
Predicting the Reliability of Package-on-Package-Package (PoPoP) Interconnections Based on Accelerated Aging Experiments and Computational Modeling

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Acknowledgements

- ◆ The authors would like to thank the engineers and supporting staff at **STI Electronics (Madison, AL)** for developing and executing the processes used to assemble the test vehicles.
- ◆ The authors wish to and **Brian Wroblewski** of Sandia for his thorough review of the proceedings.

Introduction

◆ The high-reliability electronics community ...

- Military systems,
- Space vehicles
- Satellite hardware

... is demanding increased functionality from products, which must also meet stricter **size, weight, and power (SWaP)** requirements.



◆ Three-dimensional (3-D) packaging ...

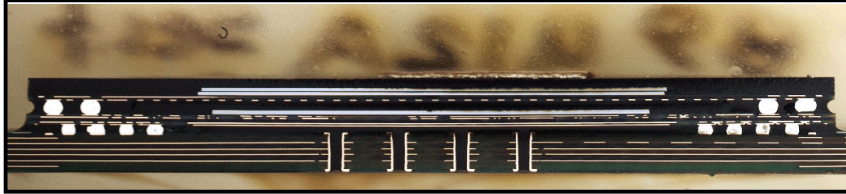
- Stacked packages
- Stacked die

... provides an effective approach to meet these objectives in the next generation of flight and ground systems.

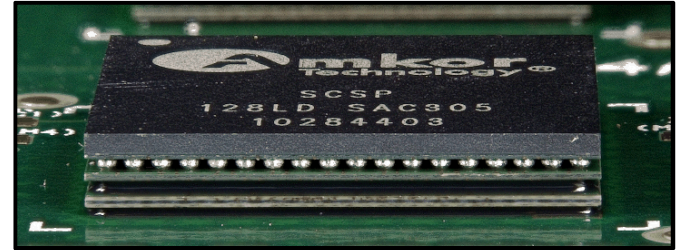


Introduction

- ◆ Currently, the high-reliability community favors stacked package technology based upon the “*known good package*” concept.



Package-on-Package (PoP)



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

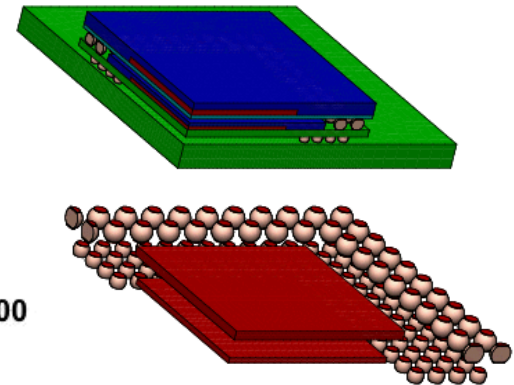
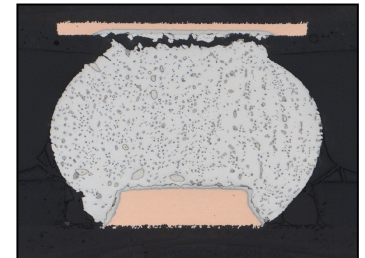
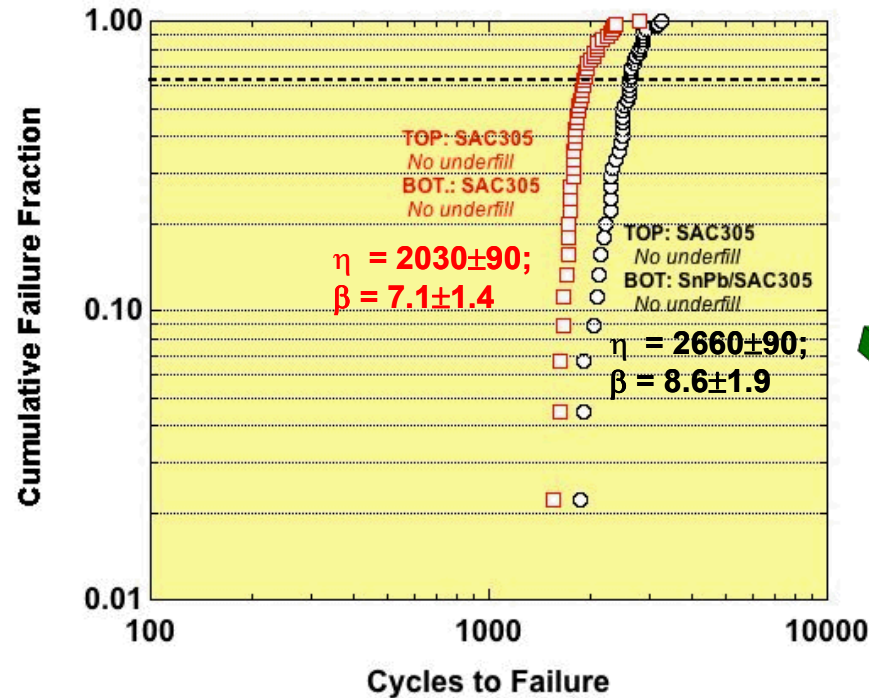
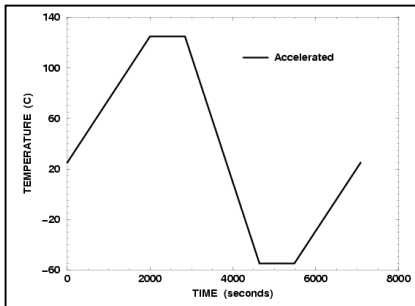
- ◆ The qualification of 3-D packaging must consider **temperature cycling** conditions, including assemblies that may also have these unique features:

- **Backwards compatible, second-level interconnections**
- **Underfill and/or staking**
- **Conformal coatings**



Introduction

- ◆ A multi-year study is developing both the **empirical database** and **computational modeling** tools for predicting the long-term reliability of stacked package interconnections.
- ◆ The project began with a **package-on-package (PoP)** investigation* †:

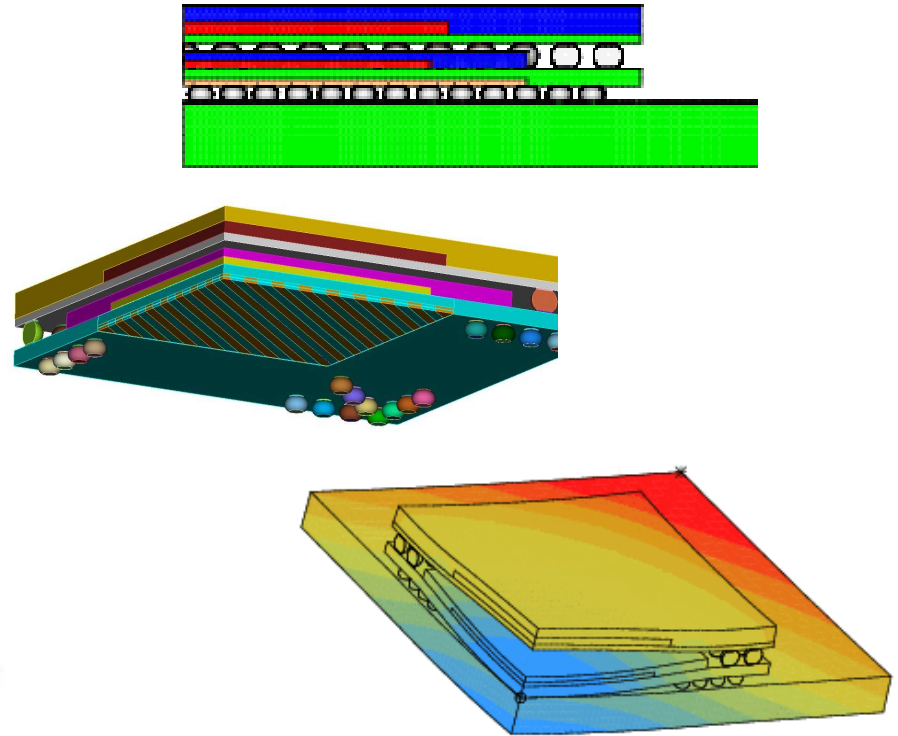
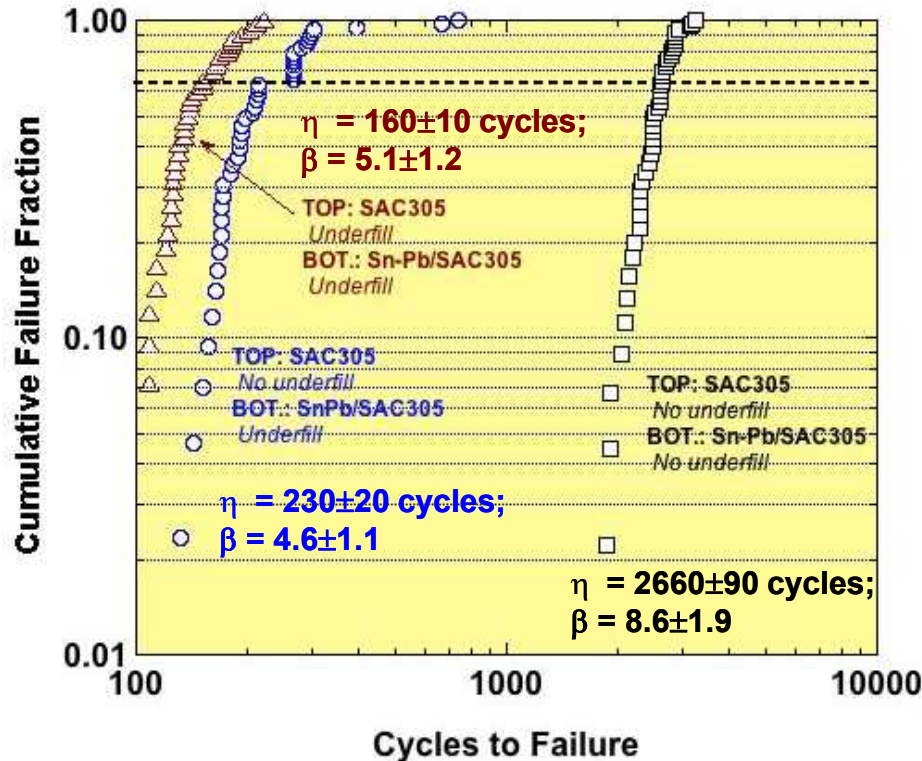


*P. Vianco, J. Grazier, J. Rejent, A. Kilgo, F. Verdi, and C. Meola, *Proc. Surf. Mount. Tech. Assoc. Inter.* (2009)

†P. Vianco, M. Neilsen, J. Rejent, J. Grazier, and A. Kilgo, *Proc. Surface Mount Tech. Assoc. Inter.* (2013)

Introduction

- ◆ The results of the PoP study *were not intuitively obvious* – e.g., the effect of underfill on thermal mechanical fatigue (TMF) behavior:



- ◆ The synergistic effects between multiple materials results in the complex response of PoP interconnections to thermal cycles.

Experimental Procedure

◆ The test vehicle details are listed below:

• Printed circuit board:

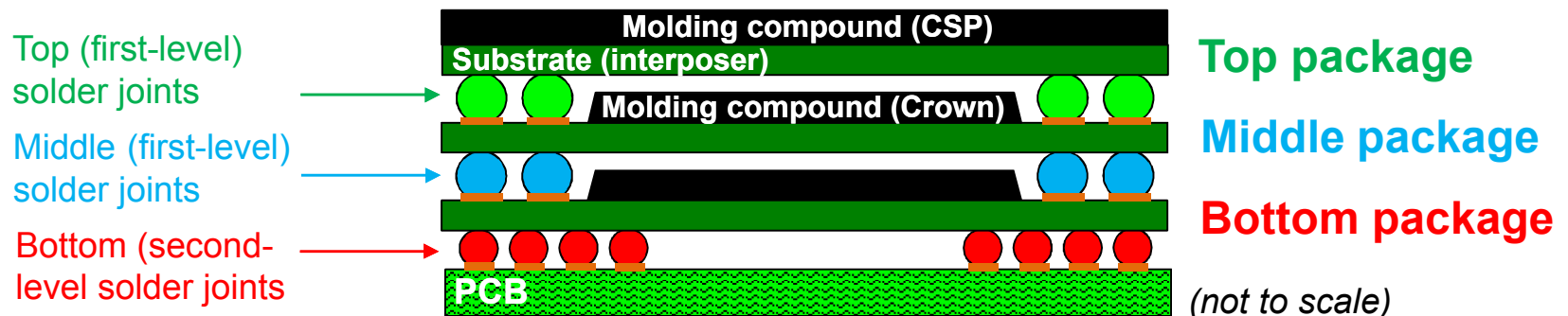
- 1 mm thick
- High temperature FR-4 laminate ($T_g = 180^\circ\text{C}$)
- Organic solderability preservative (OSP) surface finish



Test vehicle

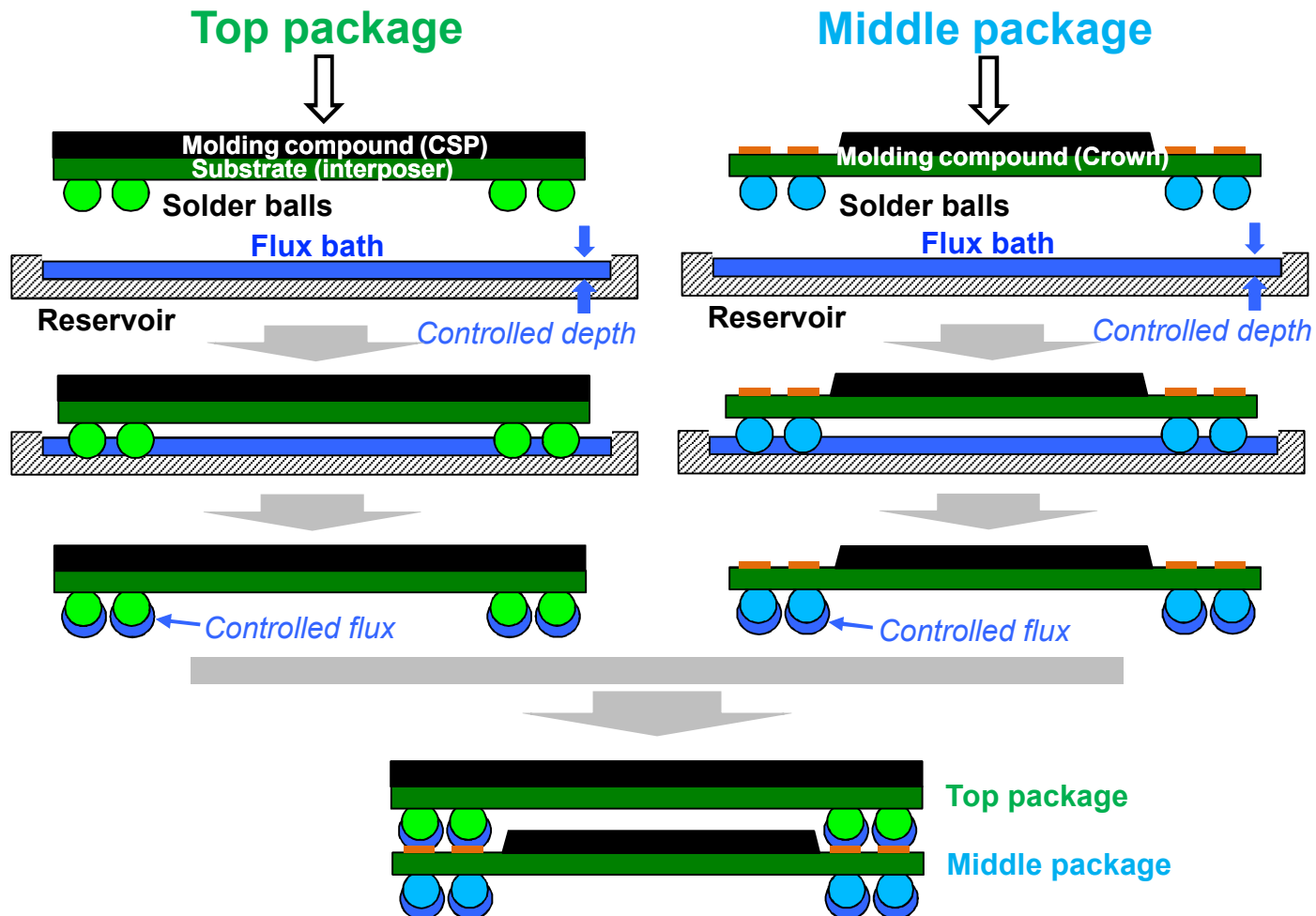
• Packages:

- Top package. *bottom*: 128 I/O; 0.65 mm pitch; ENIG finish; SAC305 balls
- Middle package. *top*: 128 I/O; 0.65 mm pitch; ENIG finish;
bottom: 128 I/O; 0.65 mm pitch; ENIG finish; SAC105 balls
- Bottom package. *top*: 128 I/O; 0.65 mm pitch; ENIG finish;
bottom: 305 I/O; 0.50 mm pitch; bare Cu; SAC305 balls



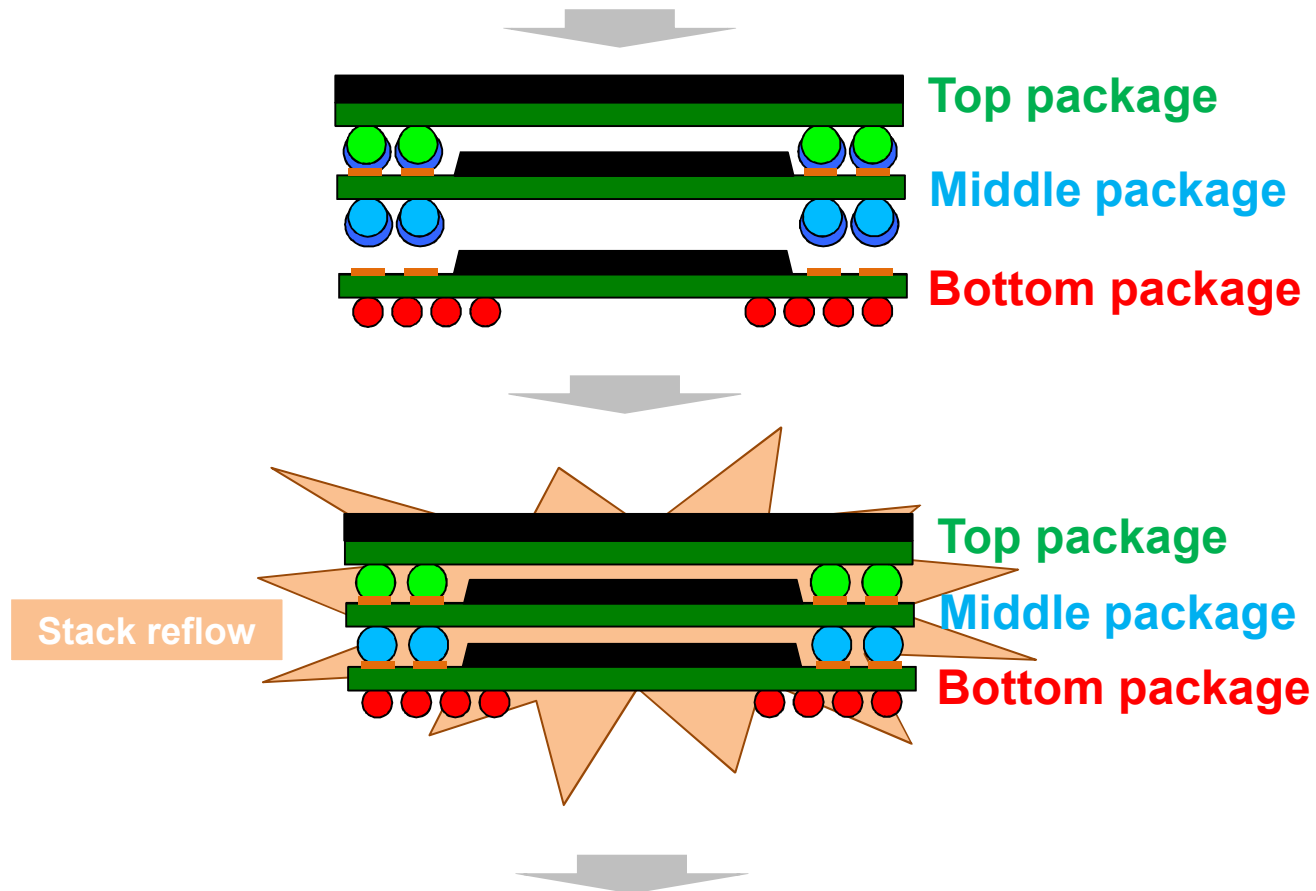
Experimental Procedure

- ◆ A two-step, assembly process was used to build the test vehicles.
- ◆ **Step (1):** construct the individual PoPoP component (stacks):



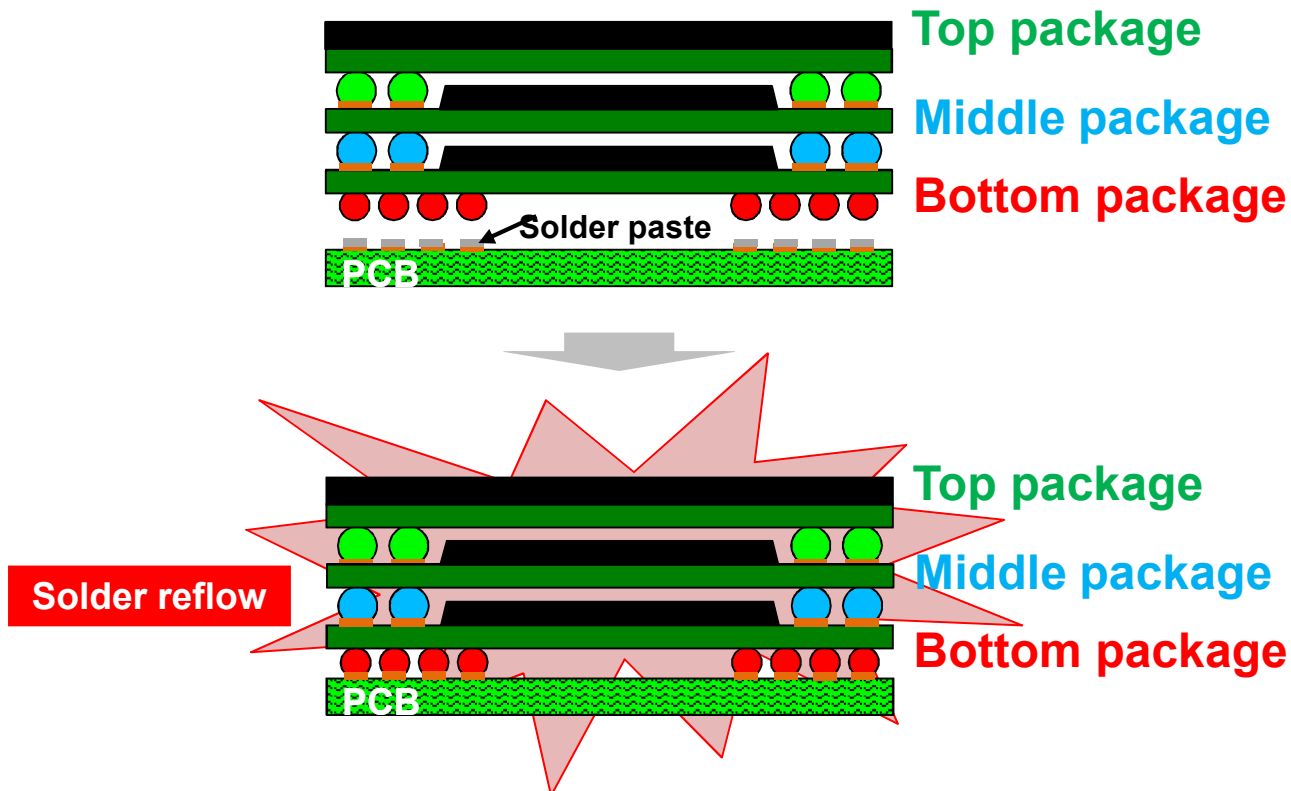
Experimental Procedure

- ◆ The **stack reflow** step creates the **first-level, Pb-free interconnections** that stacks individual packages into the PoPoP component.



Experimental Procedure

- ◆ The **solder reflow** step forms the **second-level interconnections** between the PoPoP component to the printed circuit board (PCB).
- ◆ There are two solder reflow profiles:
 - Low-temperature, Sn-Pb reflow profile for backwards compatibility.
 - High-temperature, Pb-free reflow profile.



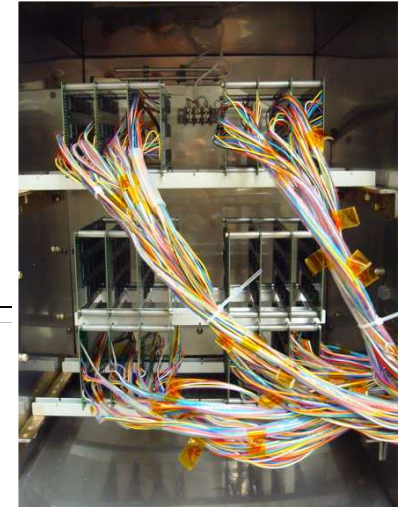
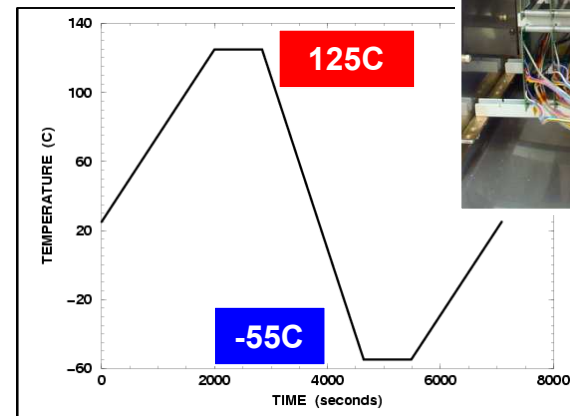
Experimental Procedure

◆ Thermal cycling provided the accelerated aging environment.

- Temperature extremes -55°C / 125°C .
- Hold times 15 min.
- Ramp rates 10°C / min.

◆ Sample counts:

- $N = 20$ backwards compatibility
- $N = 20$ Pb-free solder joints
- In each group of 20 PWAs:
 - $N = 8$, *no underfill*
 - $N = 4$, underfill; **bottom** gap only
 - $N = 4$, underfill; **bottom** and **middle** gaps
 - $N = 4$, underfill; **bottom**, **middle** and **top** gaps



◆ Duplicate PWAs were monitored to capture failures in the three levels of solder joints.

2. Top joints →

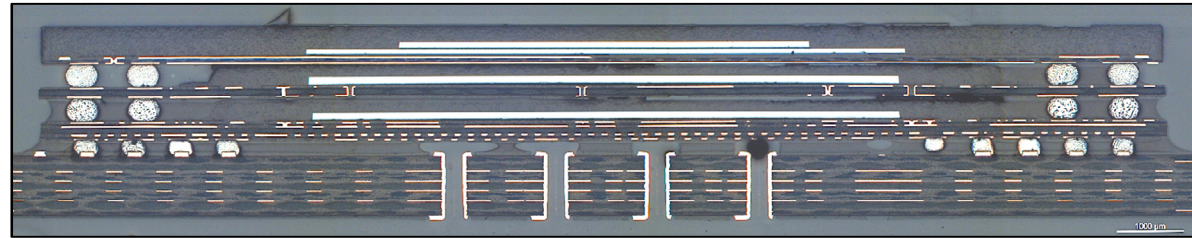
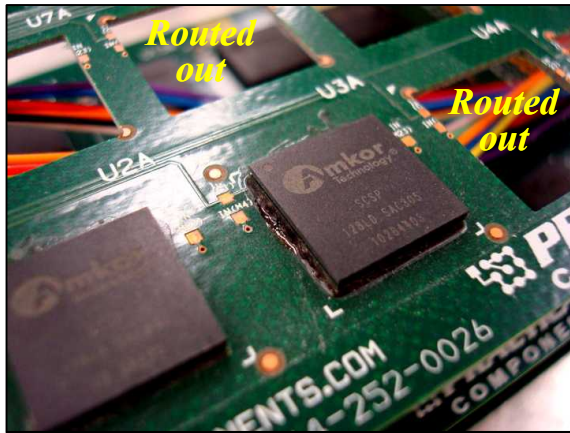
3. Middle joints →

1. Bottom joints (PCB) →

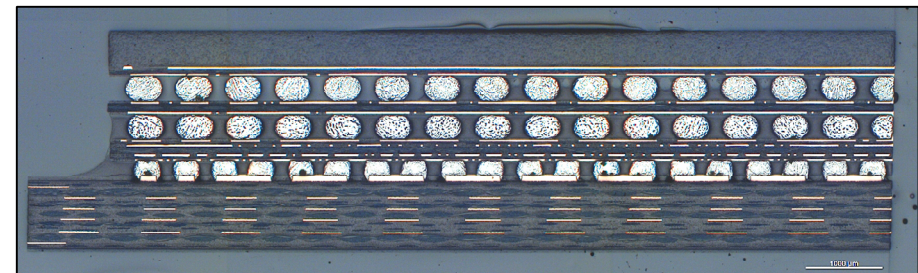
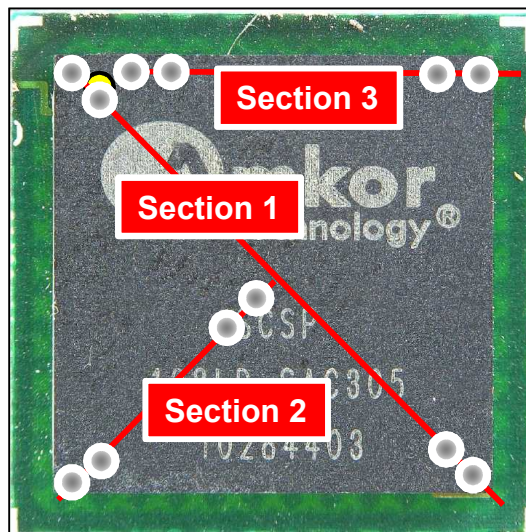


Experimental Procedure

- ◆ **Failure analysis steps** included (a) extraction of a PoPoP package; (b) cross section; and (c) microanalysis techniques (SEM, EDX, etc.).



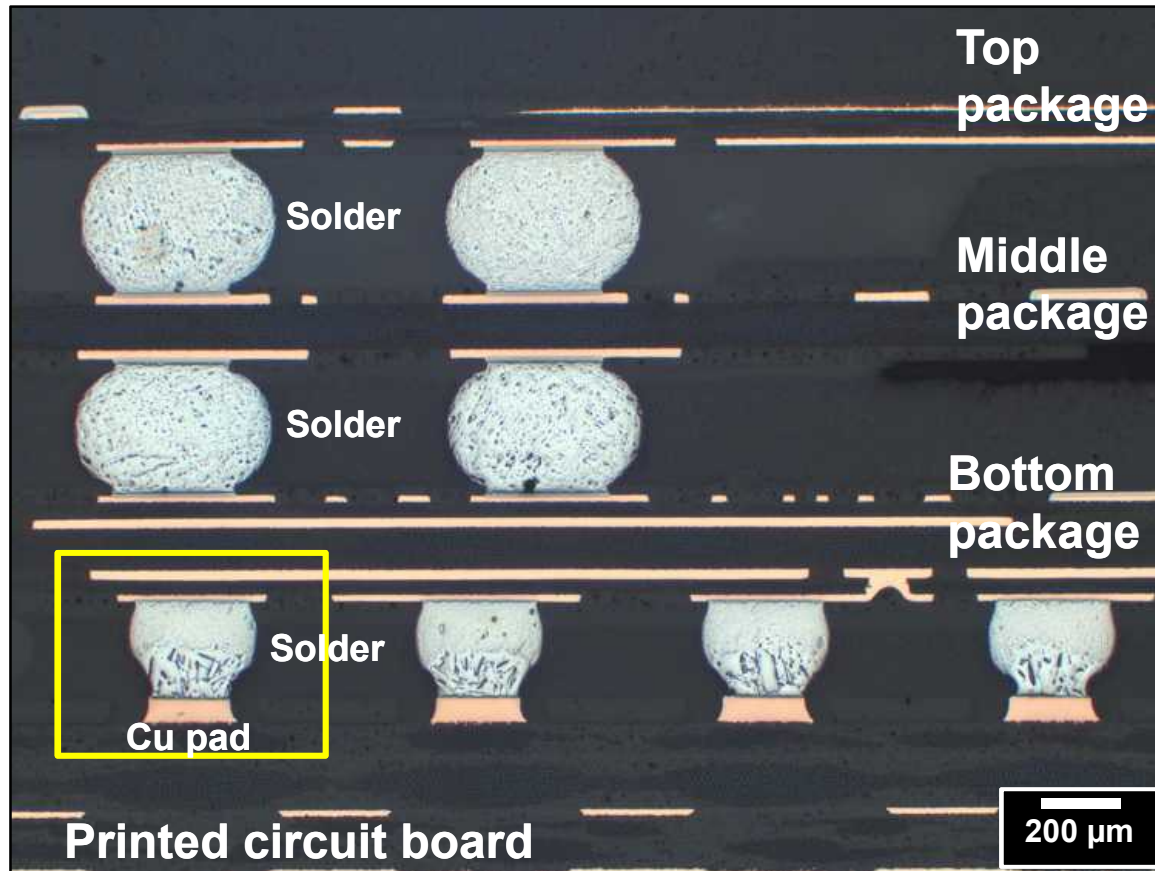
Section 1



Section 3

Results – Backwards Compatibility

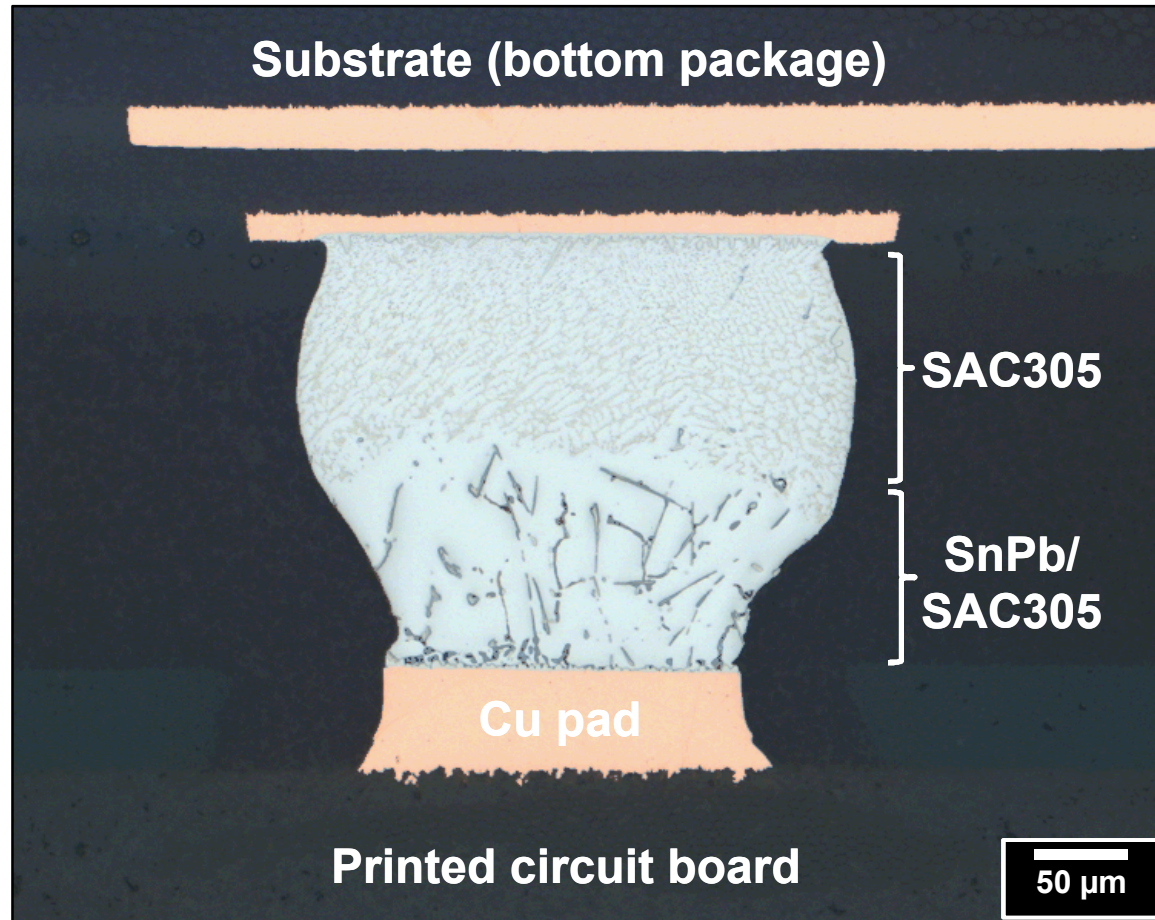
- ◆ An objective of the backwards compatible test vehicles was to assess the TMF of the **inhomogeneous microstructure**.
- ◆ This microstructure was observed on *only one (1) test vehicle*.



*S/N05:
as-fabricated;
underfill, middle
and bottom gaps*

Results – Backwards Compatibility

- ◆ The dual microstructure is illustrated by this optical micrograph:

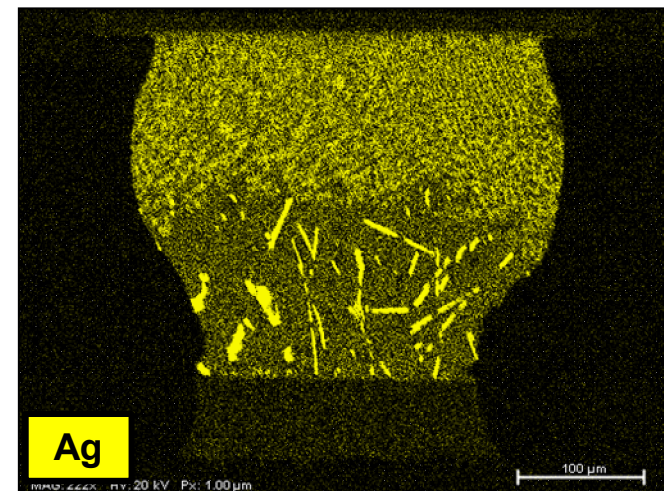
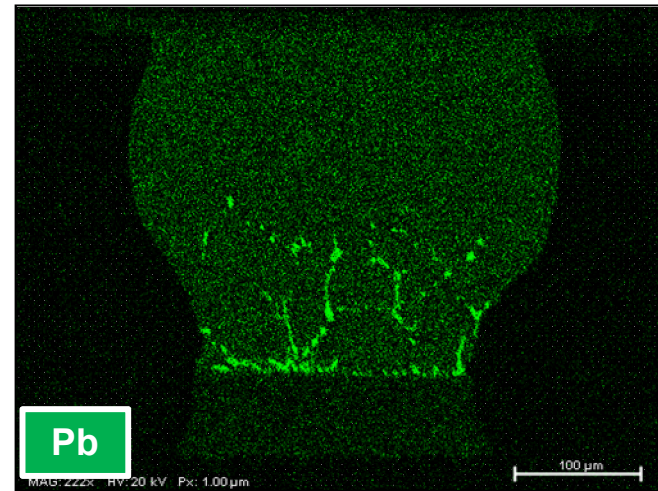
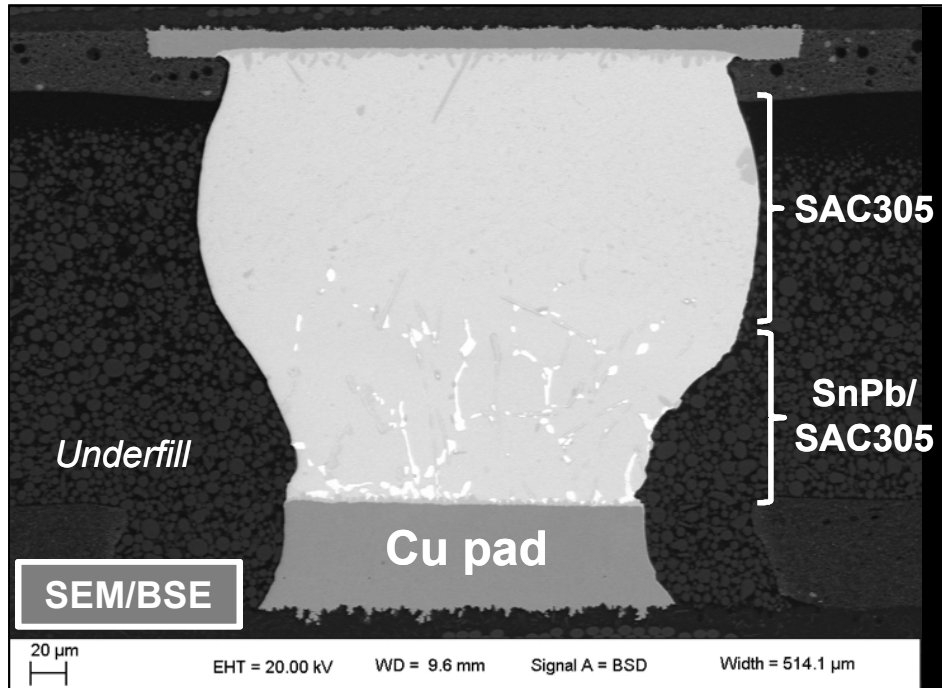


*S/N05:
as-fabricated;
underfill, middle
and bottom gaps*

- ◆ Excessive voids and cracks were not observed in any joints.

Results – Backwards Compatibility

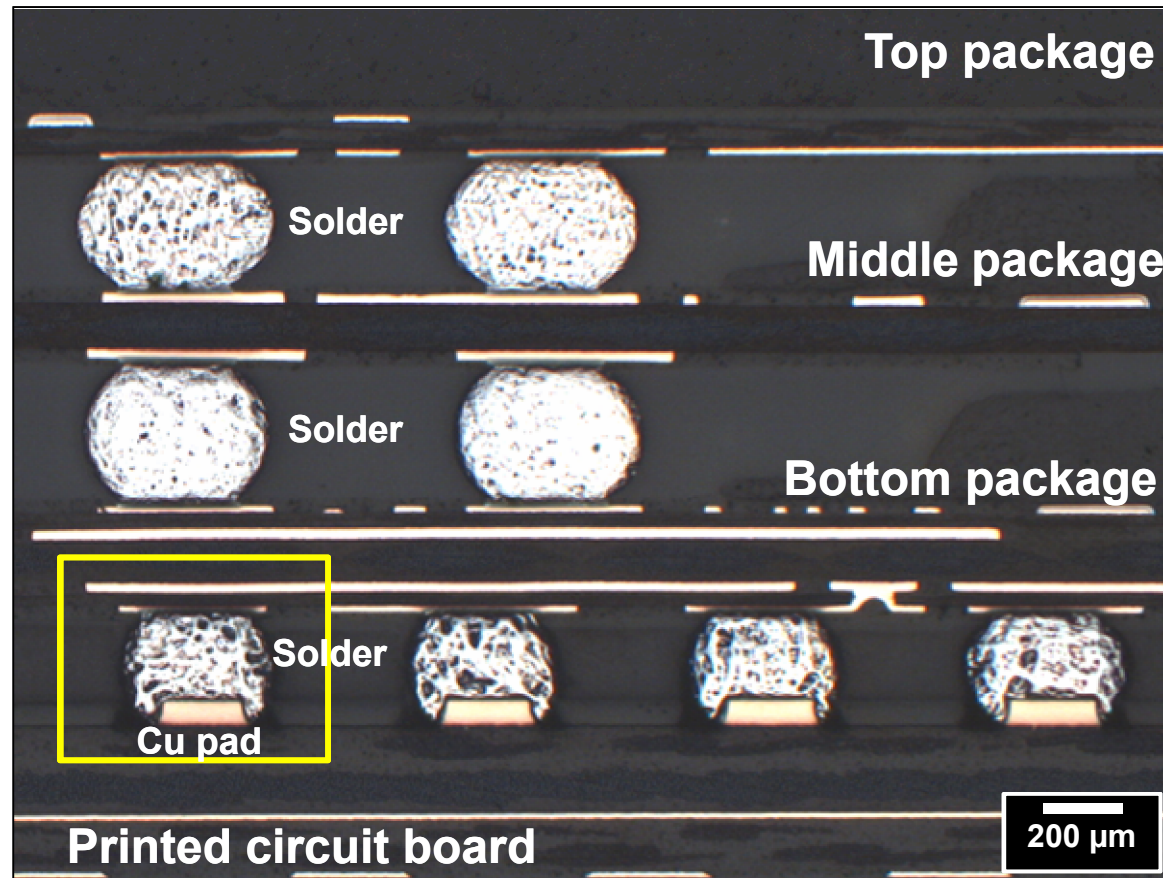
- ◆ **Understanding the mixed-metallurgy microstructure** is critical to the execution of PoPoP technology in high-reliability electronics.



Energy dispersive x-ray (EDX) analysis indicate that both the Pb-rich and Ag_3Sn phases are distributed nonhomogeneously in the “mixed” Sn-Pb/SAC 305” region.

Results – Backwards Compatibility

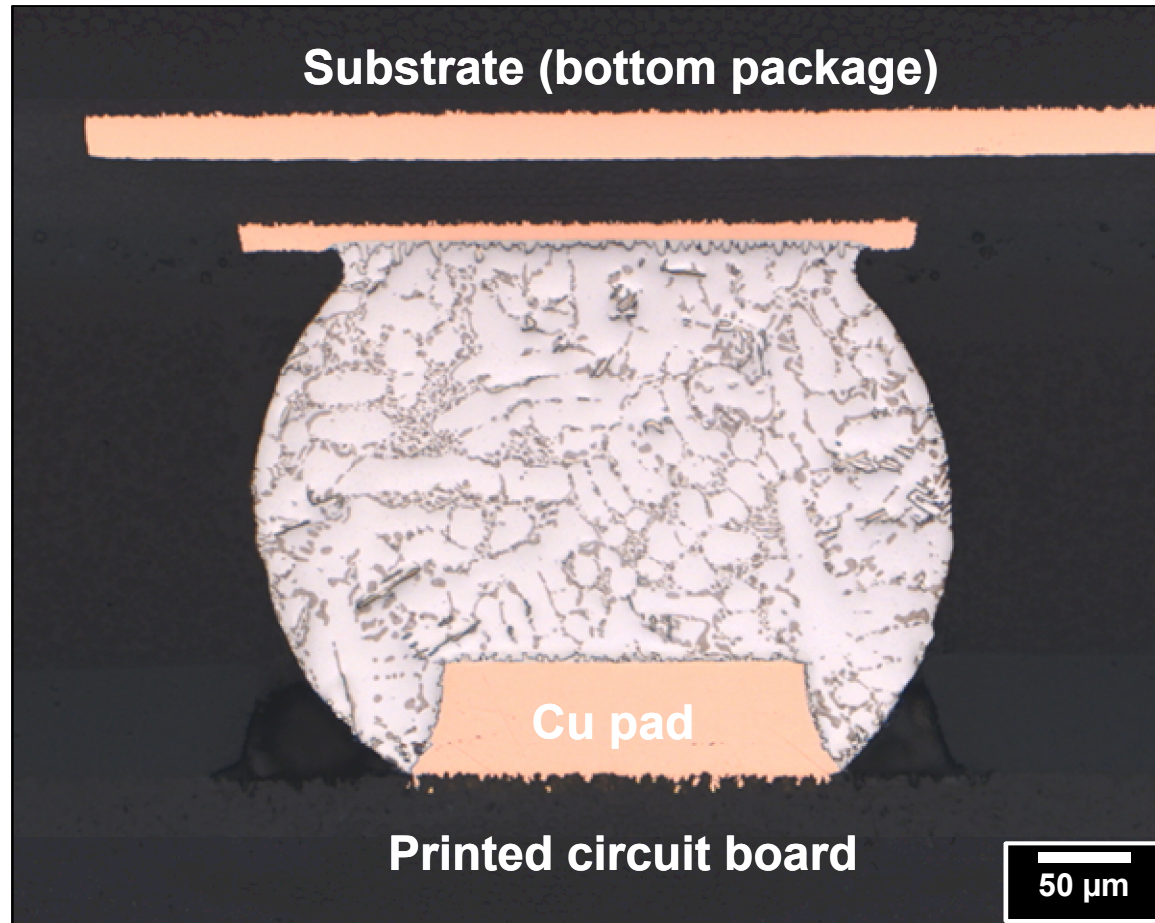
- ◆ The remaining, backwards compatible test vehicles exhibited **homogeneous distributions of Pb-rich phase** in the solder joints.



*S/N07:
as-fabricated;
underfill, middle gap*

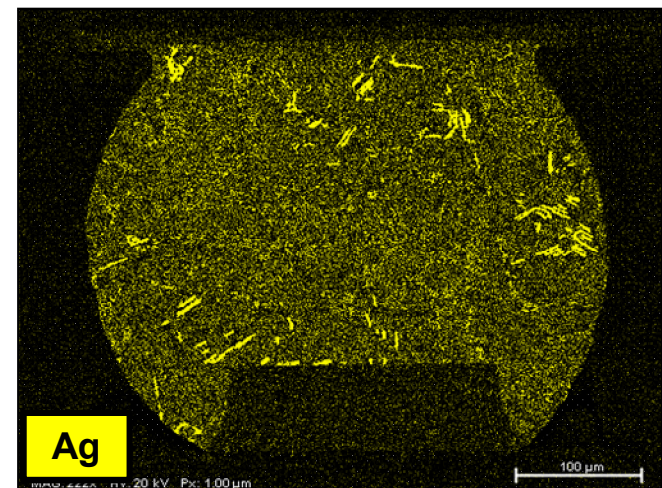
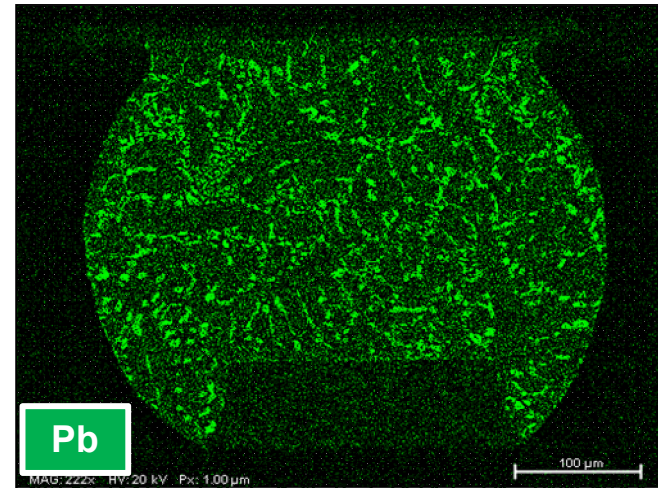
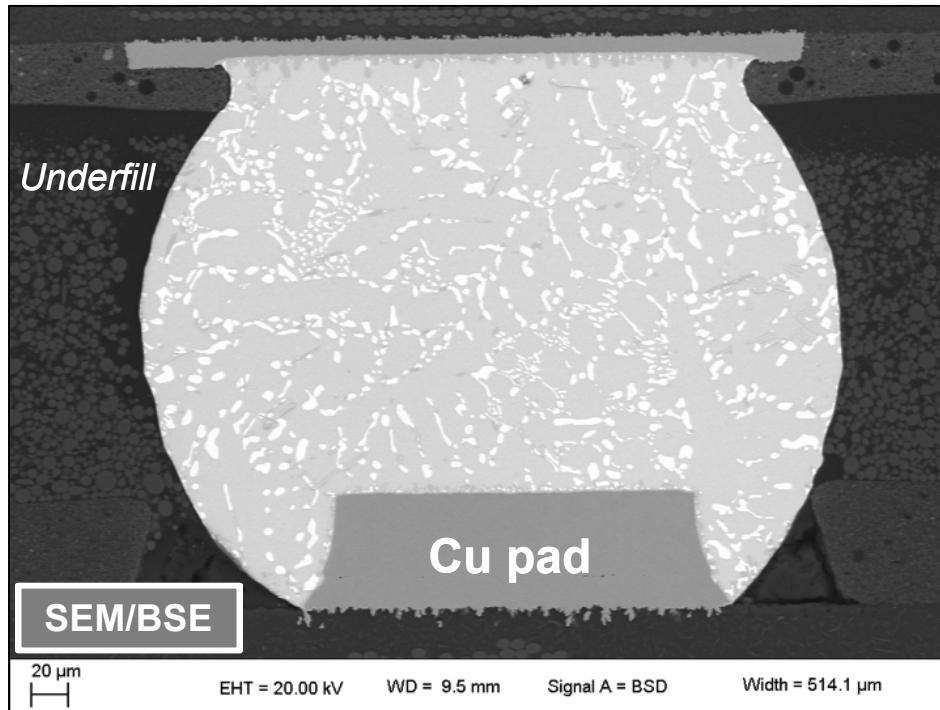
Results – Backwards Compatibility

- ◆ This optical micrograph shows the homogeneous microstructure.



Results – Backwards Compatibility

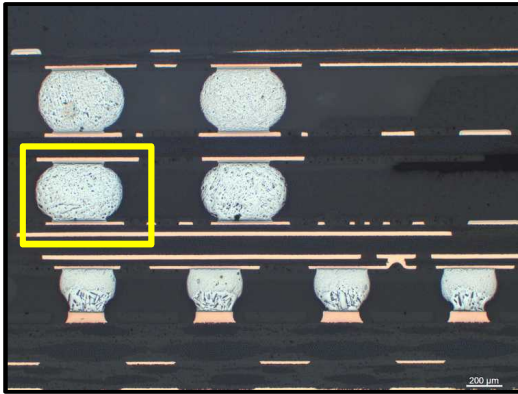
- ◆ Although the Ag_3Sn particles were not uniformly distributed across the entire joint, this trend did not affect TMF performance.



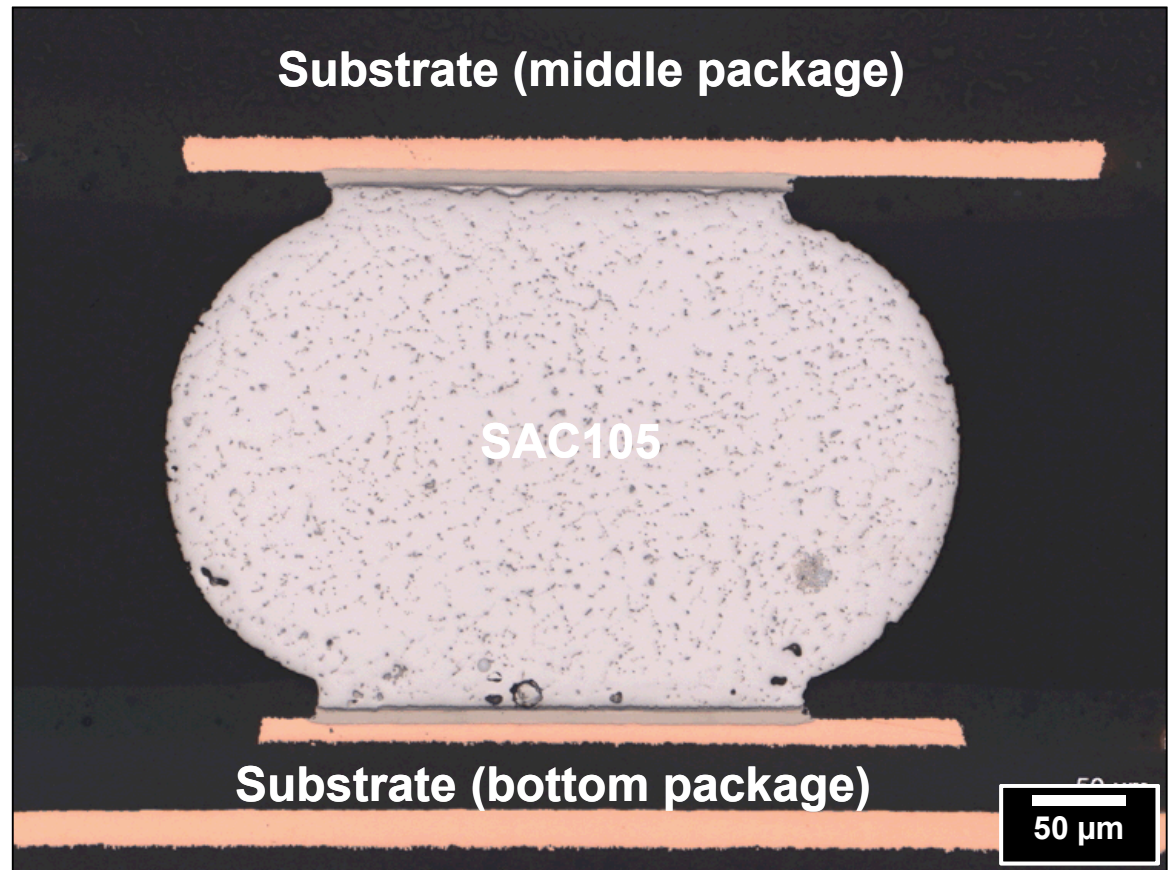
A direct correlation was not observed between the Pb-rich and Ag_3Sn phases within either the homogeneous or the inhomogeneous microstructures.

Results – Backwards Compatibility

- ◆ The microstructure analysis also confirmed the excellent integrity of the **SAC105 solder joints** that attached middle package to the bottom package ...

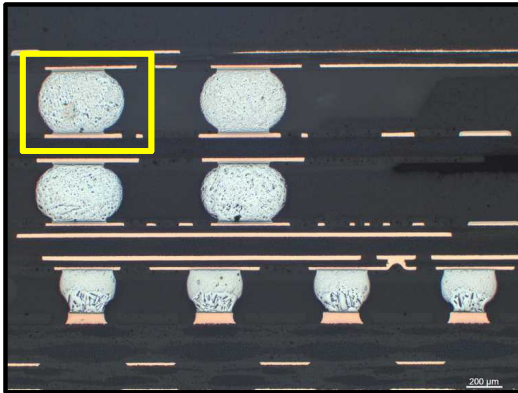


*S/N05:
as-fabricated;
underfill, middle
and bottom gaps*

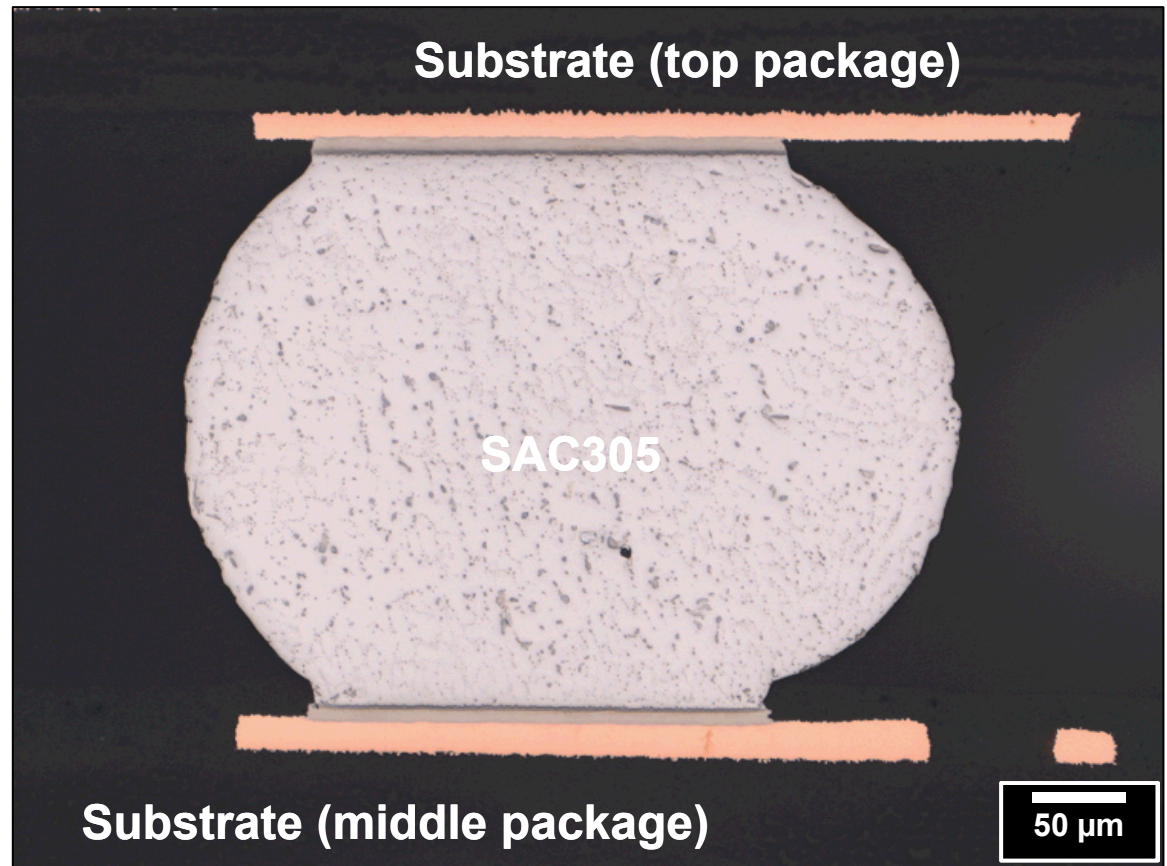


Results – Backwards Compatibility

- ◆ ... as well as **SAC305 interconnections** that joined the middle package to the top package.



*S/N05:
as-fabricated;
underfill, middle
and bottom gaps*



- ◆ Recall that the middle and top solder joints had undergone **two soldering steps**: **initial stack reflow** and **subsequent, solder reflow**.

Results – Statistical Failure Analysis

- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** The 2P Weibull data indicated that all three solder joints had nearly identical behaviors despite the different solder compositions.

Top joints:

$\eta = 2600 \pm 200$ cycles

$\beta = 8.7 \pm 4.0$

Middle joints:

$\eta = 2500 \pm 300$ cycles

$\beta = 6.6 \pm 3.4$

Bottom joints:

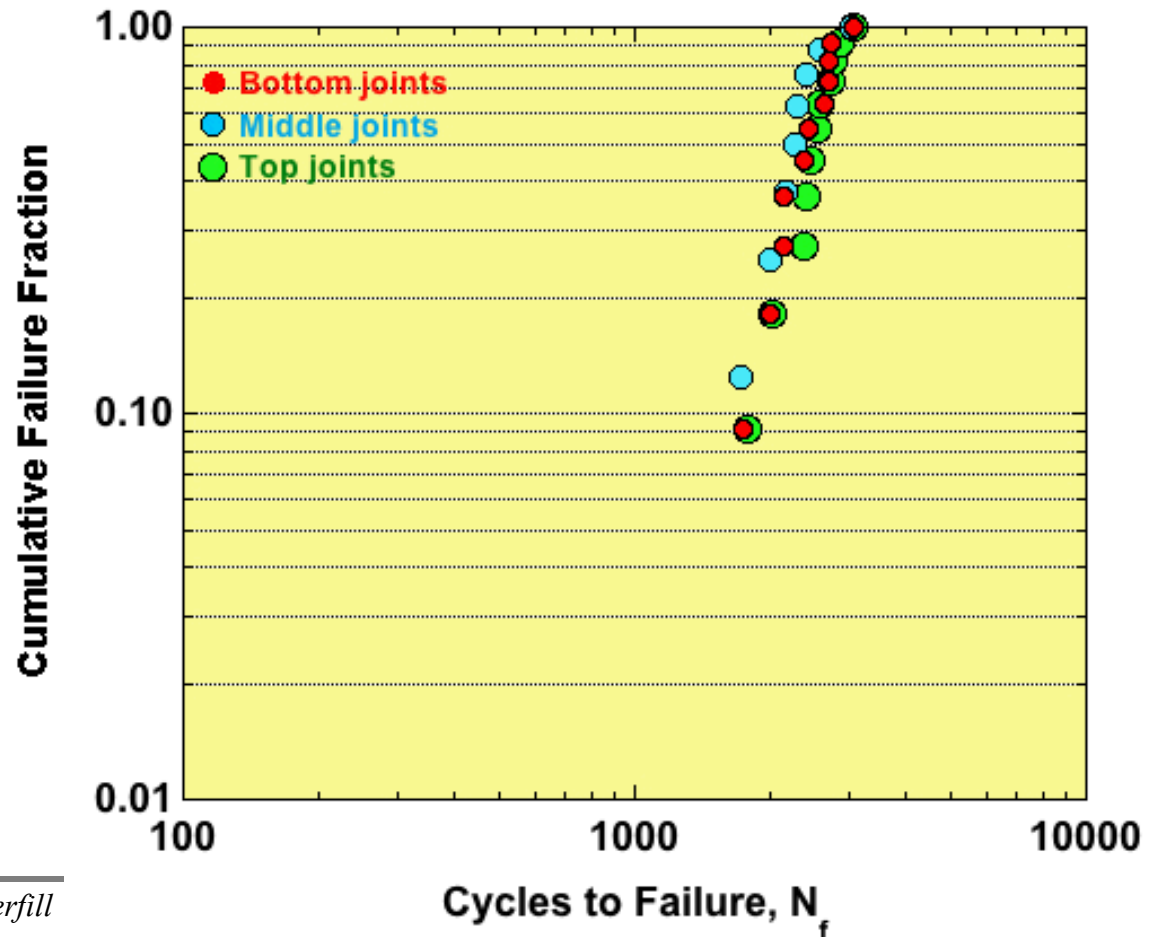
$\eta = 2600 \pm 200$ cycles

$\beta = 7.6 \pm 3.5$

Combined joints:

$\eta = 2600 \pm 100$ cycles

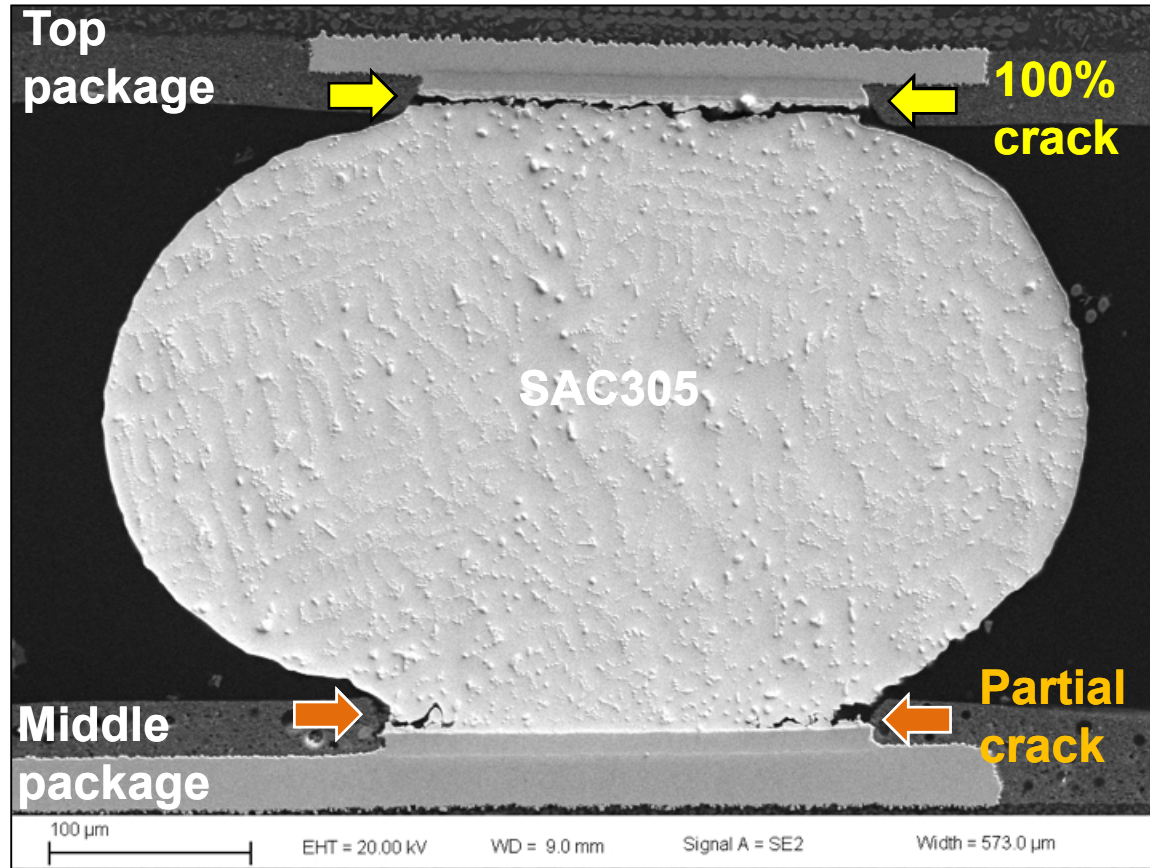
$\beta = 7.5 \pm 2.1$



S/N22 and S/N23: Mixed SnPb/SAC305; No underfill

Results – Failure Mode Analysis

- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** Failure of the **top solder joints** was caused by the “100% crack” at the top pad.

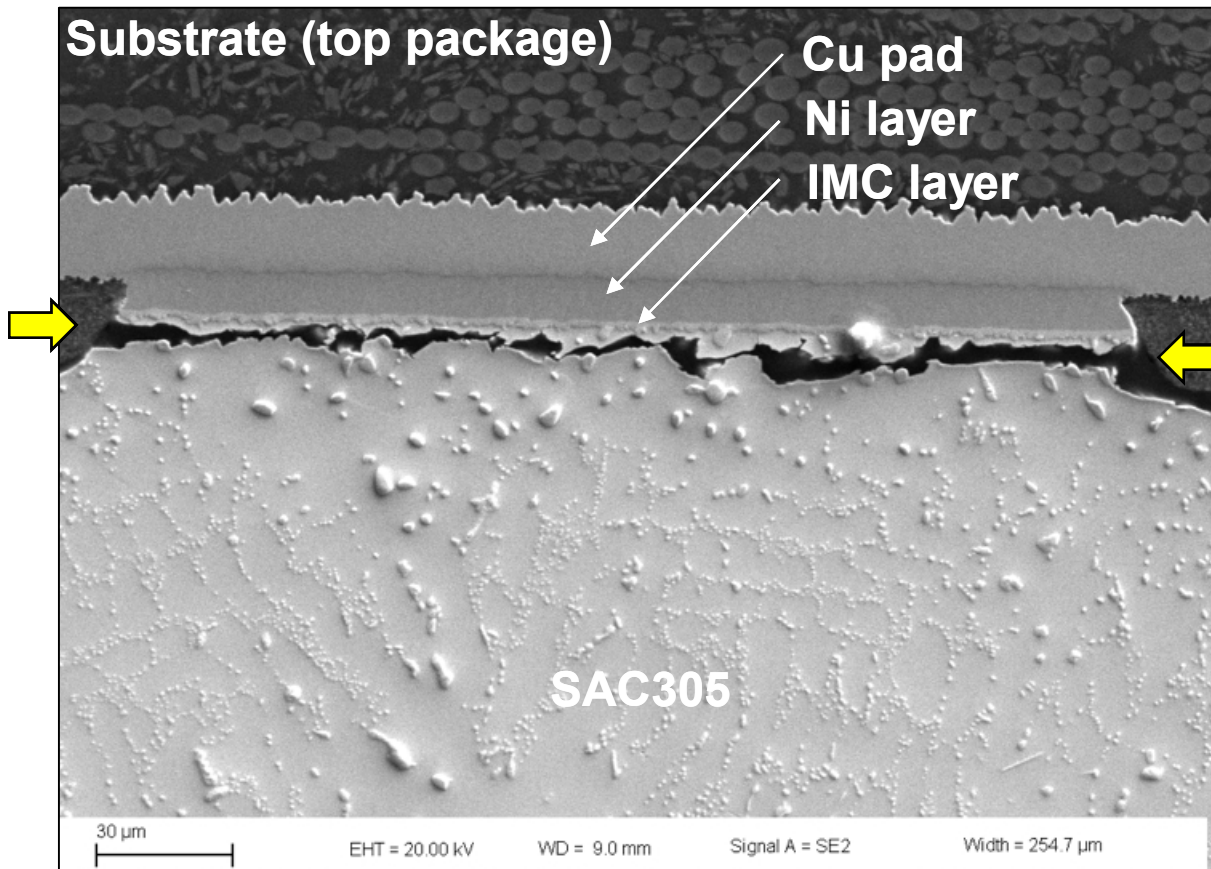


*S/N22, U10A, top;
No underfill;
Failed: 3068 cycles*

- ◆ Partial cracks were observed at the bottom pad (middle package).

Results – Failure Mode Analysis

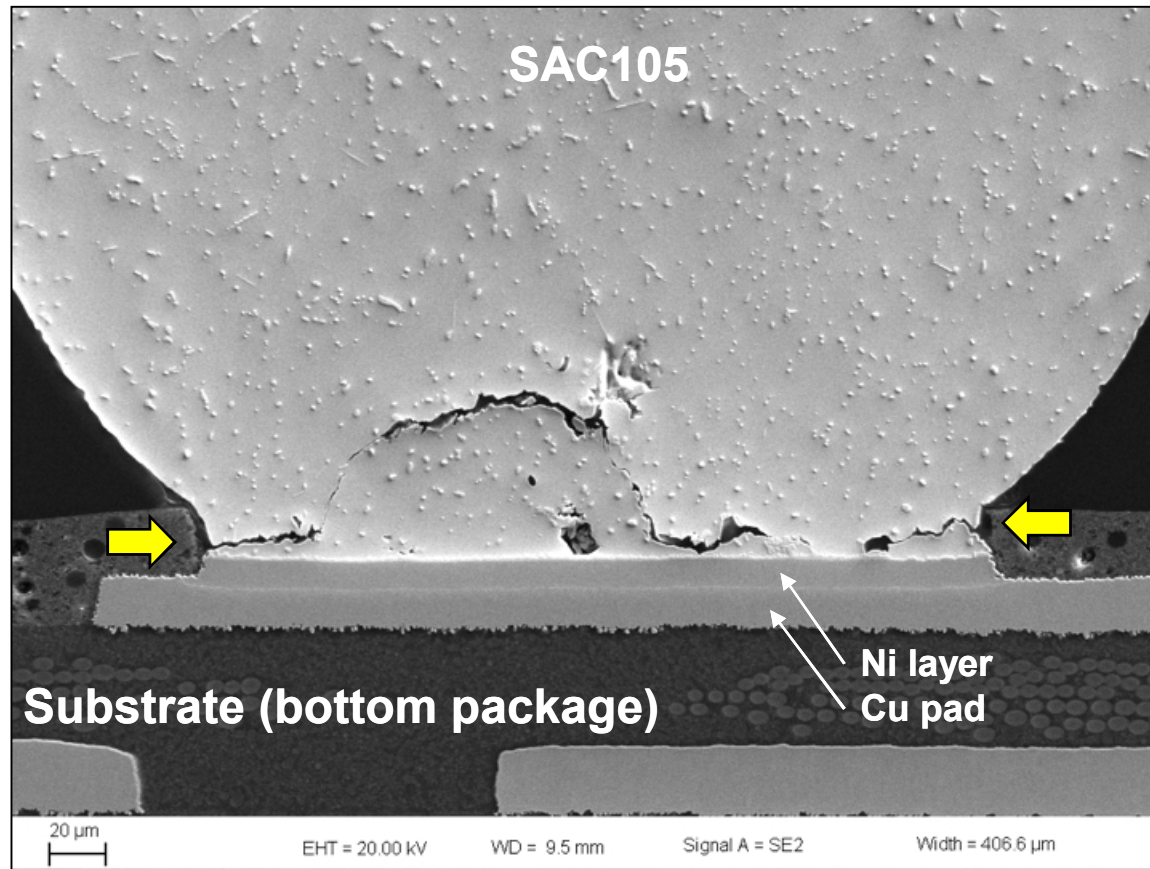
- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** The “100% crack” exhibited the expected **TMF morphology** of having developed in the SAC305 solder near to, but not at, the solder/pad interface.



*S/N22, U10A, top;
No underfill;
Failed: 3068 cycles*

Results – Failure Mode Analysis

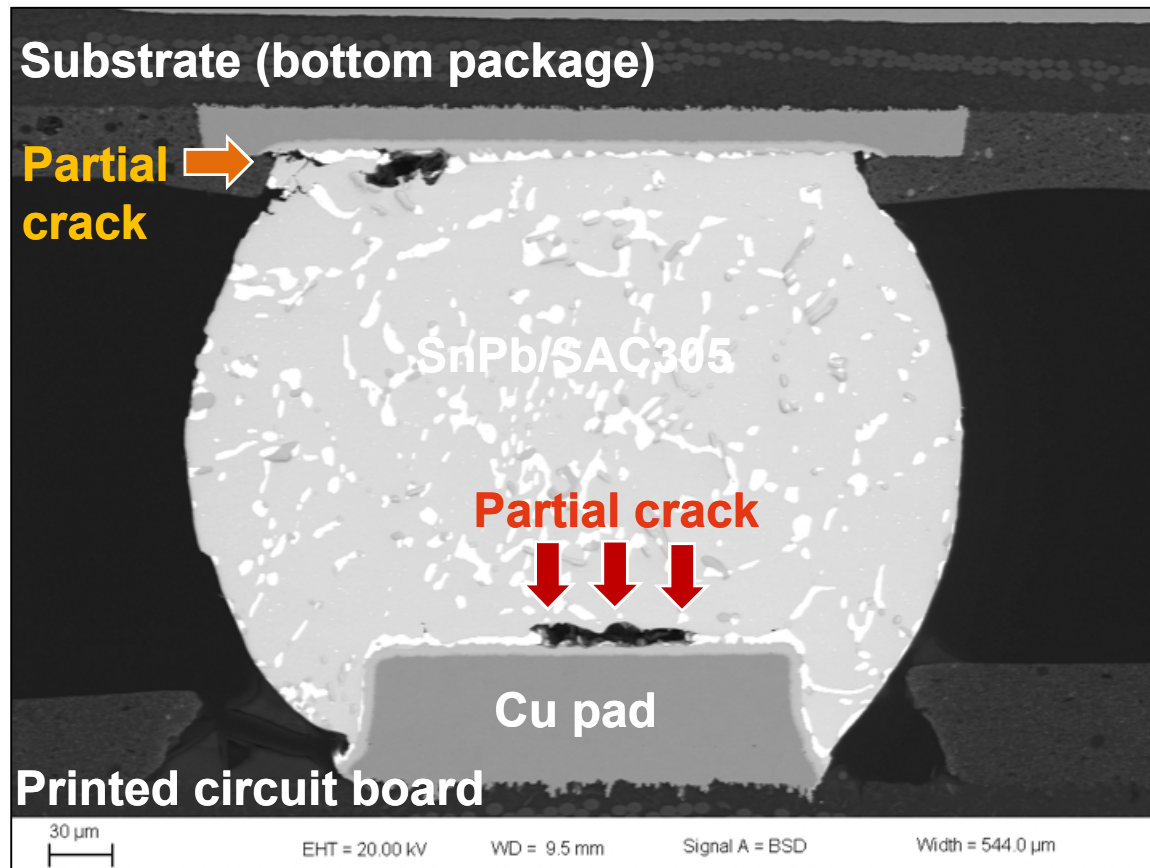
- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** The “100% crack” of the **middle solder joints** was near the bottom pad.



*S/N22, U10A, top;
No underfill;
Failed: > 3068 cycles*

Results – Failure Mode Analysis

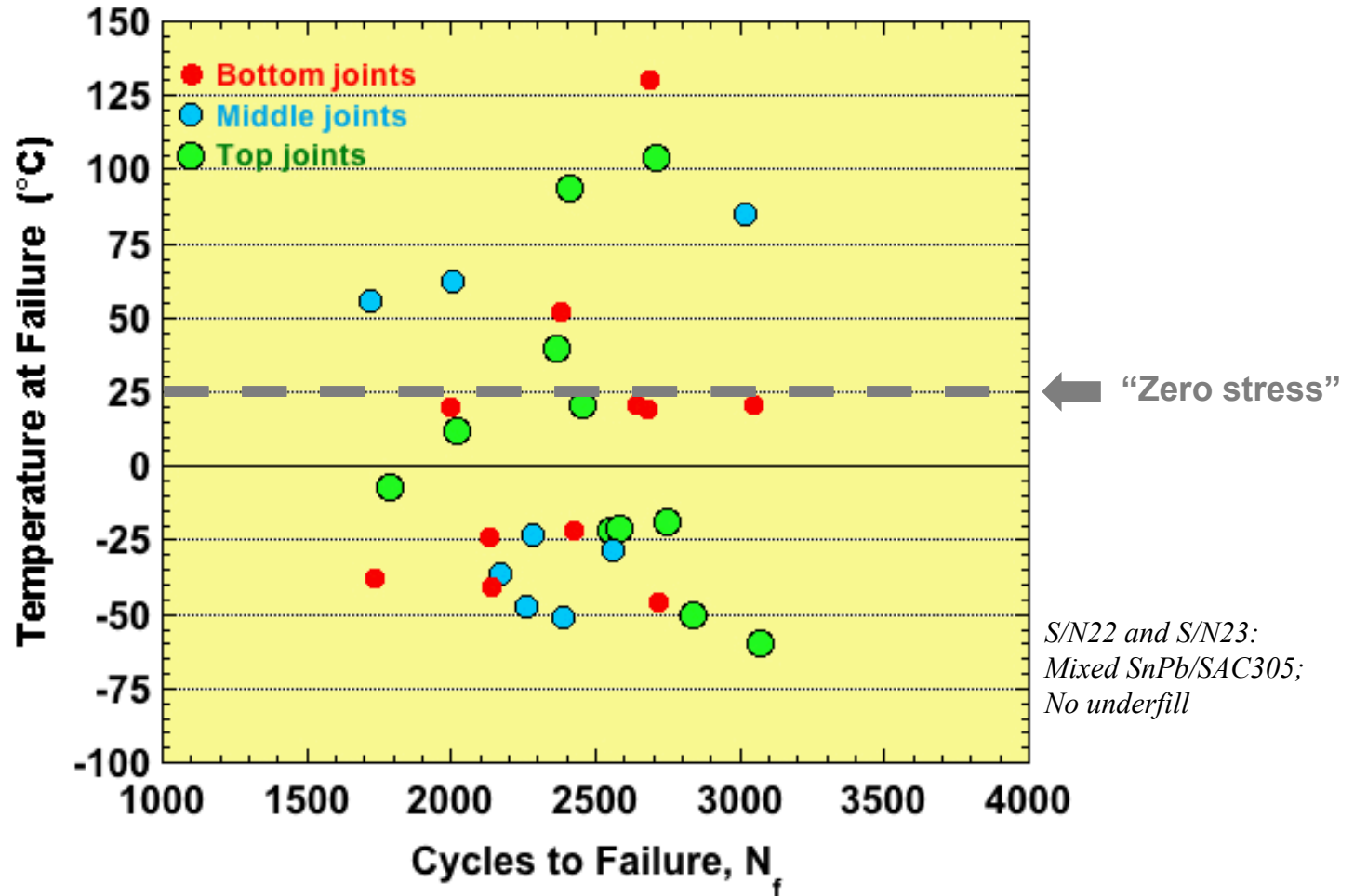
- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** An example of the “100% crack” was not captured for the **bottom solder joints** in this particular cross section; *the partial TMF crack is evident.*



*S/N22, U10A, top;
No underfill;
Failed: > 3068 cycles*

Results – Failure Mode Analysis

- ◆ **Mixed SnPb/SAC305 bottom joints; no underfill:** The data show a slight preference for failures to occur at low temperatures.



Results – Statistical Failure Analysis

- ◆ **100% SAC305 bottom joints; no underfill:** The 2P Weibull data show that the TMF was more distinct vis-a-vis the three solder joint types.

Top joints:

$\eta = 2400 \pm 200$ cycles

$\beta = 10.6 \pm 6.0$

Middle joints:

$\eta = 2600 \pm 500$ cycles

$\beta = 5.0 \pm 2.0$

Bottom joints:

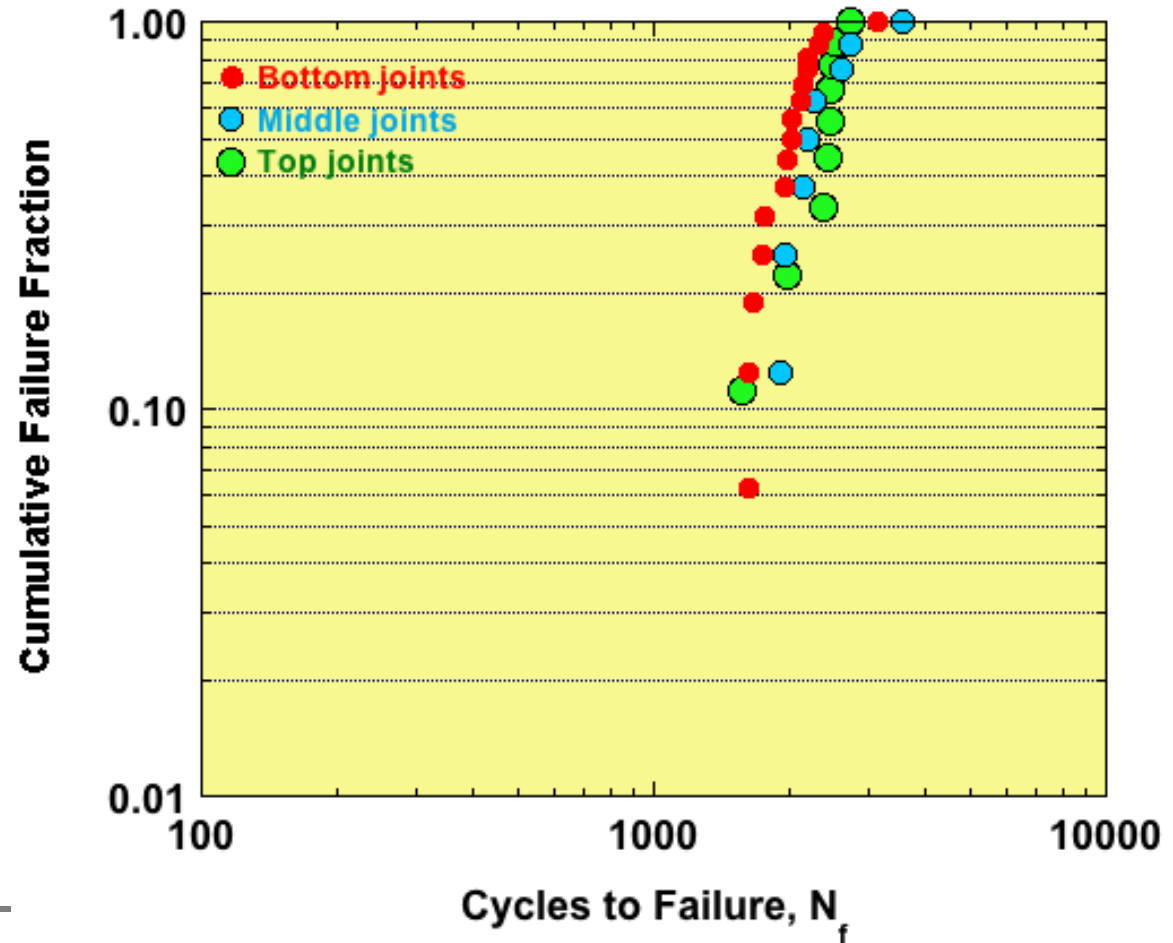
$\eta = 2200 \pm 200$ cycles

$\beta = 5.2 \pm 2.0$

Combined joints:

$\eta = 2400 \pm 200$ cycles

$\beta = 5.0 \pm 1.2$



Results – Statistical Failure Analysis

- ◆ **100% SAC305 bottom joints; no underfill:** The outliers that caused the small β terms for the middle and bottom joints occurred at the high-cycle counts rather than the typical, “early failures”.

Top joints:

$$\eta = 2400 \pm 200 \text{ cycles}$$

$$\beta = 10.6 \pm 6.0$$

Middle joints:

$$\eta = 2600 \pm 500 \text{ cycles}$$

$$\beta = 5.0 \pm 2.0$$

Middle joints, censored:

$$\eta = 2400 \pm 500 \text{ cycles}$$

$$\beta = 8.2 \pm 4.7$$

Bottom joints:

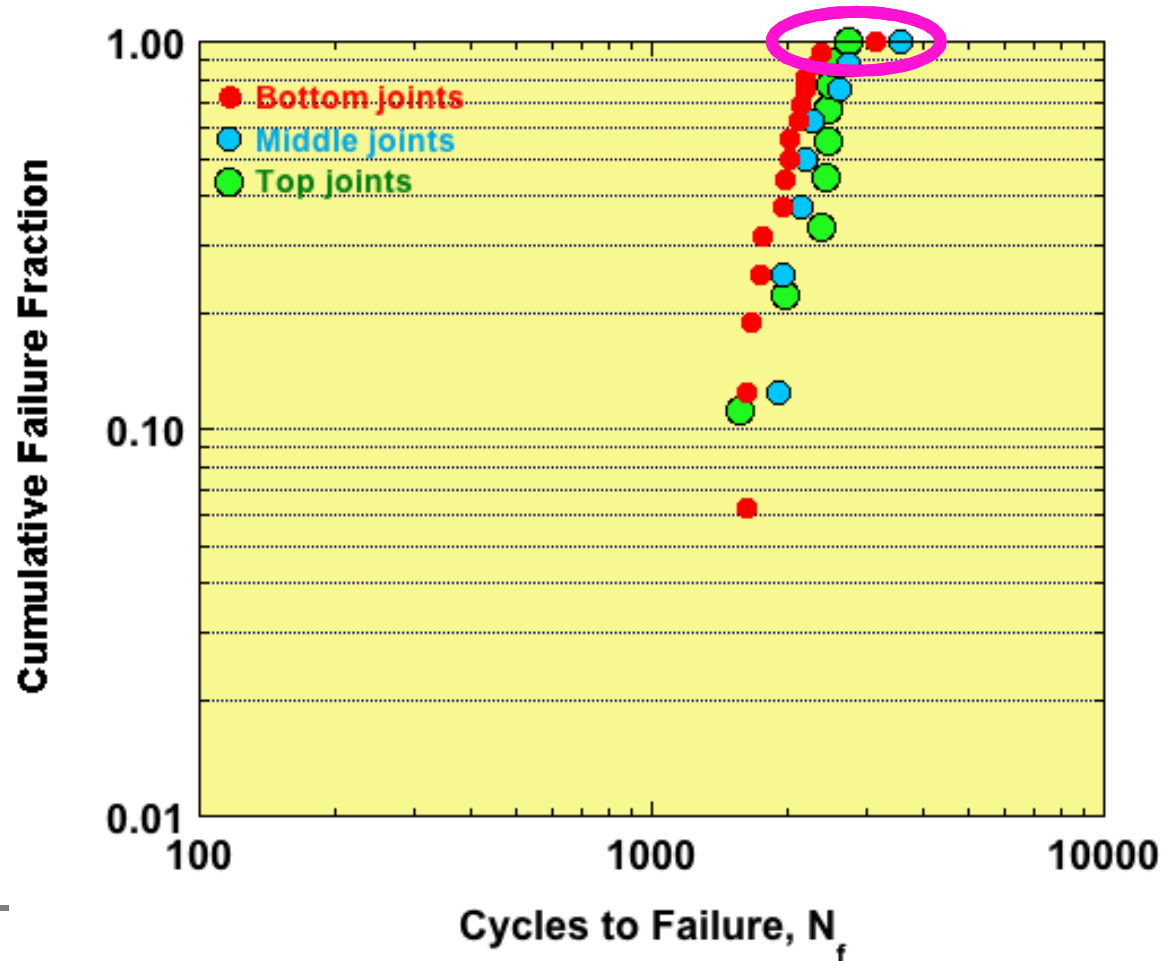
$$\eta = 2200 \pm 200 \text{ cycles}$$

$$\beta = 5.2 \pm 2.0$$

Bottom joints, censored:

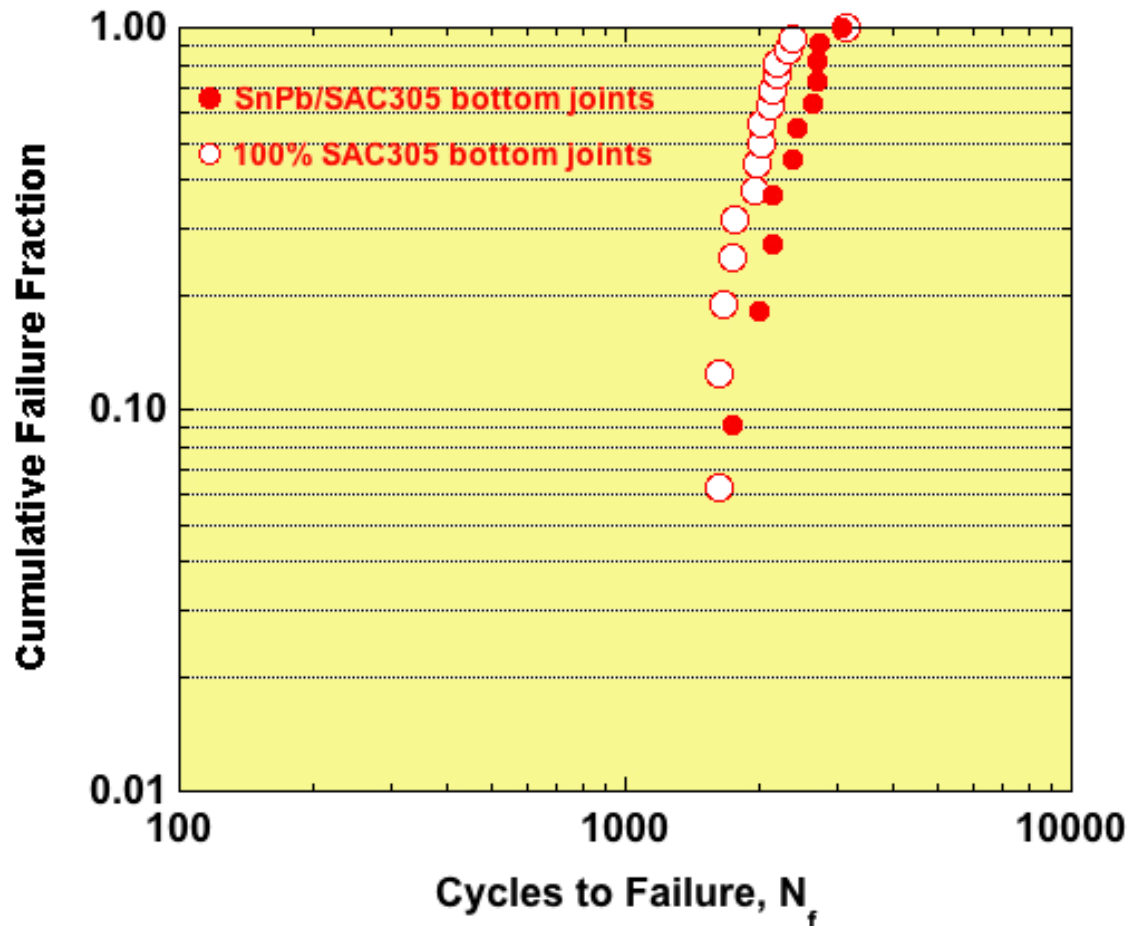
$$\eta = 2100 \pm 100 \text{ cycles}$$

$$\beta = 9.6 \pm 3.8$$



Results – Statistical Failure Analysis

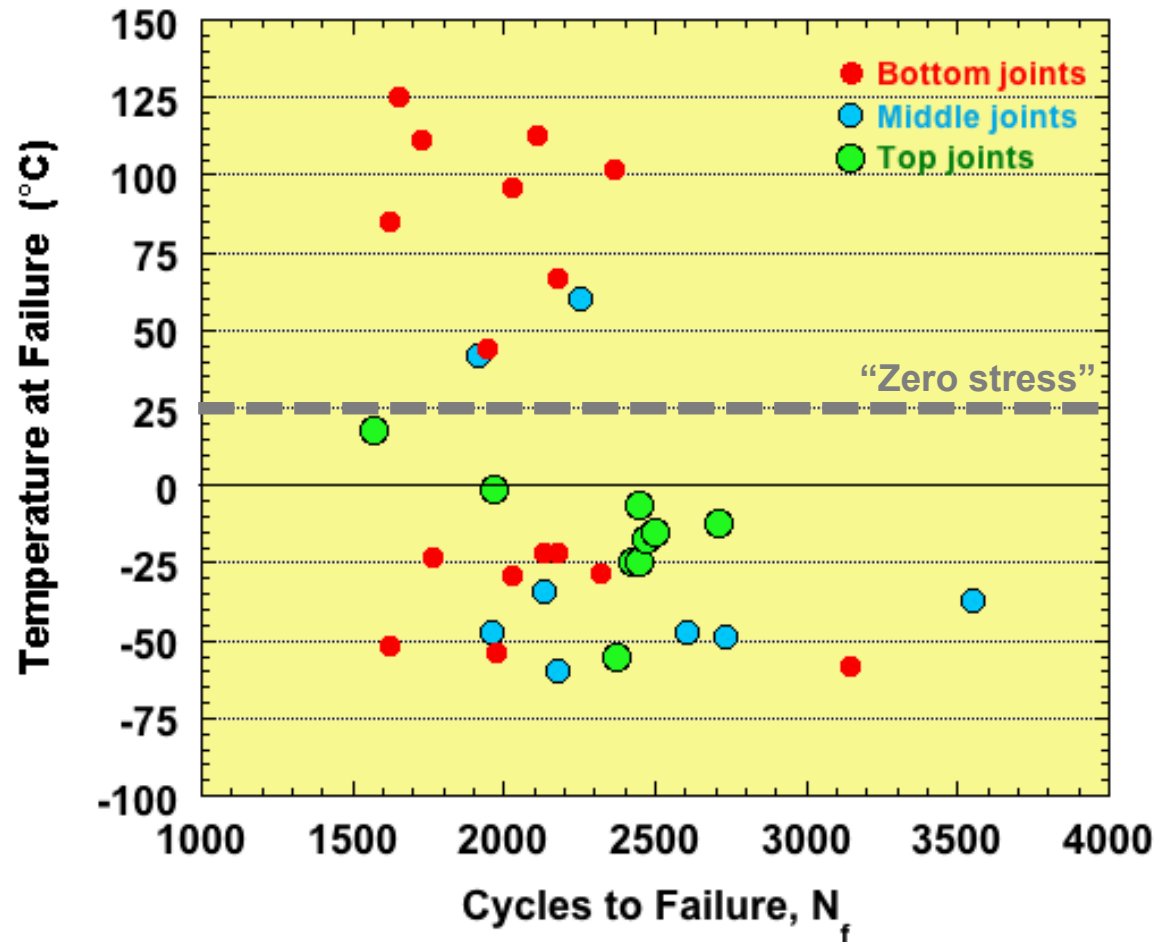
- ◆ 100% SAC305 vs. Mixed SnPb/SAC305 bottom joints; *no underfill*:
- ◆ The SnPb/SAC305 bottom joints exhibited a slightly “better” fatigue behavior (higher values of η and β) than the 100% SAC305 joints.
- ◆ The SnPb/SAC305, **bottom joints** exhibited higher values of both η and β :
 - Mixed SnPb/SAC305:
Bottom joints:
 $\eta = 2600 \pm 200$ cycles
 $\beta = 7.6 \pm 3.5$
 - 100% SAC305:
Bottom joints:
 $\eta = 2200 \pm 200$ cycles
 $\beta = 5.2 \pm 2.0$



Results – Failure Mode Analysis

◆ 100% SAC305 bottom joints; no underfill:

- The **top** and **middle** solder joints showed the same, slight preference for failure towards the low temperatures.
- The **bottom joints** exhibited failures at the high and low temperatures to relatively a similar degree.



- ◆ The TMF performance of the PoPoP is not coupled between the three levels of interconnections in the absence of underfill.

Results – Statistical Failure Analysis

◆ Mixed SnPb/SAC305 bottom joints; Underfill, bottom gap, only:

- Failure data were collected only for the **middle joints** and **top joints** because the **bottom joints** “out-lived” the other joints.

Top joints:

$\eta = 3100 \pm 300$ cycles

$\beta = 5.5 \pm 2.0$

Middle joints:

$\eta = 3000 \pm 400$ cycles

$\beta = 5.3 \pm 2.1$

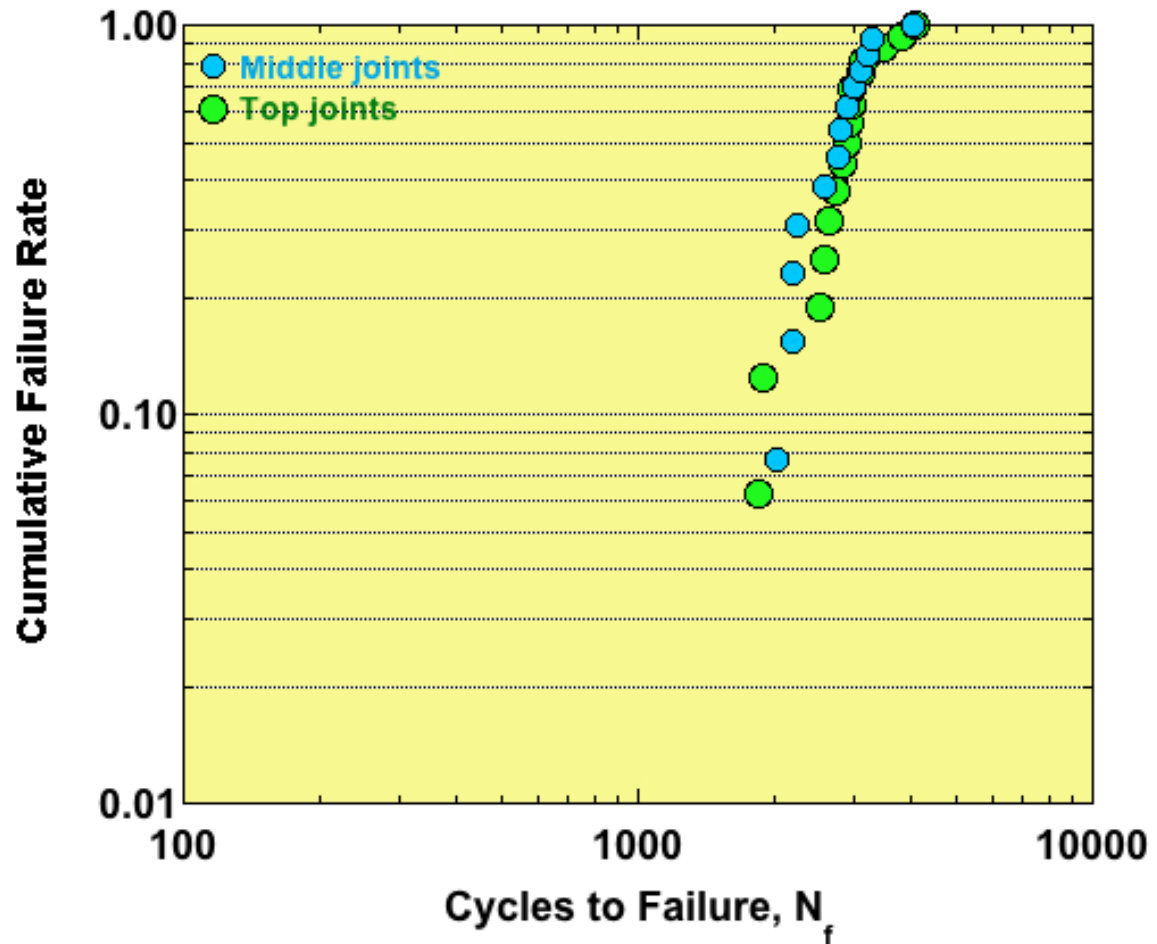
Combined joints:

$\eta = 3200 \pm 300$ cycles

$\beta = 4.8 \pm 1.2$

Bottom joints (N = 1):

$\eta = 4506$ cycles



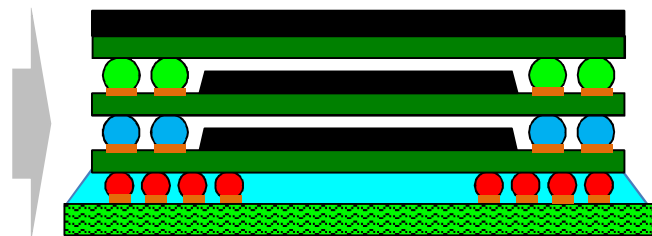
S/N09 and S/N10: Mixed SnPb/SAC305; Underfill, bottom, only

Results – Statistical Failure Analysis

- ◆ Mixed SnPb/SAC305 bottom joints; *Underfill, bottom gap* ... versus ...
Mixed SnPb/SAC305 bottom joints; *No underfill.*

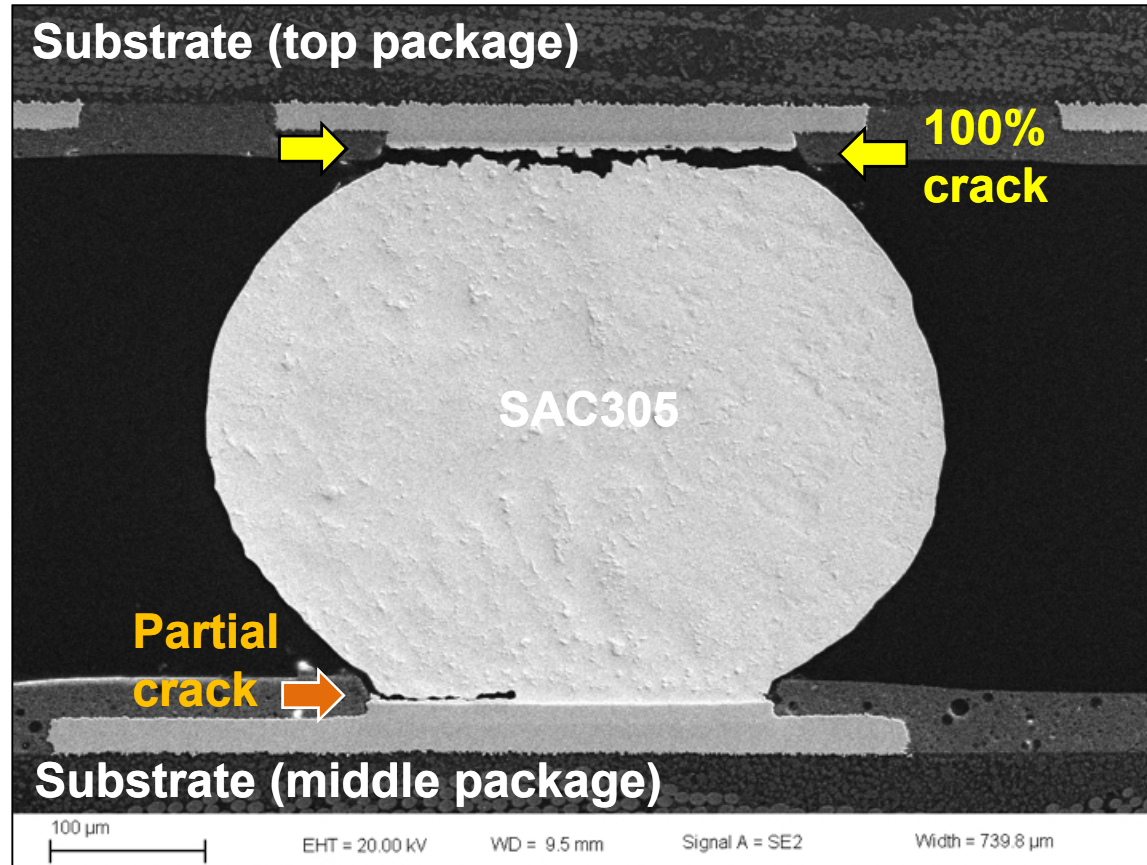
Solder Joint Level	No underfill		Underfill, bottom	
	η	β	η	β
Top solder joints	2600 ± 200	8.7 ± 4.0	3100 ± 300	5.5 ± 2.1
Middle solder joints	2500 ± 300	6.6 ± 3.4	3000 ± 400	5.3 ± 2.1
Bottom solder joints	2600 ± 200	7.6 ± 3.5	3500 (N = 1)	-----

- ◆ The presence of underfill in the bottom gap, only, improved the TMF resistance of all three levels of interconnections.



Results – Failure Mode Analysis

- ◆ **Mixed SnPb/SAC305 bottom joints; Underfill, bottom gap, only:**
The **top solder joints** failed by a “100% crack” at the top pad.

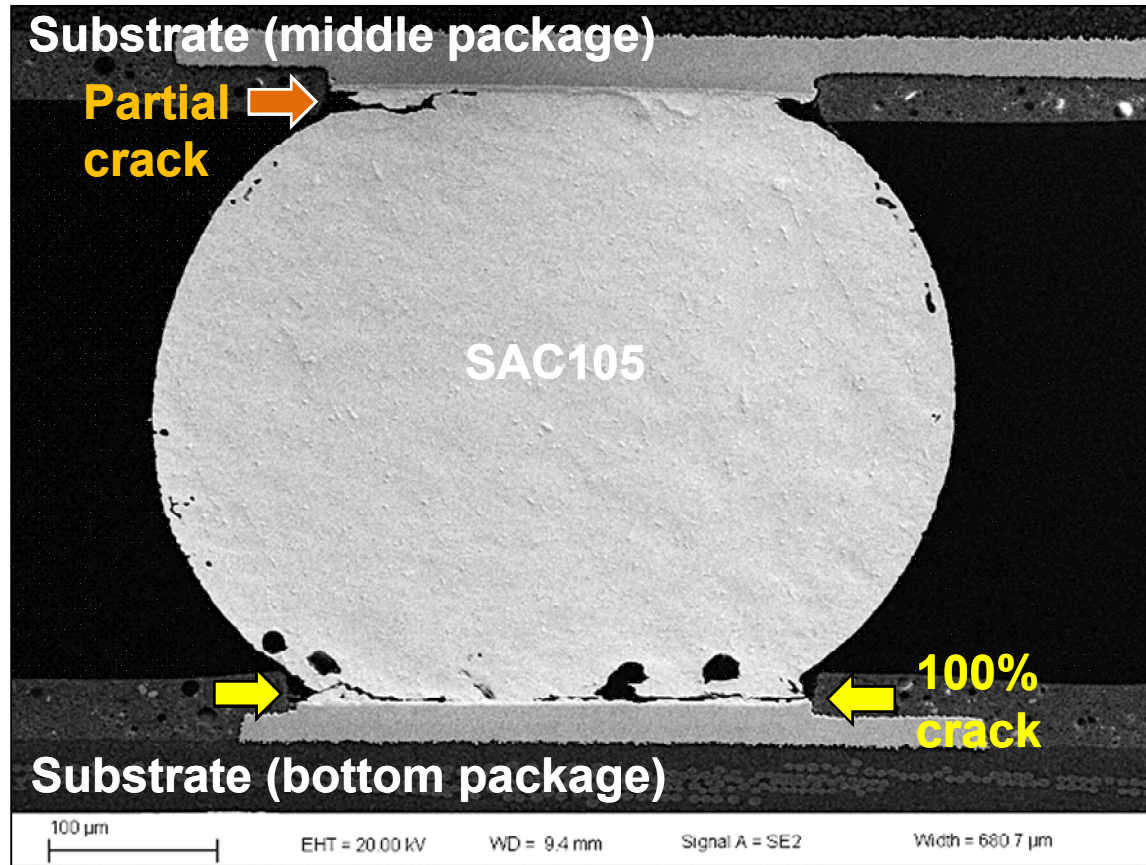


*S/N10, U10A, top;
Underfill, bottom;
Failed: ≥ 4506 cycles*

- ◆ **A partial crack was observed at the bottom pad (middle package).**

Results – Failure Mode Analysis

- ◆ **Mixed SnPb/SAC305 bottom joints; Underfill, bottom gap, only:**
The **middle joints** failed by a “100% crack” at the bottom pad.

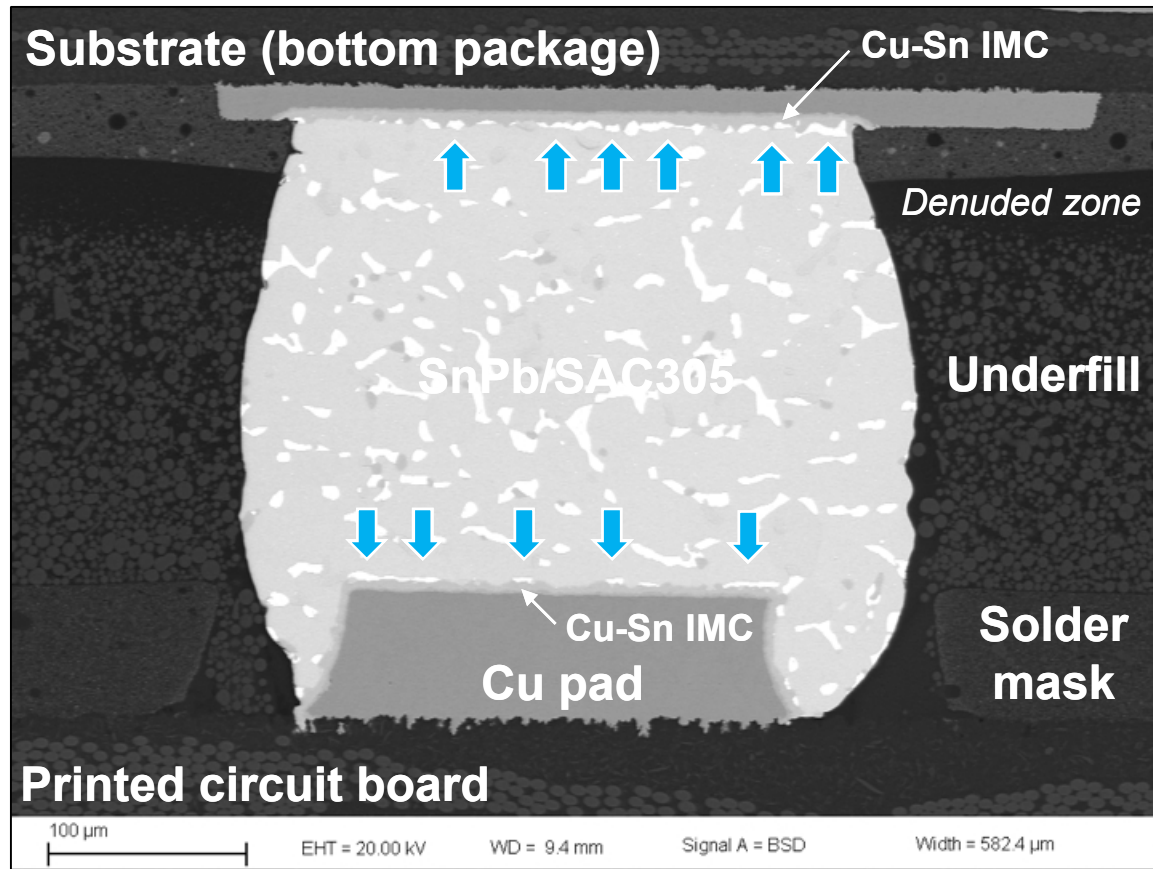


*S/N10, U10A, top;
Underfill, bottom;
Failed: ≥ 4506 cycles*

- ◆ **A partial crack was observed at the top pad (top package).**

Results – Failure Mode Analysis

- ◆ Mixed SnPb/SAC305 bottom joints; Underfill, bottom gap, only:
- ◆ The **bottom solder joints** had not failed; but, they did exhibit the development of the Pb-rich layer ahead of IMC growth (blue arrows.)



Results – Statistical Failure Analysis

- ◆ 100% SAC305 bottom joints; Underfill, bottom gap, only:
- ◆ The **bottom solder joints** were the life-limiting interconnections.

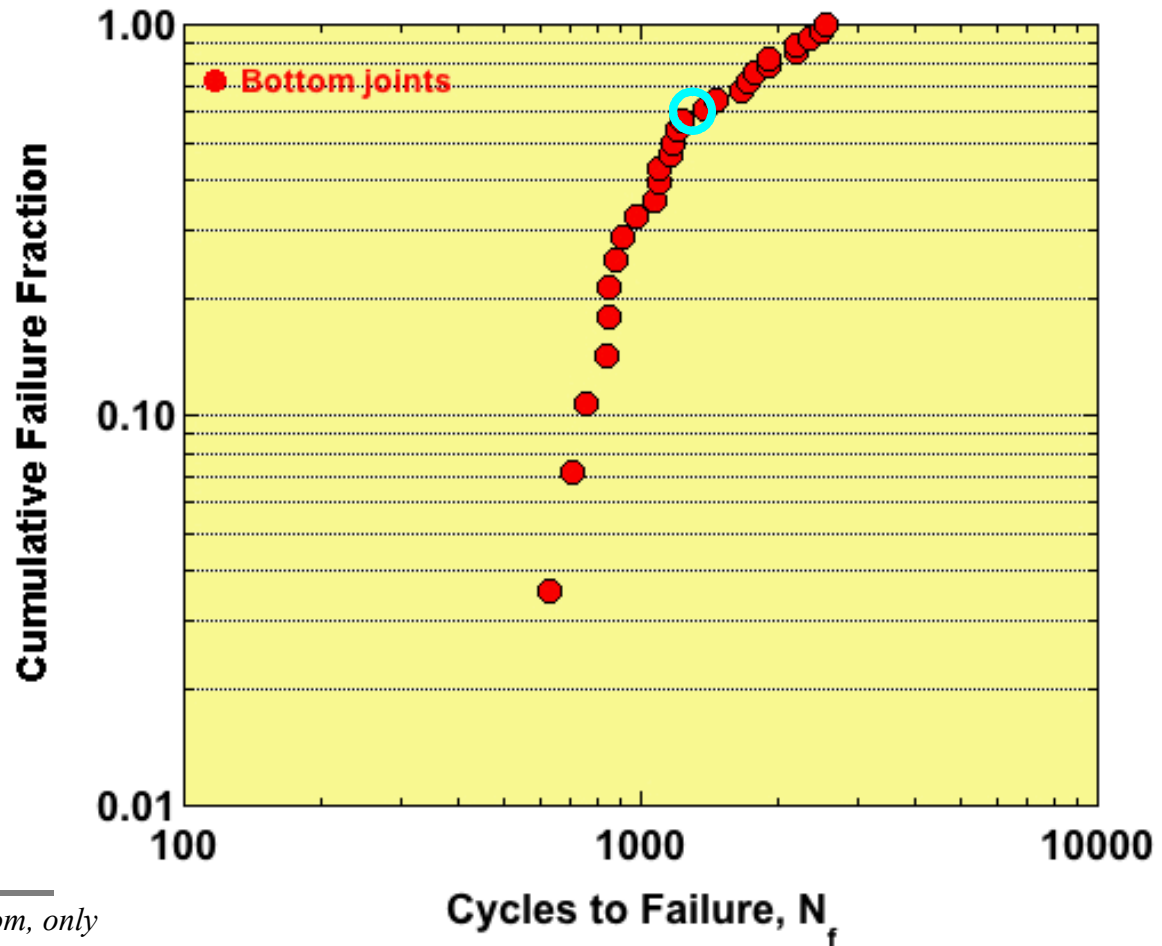
- 2P Weibull failure statistics are shown for the **bottom joints**.

Bottom joints:

$$\eta = 1600 \pm 200 \text{ cycles}$$

$$\beta = 2.7 \pm 0.8$$

- The interconnections had a relatively low η value very wide failure distribution (low β).
- A “knee” is observed at a cumulative failure fraction (CFF) ≈ 0.6 , or 1300 cycles.



S/N33 and S/N36: 100% SAC305; Underfill, bottom, only

Results – Statistical Failure Analysis

- ◆ 100% SAC305 bottom joints; Underfill, bottom gap, only:

- ◆ A "knee" CFF plot *suggests* that the solder joint TMF is governed by **two failure mechanisms**.
- ◆ The 2P Weibull failure statistics were recalculated, assuming that there were two populations:

CFF < 0.6 (N = 16):

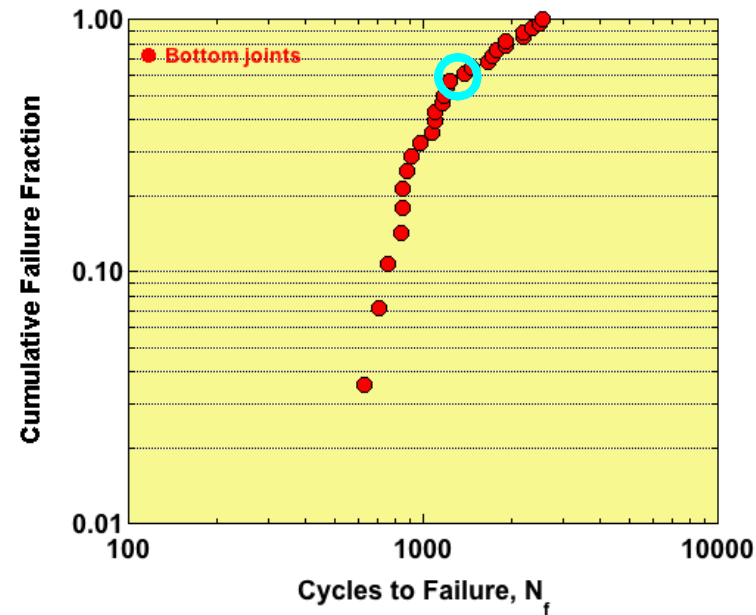
$\eta = 1000 \pm 100$ cycles

$\beta = 6.3 \pm 2.5$

CFF < 0.6 (N = 12):

$\eta = 2100 \pm 200$ cycles

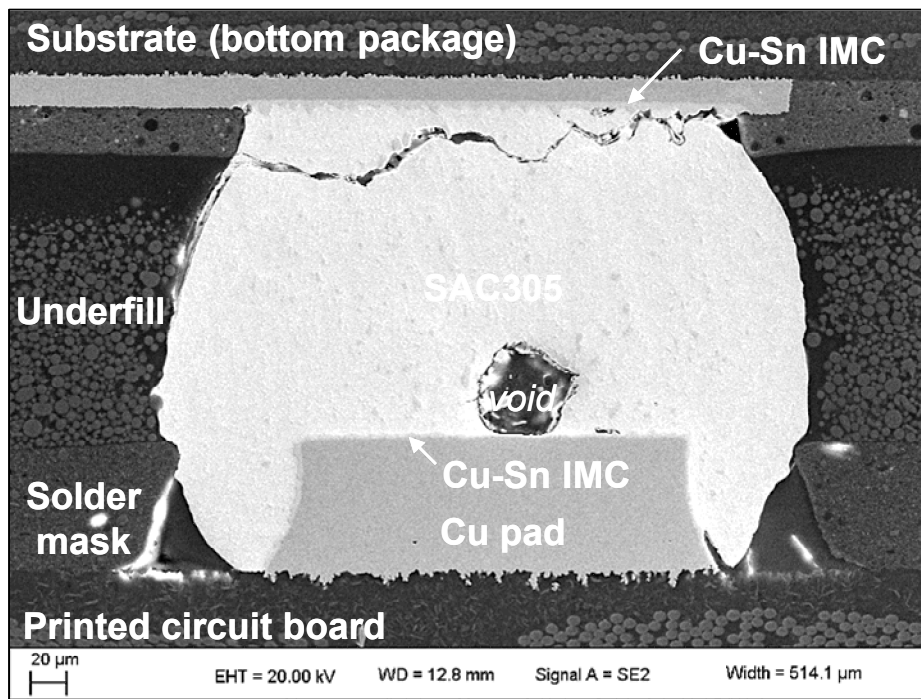
$\beta = 6.0 \pm 2.6$



- ◆ The "high- η " mechanism must avoid the "low- η " mechanism.
- ◆ Since both failure regimes had similar populations, it is inferred that any solder joint has roughly an equal chance of failing under either mechanism.

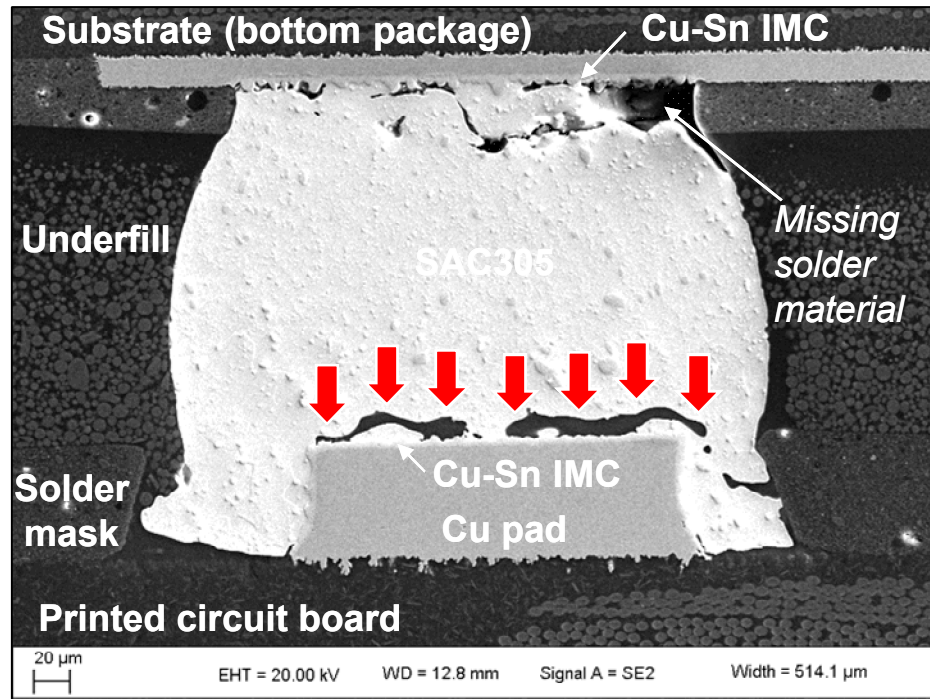
Results – Failure Mode Analysis

- ◆ 100% SAC305 bottom joints; Underfill, bottom gap, only:
- ◆ The microstructures were examined, which belonged to both “high- η ” and “low- η ” mechanisms.



100% SAC305; S/N33, U14 Underfill, bottom, only

“Low- η ” mechanism



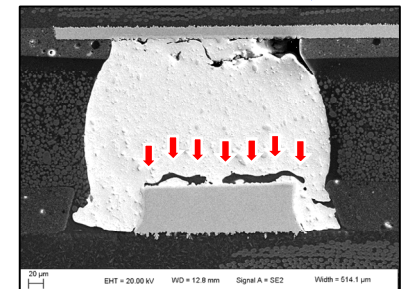
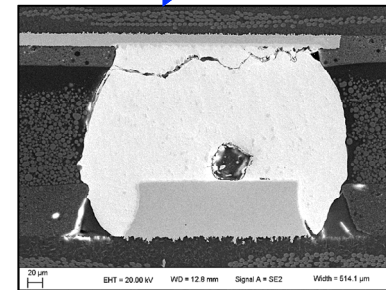
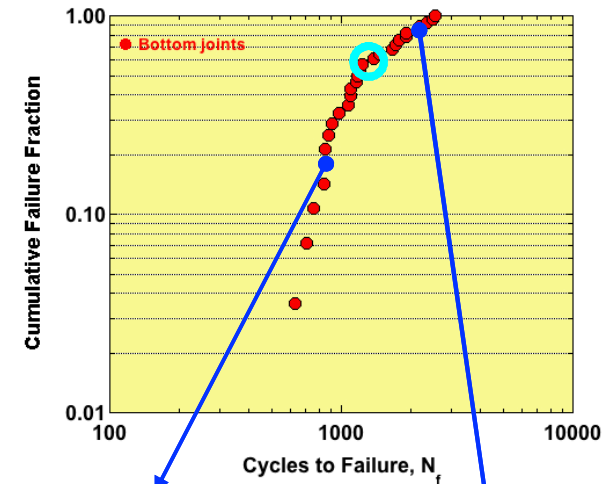
100% SAC305; S/N33, U01 Underfill, bottom, only

“High- η ” mechanism

- ◆ The “high- η ” mechanism included cracks at the Cu pad (red arrows).

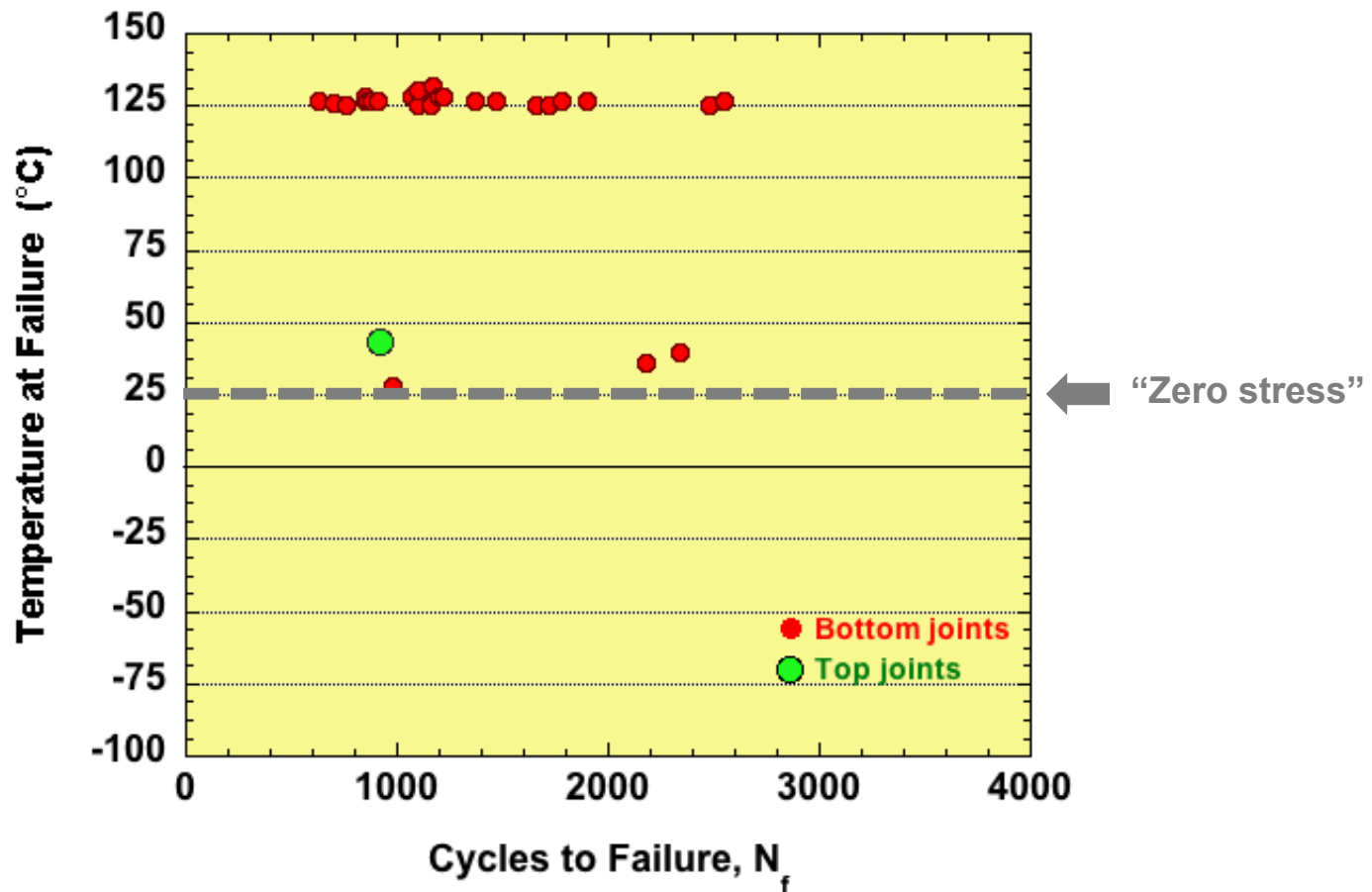
Results – Statistics versus Failure Mode

- ◆ 100% SAC305 bottom joints; Underfill, bottom gap, only:
- ◆ Several observations were compiled along with their consequences:
 - The $T_{\max}$ of the cycle, 125°C, exceeds the underfill T_g of 120°C
 - Tensile stresses due to the sharp increase of CTE generate the Cu pad cracks.
 - Greater solder joint damage was associated with a longer fatigue life.
 - “Early” damage can reduce fatigue strain by decoupling the structures (PCB, solder joint, and package) from one-another.
 - Yet, only 43% of PoPoPs were “high- η ”.
 - The glass transition “zone,” coupled with the complex construction of the PoPoP, caused this bimodal failure behavior to prevail as an “edge-of-the-cliff” behavior.



Results – Failure Mode Analysis

- ◆ 100% SAC305 bottom joints; Underfill, bottom gap, only:
- ◆ The temperature-at-failure data indicate that **tensile stresses** due to underfill thermal expansion affected bottom solder joint TMF.



Summary

- ◆ A long-term study is underway to develop a toolset for predicting the reliability of **stacked package technology**.
 - **Package-on-package (PoP).**
 - **Package-on-package-on-package (PoPoP).**
 - **Thermal mechanical fatigue (TMF).**
 - **Accelerated aging empirical data.**
 - **Computational modeling codes and software.**

- ◆ Some constructions are unique to high-reliability applications:
 - **Backwards compatibility.**
 - **Test environments.**
 - **Use of underfill materials and staking compounds.**
 - **Conformal coatings on PWA.**

Summary (con't)

- ◆ The backwards compatible, mixed SnPb/SAC305 bottom solder joints had a longer TMF lifetime than did the 100% SAC305 joints.
 - The middle and top interconnections exhibited comparable TMF lifetimes for both test vehicle genres.
- ◆ Placement of underfill in the bottom gap increased the characteristic lifetimes (η) of top, middle, and bottom for the mixed Sn-Pb/SAC305 solder joints.
 - The slope parameter (β) decreased with the addition of underfill to the bottom gap.
- ◆ The presence of underfill in the bottom gap caused the 100% SAC305 bottom solder joints to exhibited a bimodal failure mode – a “high- η ” mechanism and a “low- η ” mechanism.
 - No underfill: $\eta = 2200 \pm 200$ cycles
 - Underfill, “low- η ” mechanism: $\eta = 1000 \pm 100$ cycles
 - Underfill, “high- η ” mechanism: $\eta = 2100 \pm 200$ cycles

Summary (*con't*)

- ◆ **The bimodal failure mode of the 100% SAC305 bottom solder joints with underfill was correlated to different fracture microstructures..**