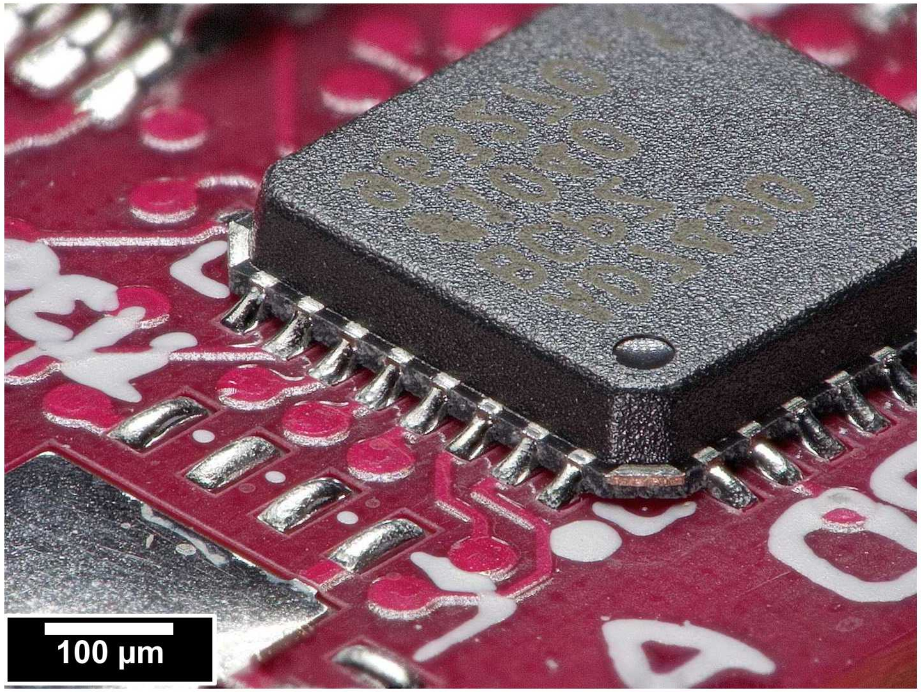
Model prediction

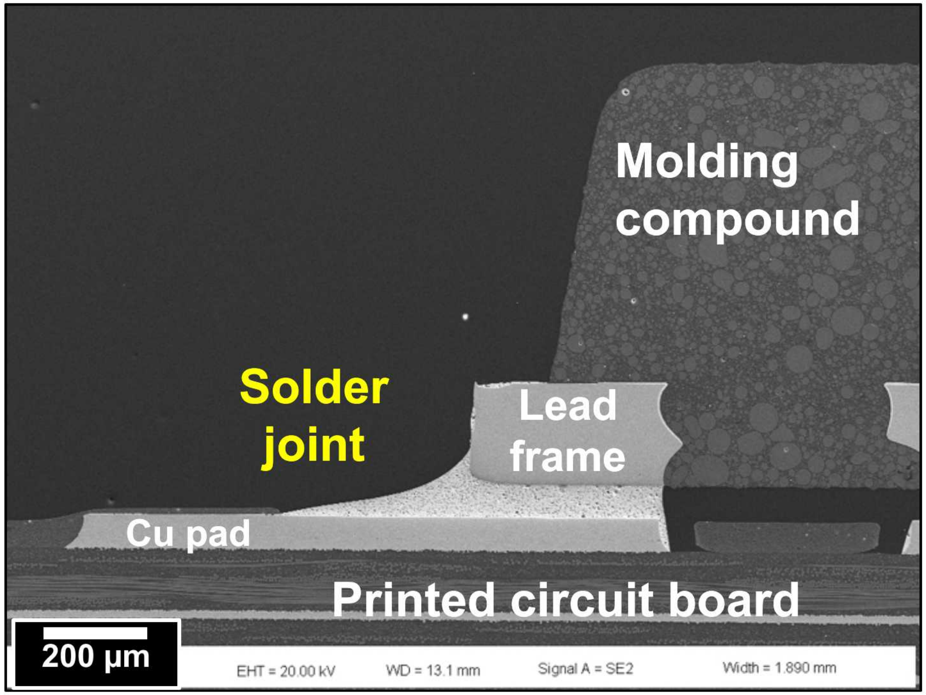


- **Voids of 0 – 16 vol.% content do not affect reliability.**

Case Study C: Conformal Coating and Underfill Effects

- The **crack propagation model** is demonstrated for the popular **quad flat, no-lead (QFN)** electronic package.

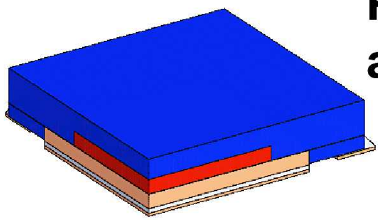


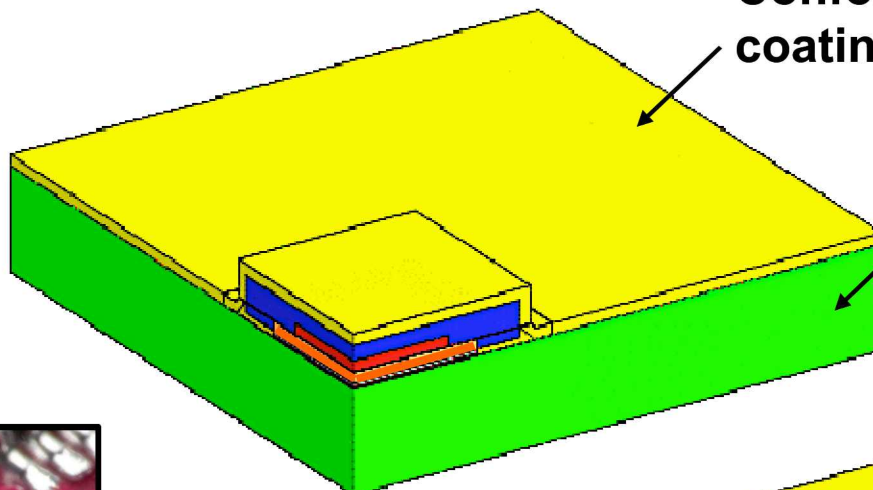


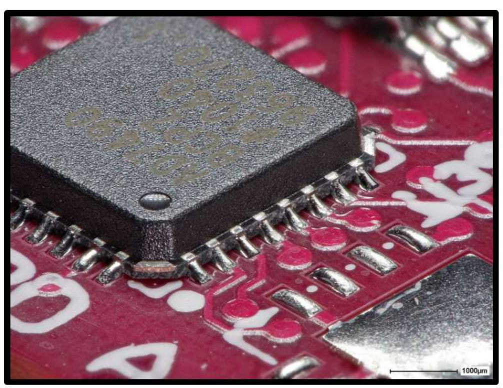
- There are too many variants of the QFN package so that **empirical testing is cost and schedule prohibitive**, which leaves only the modeling approach to optimize package selection.

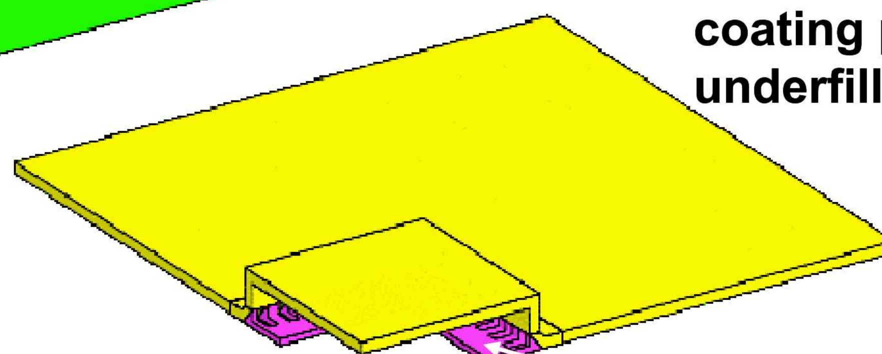
Case Study C: Conformal Coating and Underfill Effects

- Examine **fatigue crack propagation** that results from the use of **conformal coatings** and **underfills**.



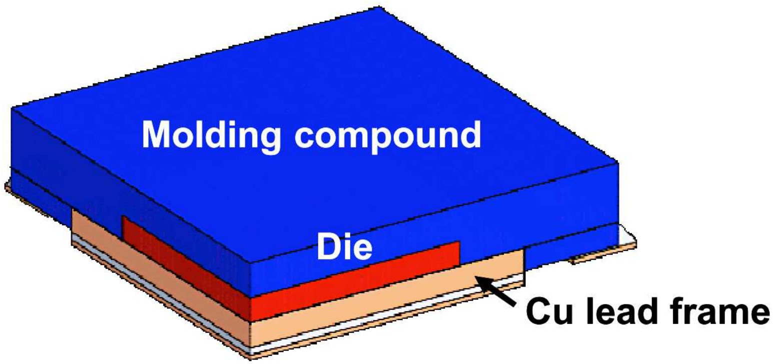






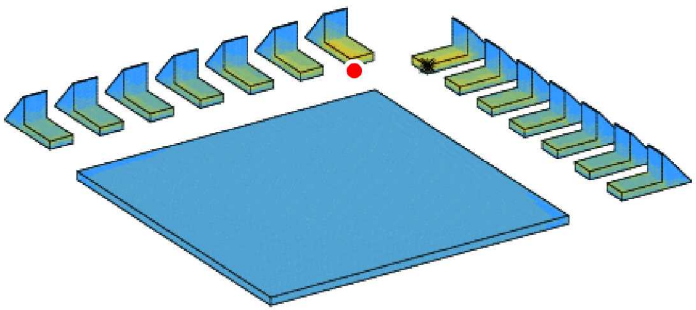
Case Study C: Conformal Coating and Underfill Effects

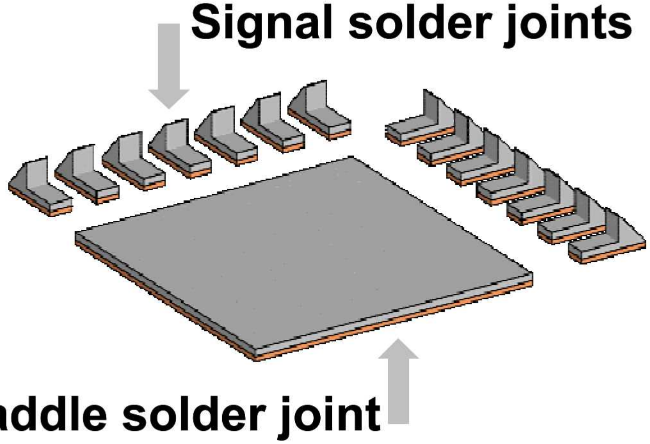
- **The computational model predicts crack growth for temperature cycling: -50°C / 85°C; 3°C/min ramp rates; and 90 min holds times.**



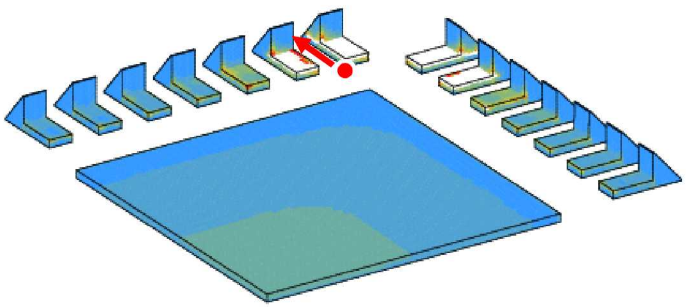
QPFN package *(quarter-symmetry)*

Crack initiation … 1800 cycles





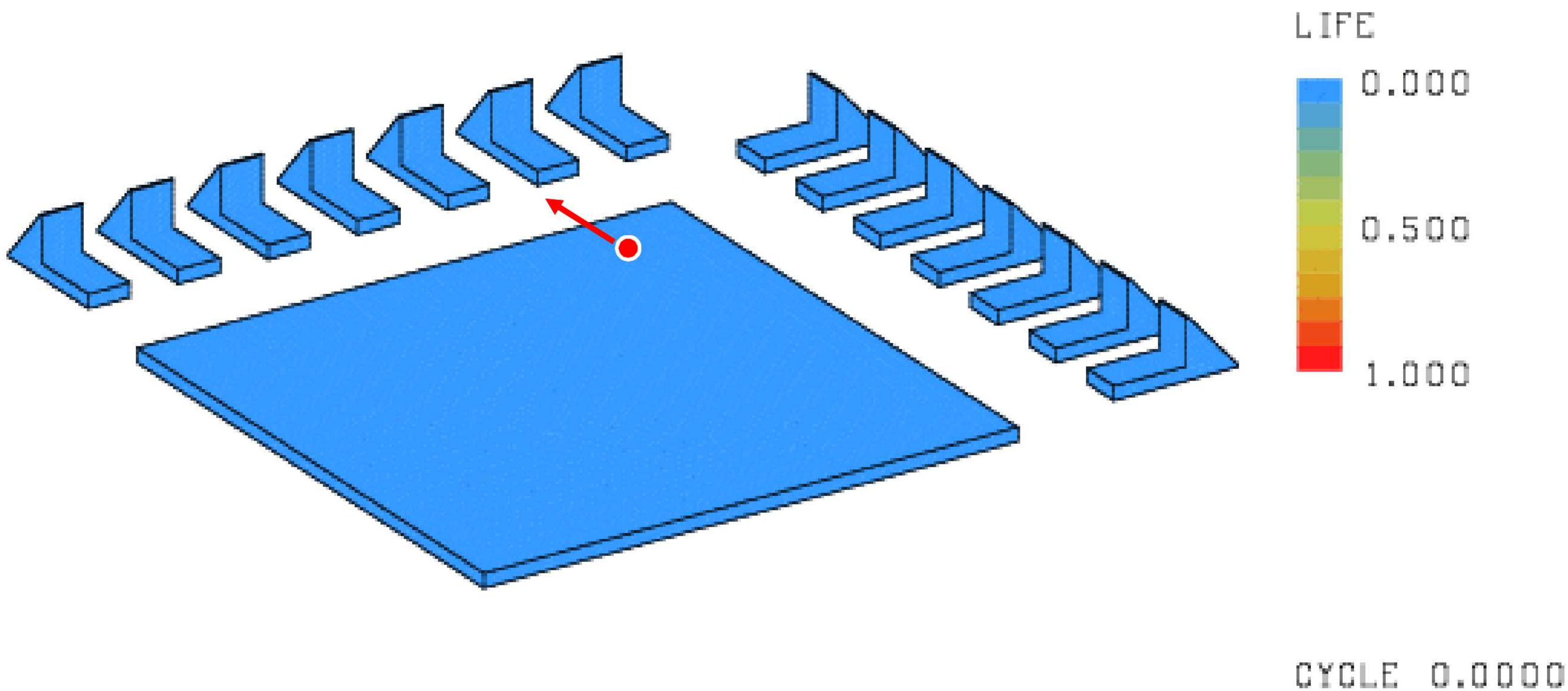
100% crack … 7800 cycles



Case Study C: Conformal Coating and Underfill Effects

- The software shows the morphology of crack propagation.

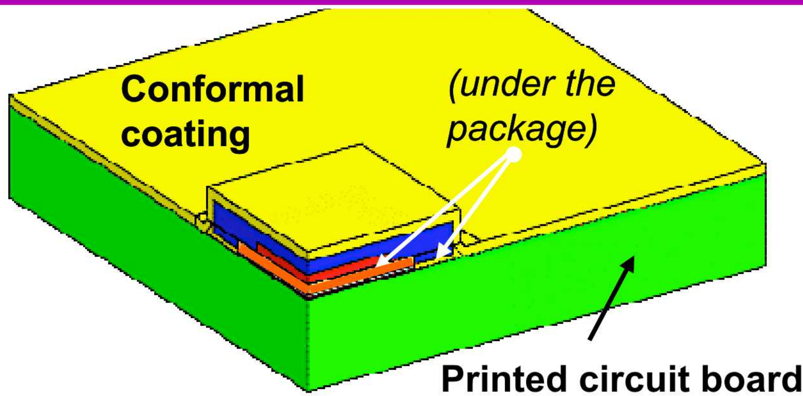
100% crack … 7800 cycles



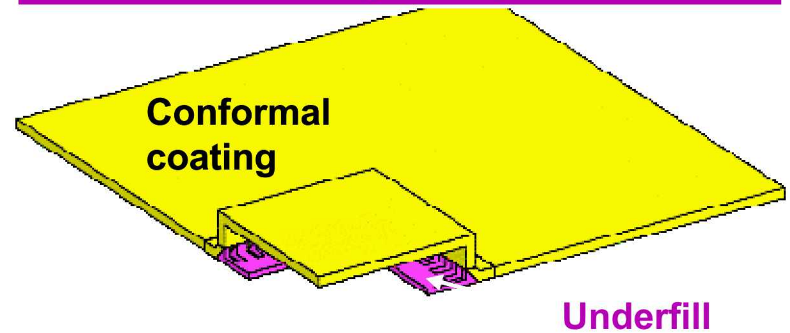
Case Study C: Conformal Coating and Underfill Effects

- **The effects are shown of conformal coating that fills the gap under the PQFN, and preventing this scenario with the use of an underfill.**

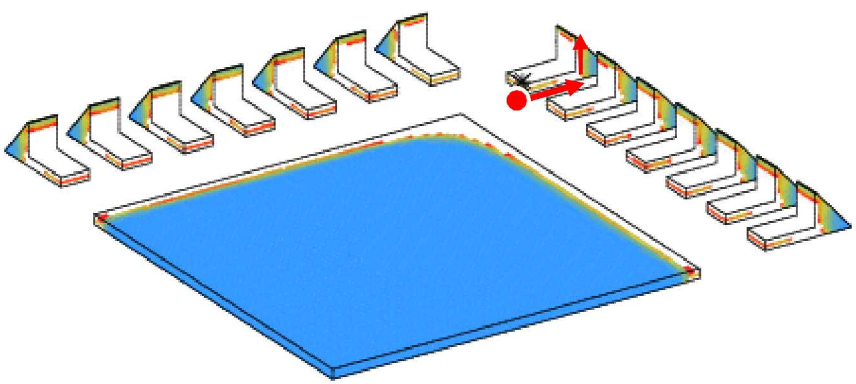
Conformal Coating: On Top and Underneath



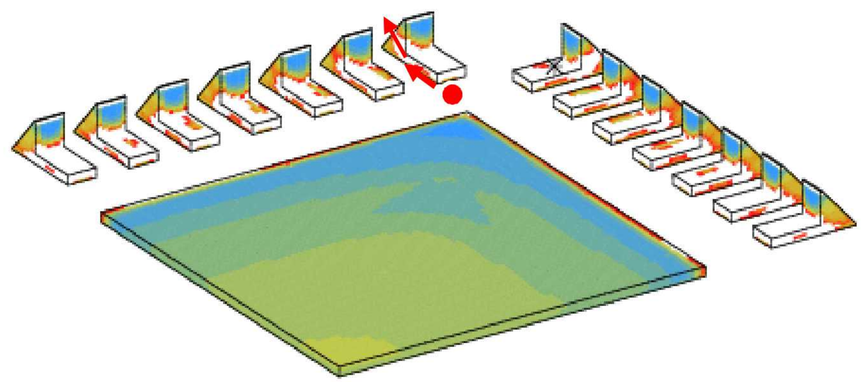
Conformal Coating on Top *and Underfill*



100% crack … 160 cycles



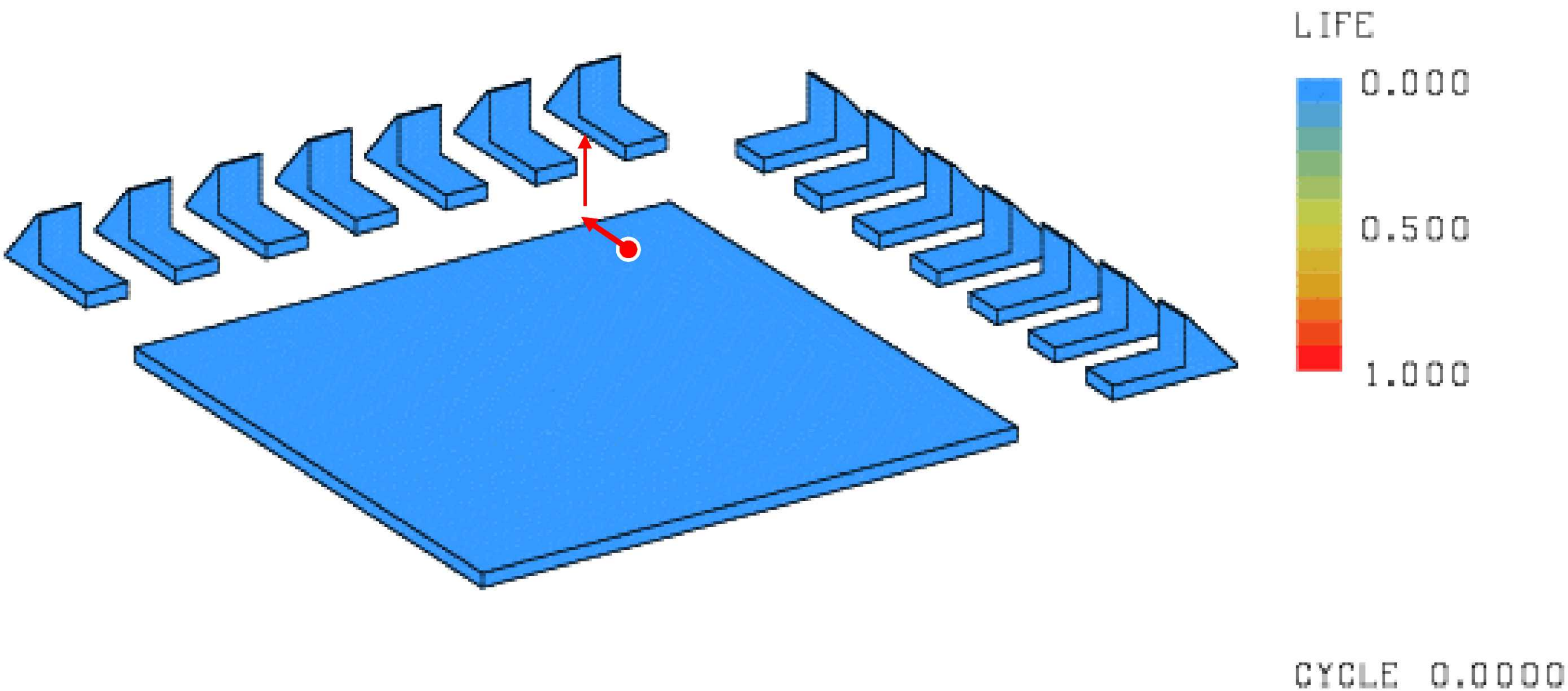
100% crack … 19,000 cycles



Case Study C: Conformal Coating and Underfill Effects

- Solder joint cracking is shown when conformal coating is on top of, and underneath, the PQFN package.

100% crack … 160 cycles

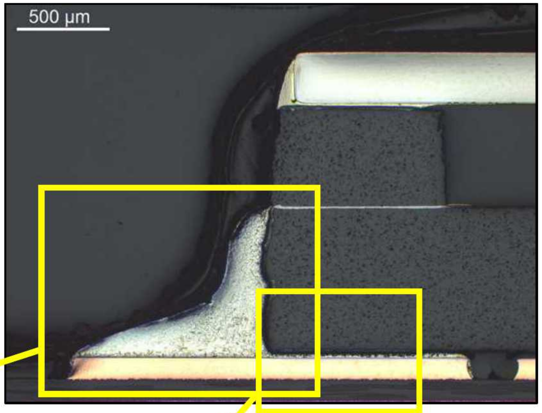


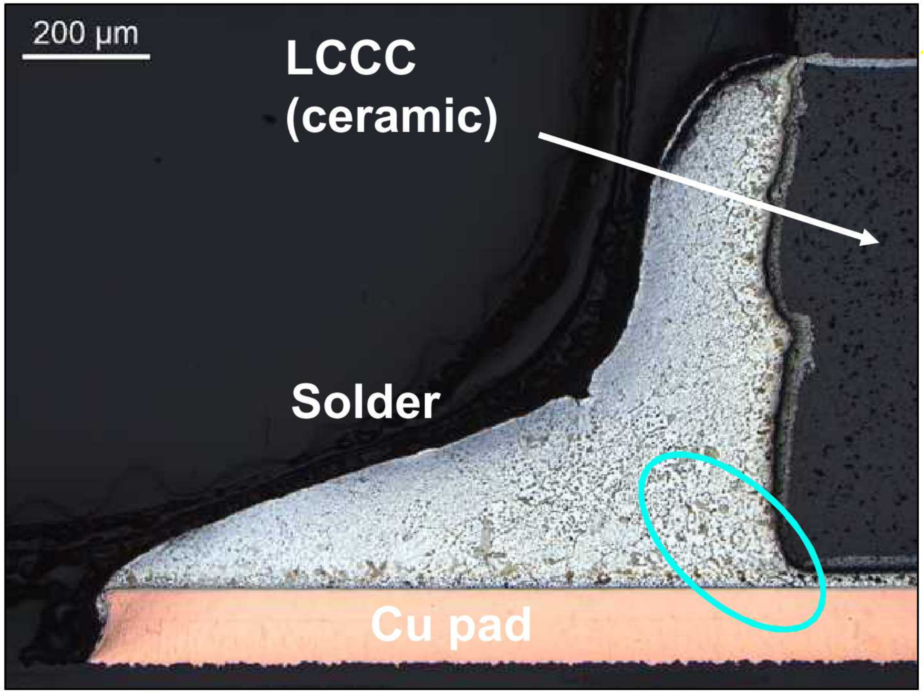
Case Study D: Current Packaging Techniques

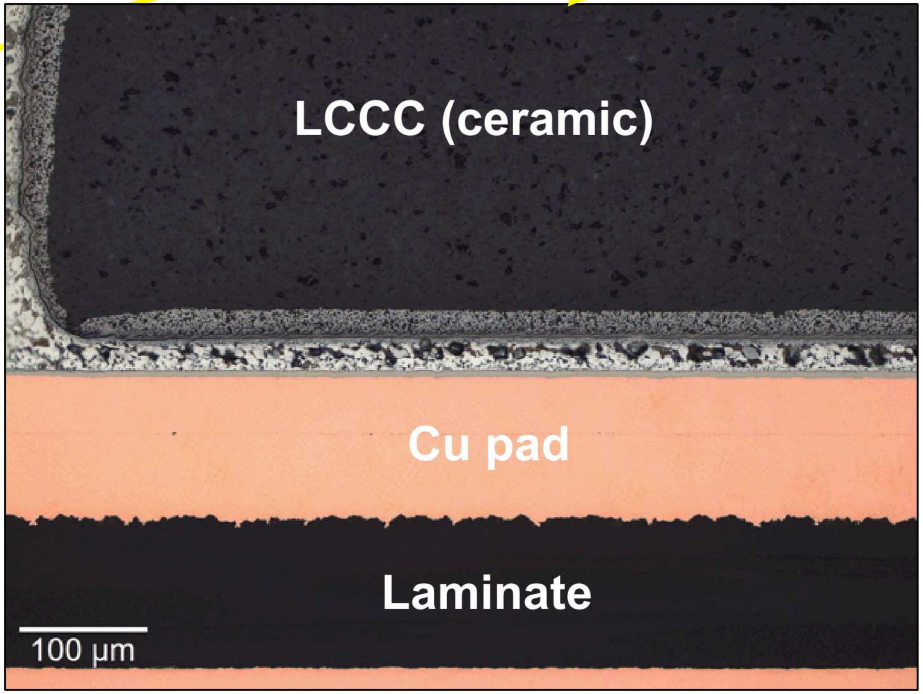
- **A high-reliability product required the use of a leadless ceramic chip carrier (LCCC) on an organic laminate printed circuit board.**

  … NOT a preferred design configuration.

- **Lead-rich phase coarsening occurred in the gap to the point of TMF crack initiation and the presence of some micro-cracks.**

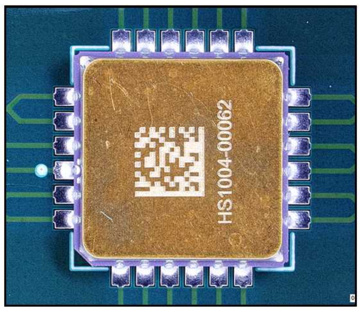


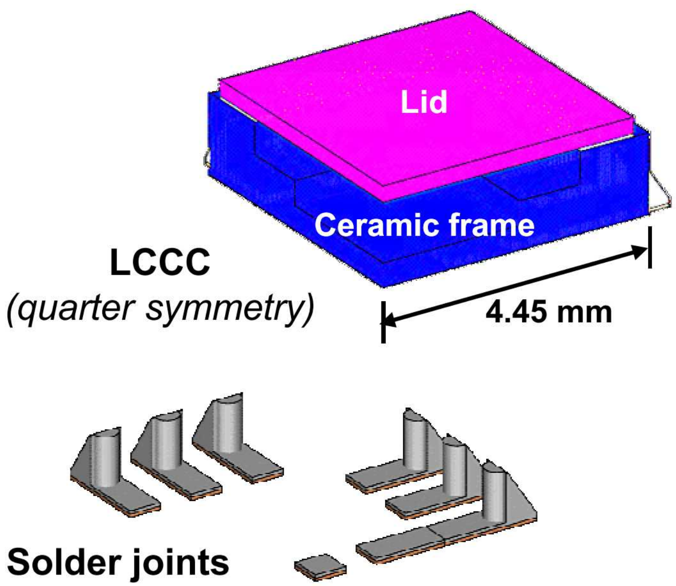


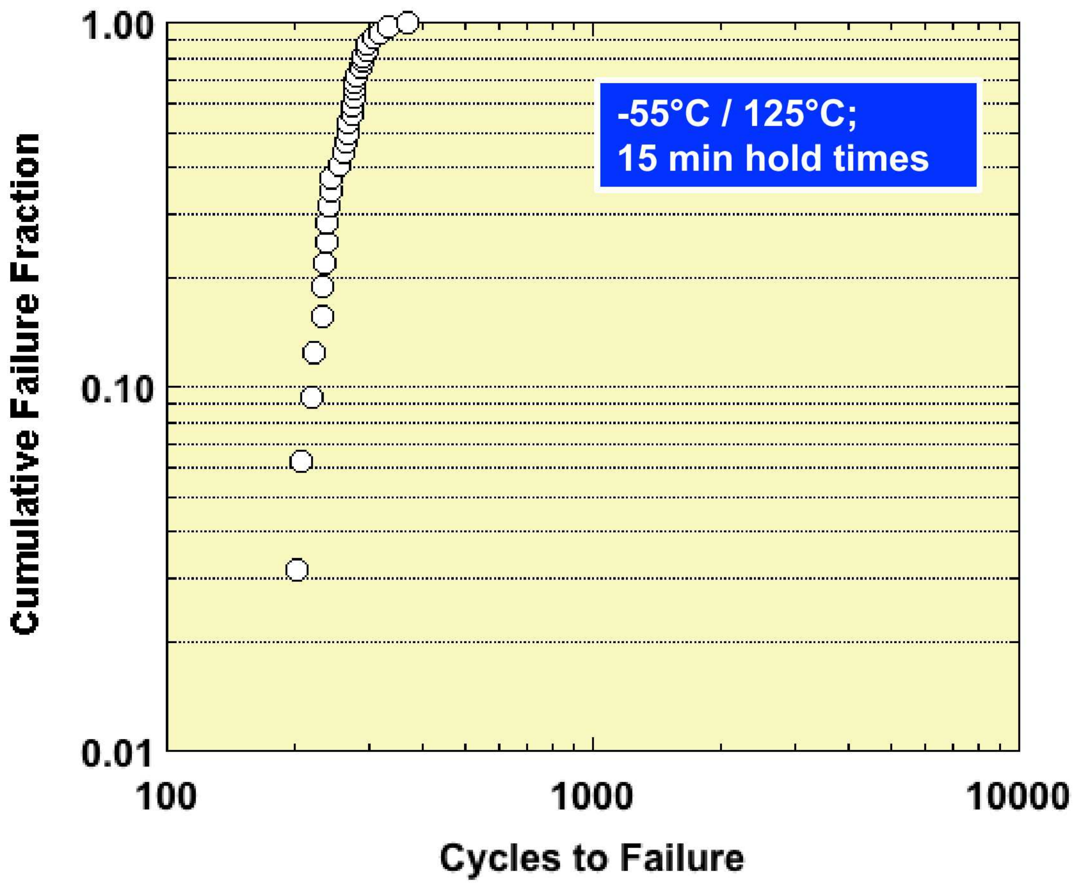


Case Study D: Current Packaging Techniques

- **As expected, solder joints belonging to an LCCC package – even one this small –** ***have a relatively limited fatigue lifetime.***
- **The 2P Weibull plot parameters are:** $\eta = 280 \pm 15$ cycles **and** $\beta = 7 \pm 2$.

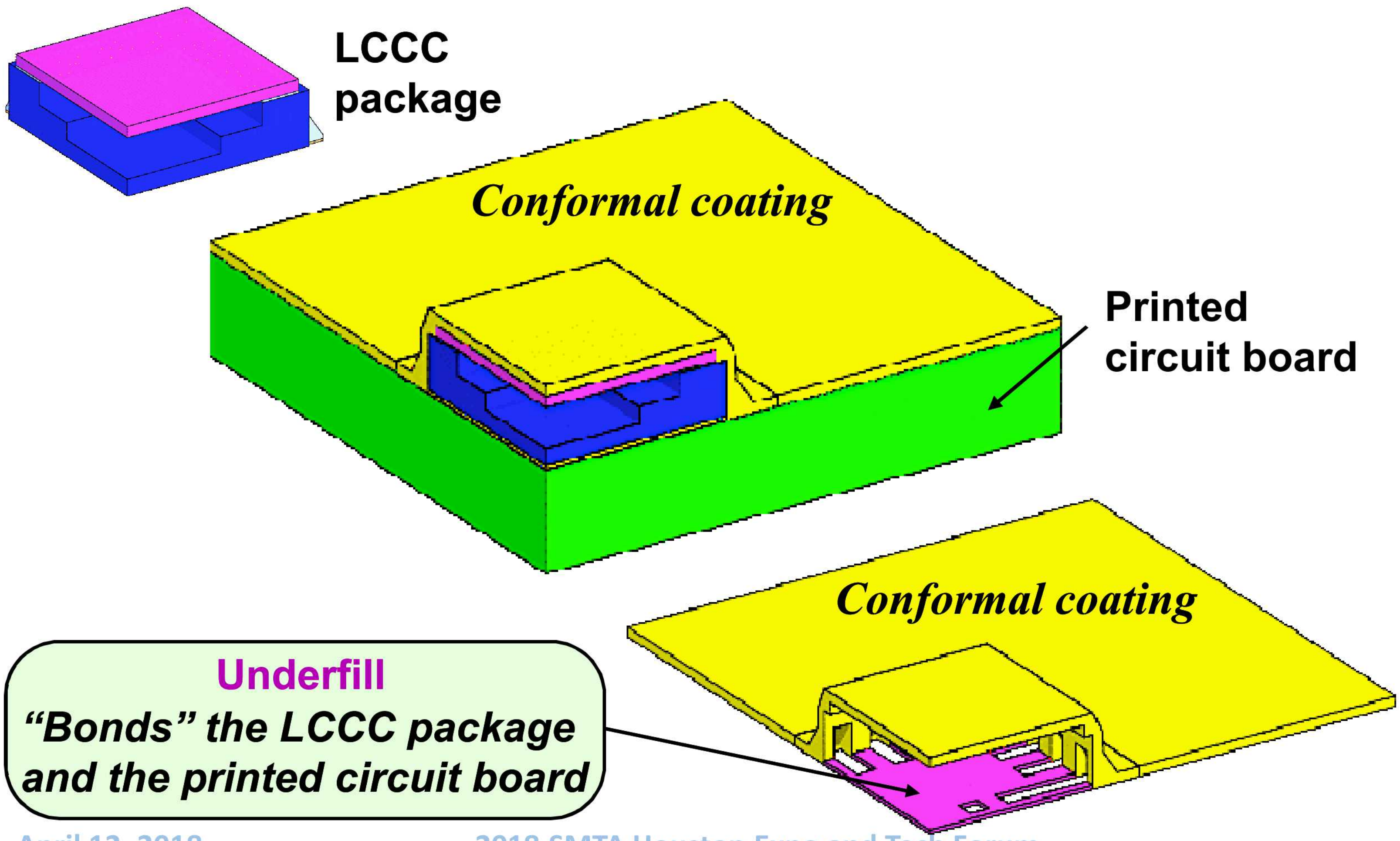






Case Study D: Current Packaging Techniques

- **The computational model documents the roles of conformal coatings and underfills to optimize the solder joint fatigue lifetime.**

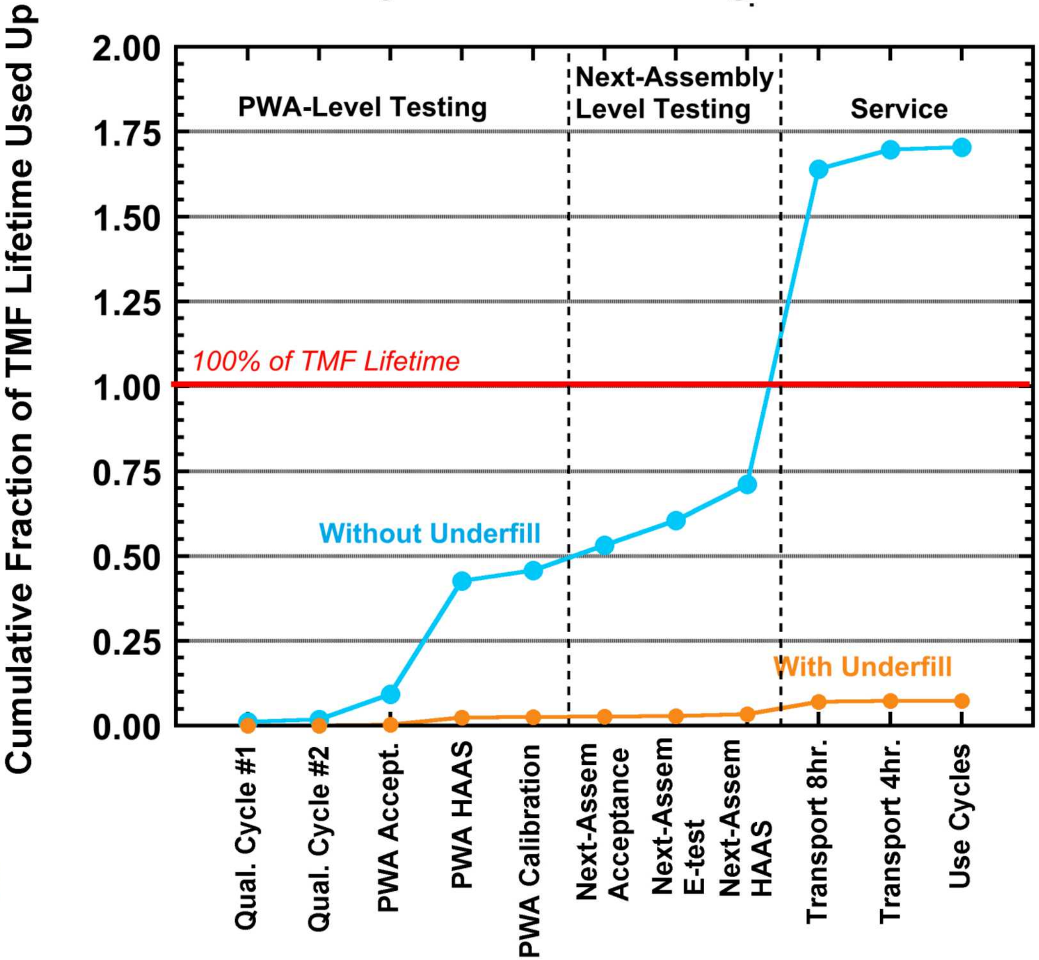


Case Study D: Current Packaging Techniques

- **The model can quickly take into consideration the effects of underfill and conformal coating type on solder joint fatigue.**
- ***Multiple environments* can be considered by the modeling method.**

Conformal Coating A
(hard coating layer)

Condition	Temperature Cycle (C)
Qual 1	-18 to 40 C
Qual 2	21 to 50 C
PWA Acceptance	-5 to 71 C
PWA HAAS	-10 to 100 C
PWA Calibration	0 to 85 C
Next Assem. Acceptance	-5 to 71 C
Next Assem. E-Test	-5 to 71 C
Next Assem. HAAS	-40 to 80 C
Transport - 8 Hour Hold	-18 to 50 C
Transport - 4 Hour Hold	-18 to 49 C
USE (17.78 to 22.23)	17.78 to 22.23 C



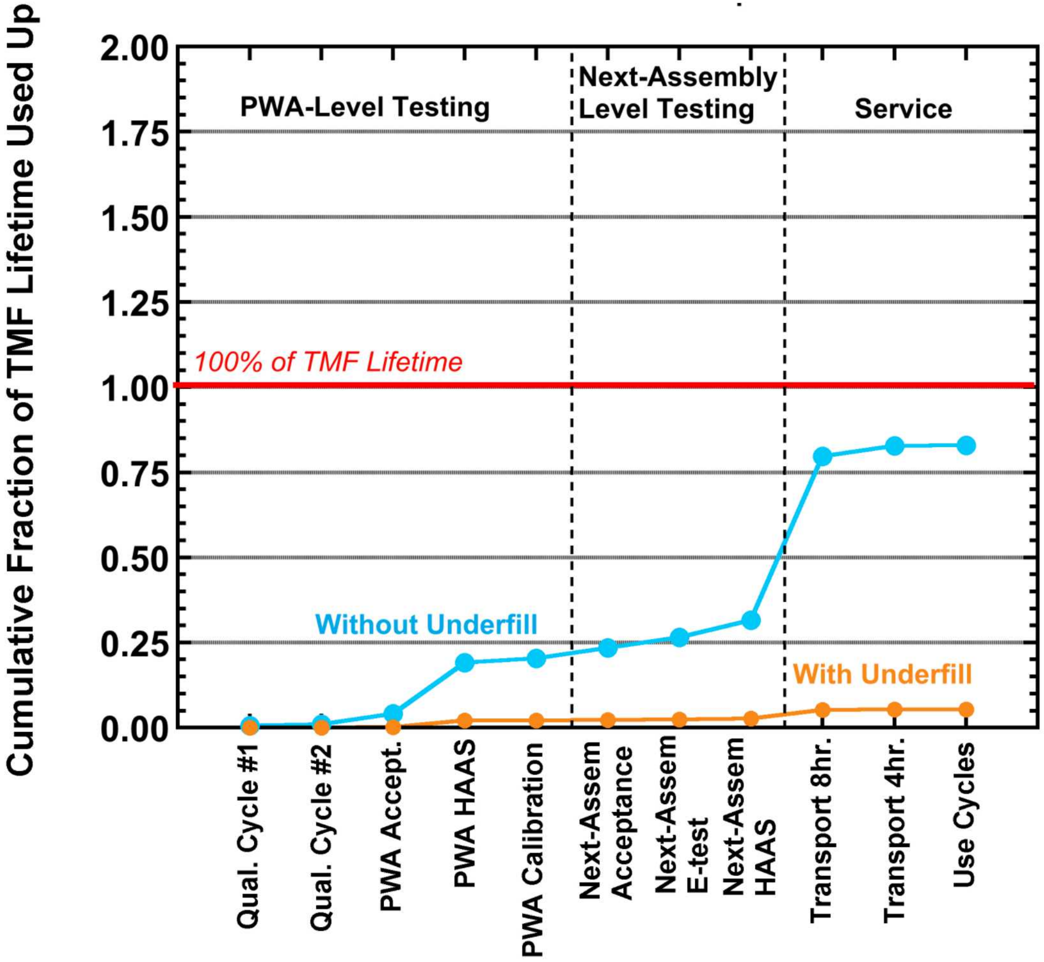
- **If the hard conformal coating A is necessary, then underfill must be applied under the LCCC.**

Case Study D: Current Packaging Techniques

- **Replacing the hard coating, A, with the soft coating, B, prevents the need to use underfill in order to minimize solder joint fatigue.**

Conformal Coating B
(soft coating layer

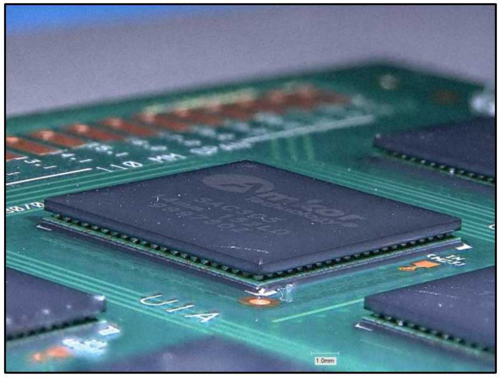
Condition	Temperature Cycle (C)
Qual 1	-18 to 40 C
Qual 2	21 to 50 C
PWA Acceptance	-5 to 71 C
PWA HAAS	-10 to 100 C
PWA Calibration	0 to 85 C
Next Assem. Acceptance	-5 to 71 C
Next Assem. E-Test	-5 to 71 C
Next Assem. HAAS	-40 to 80 C
Transport - 8 Hour Hold	-18 to 50 C
Transport - 4 Hour Hold	-18 to 49 C
USE (17.78 to 22.23)	17.78 to 22.23 C

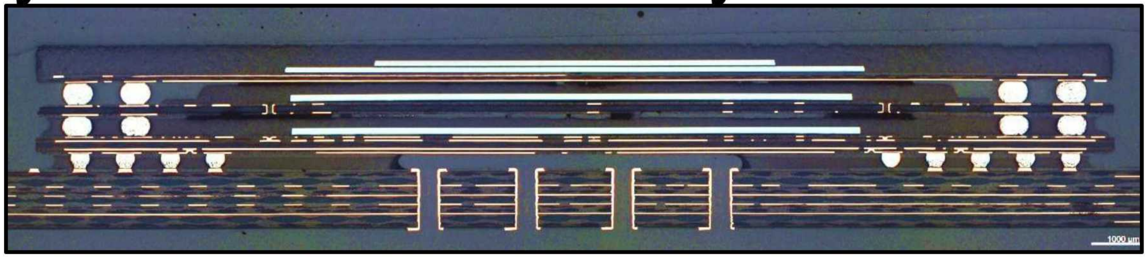


- **The soft conformal coating A eliminates the need for an underfill with the LCCC.**

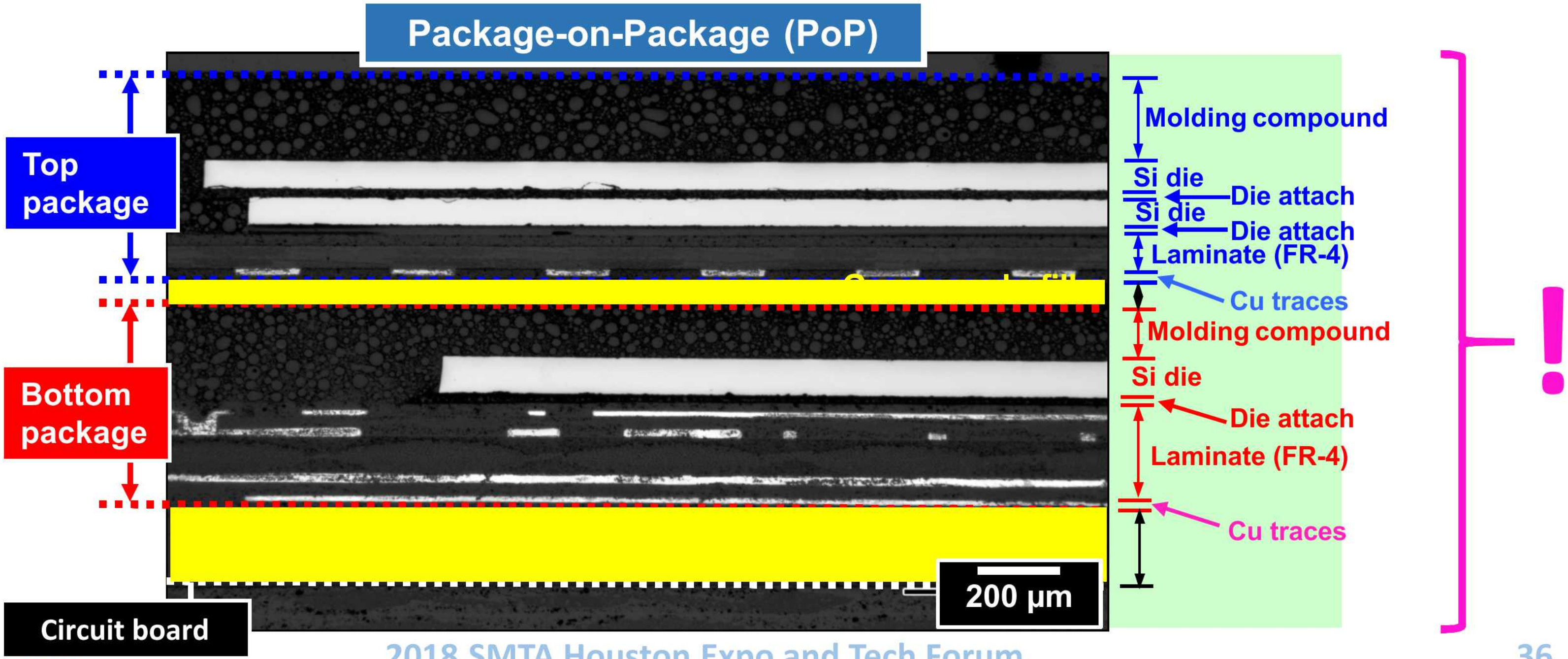
Case Study D: Current Packaging Techniques

- **Stacked packaging technology (PoP and PoPoP) can significantly increase the functionality of advanced electronics systems.**



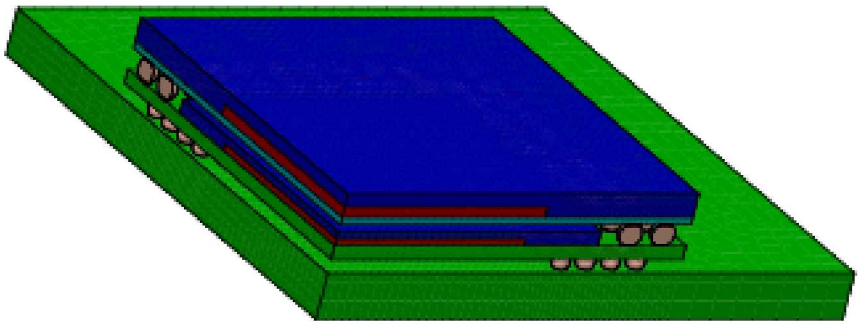
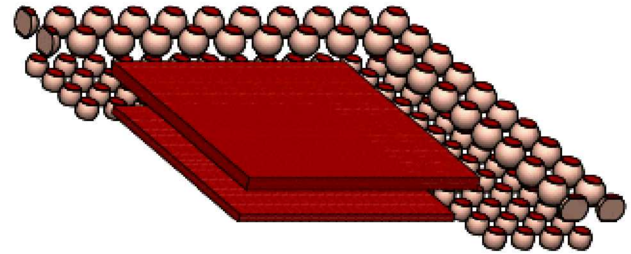
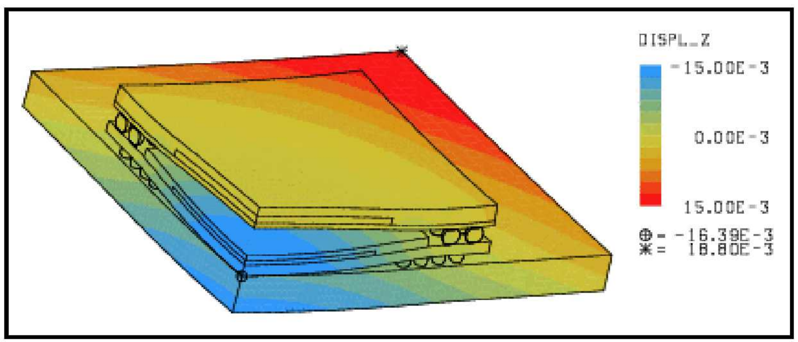


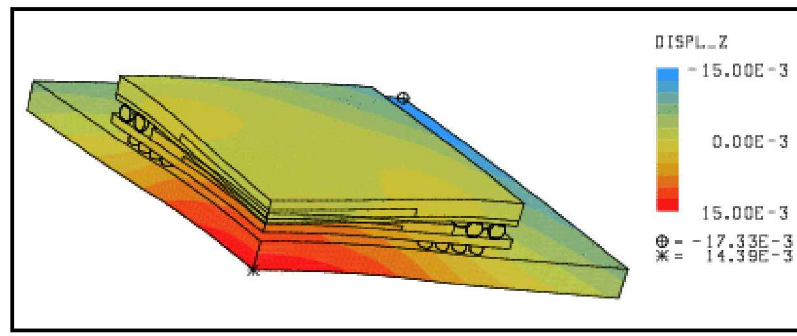
Package-on-Package-on-Package (PoPoP)

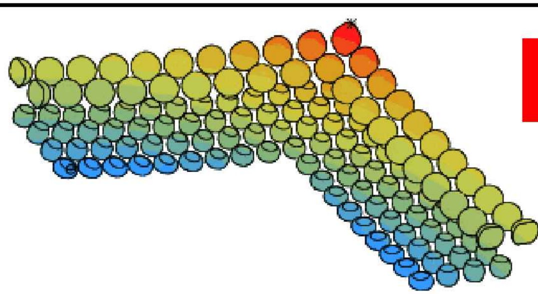


Case Study D: Current Packaging Techniques

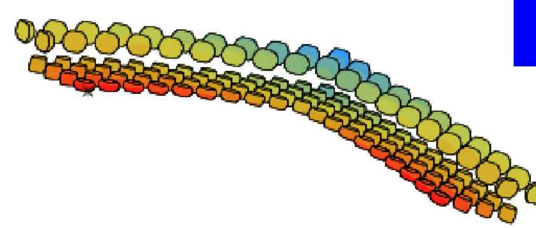
- **Computational modeling predicts behaviors that are not intuitively obvious due to the complex construction.**





125C

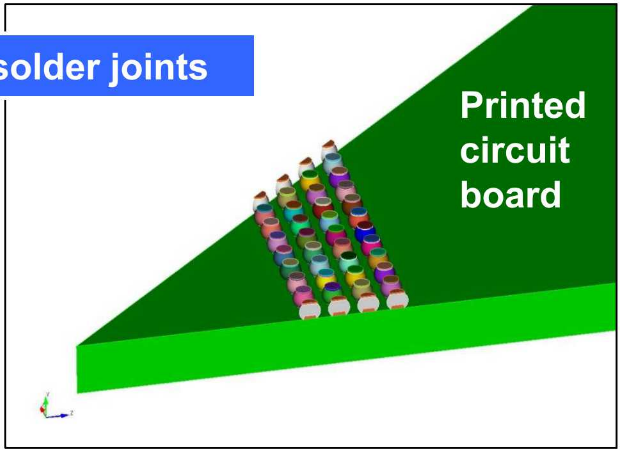


-55C

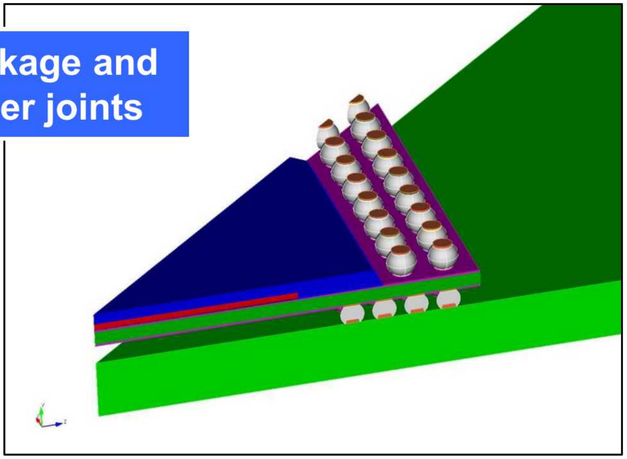
Case Study D: Current Packaging Techniques

- **The computational tool is based upon a one-eighth symmetry solid model, which is built up by the sequence, below:**

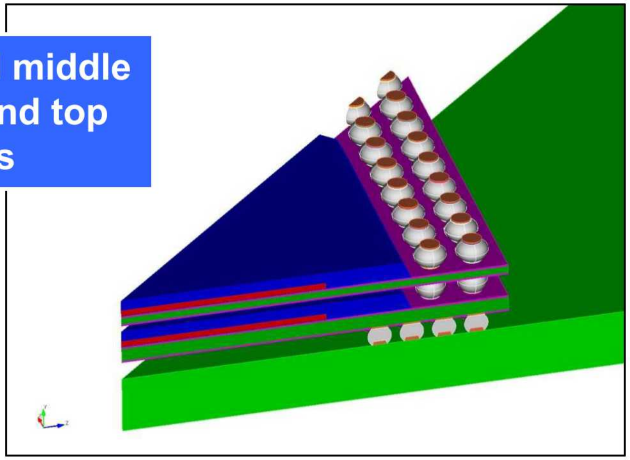
Bottom solder joints



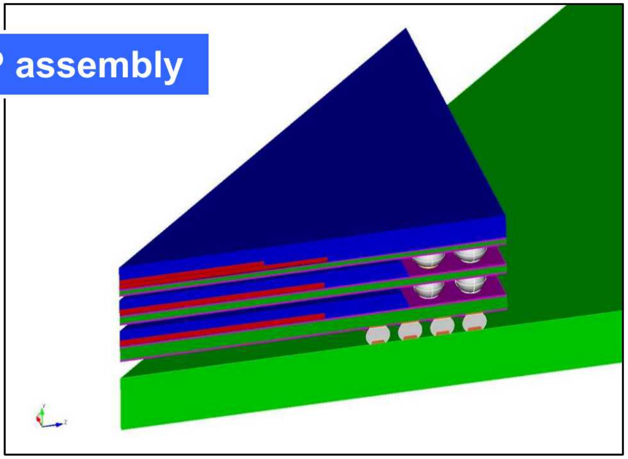
Bottom package and middle solder joints



Bottom and middle packages and top solder joints

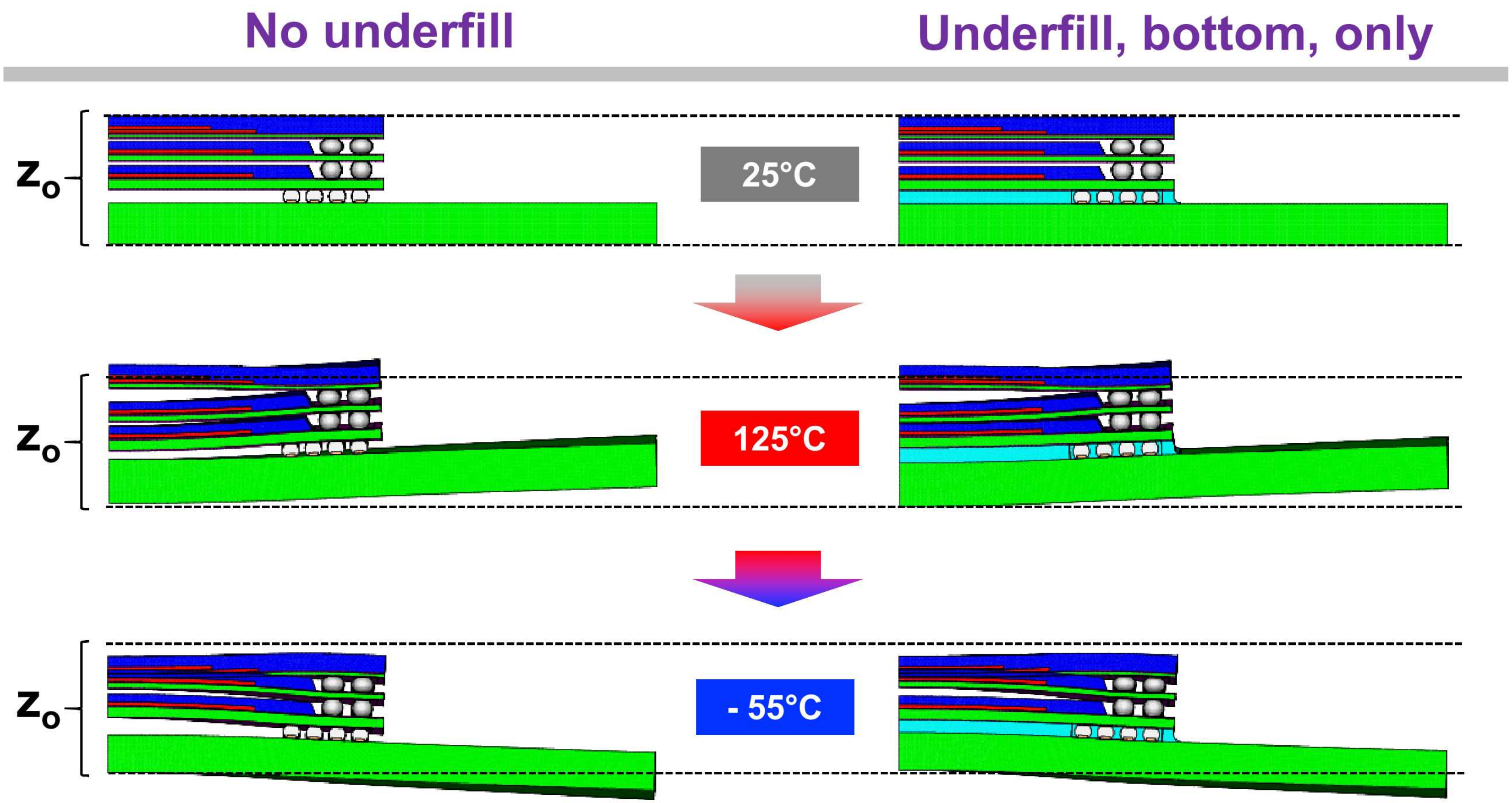


Full PoPoP assembly



Case Study D: Current Packaging Techniques

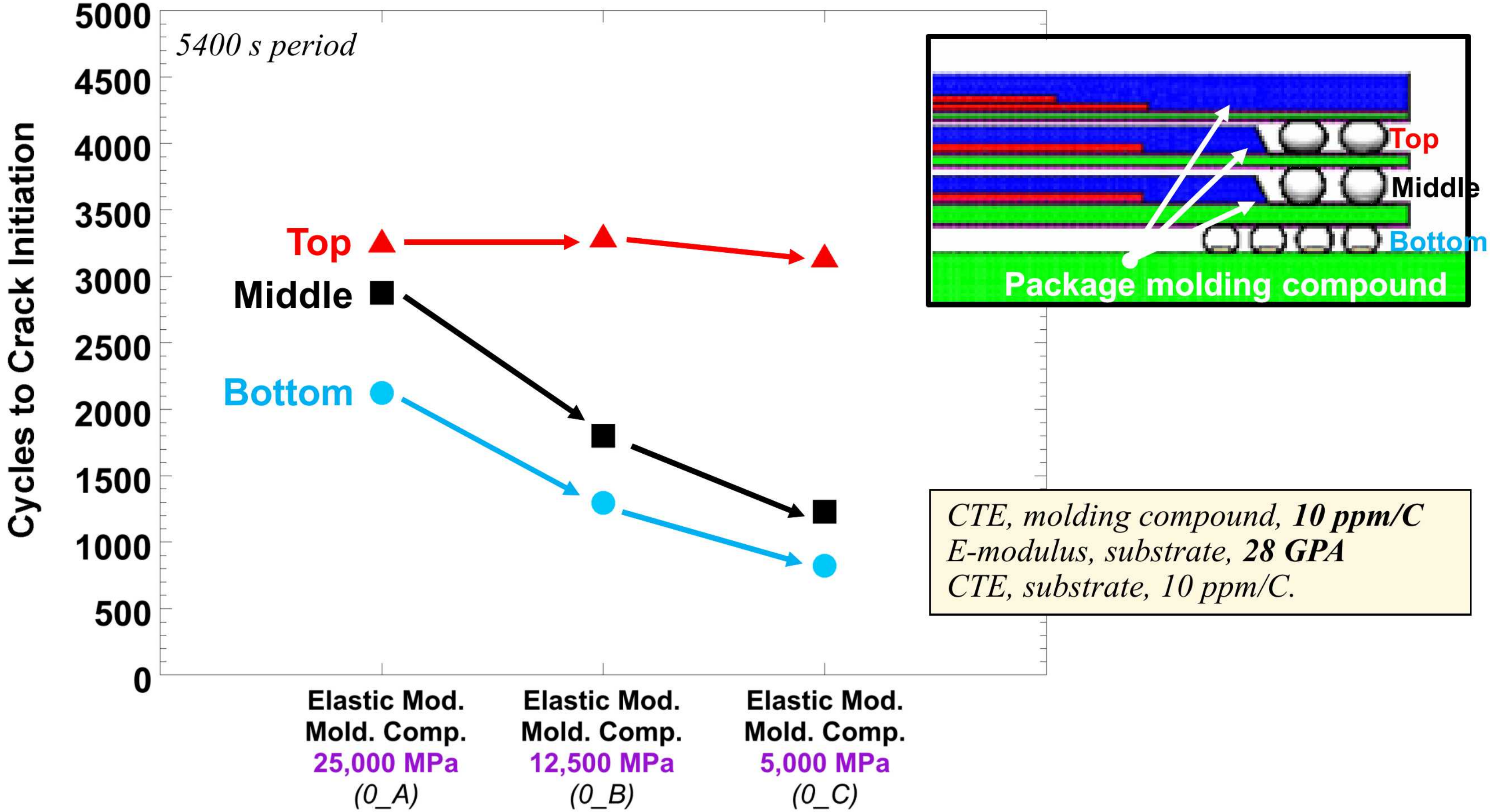
- A particular attribute of the model is to illustrate **warpage behavior**.



- **Underfill, bottom only**, does not significantly affect warpage.

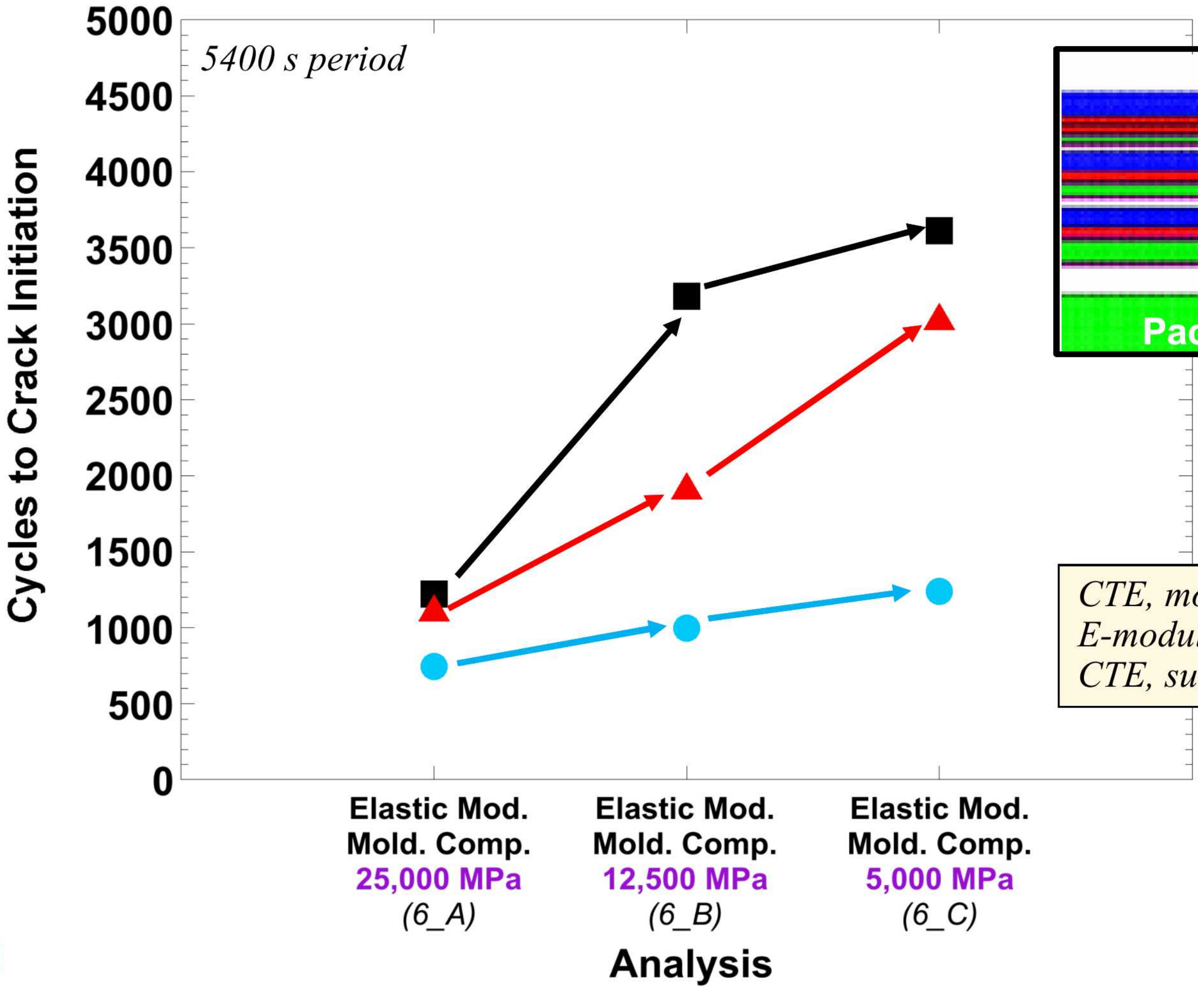
Case Study D: Current Packaging Techniques

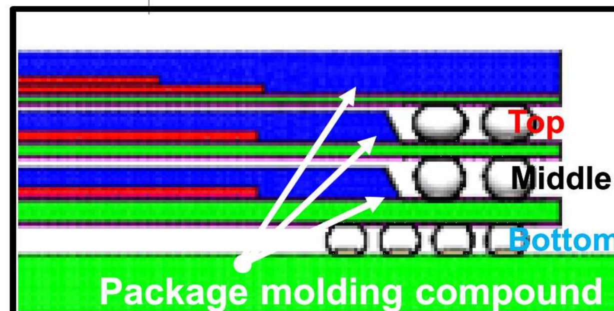
- **Decreasing the elastic modulus of the molding compound increases TMF degradation of the middle and bottom solder joints,** ***but does not have a significant effect on the top solder joints*****.**



Case Study D: Current Packaging Techniques

- **However, simply by changing the CTE of the molding compound and substrates' modulus, *the reversed trend* has taken place.**
  - **The effect was most greatly felt by the middle solder joints.**

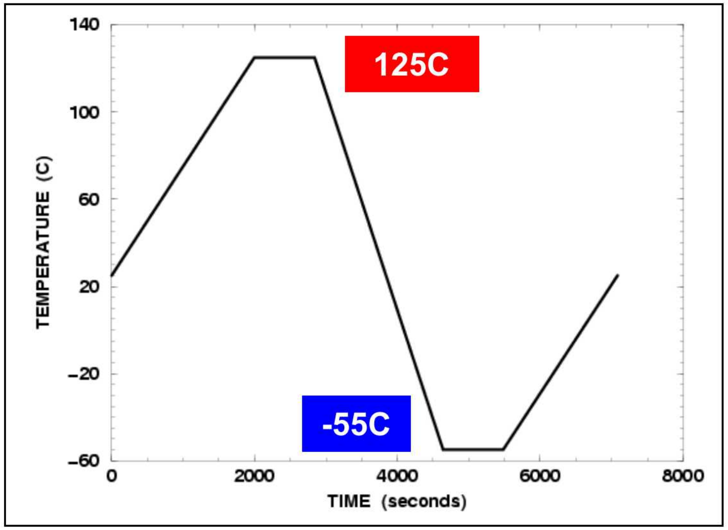




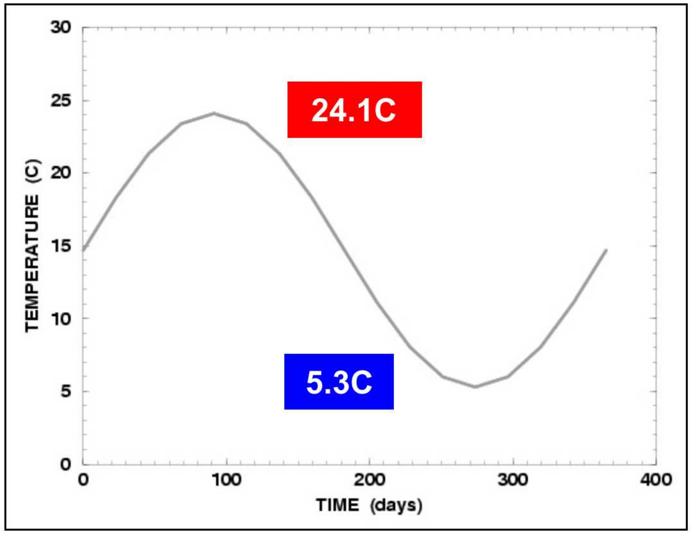
*CTE, molding compound, **24 ppm/C***
*E-modulus, substrate, **41 GPA***
CTE, substrate, 10 ppm/C.

Case Study D: Current Packaging Techniques

- **The accelerated aging cycles can be "put into perspective" with respect to the service conditions – the acceleration factor (AF).**



Accelerated Aging



Service Condition

Level *(no underfill)*	**Accelerated Aging**	**Service Condition**	**AF**
Top solder joints	3,400	1,300,000	380
Middle solder joints	3,100	1,500,000	480
Bottom solder joints	2,300	1,700,000	740

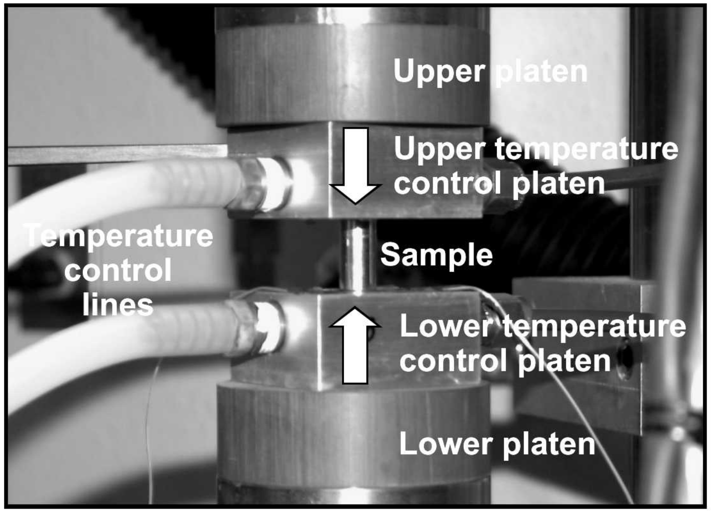
On-going Constitutive Model Development

- **Constitutive (UCP) equations) are being added to the TurboSiP© library in order to address new solder alloys.**
  - Stress-strain tests
  - Creep tests
  - Thermal expansion

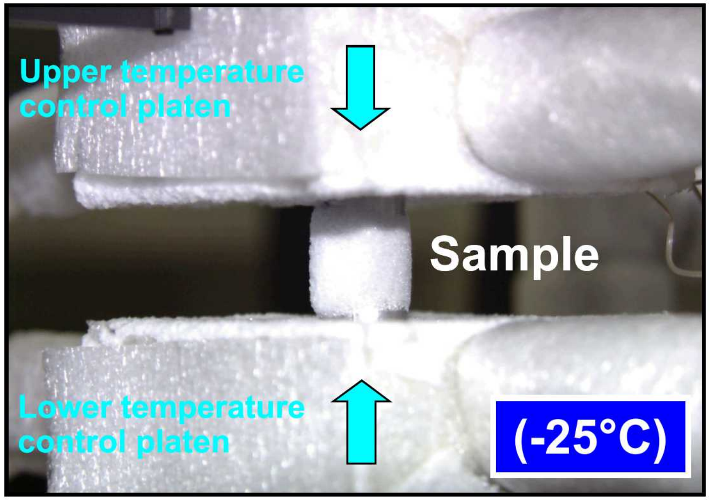
- **Completed mechanical testing:**
  - 63Sn-37Pb
  - SAC396
  - SAC397
  - 97In-3Ag*
  - 52In-42Sn*
  - 80Au-20Sn*

* Not yet in the software library

- **Currently in mechanical testing:**
  - 100In
  - SAC396 + x wt.% Pb (2 < x < 8%)
  - 63Sn-37Pb + *x wt.% Au (2 < x < 10%)*

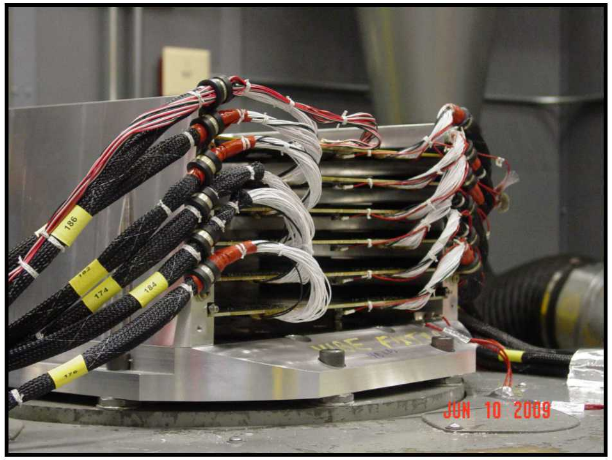


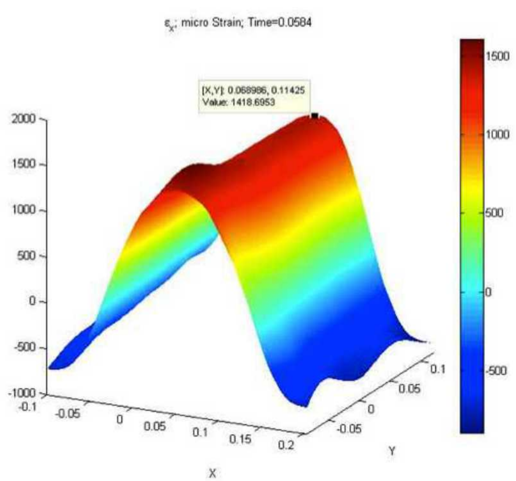
Compression Testing

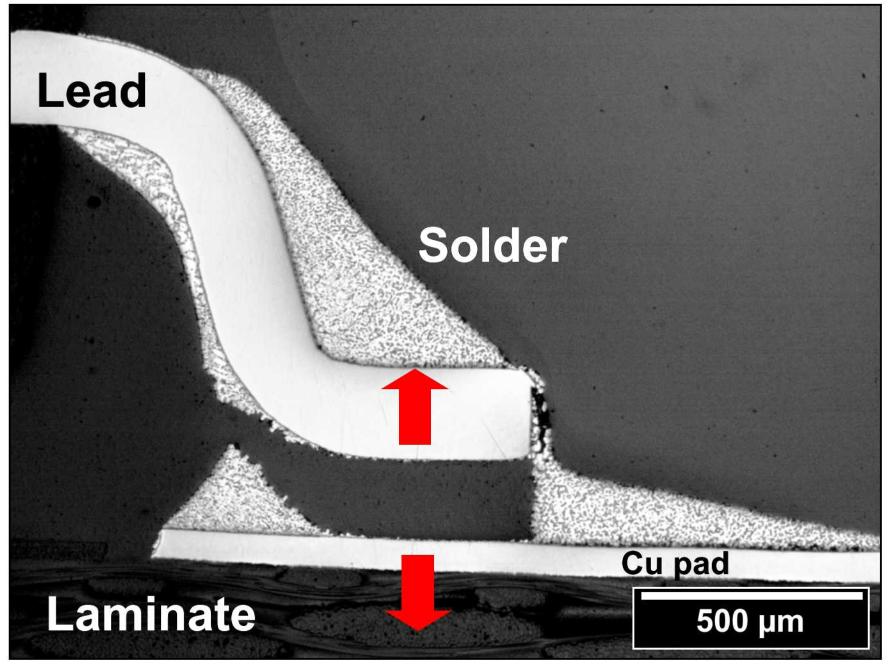


High Cycle Fatigue – Modeling Vibration Environments

- **Vibration performance** **(high-cycle fatigue) has not received a great deal of attention for solder interconnections.**



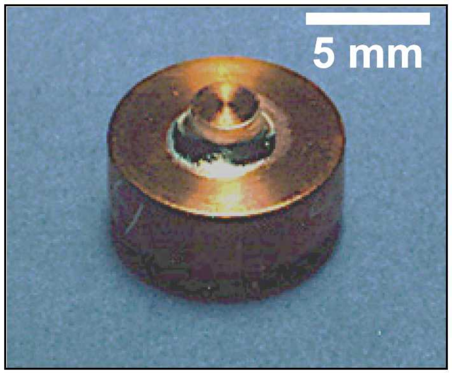




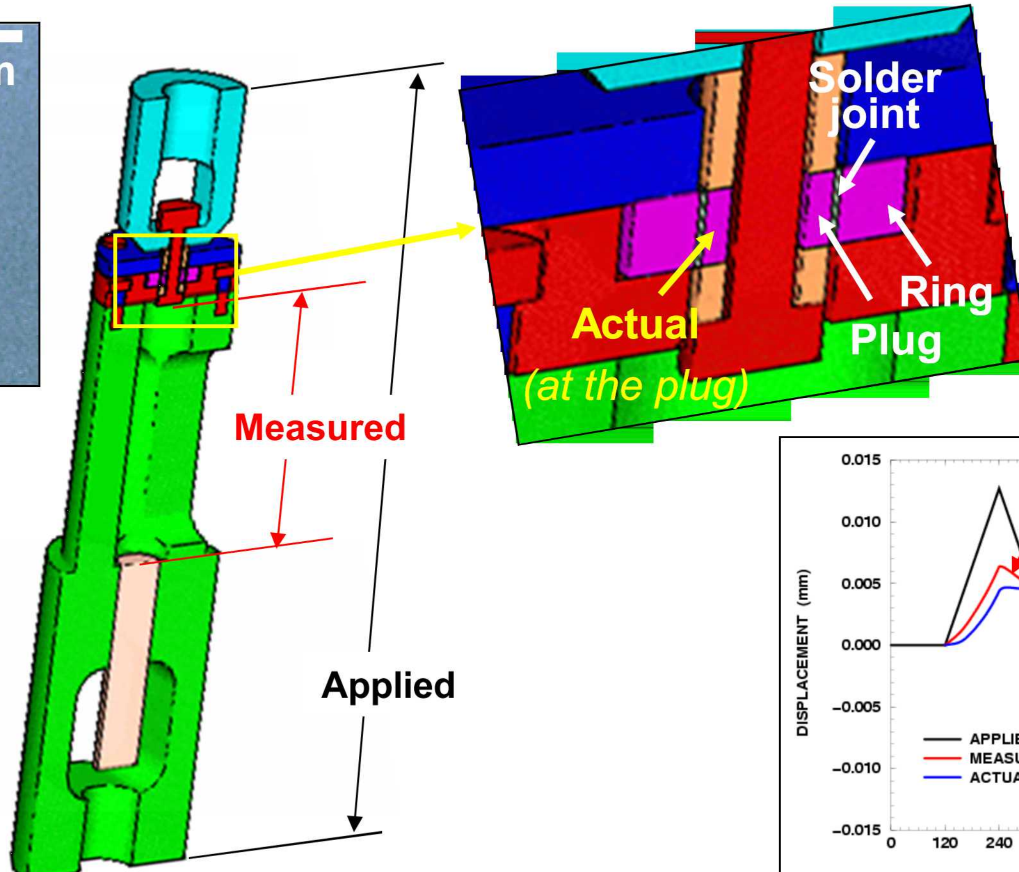
The physical and mechanical metallurgy of high-cycle fatigue is not well-understood.

High Cycle Fatigue – Modeling Vibration Environments

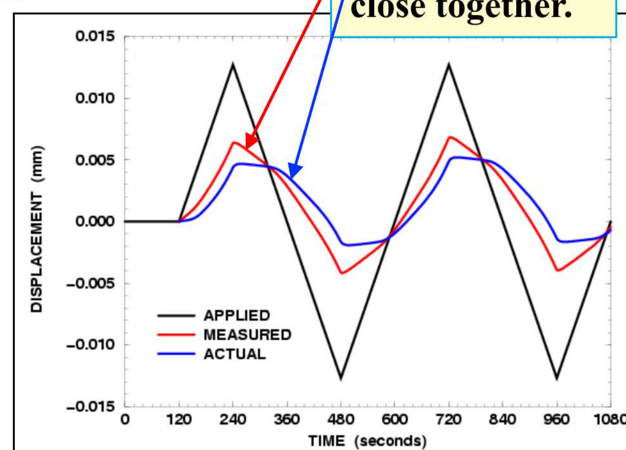
- This is the **ring-and-plug, high-cycle fatigue (HCF) test.**
- **This test will validate the computational model predictions of deformation and cracking relevant to vibration applications.**



Ring-and-plug (shear) fatigue test



Measured and actual are very close together.



Summary

- **Computational modeling will be the enabler for the rapid development and fielding of advanced electronics for downhole applications.**

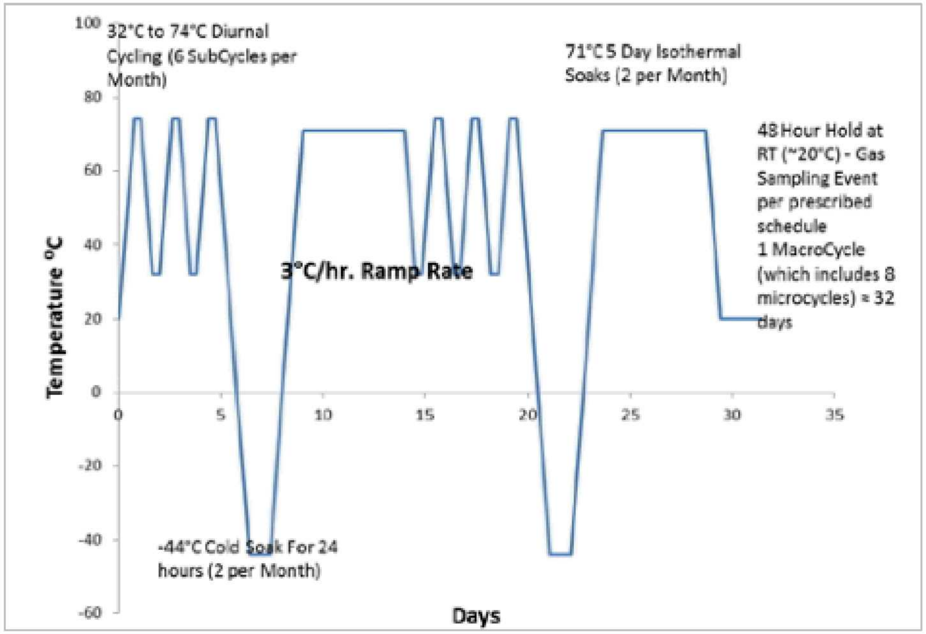
- **Modeling approaches provide comprehensive predictions of solder joint fatigue by addressing new packaging materials, alternative component configurations, and the wide variety of service conditions.**

- **Numerical techniques provide the means to determine the effects of these approaches:**
  - **Use of encapsulants, conformal coatings and underfills to prolong component and solder joint service lifetimes.**
  - **Effects of solder joint workanship and manufacturing defects.**
  - **Improved performance of new interconnection (solder) materials.**

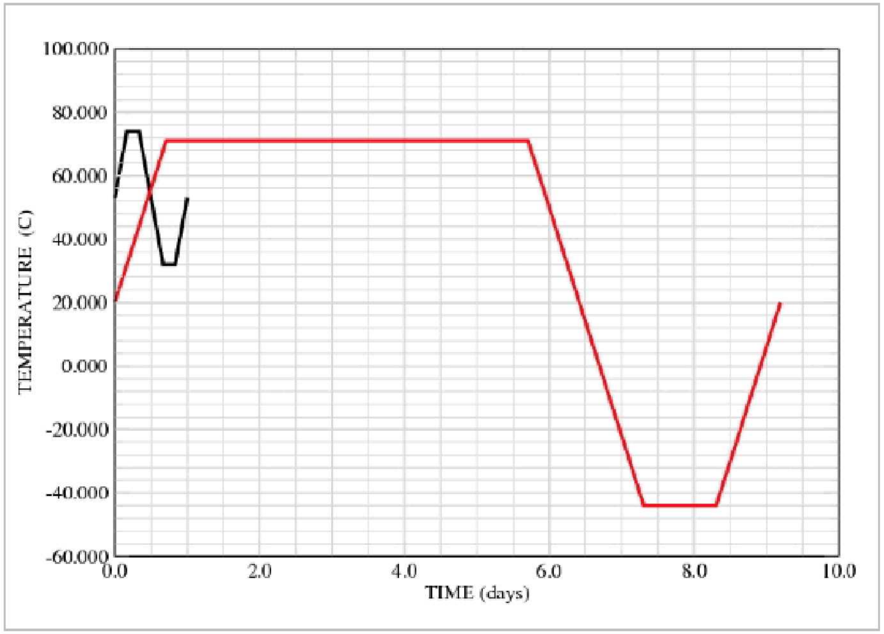
Backup-Slides

Case Study D: Stretching Package Applications

- **The first step was to determine the amount of fatigue life that is removed from the solder joints by the acceptance test.**
  - **Acceptance testing is performed on 100% of the product.**
- **The complicated qualification thermal history (left-hand side) was simplified into two "sub-cycles" (right-hand side).**



Original acceptance cycle



Composite acceptance cycle