Power Module Finite-Element Predictive Modeling

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2/01/2023

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ENGINEERING FUN

Bad Electrical Engineers become…

Good Electrical Conductors

What do you call someone who steals a charging station?

A Joule Thief

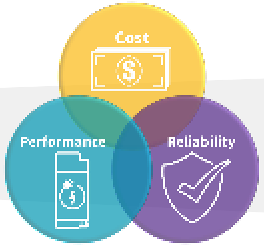
Have you heard about Ford's new electric coffee car?

It's the Mach-E Auto

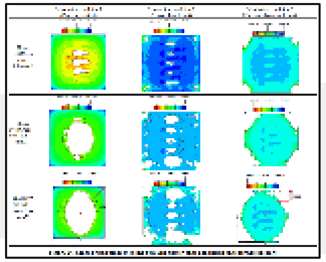
OVERVIEW

WOLFSPEED AT A GLANCE

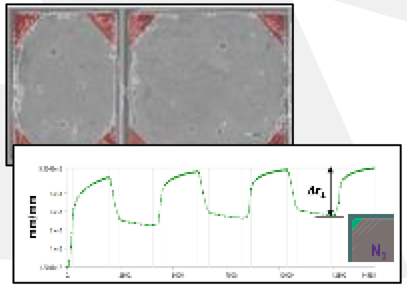
PURPOSE OF PREDICTIVE MODELING



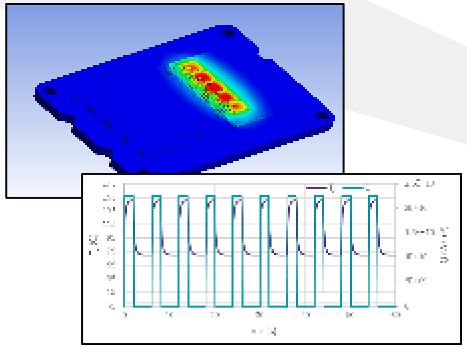
BACKGROUND AND PREVIOUS WORK



THERMAL SHOCK PREDICTION



POWER CYCLING PREDICTION



SUMMARY

WOLFSPEED AT A GLANCE

Company Overview

241.3M
FY23 Q1 Revenue

World's First, Largest & Only 200mm Silicon Carbide Fab

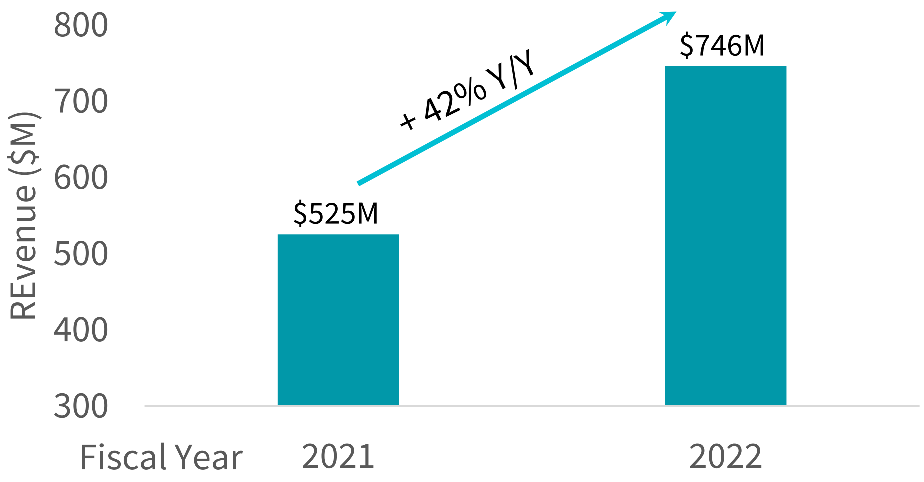
$1.3B Materials Capacity Expansion

Partnership with Jaguar Land Rover

First Fully Qualified Silicon Carbide MOSFET in 2011

> 2,100 Patents
Substantial IP Position

Wolfspeed Annual Revenue (M)



By the Numbers

#1
Producer of Silicon Carbide substrates

>60%
Wolfspeed makes more than 60% of the worlds Silicon Carbide today

>90%
Wolfspeed manufactured >90% of the Silicon Carbide ever produced

400 years
Crystal growth team has 400 combined years of Silicon Carbide growth experience

35+ years
Wolfspeed has been vertically integrated making Silicon Carbide semiconductors

7+ trillion
Silicon Carbide device field hours

PURPOSE OF PREDICTIVE MODELING

- Reduce product cost
- Accelerate time to market by minimizing testing time and resources

- Quantify impact of material, geometry, or feature trade-offs
- Predict performance characteristics

- **Estimate fatigue and lifetime**
- Minimize over design

SOLDER FATIGUE PRIOR WORK

- Coupled physics approach with electrical, thermal, and mechanical physics
- Methodology used for both **TC** and **PC** loading conditions
- **Creep and plastic strain values** derived in FEA and combined **Coffin-Manson** equation for fatigue prediction within Abaqus
- **Ball Grid Array (BGA)** test vehicles were used in order to investigate the fatigue characteristics of **SnAgCu** solder and relationships between number of cycles and the initiation of fatigue cracking and strain range

The **Coffin-Manson equation** is the most popular equation in literature for predicting solder joint fatigue:

$$N_f = A(X)^B$$

N_f = number of cycles to failure
A and B = constants
X = damage metric

A. Perkins, "Investigation…", PhD Dissertation, GIT 2007.

Engineering, 2010, 2, 1006-1018
doi:10.4236/eng.2010.212127 Published Online December 2010 (http://www.scirp.org/journal/eng).

Scientific Research

Evaluation of Fatigue Life of Semiconductor Power Device by Power Cycle Test and Thermal Cycle Test Using Finite Element Analysis

Kazunori Shinohara[1], Qiang Yu[2]

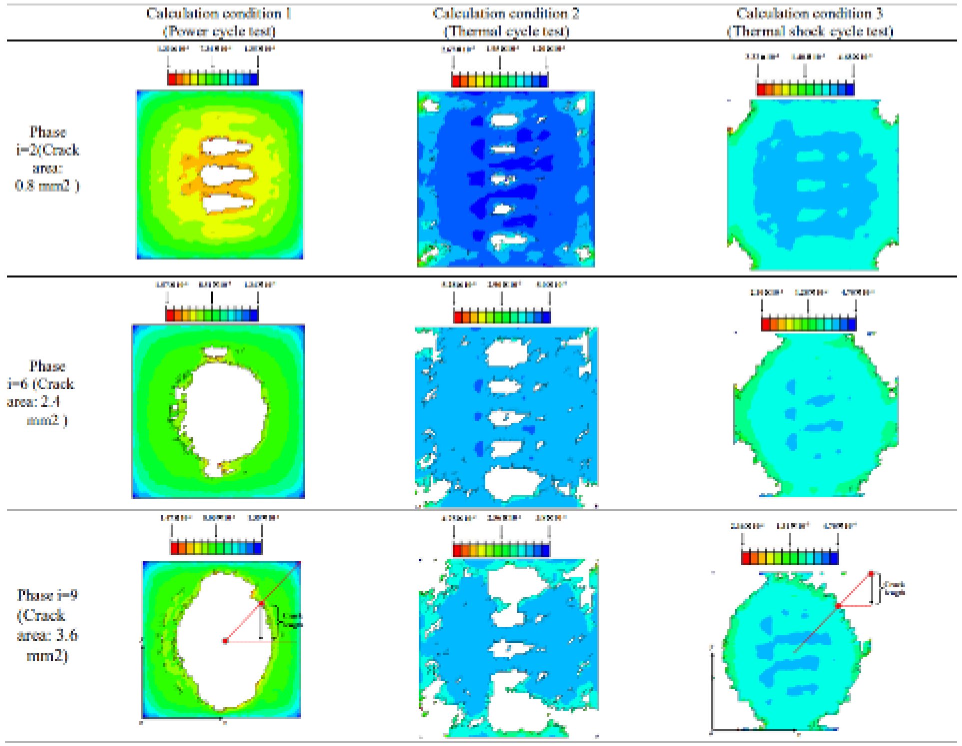
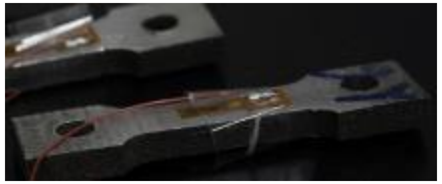


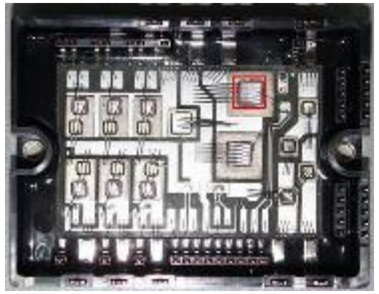
Figure 24. Crack propagation on solder between copper plate and silicon plate (creep contour).

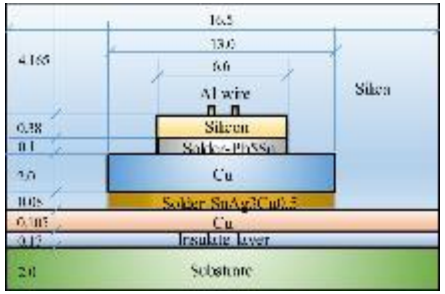
SOLDER FATIGUE PRIOR WORK – CONT.

- Dedicated coupon material testing used to determine stress-strain vs temp and creep of SAC and applied to power module model
- TC load (-40 °C to 120 °C) applied in FEA model
- Fatigue life was predicted using **accumulated creep strain** and **creep strain energy density** estimated with FEA simulation and a hyperbolic sine power law

Test Coupon for Material Characterization







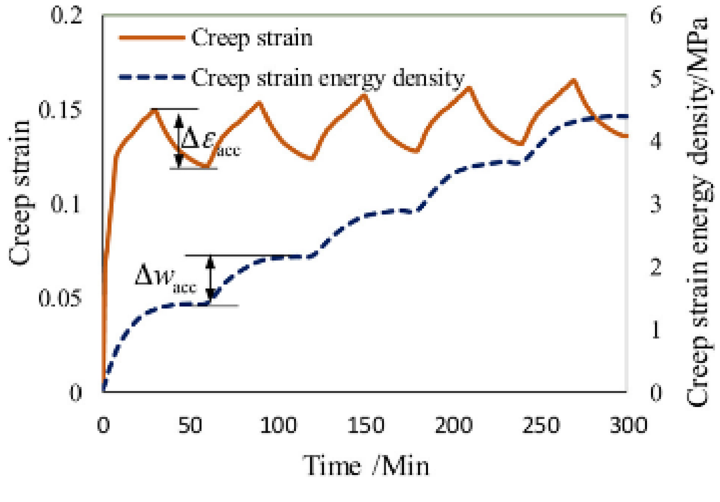


Fig. 17 – Creep strain and creep strain energy density with temperature cycles.

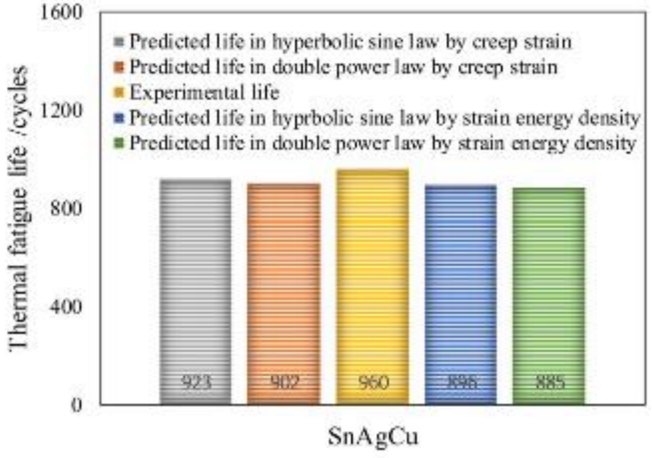
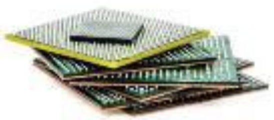


Fig. 19 – Comparison of thermo-mechanical fatigue lives from the FEM simulation and the test.

SOLDER FATIGUE PRIOR WORK – CONT.

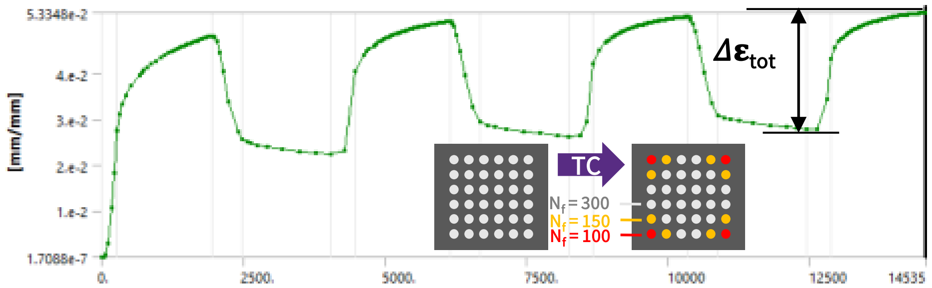
INVESTIGATION AND PREDICTION OF SOLDER JOINT RELIABILITY FOR CERAMIC AREA ARRAY PACKAGES UNDER THERMAL CYCLING, POWER CYCLING, AND VIBRATION ENVIRONMENTS

Andrew Eugene Perkins



- Original method developed for **BGA style** packages
- Experimental N_f based on ten samples varying sub size, sub thickness, board thickness, pitch…
- Damage metric for fatigue life prediction: **total strain range** ($\boldsymbol{\Delta\varepsilon}_{tot}$)
  – $\boldsymbol{\Delta\varepsilon}_{tot} = \boldsymbol{\Delta\varepsilon}_{e} + \boldsymbol{\Delta\varepsilon}_{in}$ (strain data taken at last cycle)
- Coffin-Manson style power law for cycles to failure (N_f)
  – Model based on Pb90Sn10

Modeled Creep strain for solder ball



Experimental Cycles to Failure

Case [ref.]	Substrate Size (mm)	Substrate Thickness (mm)	Board Thickness (mm)	Pitch (mm)	Lid	Load	Die	$N50_{exp}$
1 [133]	42.5x42.5	3.0	1.57	1.27	-	-55/110 2cph	-	763
2 [133]	42.5x42.5	1.4	2.79	1.27	-	-55/110 2cph	-	895
3 [133]	42.5x42.5	1.4	1.57	1.27	-	-55/110 2cph	-	1035
4 [133]	42.5x42.5	3.0	2.79	1.27	Yes	-55/110 2cph	-	715
5 [133]	42.5x42.5	3.0	1.57	1.27	Yes	-55/110 2cph	-	636
6 [133]	42.5x42.5	1.4	1.57	1.27	Yes	-55/110 2cph	-	607
7 [in-house]	42.5x42.5	4.0	2.79	1.27	Yes	-25/105 2cph	-	1148
8 [49]	40.0x40.0	2.3	1.5	1.27	Yes	0/100 2cph	Y	1730
9 [49]	40.0x40.0	2.3	3.6	1.27	Yes	0/100 2cph	Y	2290
10 [49]	40.0x40.0	2.3	3.6	1.27	Yes	0/100 2cph PC	Y	11000

Exp. CTF vs Modeled Δε

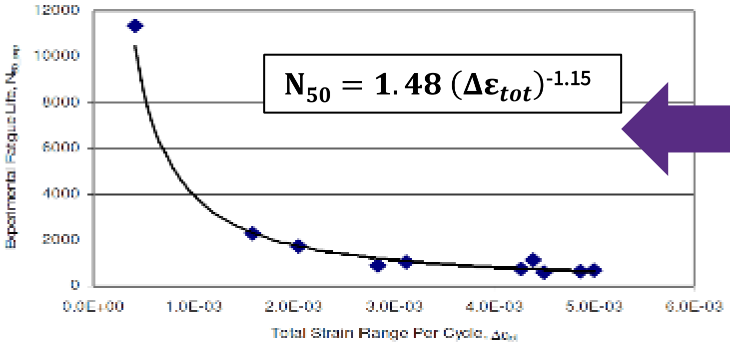


Figure 7-2. Total strain range strain vs fatigue life

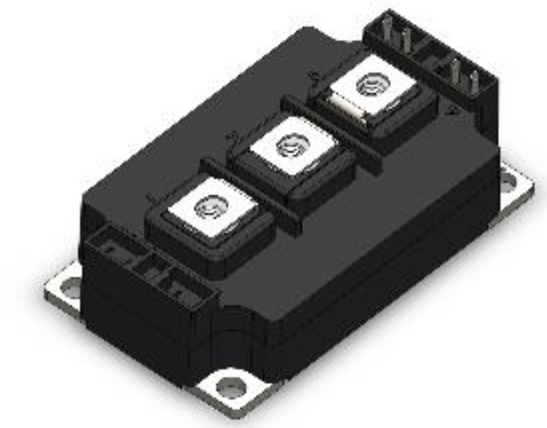
Predictive Model Validation

Case [ref.]	Substrate Size (mm)	Substrate Thickness (mm)	Board Thk. (mm)	Pitch (mm)	Lid	Load	Die	$N50_{exp}$	$N50_{pred}$ (Eq. (7.4))
1 [133]	42.5x42.5	3.0	2.79	1.27	-	-55/110 2cph	-	775	803
2 [133]	42.5x42.5	1.4	2.79	1.27	Yes	-55/110 2cph	-	647	720
3 [134]	52.5x52.5	2.85	2.54	1.00	Direct Lid Attach	0/100 2cph	Y	2000	1975
4 [49]	40.0x40.0	2.3	1.5	1.27	Yes	0/100 2cph PC	Y	7940	7233

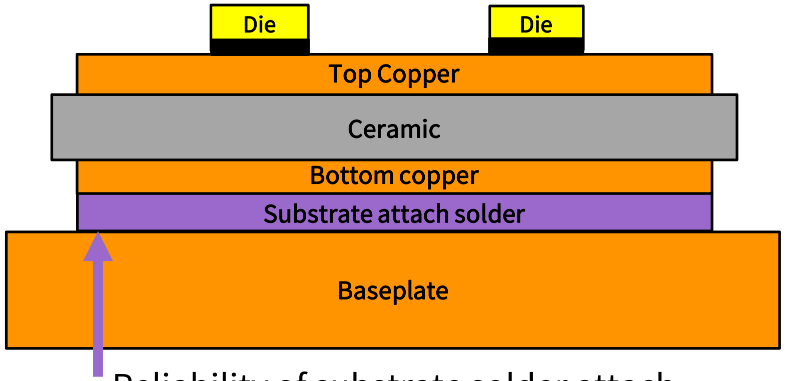
THERMAL SHOCK PREDICTION

SUBSTRATE ATTACH DEGRADATION

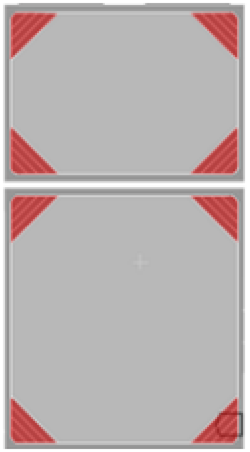
SUBSTRATE ATTACH DEGRADATION OVERVIEW



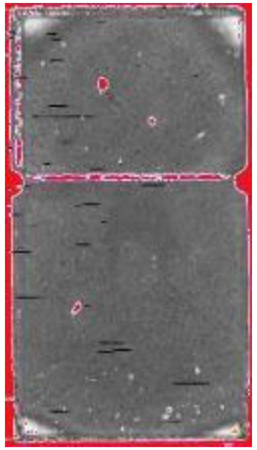
Power Module Example



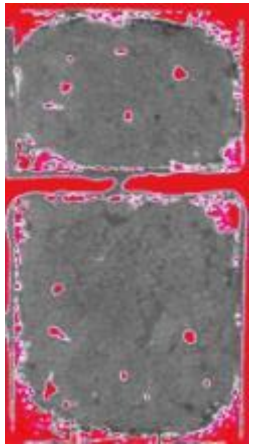
Reliability of substrate solder attach layer is focus of this work



Substrate attach solder



CSAM Time zero



CSAM post 1000 TST

Motivation: Number of Thermal Shock cycles to failure (N_f) analysis of power module substrate attach layer

- Specifically looking at power substrate solder attach cycles to failure

- Thermal Shock Test (AQG 324) will be used as thermal and mechanical loading

THERMAL SHOCK TEST CONDITIONS

- AQG324 Thermal Shock Test
- Dual chamber system that moves power modules from HT chamber to LT chamber inducing thermal stress within module
- Transfer duration, LT dwell, HT dwell temperatures defined by spec
- >1000 cycles to pass (< 20% increase in R_{th})

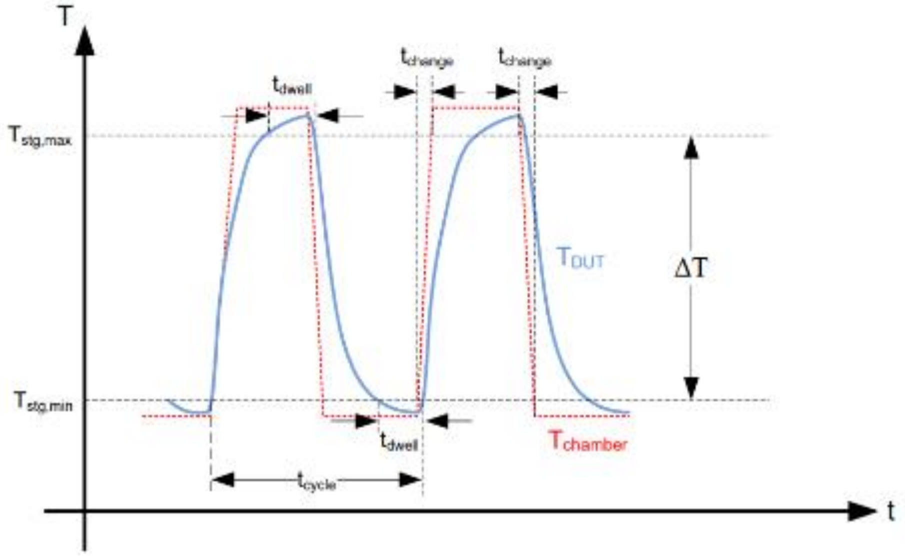
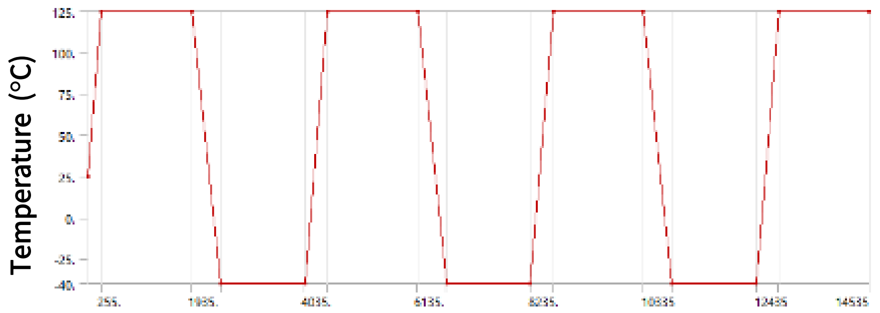


Figure 8.1: Example for TST temperature curve

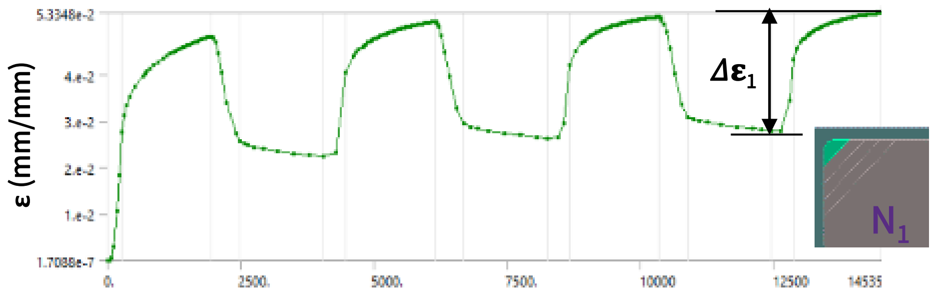
Table 8.1: TST test parameters

Lowest value of the storage temperature	$T_{stg,min}$	$-40°C^{0}_{-10}$
Highest value of the storage temperature	$T_{stg,max}$	$+125°C^{+15}_{0}$
Transfer duration	t_{change}	< 30 s
Minimum dwell time for highest/lowest temperature	t_{dwell}	> 15 min
Minimum number of cycles without failures	N_C	> 1000

MODELED SUBSTRATE ATTACH PREDICTION METHOD



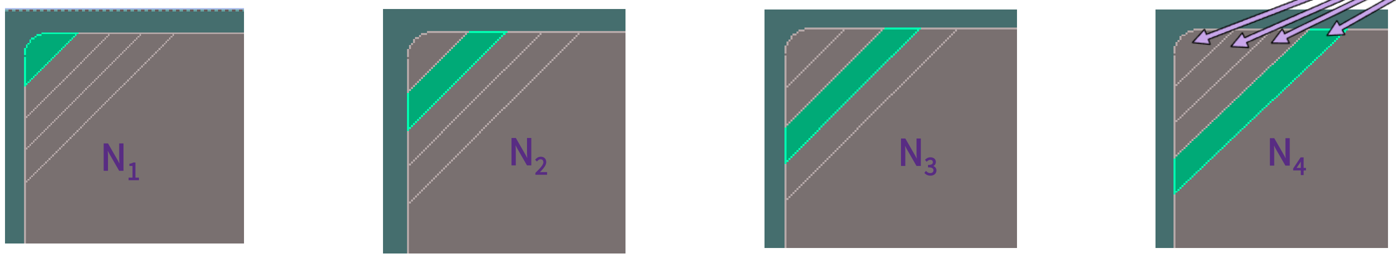
Input cyclic load



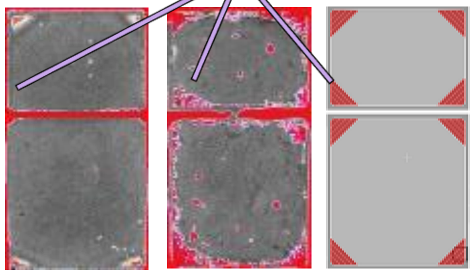
Output maximum creep strain for slice 1

- Temperature cycle input and creep strain output for Ansys Workbench Simulation
- Damage metric for fatigue life prediction: Creep strain range ($\Delta\varepsilon$)
- Total cycles to failure= N1+N2+N3+N4
- Critical solder areas divided into smaller volumes to mimic BGA solder volume
- Model assumption: Inner slices do not accumulate damage until outer slice fails

Critical solder joint concept used



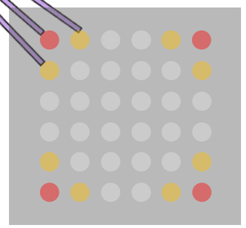
$$N_x = 1.48\,(\Delta\varepsilon_x)^{-1.36}$$



Time zero CSAM

1000 TC CSAM

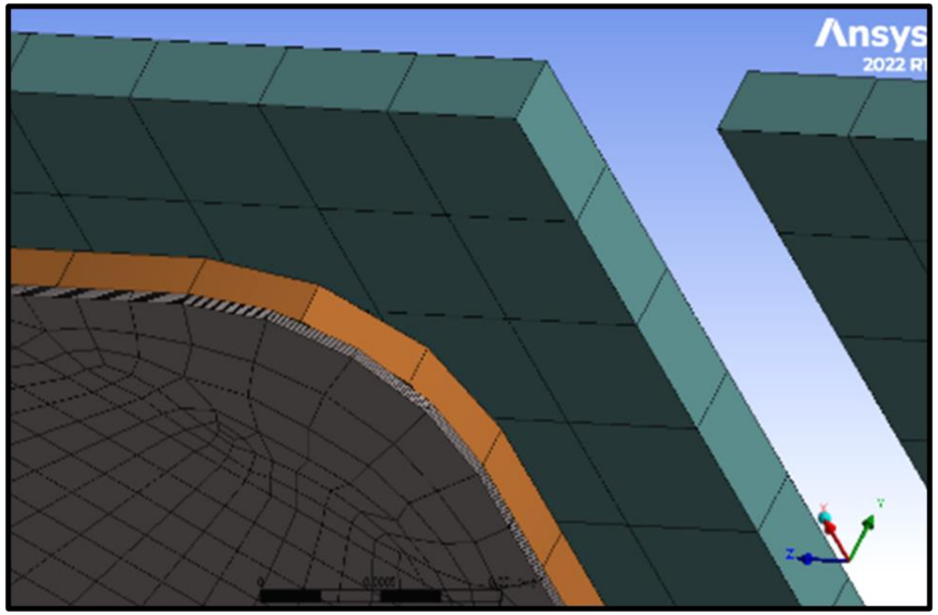
Substrate attach solder bottom view

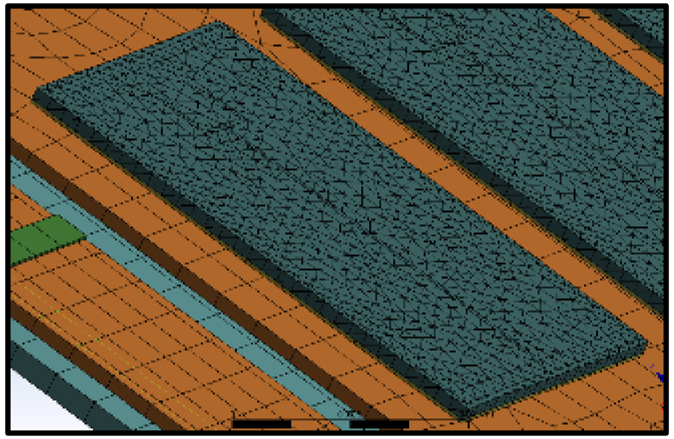


BGA example

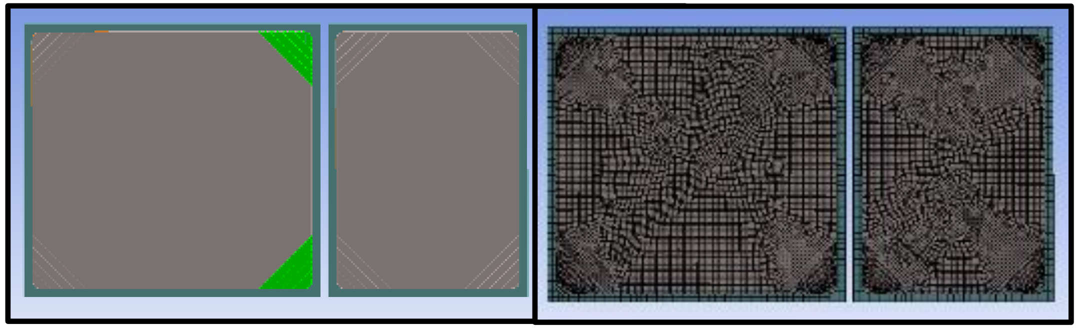
ANSYS FATIGUE MODEL SETUP

- Mesh density optimization was performed to balance accurate results and simulations time
- Mesh density was increased in critical areas
- SiC device details, location, and solder attach represented in CAD geometry
- Substrate solder corner slices remained discrete solids but incorporated into overall solder mesh





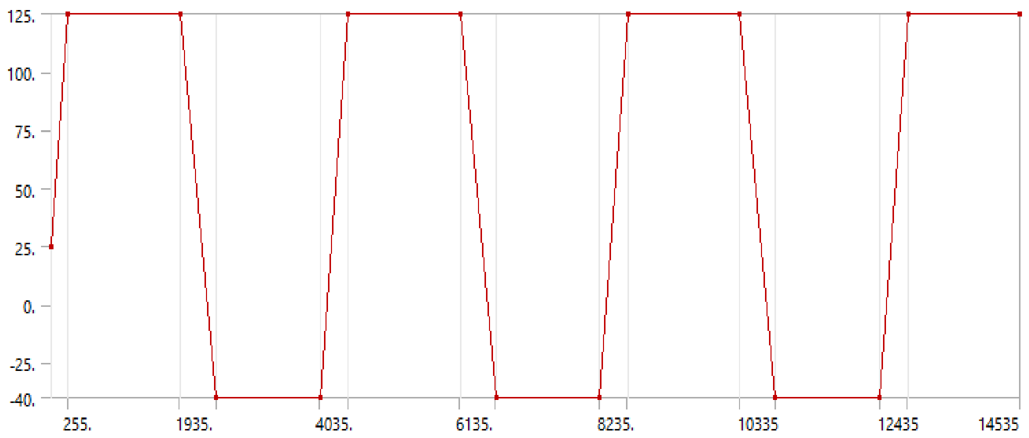
High mesh density in critical corner regions



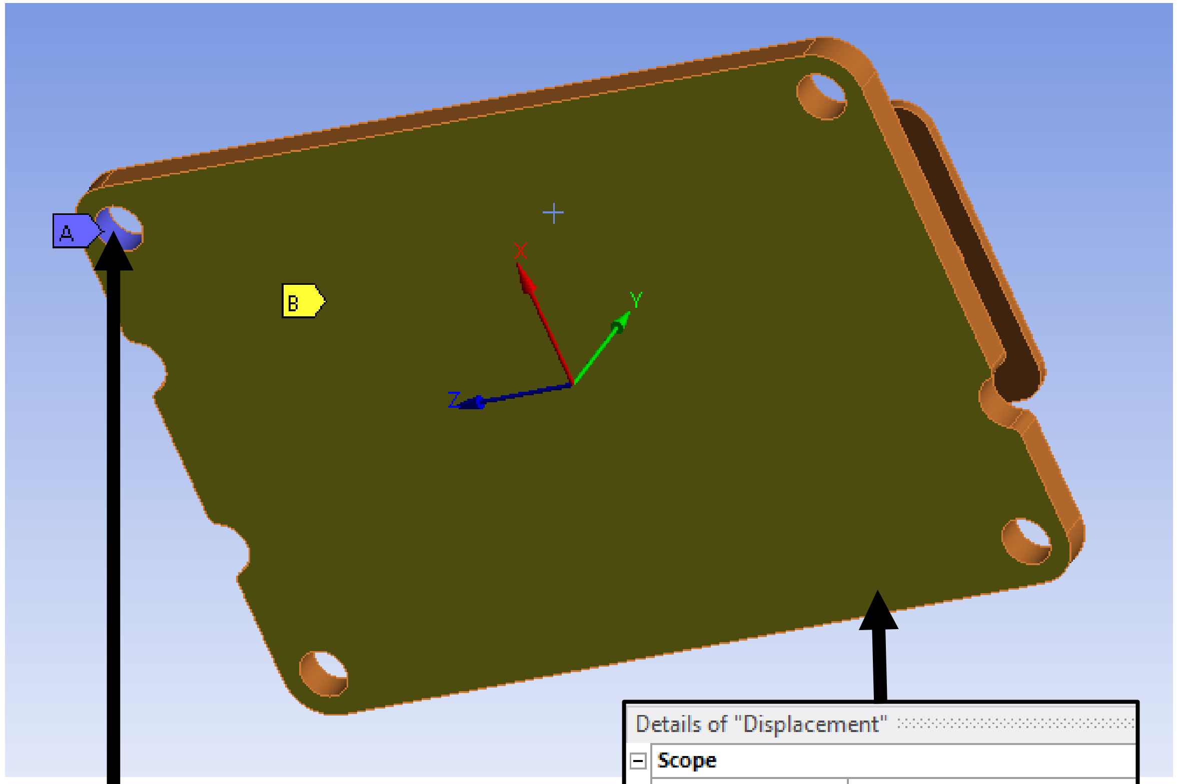
ANSYS FATIGUE MODEL SETUP – CONT.

- Two mechanical boundary conditions used on baseplate
  - Fixed support
  - Fixed y-axis displacement
  - 4 cycles (creep relaxation)
- External cyclic temperature load applied -40 °C to 125 °C

Input cyclic load



Time (s)



Details of "Fixed Support"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Fixed Support
Suppressed	No

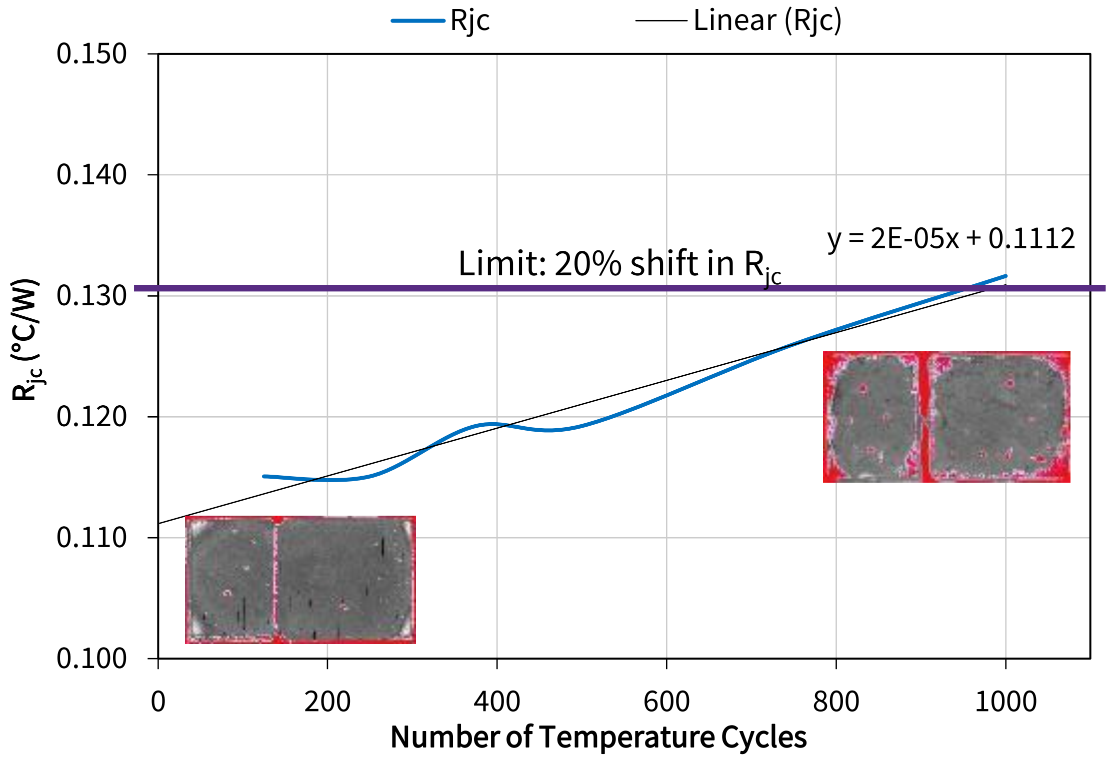
Details of "Displacement"

Scope	
Scoping Method	Geometry Selection
Geometry	1 Face
Definition	
Type	Displacement
Define By	Components
Coordinate System	Global Coordinate System
X Component	Free
Y Component	0. m (ramped)
Z Component	Free
Suppressed	No

EXPERIMENTAL TEST RESULTS

R_{JC} VS THERMAL SHOCK CYCLES

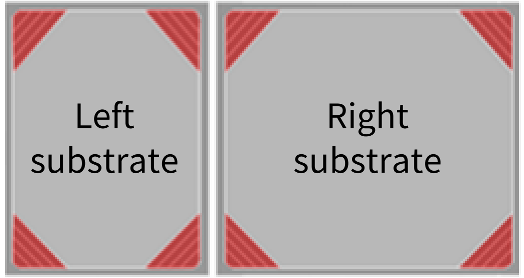
- Cyclic temperature applied: -40 °C to 125 °C
  - Ramp time = 9 min
  - Dwell time = 30 min
- Failure criteria is 20% shift in Rjc over test duration
- R_{JC} was recorded over the Temperature Cycle test
- CSAMs were recorded at each read point
- A trend was established in Rjc vs Temp. Cycles and correlated to CSAM delamination

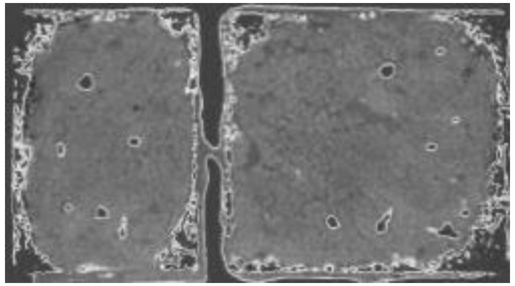


Temperature Cycles	Average Rjf (C/W)	Average Rjc (C/W)
125	0.180	0.115
250	0.180	0.115
375	0.185	0.119
500	0.185	0.119
750	0.191	0.126
1000	0.197	0.132

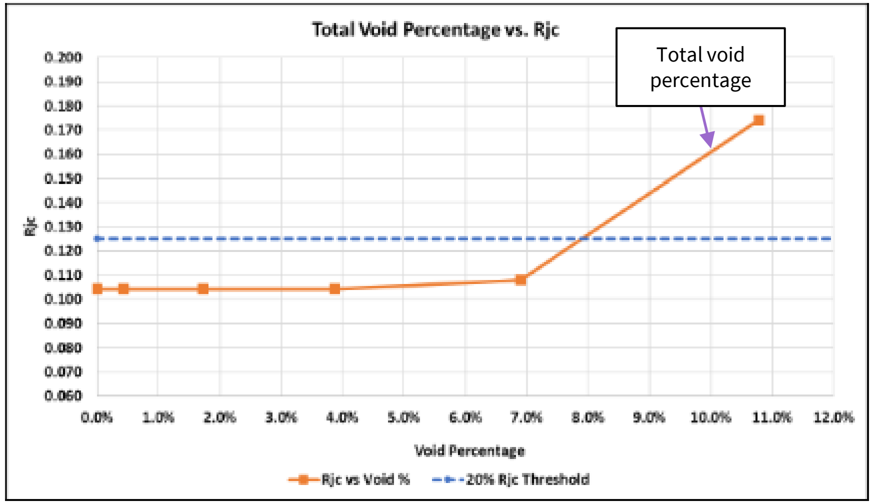
CRITICAL DELAMINATION AREA AND SLICE LOCATIONS

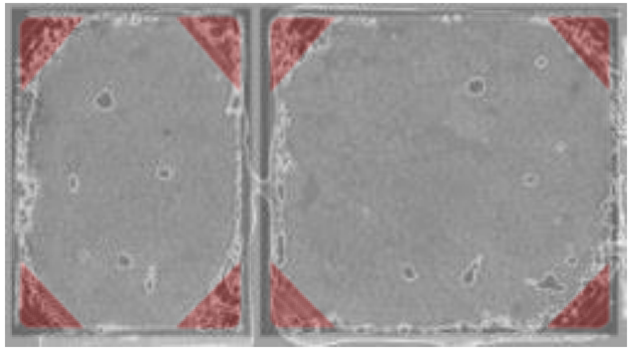
- Static thermal analysis and Rjc data show Tjmax and Rjc significantly increase when delamination occurs under and around die area
- Left substrate shows increased sensitivity due to module layout. Two critical corners identified
- Based on test results, when the 4th critical corner slice delaminates, R_{JC} will increase by 20%





CSAM Post 1000 cycles





Critical Areas - CSAM Overlay

SIMULATION RESULTS

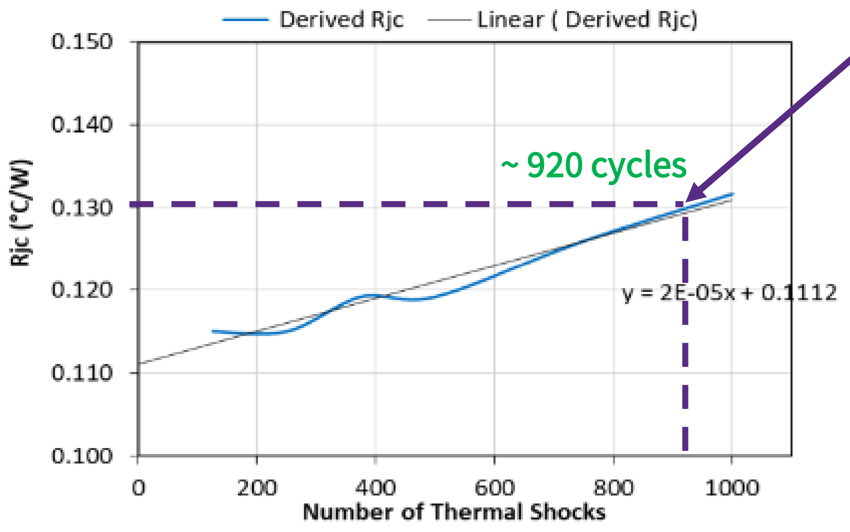
N_f ANALYSIS WITH SUBSTRATE ATTACH SOLDER BONDLINE THICKNESS (BLT) SWEEP

- By adjusting the exponent in the Coffin-Manson equation, the model is matched to the experimental results
- Coffin-Manson Exponent
  - 1-3 Soft metals
  - 3-5 Hard metals
  - 5-8 Brittle materials

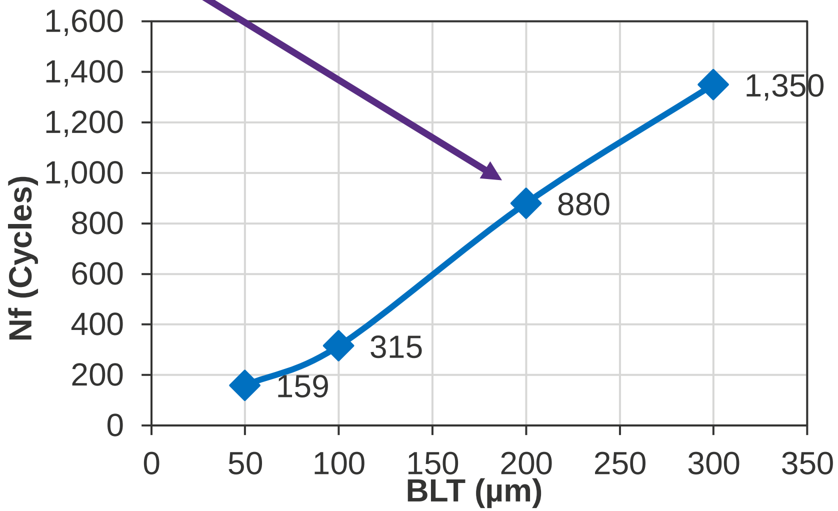
Closely aligns with physical test data

$$N_x = 1.48\,(\Delta\varepsilon_x)^{-1.36}$$

Experimental Results

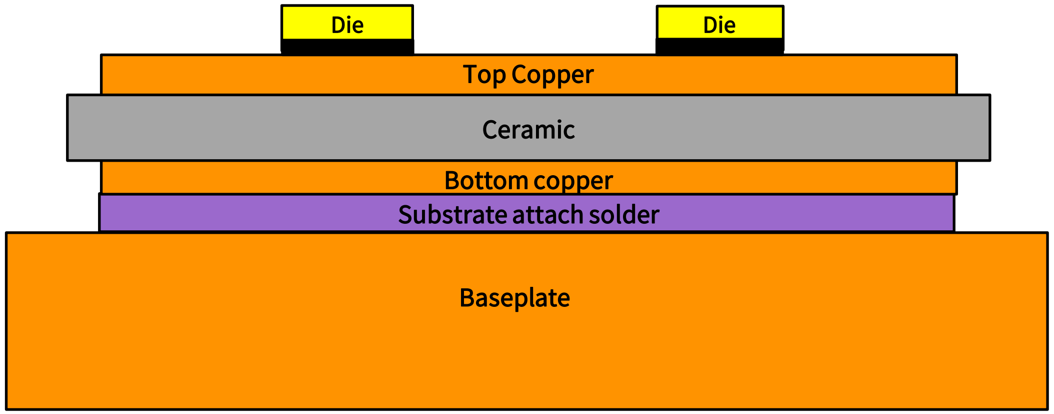


Modeled Results

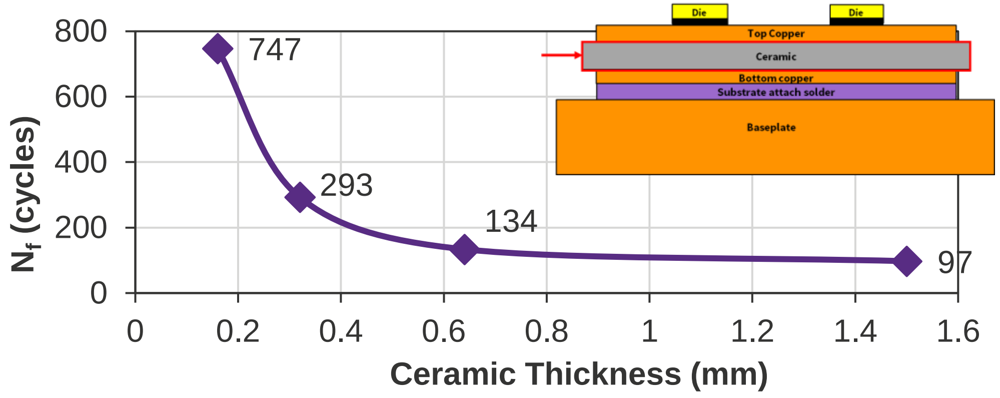


SENSITIVITY STUDY – COMPONENT PARAMETER CHANGE – EFFECT ON N_f

- Secondary components in the material stack were parameterized and swept through geometry conditions
- Cycles to failure prediction was shown to be sensitive to some secondary components
- For absolute prediction accuracy the geometry of secondary components should be accurate and could possibly account for manufacturing variation
- **Parameters**
  - Ceramic thickness
  - Top/Bottom thickness Cu of power substrate
  - Top Cu thickness of power substrate
  - Bottom Cu thickness of power substrate

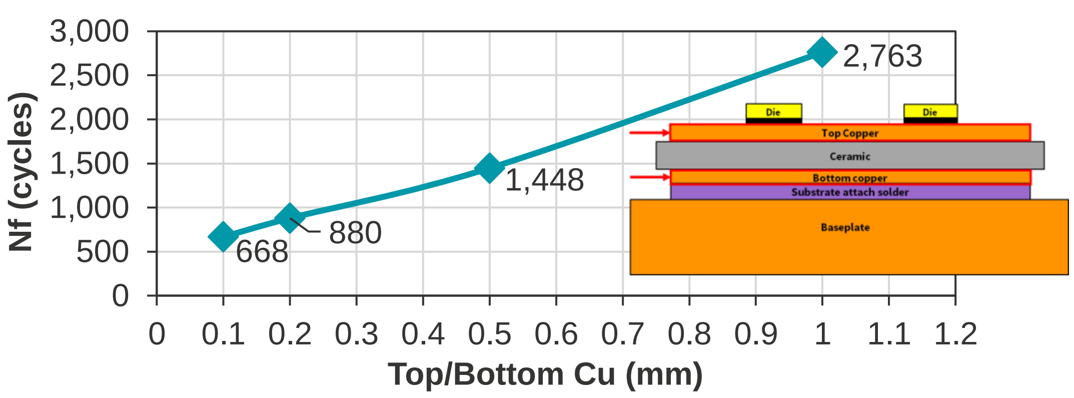


SENSITIVITY STUDY – COMPONENT PARAMETER CHANGE – EFFECT ON N_f



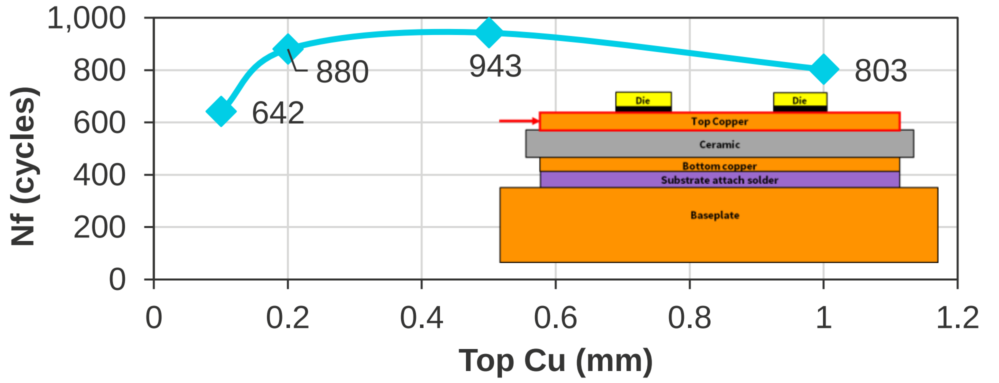
N_f VS CERAMIC THICKNESS

Substrate ceramic thickness predicted to negatively impact cycles to failure results



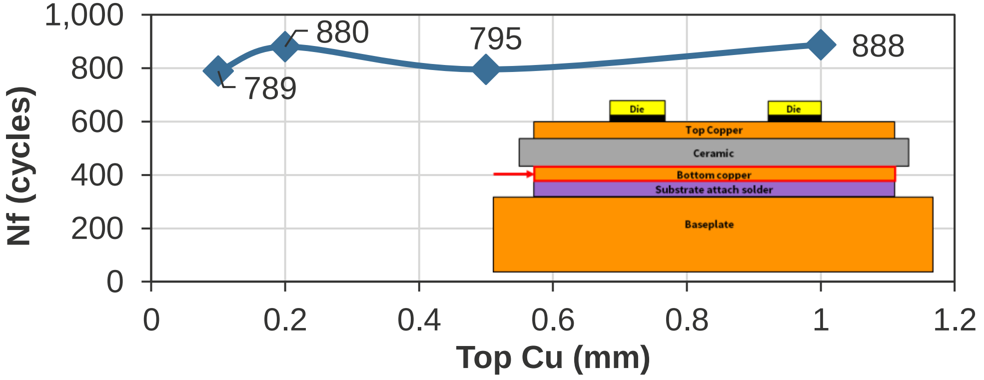
N_f VS TOP/BOTTOM Cu THICKNESS

Symmetric increase of substrate Cu metal predicted to positively impact cycles to failure results



N_f VS TOP Cu THICKNESS

Increase of substrate top Cu metal only predicted to marginally impact cycles to failure results



N_f VS BOTTOM Cu THICKNESS

Increase of substrate bottom Cu metal only predicted to marginally impact cycles to failure results

POWER CYCLING SEC PREDICTION

WIRE BOND INTERCONNECTION DEGRADATION

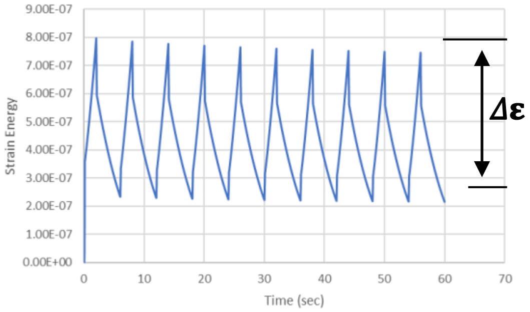
PC FATIGUE MODEL OVERVIEW

- **Motivation** – Predict the PC life due to wire bond fatigue
- **Approach**
  - Acquire experimental data from different PC conditions and geometries
  - Model different cases (5 cases)
  - Create model from damage metric ($\Delta\varepsilon_{tot}$) using Coffin-Manson

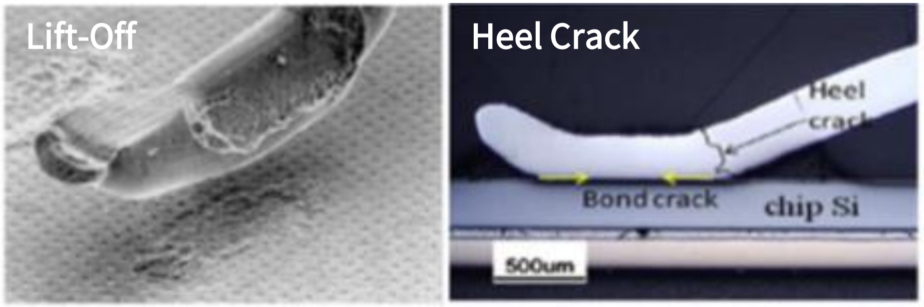
Experimental Data

Case	Module	T_{vj} (°C)	ΔT_{vj} (°C)	Activation	t_{on} (s)	t_{off} (s)
1	Module 1	150	80			
2	Module 1	150	120			
3	Module 1	175	120	Body Diode	2	4
4	Module 1	175	80			
5	Module 2	175	80			

Accumulated Total Strain Range



Standard Al WB Failure Modes



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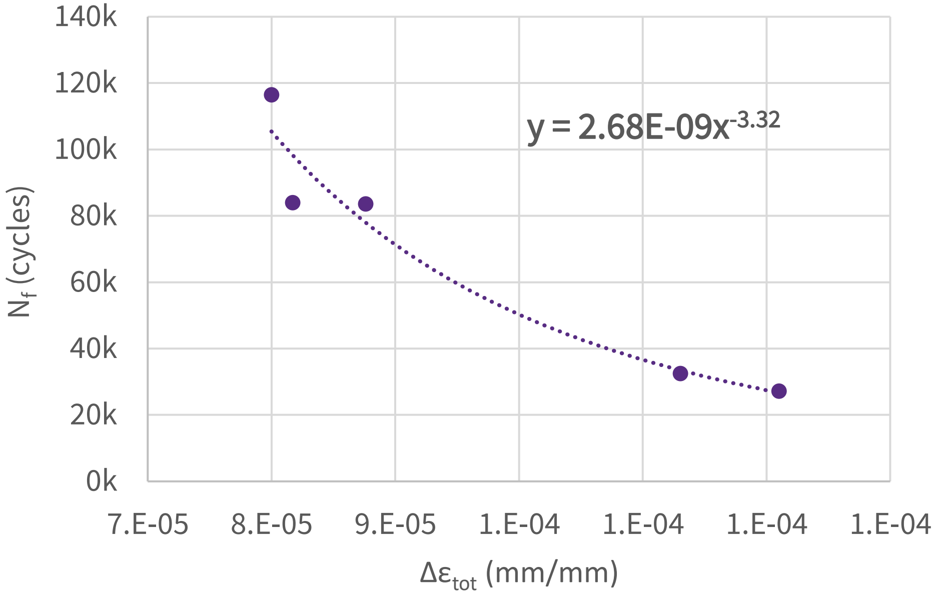


POWER CYCLING SEC TEST CONDITIONS

- Leveraged AQG 324 as a guide
- T_{vj} = 150 °C and 175 °C
- ΔT_{vj} = 80 °C and 120 °C
- t_{on} = 2 s and t_{off} = 4 s
- Failure Criteria = $V_F \geq$ 5% increase or $R_{th} \geq$ 20% increase
- Heated via body diode

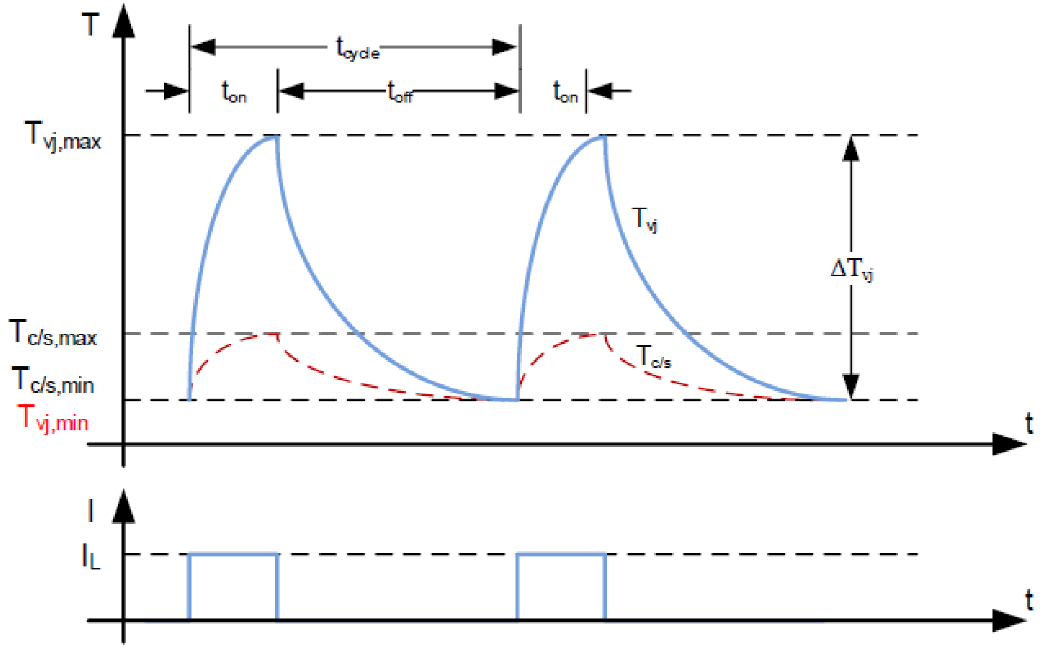
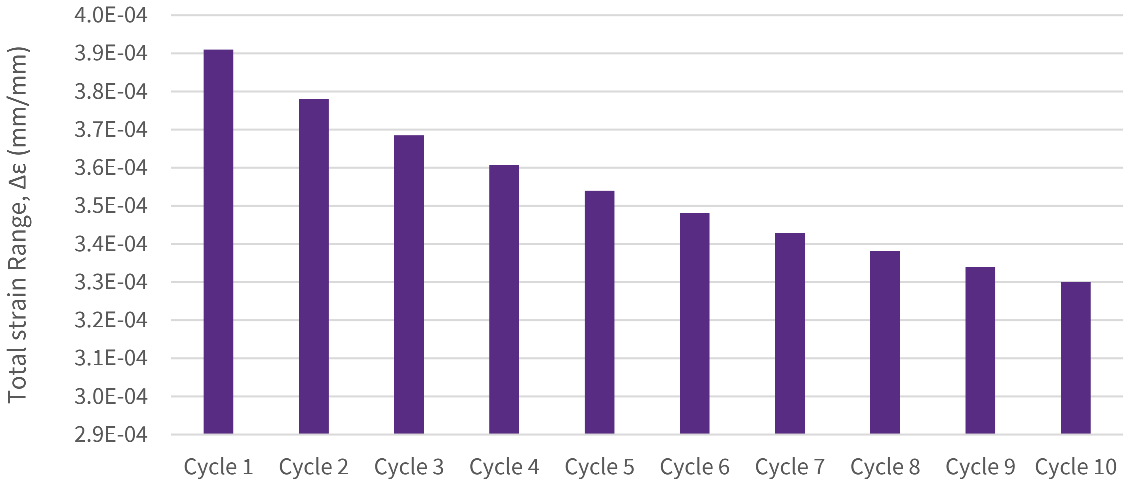
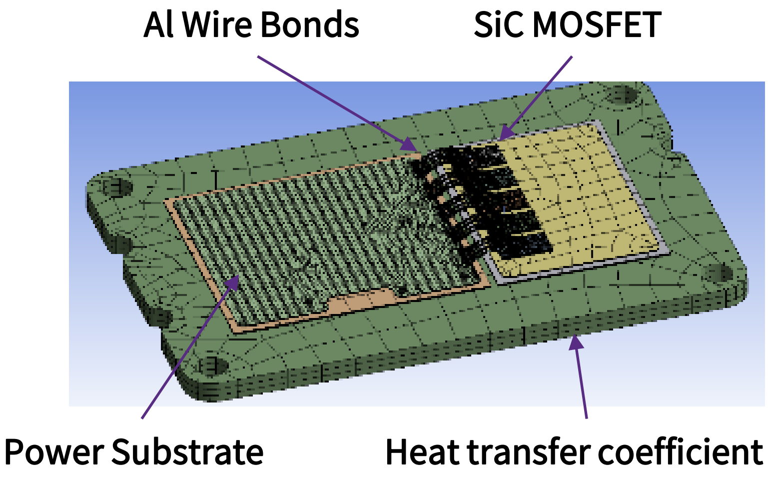


Figure 9.1: Example for current and temperature curve PC_{sec}

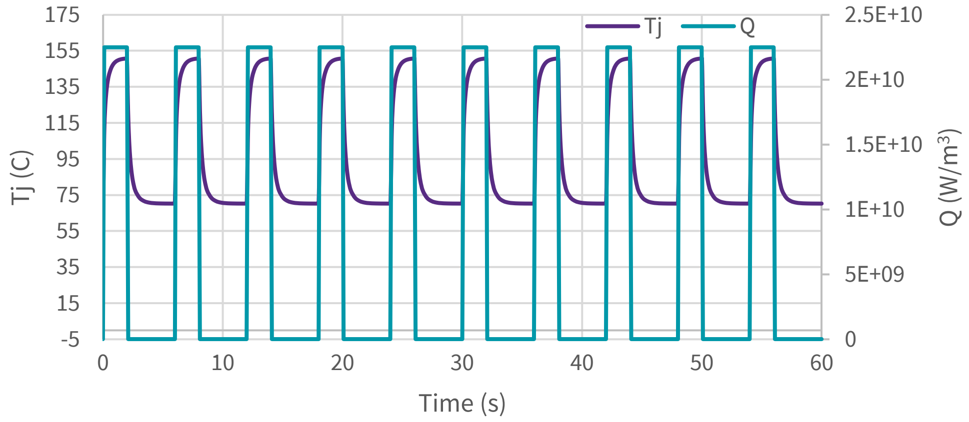
MODELING APPROACH

- Simulations were carried out using Ansys
- Top switch position was modeled
- All materials and boundary conditions were consistent for all cases
- Heat transfer coefficient applied to bottom of baseplate to represent coldplate
- Total strain range extracted from last cycle

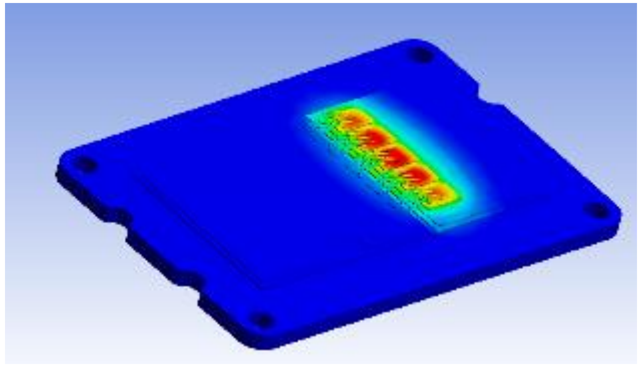




Heat Load and Resultant Thermal Profile (n = 10)



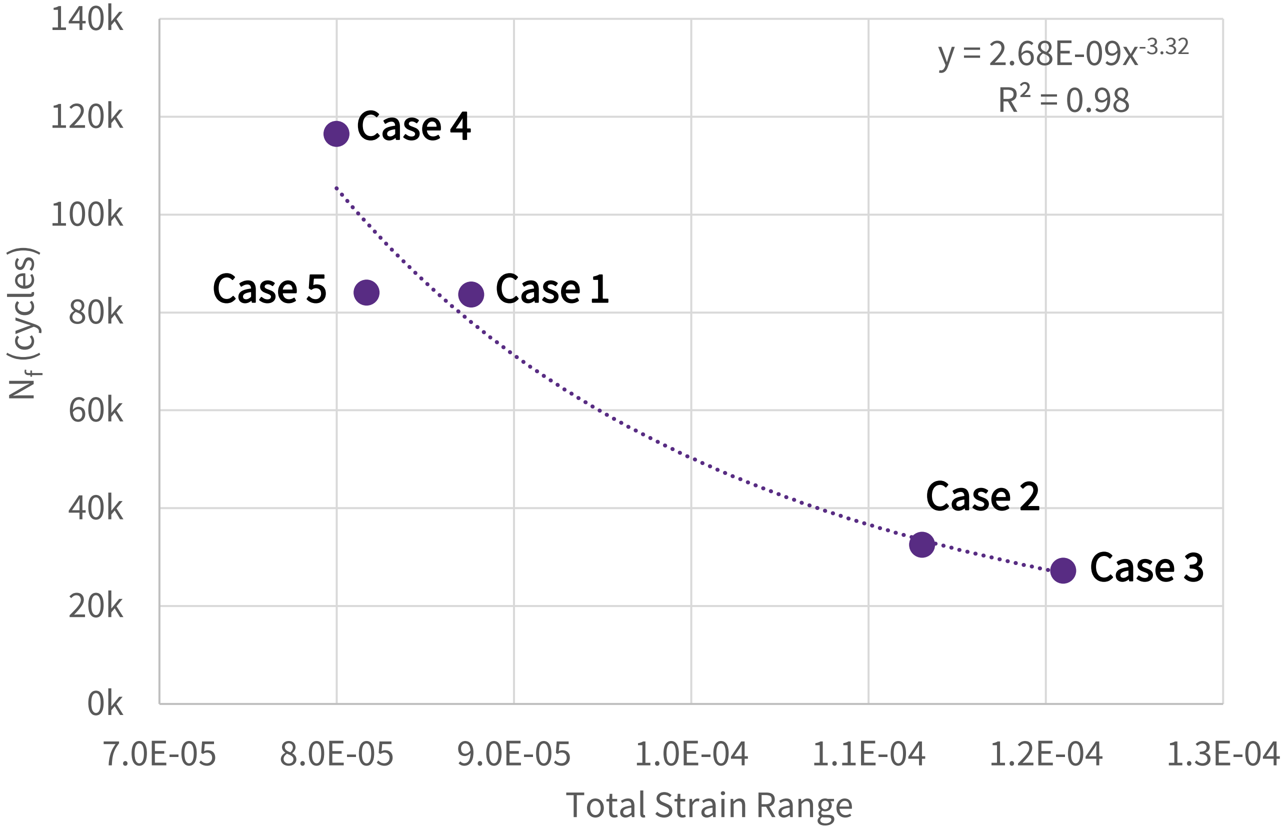
Thermal Profile



PC SEC FATIGUE MODEL

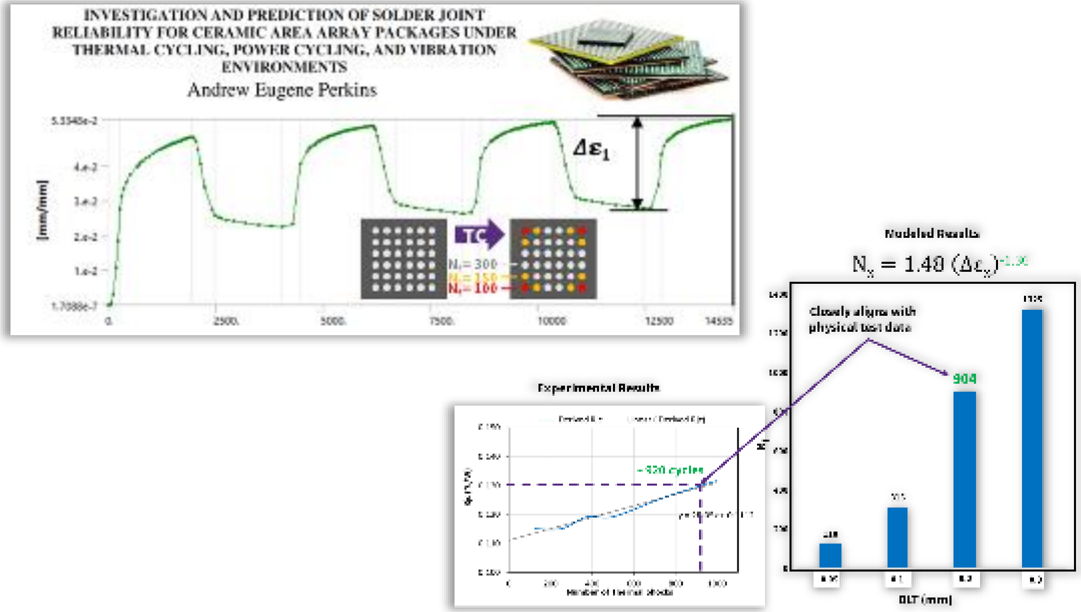
- The Coffin-Manson equation was used to fit the model to the experimental results
- An R^2 (goodness of fit) value of 0.98 is good and gives confidence in the PC prediction model

$$N_f = 2.68 \times 10^{-9} (\Delta\varepsilon)^{-3.32}$$



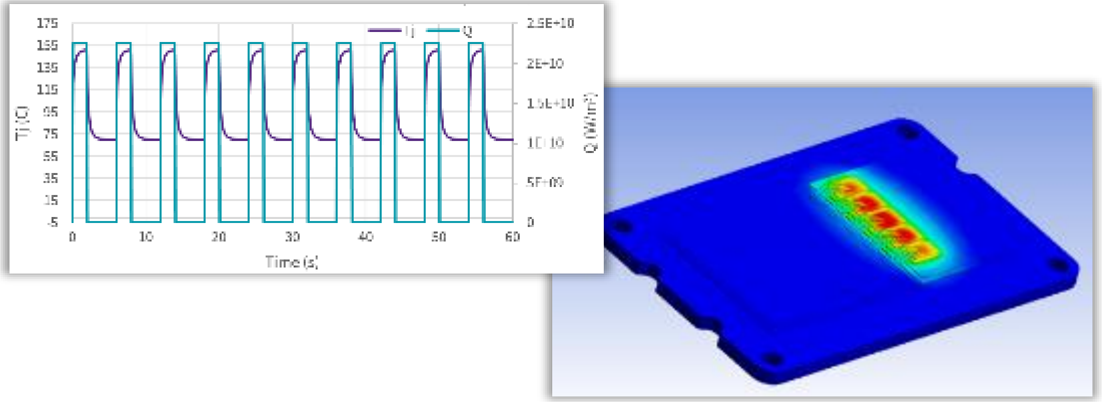
SUMMARY

- Provided background of previous fatigue modeling examples
- Discussed the details of the TS and PC test methods
- Presented **TS fatigue** modeling approach, results, and sensitivity study for a SiC power module
- Presented **PC fatigue** modeling approach and results for a SiC power module



FUTURE WORK

Continue to develop new models based on novel materials, new design features, specific failure modes, … to enable reliability life prediction at the design phase eliminating the need to build and test



“ WE HARNESS THE POWER OF SILICON CARBIDE TO CHANGE THE WORLD FOR THE BETTER. ”

THANK YOU

We would like to thank the Air Force Research Lab for supporting this work!