NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Reliability of Bonded Interfaces



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Overview

Timeline

Project Start Date: FY10

Project End Date: FY13

Percent Complete: 85%

Barriers and Targets

- Cost
- Weight
- Performance and Lifetime

Budget

Total Project Funding:

DOE Share: $2,300K

Funding Received in FY12: $650K

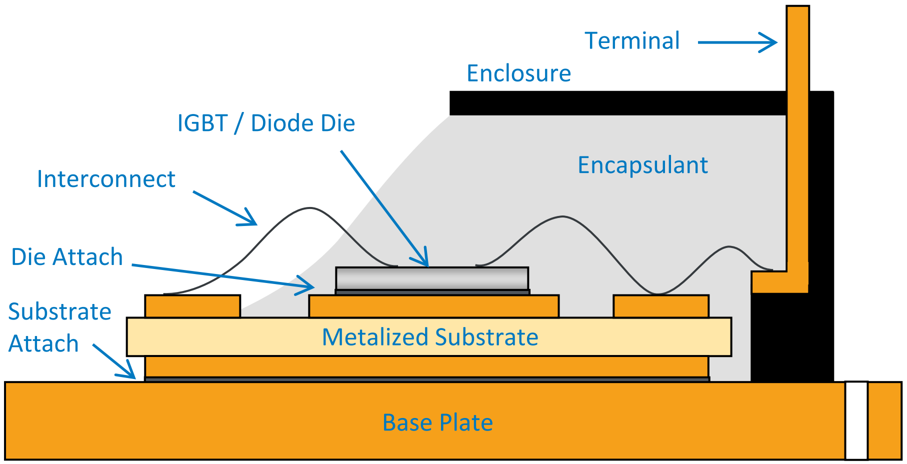
Funding for FY13: $625K

Partners

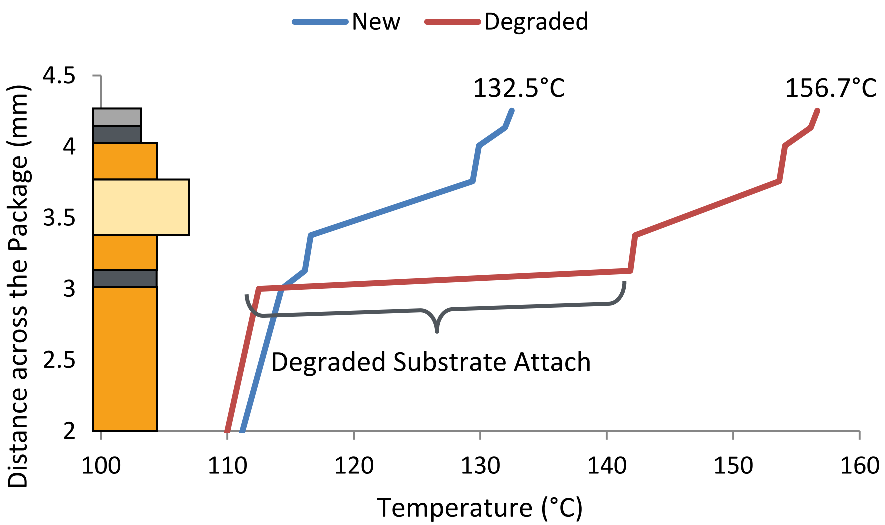
- Interactions / Collaborations
  - General Motors, Btech, Semikron, Heraeus, Kyocera, Virginia Tech, Oak Ridge National Laboratory (ORNL)
- Project Lead
  - National Renewable Energy Laboratory

Relevance

- Excessive temperature degrades the performance, life, and reliability of power electronics components.
- Interfaces can pose a major bottleneck to heat removal.
- Bonded interface materials (BIMs), such as solder, degrade at higher temperatures and are prone to thermomechanical failure.

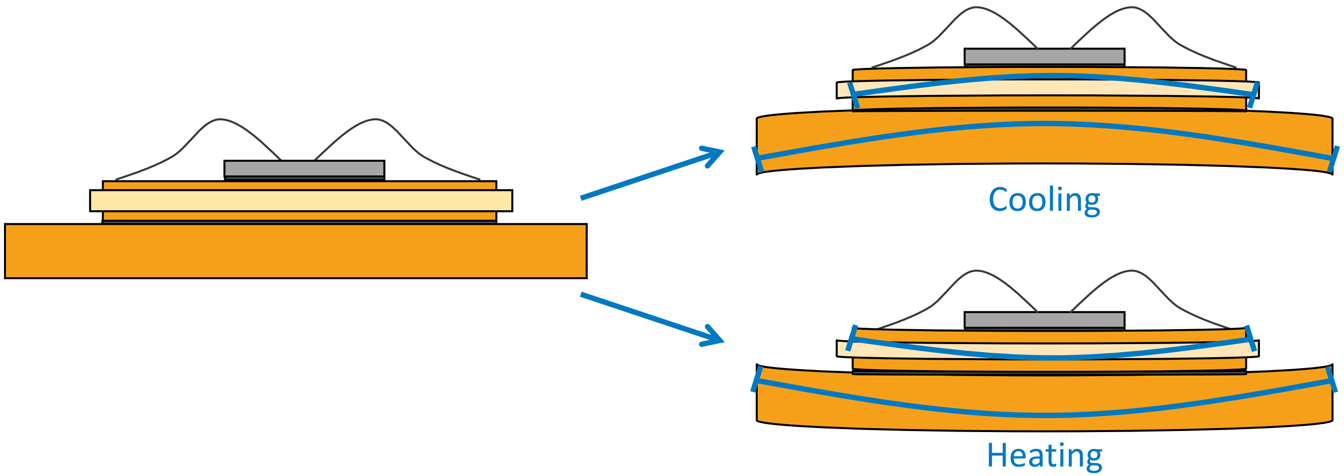


Traditional Power Electronics Package



Relevance

- As operating temperatures increase, the coefficient of thermal expansion (CTE) mismatch between the substrate and the base plate causes defect initiation and propagation in the joining layer.



CTE (ppm/°C)
Silicon: 2.6
AlN: 4.5
Si_3N_4: 3.2
Copper: 16.5
Aluminum: 22.7
Sn63/Pb37 Solder: 24.7

Objectives

- **Overall Objective**
  - Investigate the reliability of emerging BIMs (such as sintered silvers, lead-free solders, and thermoplastics with embedded carbon fibers) for power electronics applications to meet the thermal performance target of 5 mm^2K/W
  - Identify failure modes in emerging BIMs, experimentally characterize their life under known conditions, and develop lifetime estimation models

- **Address Targets**
  - High-performance, reliable, low-cost bonded interfaces enable:
    - Compact, light-weight, low-cost packaging
    - High-temperature coolant and/or air cooling

- **Uniqueness and Impacts**
  - Thermal performance and reliability of emerging sintered materials and thermoplastics for large-area attachments were characterized

Milestones

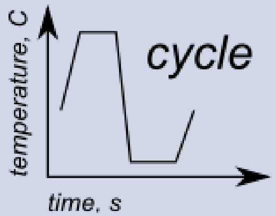
Date	Description
October 2012	Completed finite element analysis (FEA) to determine strain energy density in lead-based solder samples with various fillet radius geometries
December 2012	Completed experimental temperature cycling of Btech HM-2 and Semikron sintered silver samples to 2,000 cycles
February 2013	Completed FEA to determine strain energy density in lead-based solder samples under various temperature cycle profiles
June 2013	Complete experimental temperature cycling of lead-based solder samples to 2,000 cycles
July 2013	Complete double lap shear testing of lead-based solder samples and use stress/strain data to revise viscoplastic properties needed for FEA

Approach

Sample Synthesis

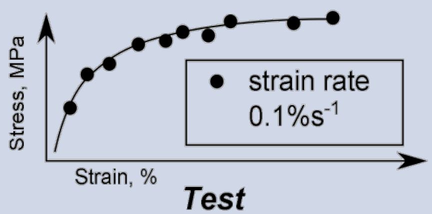
- Synthesis of samples using vacuum solder reflow station and hot press

Thermal Testing/ Characterization



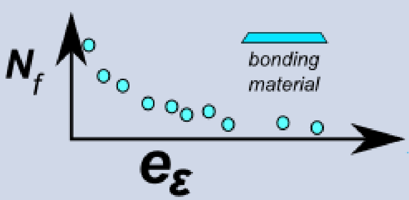
- Cycling of samples in a thermal shock chamber
- Characterization of samples via high-potential tester, acoustic microscope, and laser profilometer

BIM Mechanical Characterization



- Shear tests to extract mechanical characteristics of BIMs
- Extraction of viscoplastic parameters

Reliability Calculation

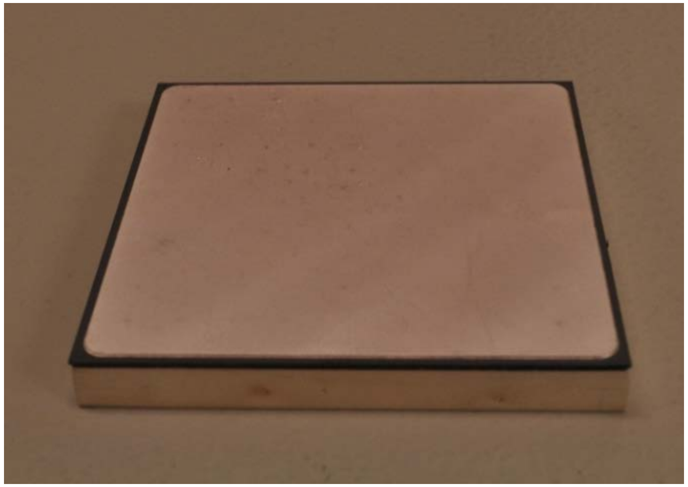


- Strain energy density per cycle
- Number of cycles to crack initiation/ delamination
- Fatigue life prediction

Experimental Approach | Modeling Approach - FEA/Calculations

Sample Assembly

- Five samples of each BIM were synthesized for testing and included:
  - Silver plating on the substrate and copper base plate
  - Substrate based on a Si_3N_4 active metal bonding process
  - An interface between 50.8-mm x 50.8-mm footprint
- Samples followed manufacturer-specified reflow profiles, and bonds were inspected for quality



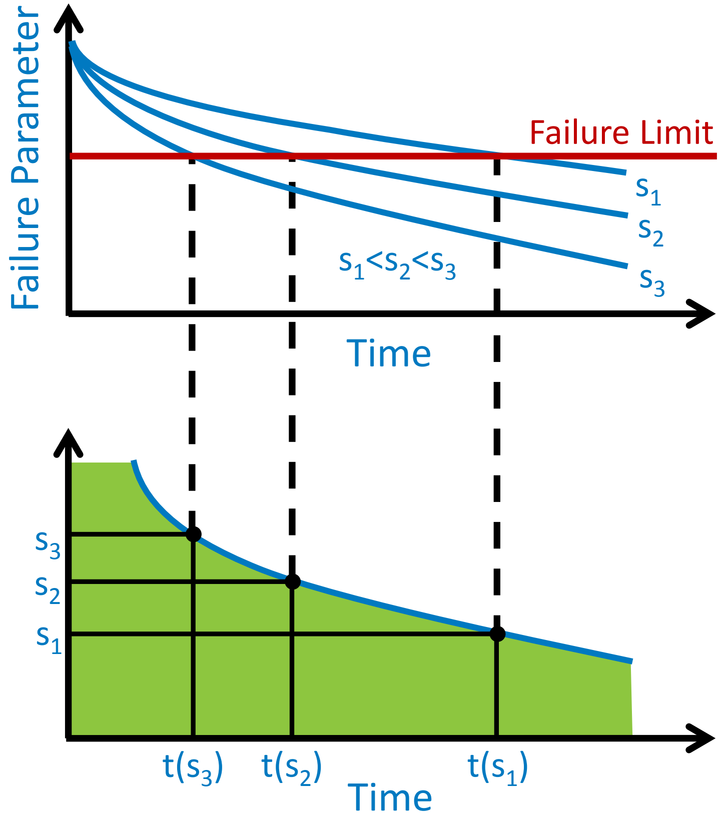
Credit: Douglas DeVoto, NREL

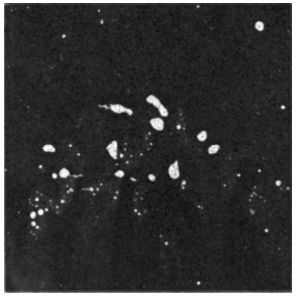
Sample Assembly

Bond Material Type	Name	Comments
Solder	Kester Sn63Pb37	Baseline (lead-based solder)
Sintered Silver	Semikron	Based on Semikron synthesis process
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers

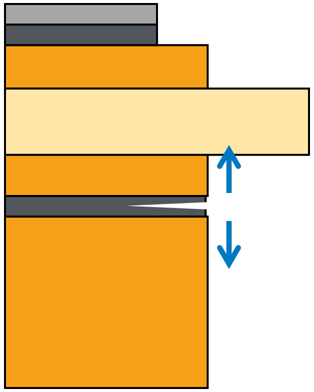
Temperature Cycling

- Cycle Profile
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Failure Mechanisms
  - BIM: voids and cohesive or adhesive/interfacial fractures
  - Substrate: Cu-to-Si_3N_4 delamination and Si_3N_4 cracking

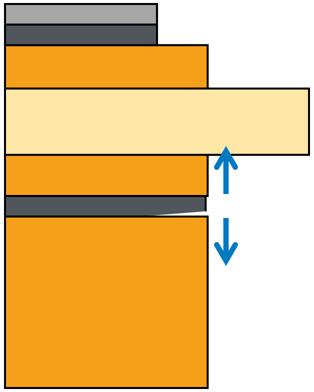




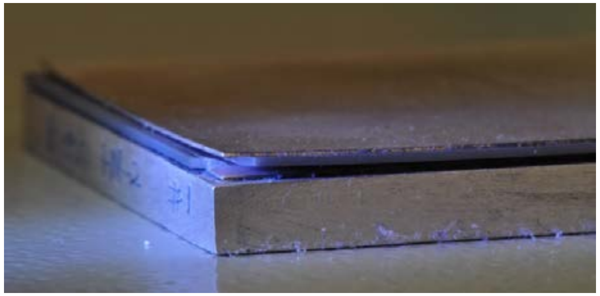
Voids



Cohesive Fracture



Adhesive/Interfacial Fracture



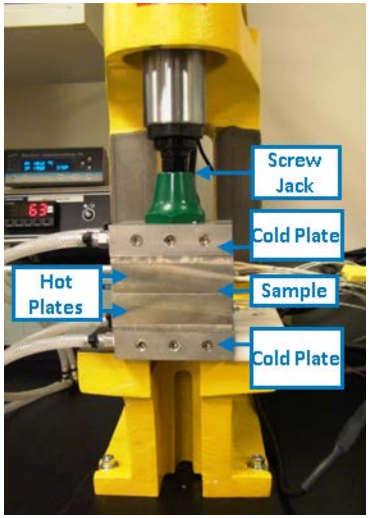
Substrate Delamination and Cracking

Credit: Douglas DeVoto, NREL (all photos)

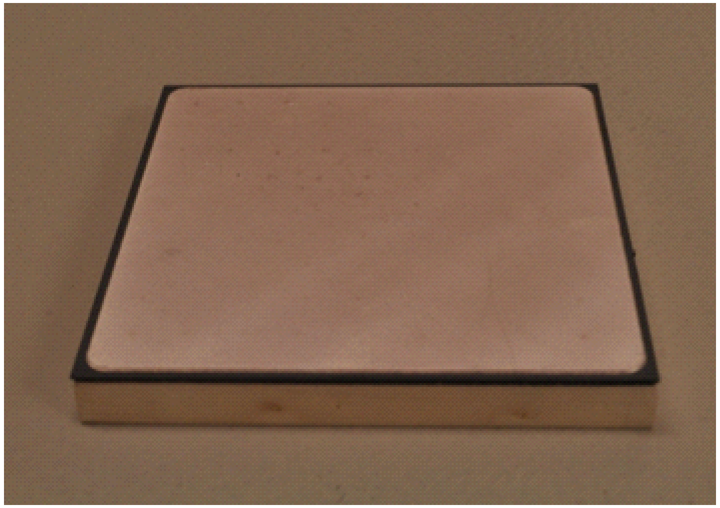
Thermoplastic Evaluation

Btech HM-2 (Carbon Fibers within Polymer Matrix)

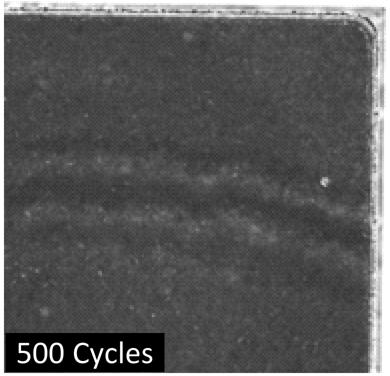
- Bonding
  - HM-2 was cut to the base plate dimensions
  - The sample assembly was placed in the hot press and raised to 195°C
  - 1 MPa (150 psi) of pressure was applied
  - Bond line thickness was measured to be 88.9 µm
- Reliability Results
  - After 2,000 cycles, the bonded interface remained defect-free



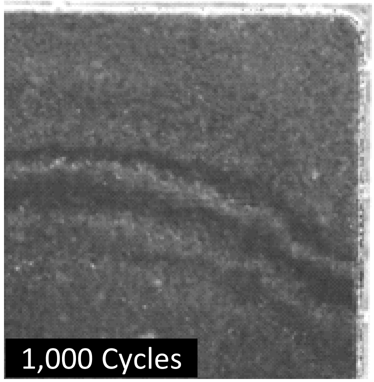
Hot Press



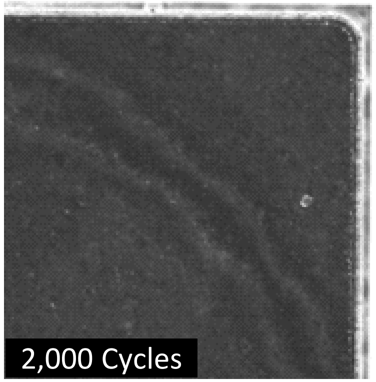
Sample Assembly



500 Cycles



1,000 Cycles



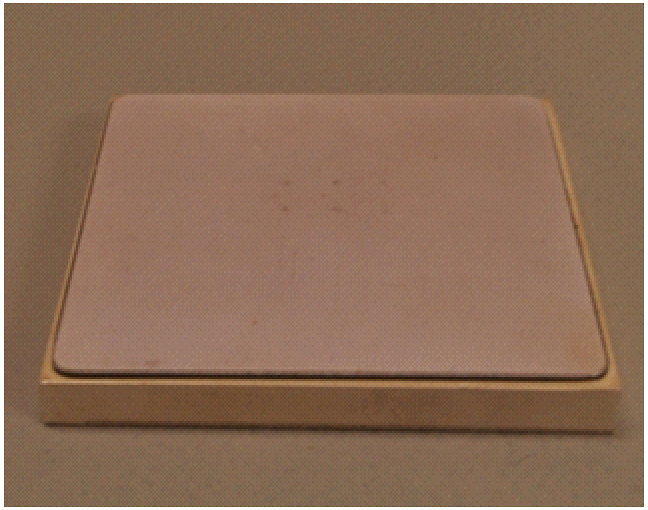
2,000 Cycles

Credit: Douglas DeVoto, NREL (all photos)

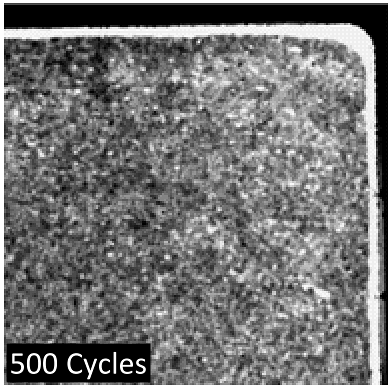
Sintered Silver Evaluation

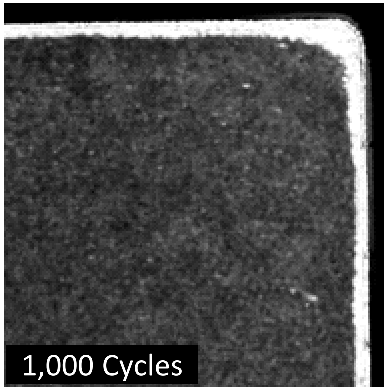
Semikron Sintered Silver

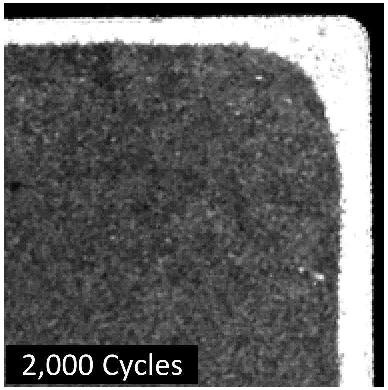
- Bonding
  - Si_3N_4 edges were ground off to match the metallization layer
  - The sample assembly was placed in a hot press and raised to its processing temperature; then pressure was applied
  - Compression testing of substrates at ORNL showed cracking of substrates required between 30 MPa to 50 MPa of pressure
- Reliability Results
  - Uniform bonds were obtained
  - Cohesive fracture initiated at bonding perimeter



Sample Assembly



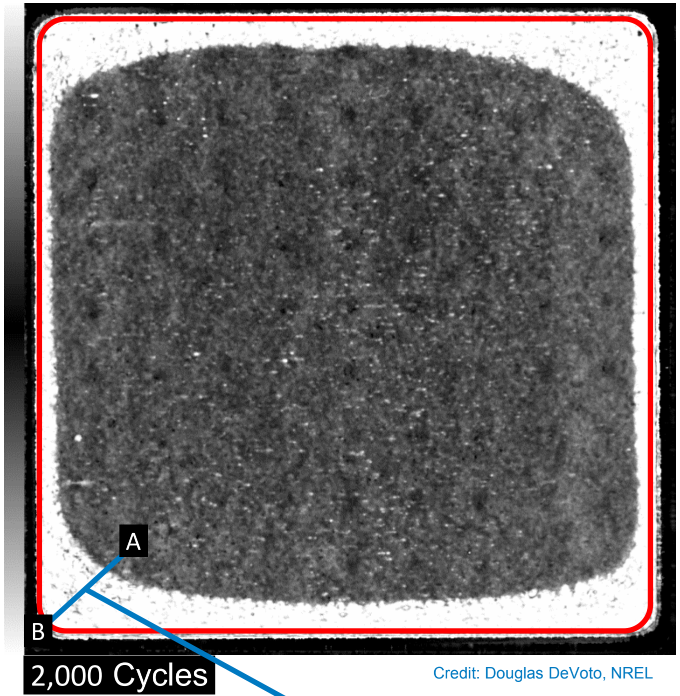




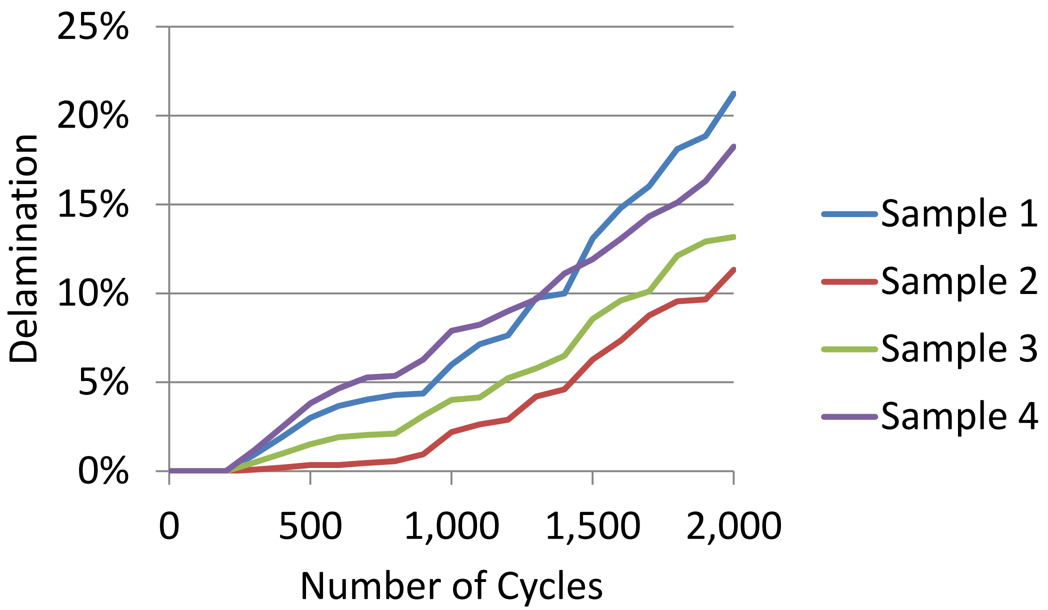
Credit: Douglas DeVoto, NREL (all photos)

Sintered Silver Evaluation

- After 2,000 cycles, perimeter fracturing reached 11% to 21%



Credit: Douglas DeVoto, NREL

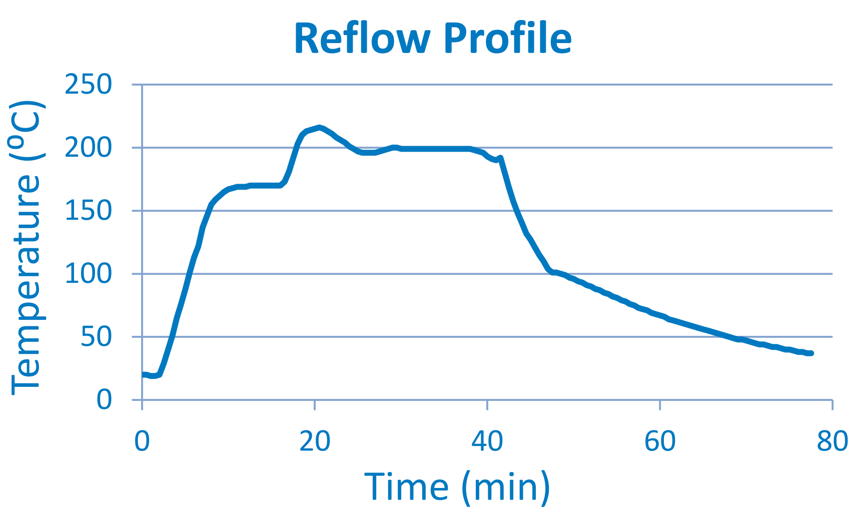


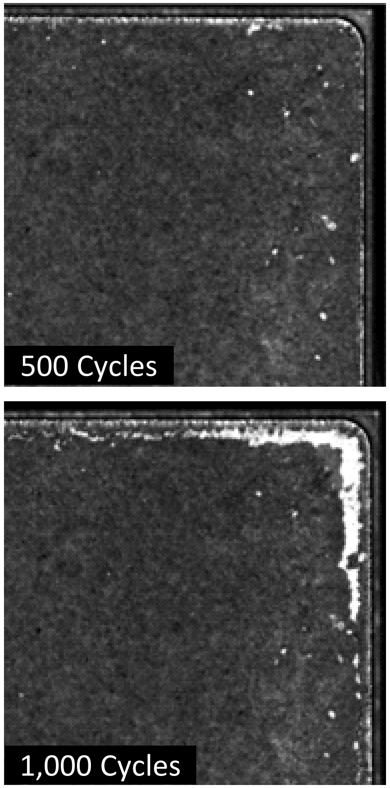
Credit: Paul Paret, NREL

Solder Evaluation

Lead-based (Sn63Pb37) Solder

- Bonding
  - Manual stencil was used to apply a 127-µm-thick solder layer to the substrate and base plate surfaces
  - The assembled sample was placed in a vacuum solder reflow oven and raised to its processing temperature
- Reliability Results
  - Bonds with voiding under 2% were obtained
  - Cohesive fracture initiated at bonding perimeter

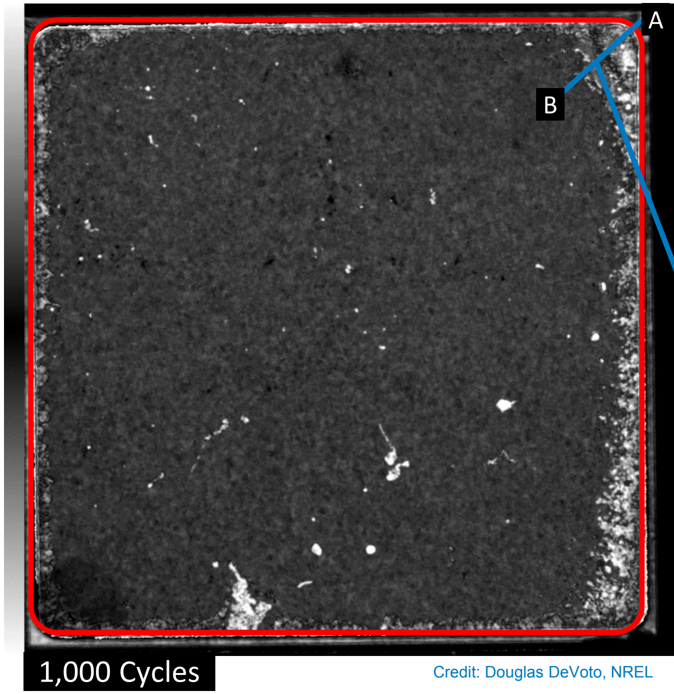




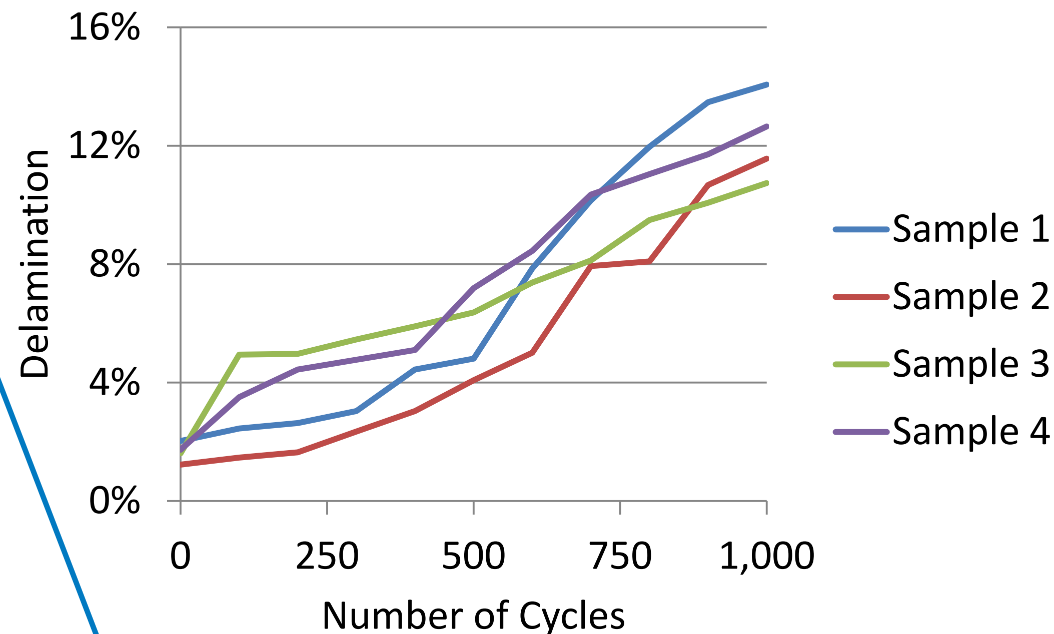
Credit: Douglas DeVoto, NREL (all photos)

Solder Evaluation

- After 1,000 cycles, perimeter fracturing reached 11% to 14%

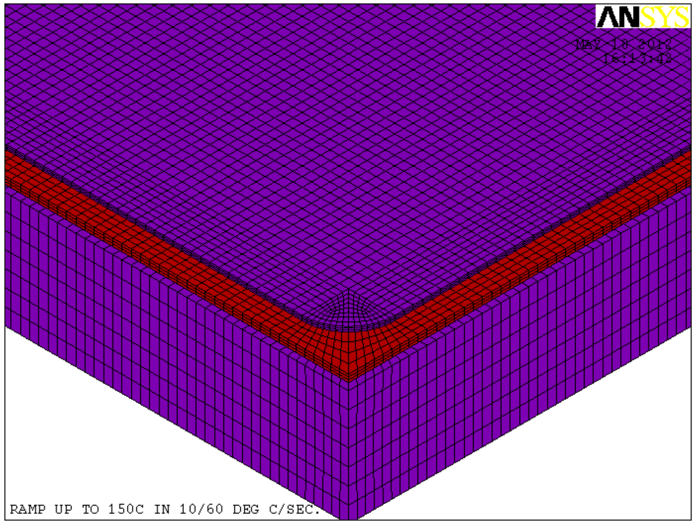


Credit: Douglas DeVoto, NREL

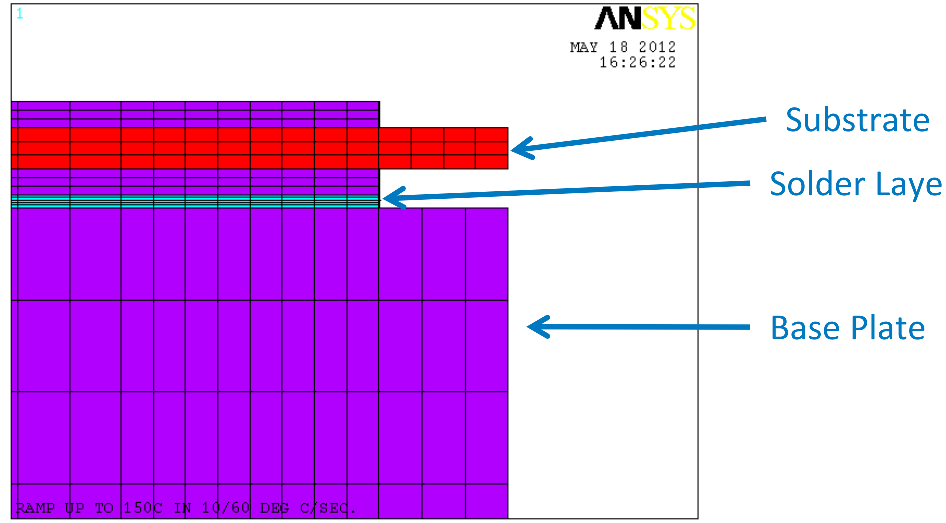


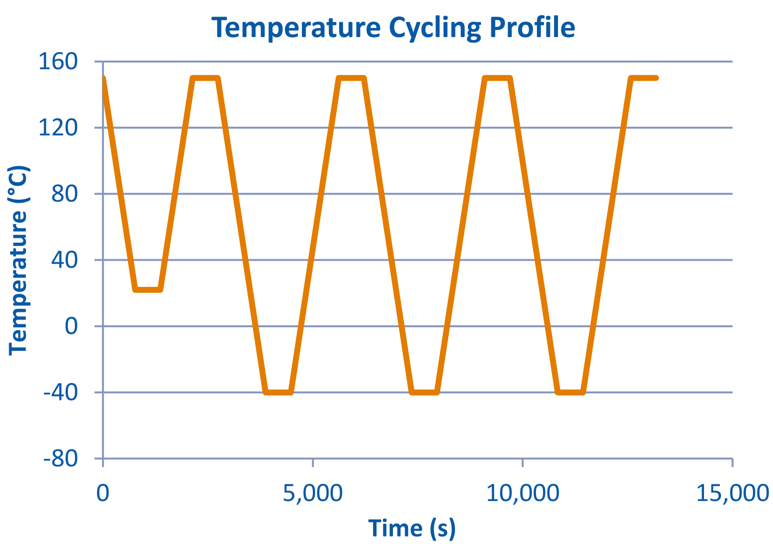
Credit: Paul Paret, NREL

BIM Finite Element Modeling



Quarter Symmetry Model

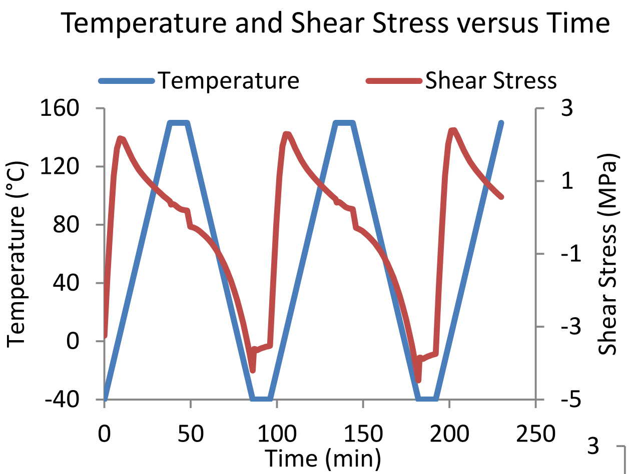


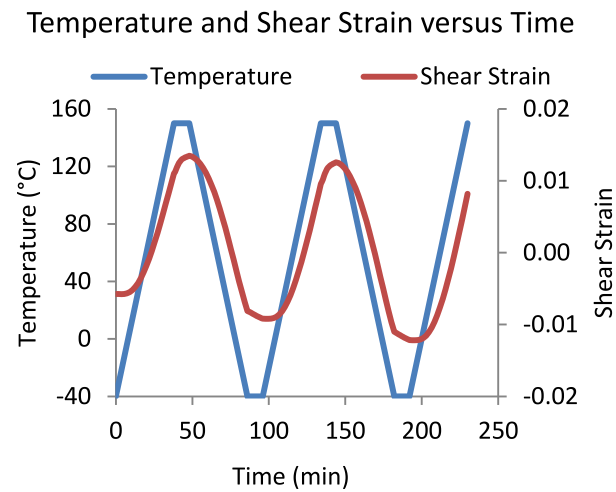


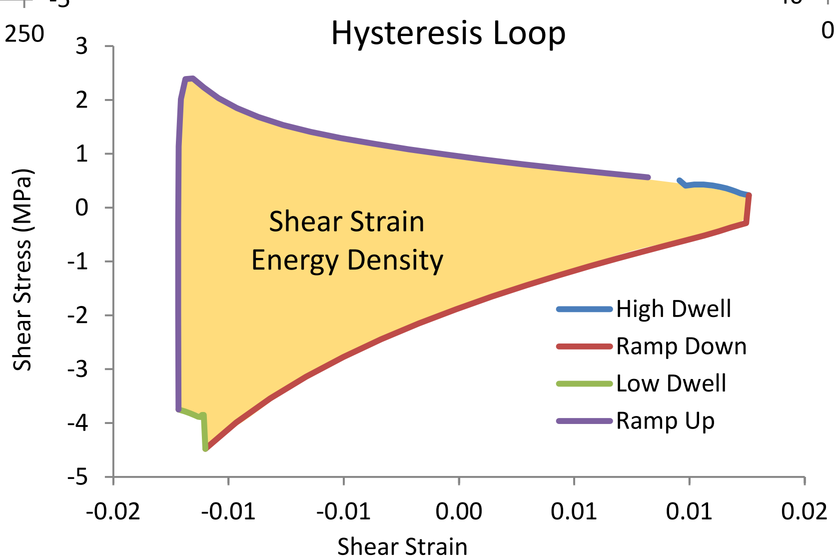
- Temperature cycling parameters:
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Viscoplastic material model applied to solder layer
- Temperature-dependent elastic material properties incorporated for base plate and substrate

BIM Finite Element Modeling

- Stress-strain hysteresis loops help to understand the inelastic behavior of the solder interface
- Energy stored in the solder interface region due to deformation during thermal loading is referred to as the strain energy density

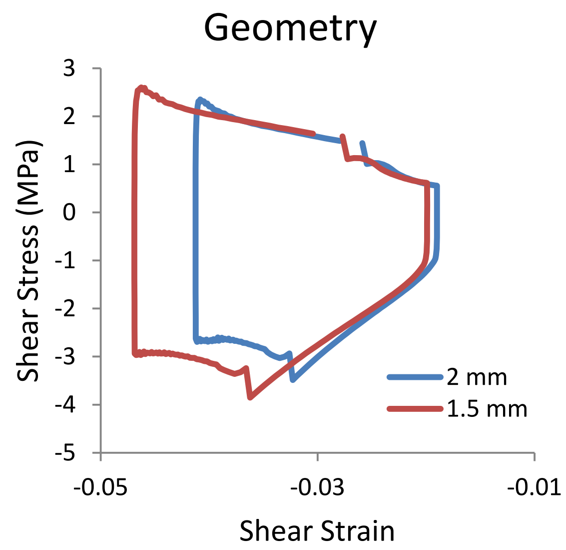


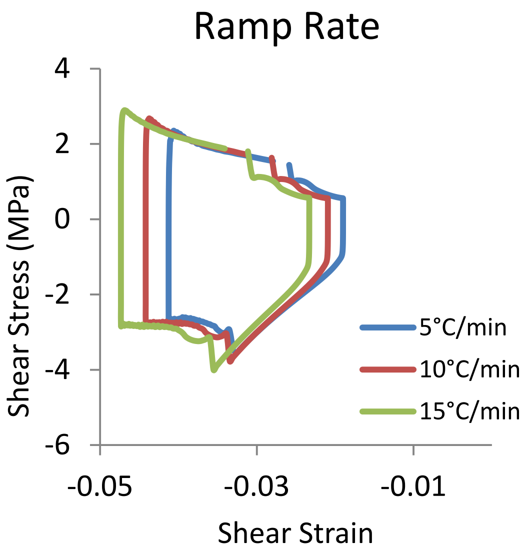


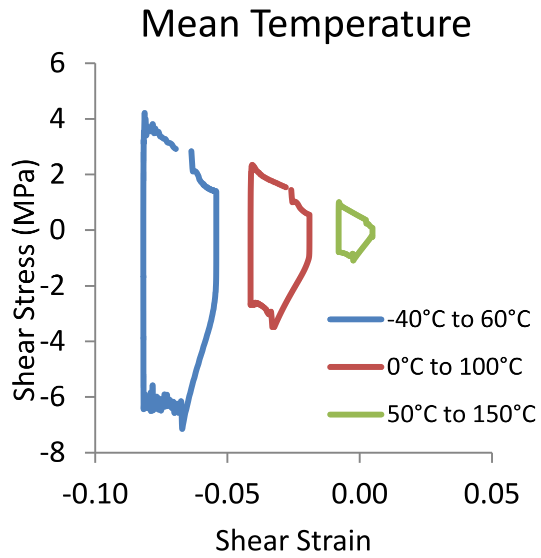


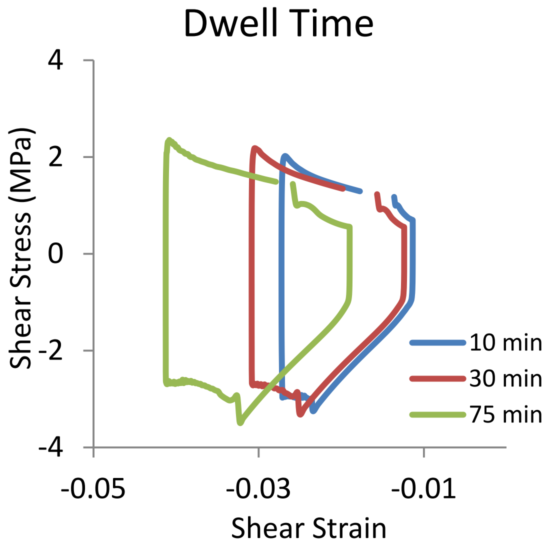
BIM Finite Element Modeling

- Hysteresis loops for variations in package geometry, dwell time, and ramp rate were explored
  - Geometry: 1.5 mm and 2 mm fillet radius
  - Ramp rate: 5°C/min, 10°C/min, and 15°C/min
  - Mean temperature: 50°C, 10°C, and 100°C
  - Dwell time: 10 min, 30 min, and 75 min
- Strain energy density value will be compared to experimental fracture rate to obtain a cycles-to-failure correlation for lead-based solder









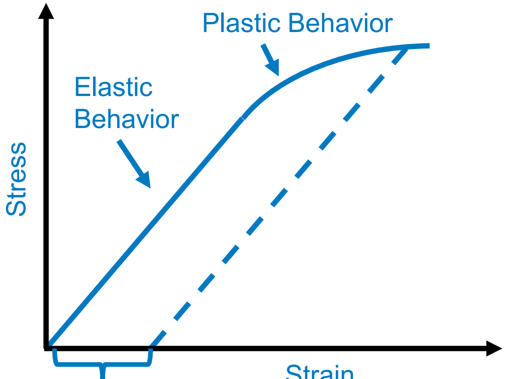
BIM Mechanical Characterization

- Strain prediction of solder material is dependent on stress, temperature, and time
  - A high enough stress will cause the material to plastically deform
  - Solder has a tendency to creep (time-dependent plasticity) at room temperature; this increases as operating (absolute) temperature approaches the melting temperature
- Viscoplasticity models combine plasticity and creep deformations into one equation to properly define solder in FEA
- Sample testing using a double-lap shear test fixture at various strain rates and temperatures generates the needed data to characterize the viscoplastic nature of solder

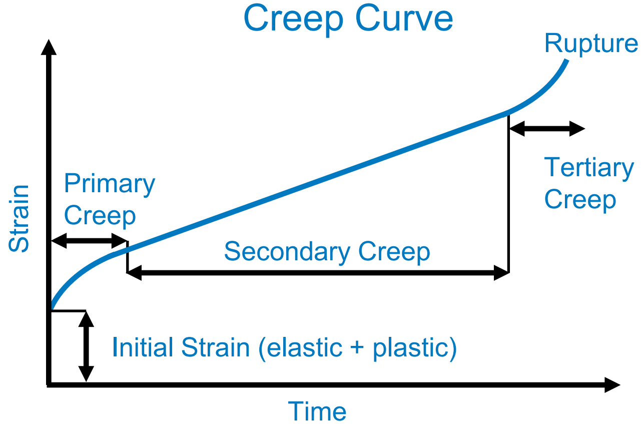
Double-Lap Shear Fixture and Sample

Credit: Douglas DeVoto, NREL

Stress-Strain Curve



Creep Curve



Collaboration and Coordination

- Partners
  - **Btech** (Industry): collaboration on optimizing thermoplastic BIM for large area attachment
  - **General Motors** (Industry): technical guidance
  - **Heraeus** (Industry): collaboration on using low-pressure sintered silver materials before products are commercially available
  - **Kyocera** (Industry): provided insight on Si_3N_4 substrate bonding process and advantages over AlN substrates
  - **ORNL** (Federal): collaboration to determine maximum pressure that Si_3N_4 substrates could withstand
  - **Semikron** (Industry): provided bonded samples to NREL using company's silver sintering process
  - **Virginia Tech** (University): collaboration on synthesis of samples using sintered silver material

Proposed Future Work (FY13)

- Derive viscoplastic parameters for lead-based solder from double-lap shear test experiments
- Expand strain energy density versus cycles-to-failure models to lead-free solders
- Complete 2,000 thermal cycles on lead-based solder samples
- Report on reliability of each BIM under specified accelerated test conditions

Summary

- **DOE Mission Support**
  - BIMs are a key enabling technology for compact, light-weight, low-cost, reliable packaging and for high-temperature coolant and air-cooling technical pathways
- **Approach**
  - Synthesis of various bonds between substrates and base plate, thermal shock/temperature cycling, high-potential test and bond inspection (acoustic microscope), and strain energy density versus cycles-to-failure models
- **Accomplishments**
  - Evaluated a number of bonded interfaces subjected to temperature cycling
    - Lead-based solder, sintered silver, thermoplastic
  - Implemented FEA for solder bonded interface geometries

Summary

- **Collaborations**
  - General Motors, Virginia Tech, ORNL, Btech, Semikron, Heraeus, Kyocera
- **Future Work**
  - Derive viscoplastic parameters for lead-based solder from double-lap shear test experiments
  - Expand strain energy density versus cycles-to-failure models to lead-free solders
  - Complete 2,000 thermal cycles on lead-based solder samples
  - Report on reliability of each BIM under specified accelerated test conditions

NATIONAL RENEWABLE ENERGY LABORATORY

Acknowledgments:

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