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NATIONAL RENEWABLE ENERGY LABORATORY

Performance and Reliability of Bonded Interfaces for High-Temperature Packaging

P.I.: Douglas DeVoto
National Renewable Energy Laboratory
Vehicle Technologies Office (VTO) Annual Merit Review
Washington, D. C.
June 8, 2016

Project ID: EDT063
NREL/PR-5400-66048

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Overview

Timeline

- **Project Start Date:** FY14
- **Project End Date:** FY17
- **Percent Complete:** 50%

Barriers and Targets

- Cost
- Weight
- Performance and Lifetime

Budget

- **Total Project Funding: $1,300K**
  - DOE Share: $1,300K
- **Funding for FY16:** $400K

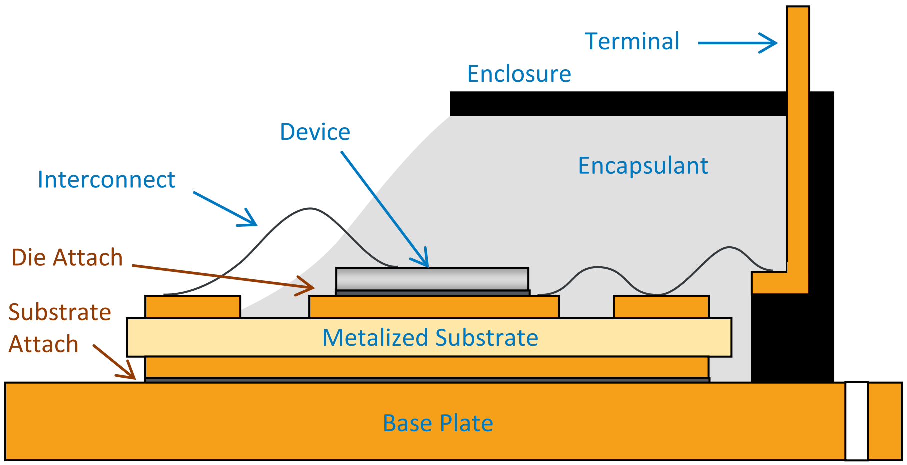
Partners

- Interactions / Collaborations
  - Oak Ridge National Laboratory (ORNL) (Andrew Wereszczak)
- Project Lead
  - National Renewable Energy Laboratory (NREL)

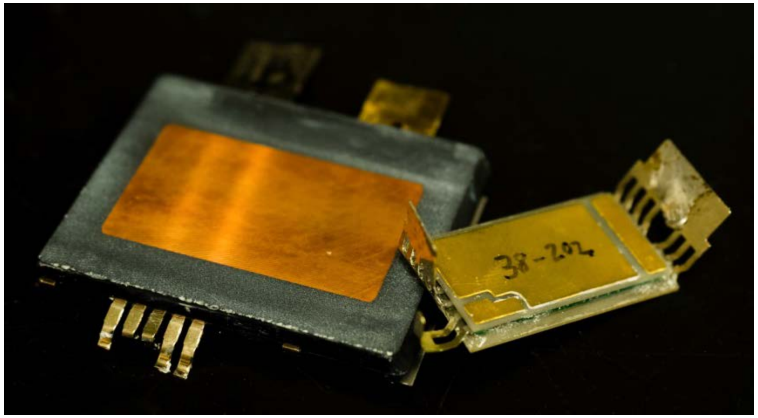
Relevance

- Packaging designs must thermally allow for:
  - High operating temperatures
  - High heat fluxes
  - Hot spots
- Coefficient of thermal expansion (CTE) mismatch between layers of the module will impose stresses that can initiate and propagate defects

CTE (x 10^{-6} / K)
Si: 2.6
AlN: 4.5
Si_3N_4: 3.2
Cu: 16.5
Al: 22.7
$Sn_{63}Pb_{37}$ Solder: 24.7
Ag: 19.5



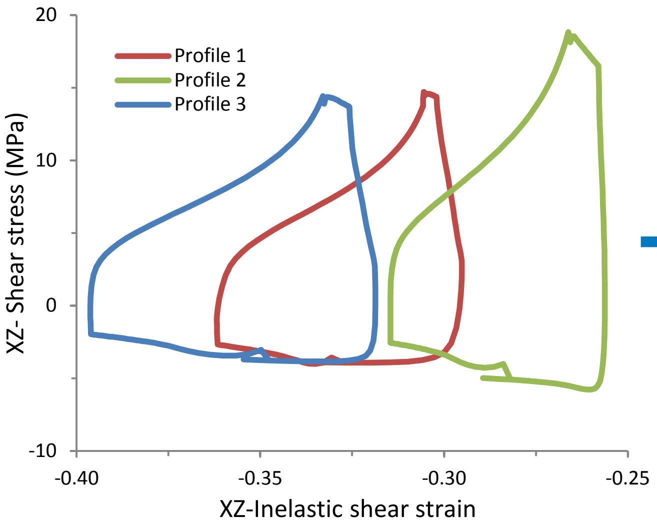
Traditional Power Electronics Package

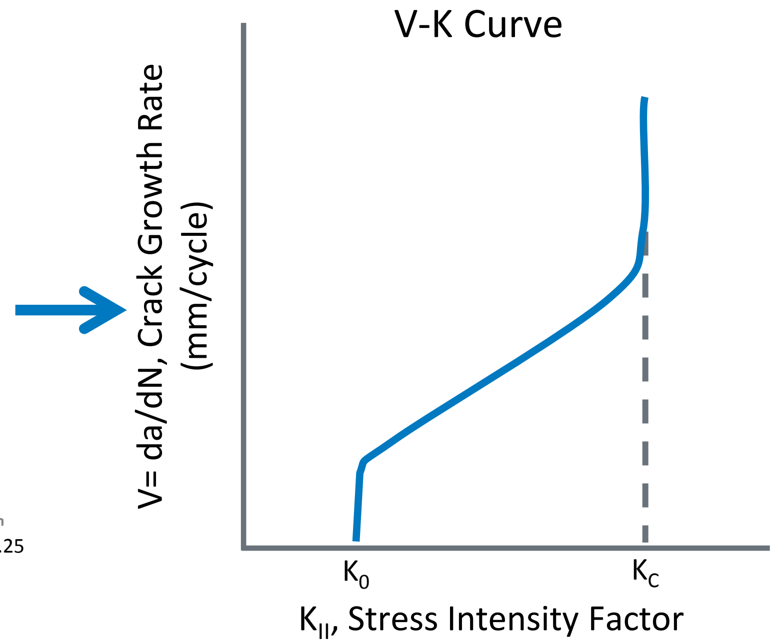


State-of-the-Art Packages

Strategy

- Sintered-silver reliability has not been documented at 200°C conditions for the substrate-attach layer
  - ORNL and NREL's prior experience with sintered-silver processing will generate recommended practices for synthesis of reliable interfaces
- Identify threshold at which stress field is sufficient to cause delamination initiation and measure the resulting crack growth rate

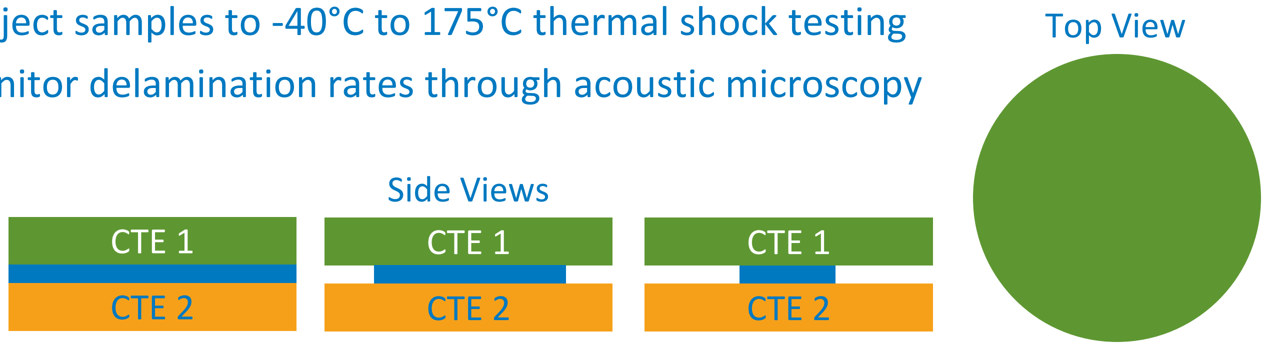




V= da/dN, crack growth rate (mm/cycle)
K = stress intensity factor

Strategy

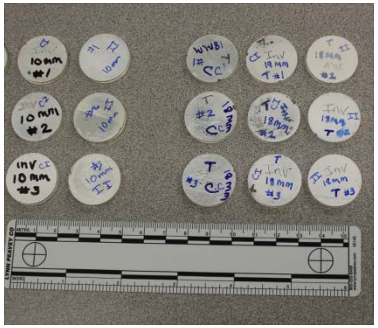
1. Process CTE-mismatched disk samples with various diameter bond pads to validate stress field relationship with delamination initiation
   - Subject samples to -40°C to 175°C thermal shock testing
   - Monitor delamination rates through acoustic microscopy

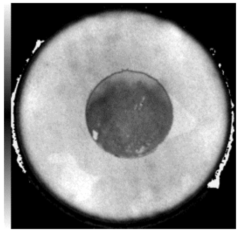


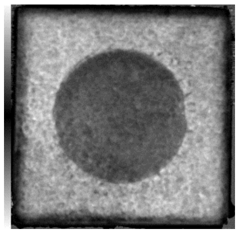
2. Synthesize double-lap shear samples for mechanical characterization of sintered-silver
   - Subject samples to shear tests and compare sintered-silver material properties to bulk silver properties
   - Attempt to measure residual stress at room temperature
   - Estimate stress-strain curves
   - Use information to model plastic deformation
3. Synthesize Si-Si wafer samples for thermal characterization of bulk and contact resistances

Strategy

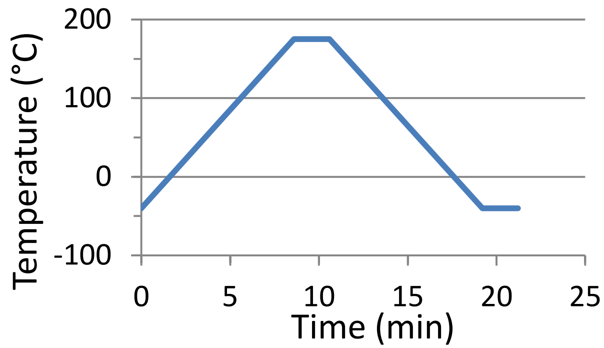
Sample Synthesis



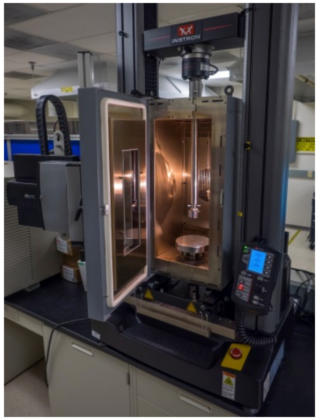




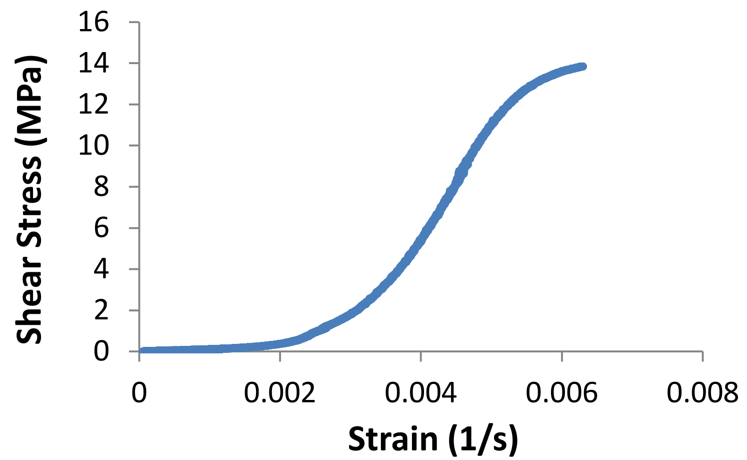
Accelerated Testing



Shear Testing

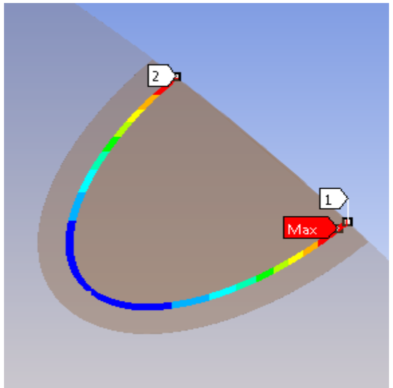


Shear Stress Measurement

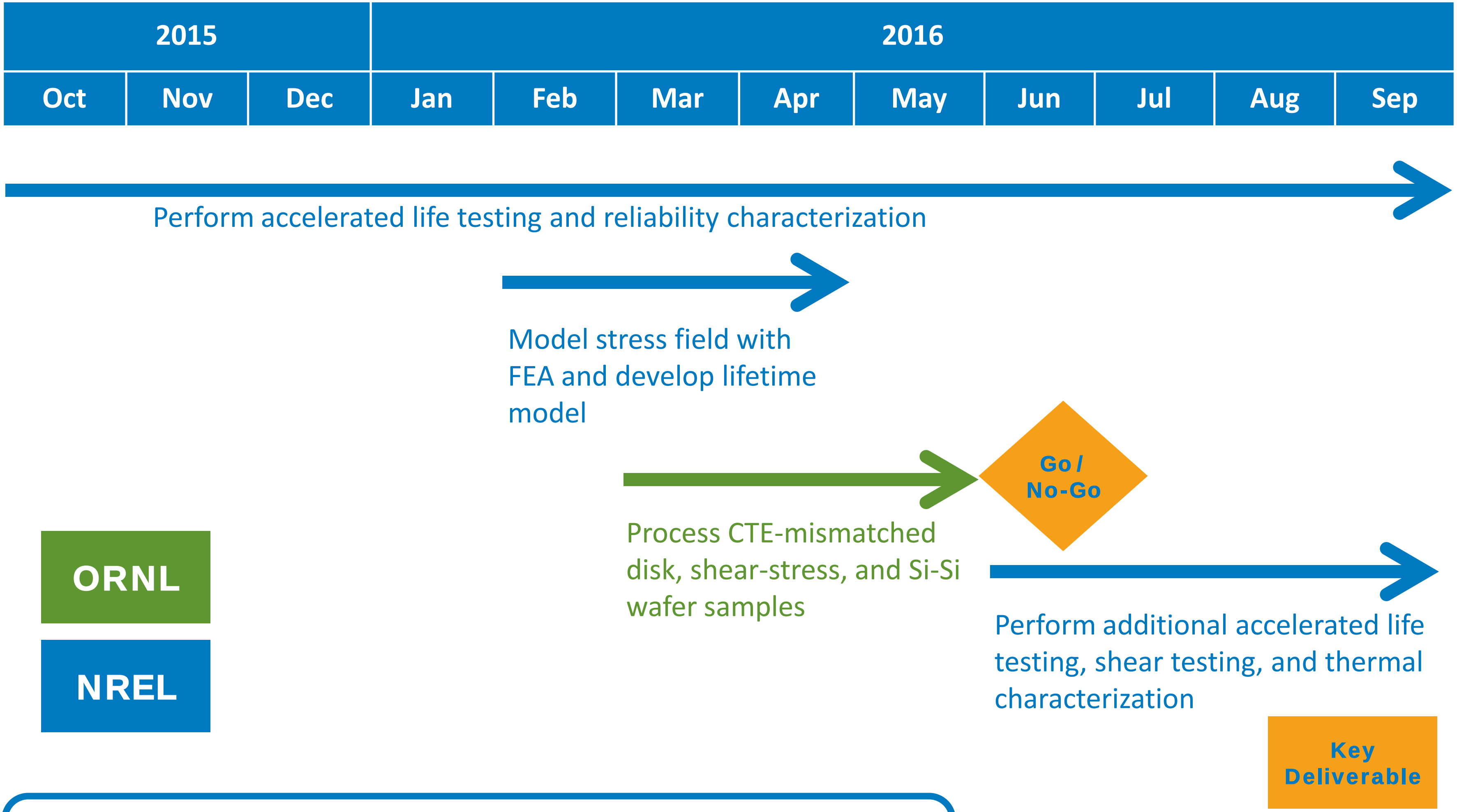


Literature Comparison

Interface Modeling



Milestones



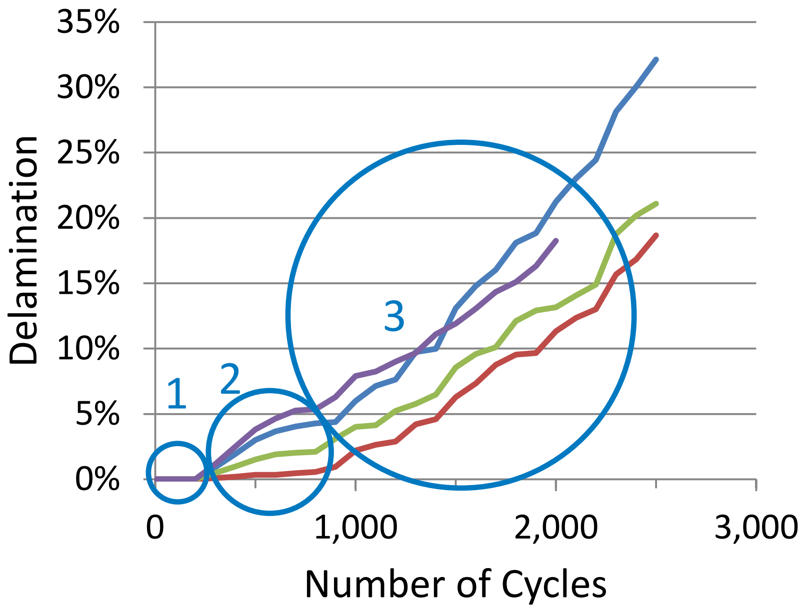
Go/No-Go: Do bonds meet minimum strength requirements?

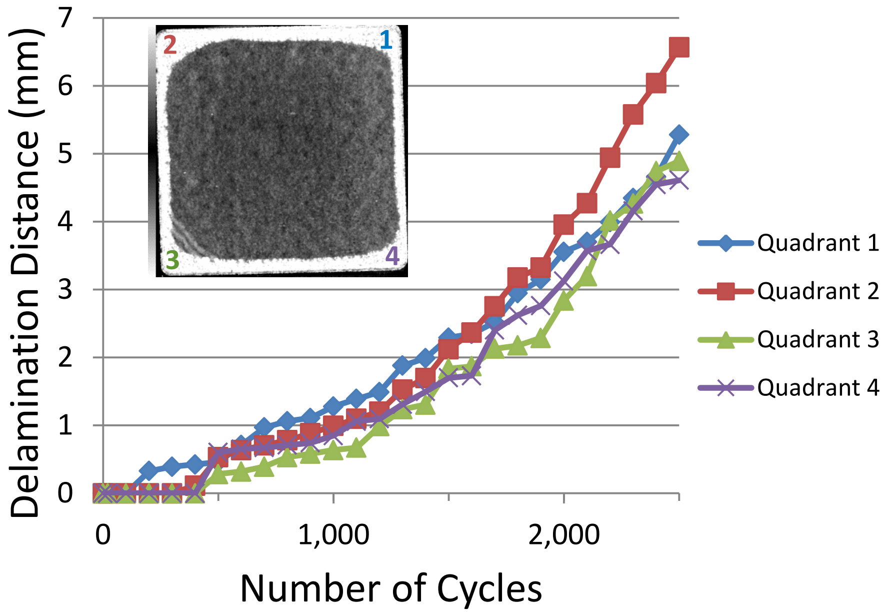
Key Deliverable: Publish stress analysis for sintered-silver

FEA = finite element analysis

Crack Evaluation

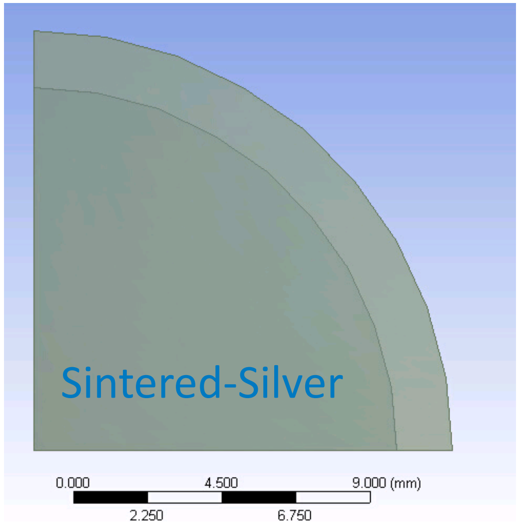
- Identified threshold at which stress field is sufficient to cause delamination initiation
  - o Measured delamination rate of 50-mm-x-50-mm sintered-silver samples
    1. Identified threshold at which stress intensities are sufficient to cause defect initiation
    2. Evaluated the defect region where a transient delamination rate occurs
    3. Evaluated the defect region where a constant slope delamination rate occurs
  - o Modeled stress field with FEA



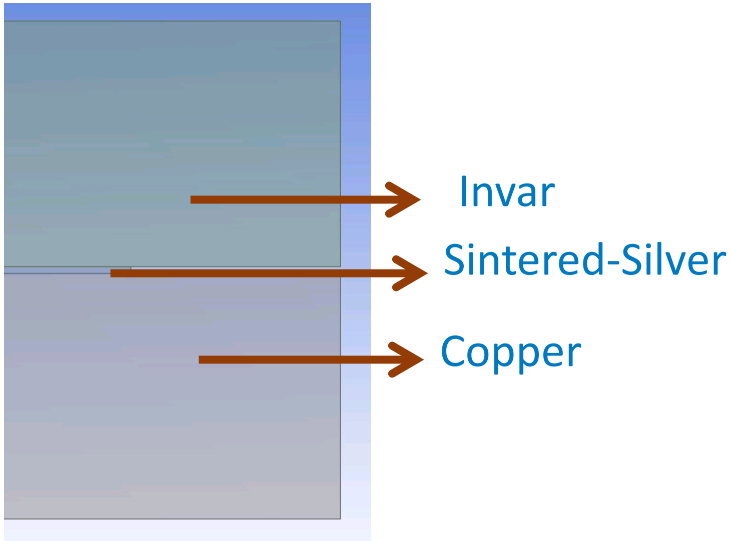


Modeling Methodology

- A fracture mechanics-based approach has been adopted to study the crack growth behavior of sintered-silver under thermal cycling
- A quarter-symmetry model of the round coupon samples was created in ANSYS Workbench
- Strain energy density/cycles results were evaluated



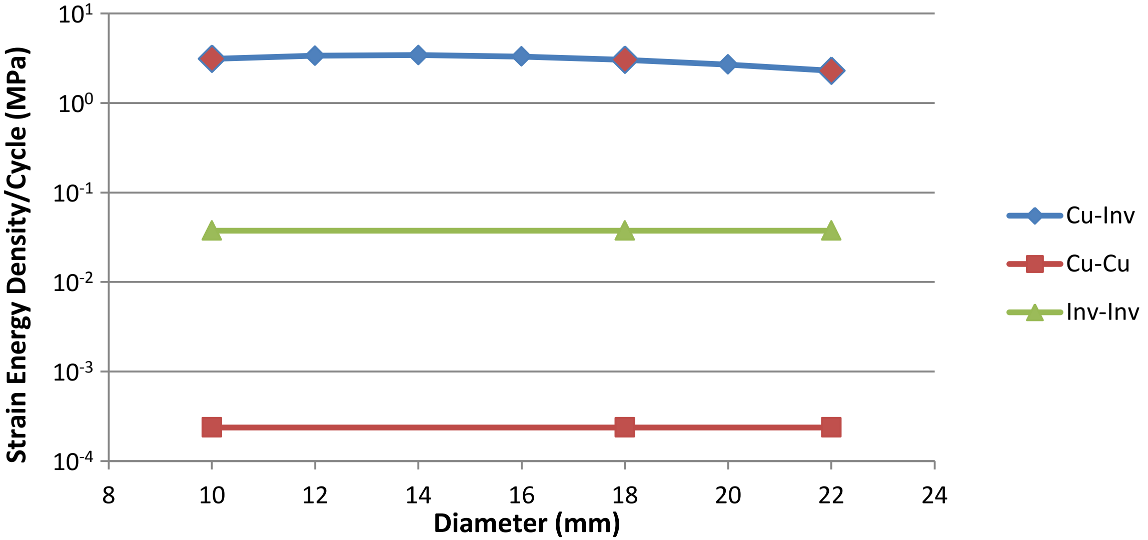
Top view

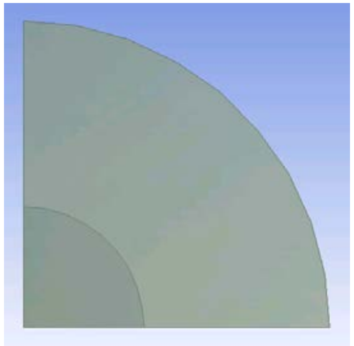


Side view

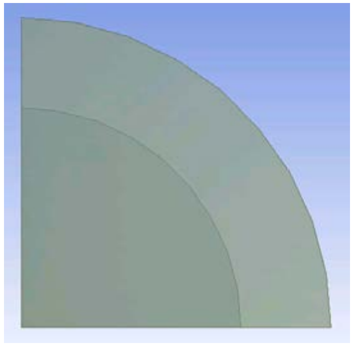
Modeling Results

- Evaluated separate simulations with variations in sintered-silver diameter

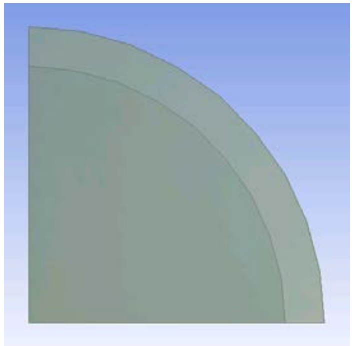




10 mm



18 mm



22 mm

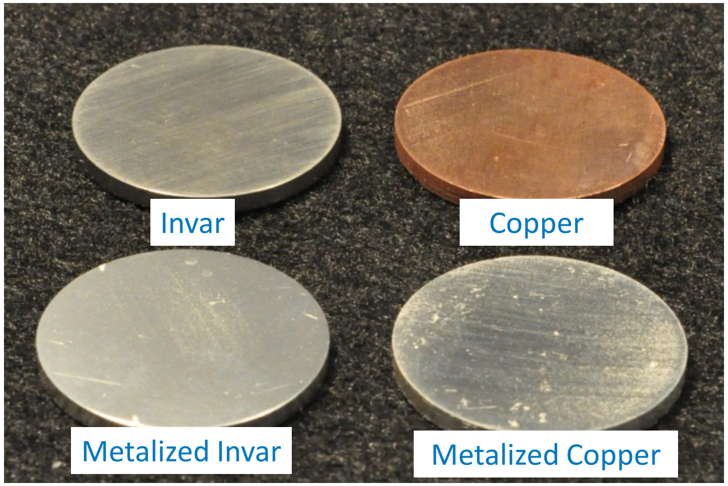
- Cu-Inv simulations generated the highest strain energy density/cycle results

Next Steps

- J-integral implementation in ANSYS (cyclic versus non-cyclic loading
- Crack propagation modeling
- Updated material properties

CTE-Mismatched Disk Samples

- Processed CTE-mismatched disk samples with various diameter bond pads (10 mm, 18 mm, and 22 mm) to validate stress field relationship with delamination initiation
- Invar and copper were selected for round test coupons
  - Coupon dimensions are 25.4 mm in diameter and 2 mm in thickness
  - Surfaces were blanchard ground and metalized with silver
- Process conditions
  - Loctite Ablestik SSP 2020 (Henkel) silver paste was stencil printed to bottom coupon
  - Dried at 100°C in nitrogen for 2 hours, then top coupon applied
  - Sintered at 250°C for 1 hour at a pressure of 1 MPa, then cooled while under pressure

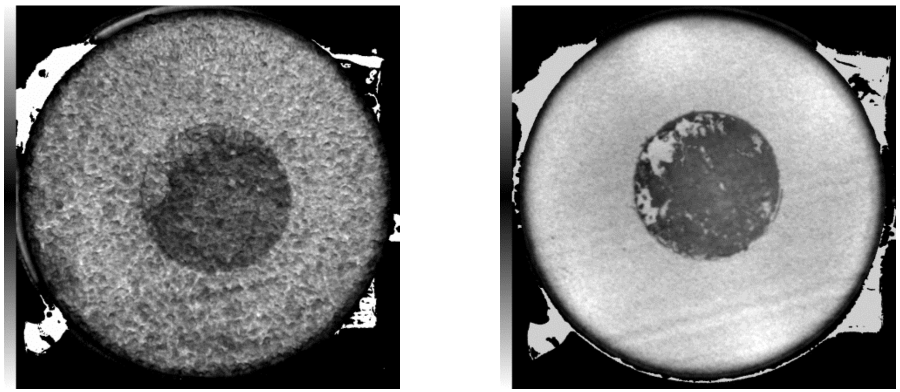


Invar and Copper Test Coupons

Sample Sintering Assembly

CTE-Mismatched Disk Samples

- Samples have reached 1,700 cycles
  - o Cu-Invar samples failed after 100-400 cycles
  - o No additional samples have failed after initial delaminations

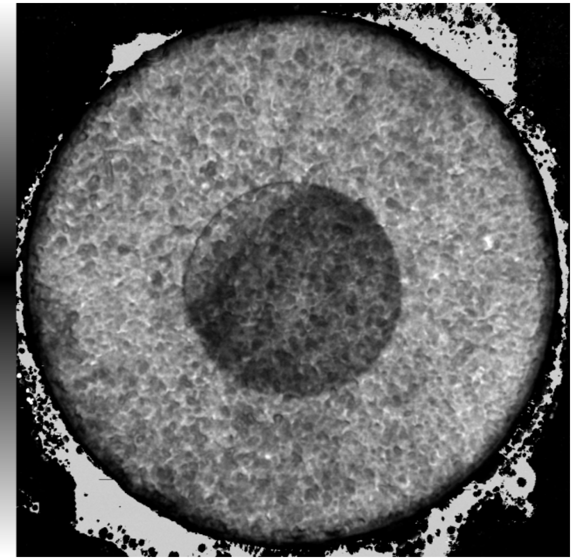


Scan through 10 mm Cu (left) and Invar (right)

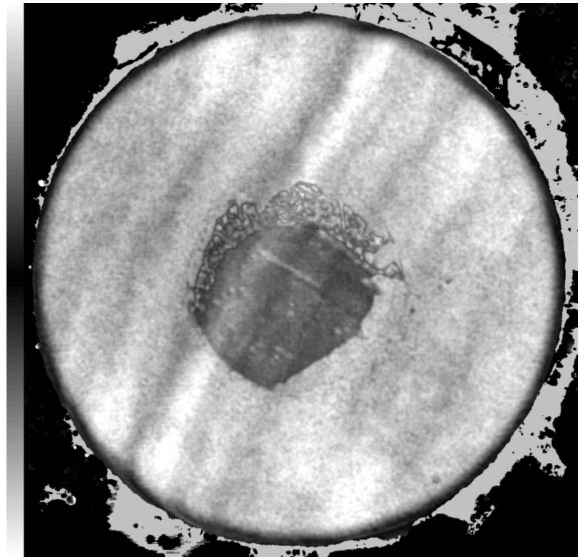
22 mm Cu-Invar sample failure after 100 cycles

Coupons	Stencil Diameter (mm)	Cycles 0	100	200	300	400	1,700
Cu-Cu	10						
Invar-Invar							
Cu-Invar							
Cu-Cu	18						
Invar-Invar							
Cu-Invar							
Cu-Cu	22						
Invar-Invar							
Cu-Invar							

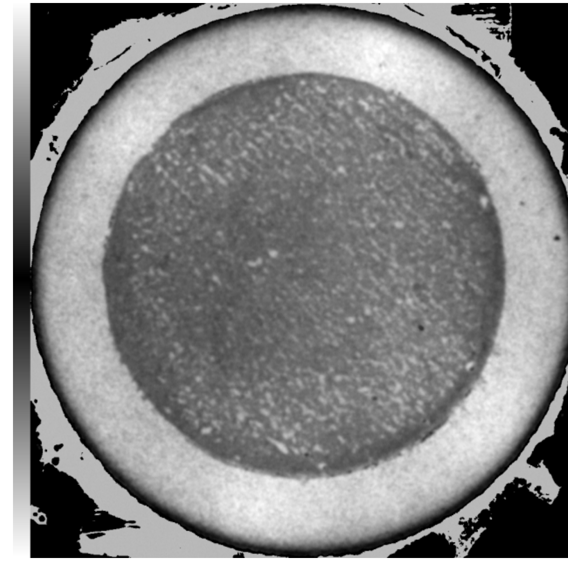
CTE-Mismatched Disk Samples



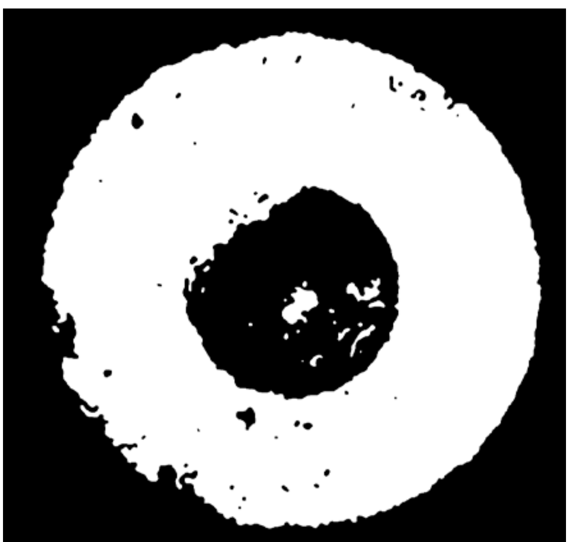
Copper, 10 mm



Invar, 10 mm



Invar, 18 mm



Copper, 10 mm, Processed

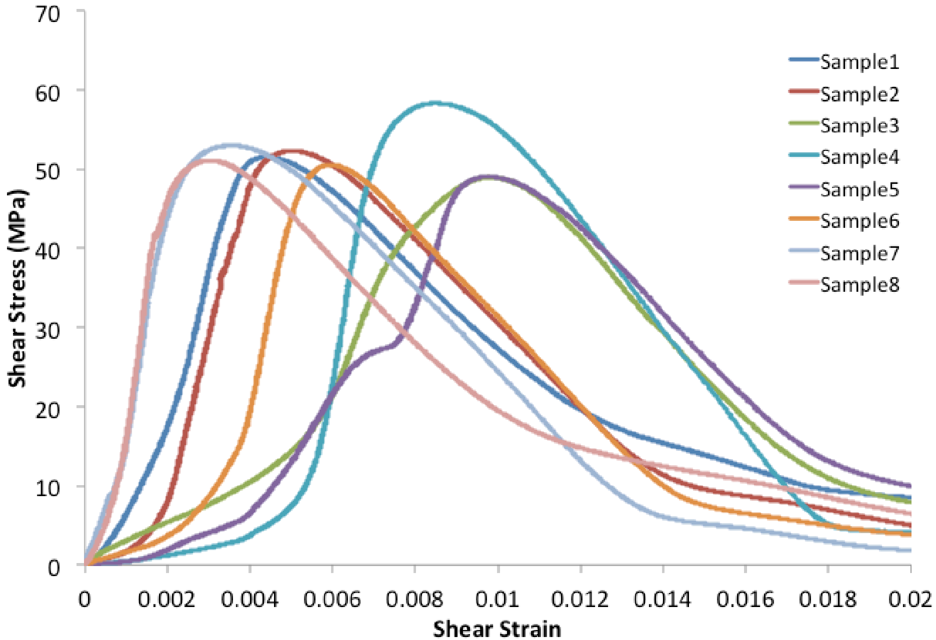
Invar, 10 mm, Processed

Invar, 18 mm, Processed

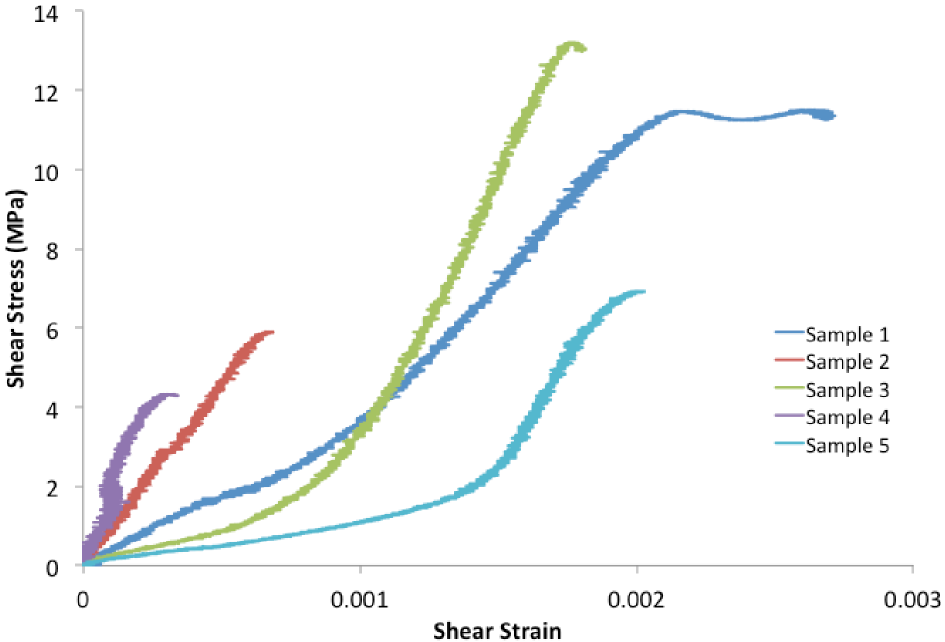
Double-Lap Shear Samples

- Sintered-silver samples exhibited minimal creep during shear testing and lower shear strength than solder samples
- Completed shear fixture modification to allow an additional pivot point to aid in alignment
  - Misalignment the cause for sintered-silver variations

$Sn_{63}Pb_{37}$

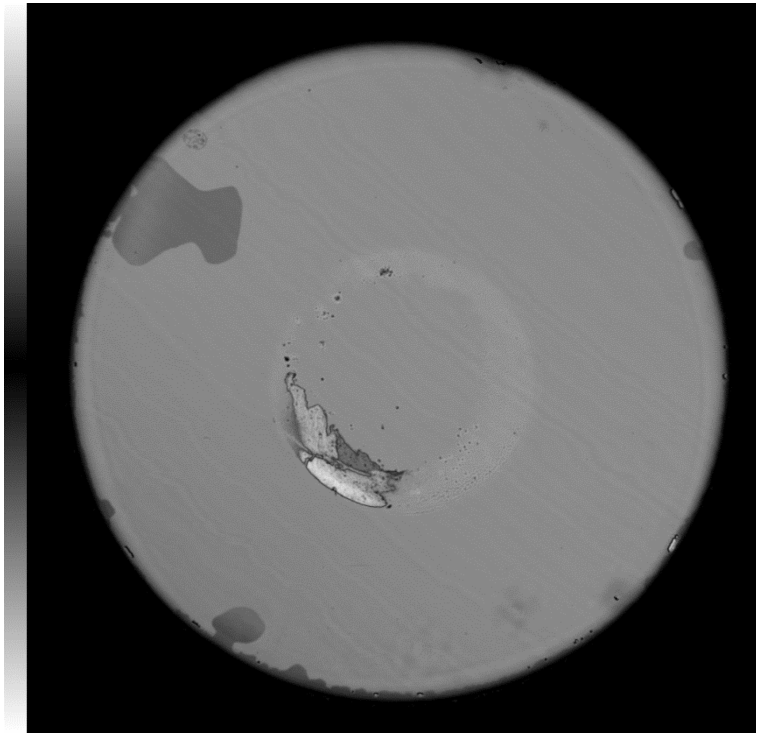


Sintered-Silver

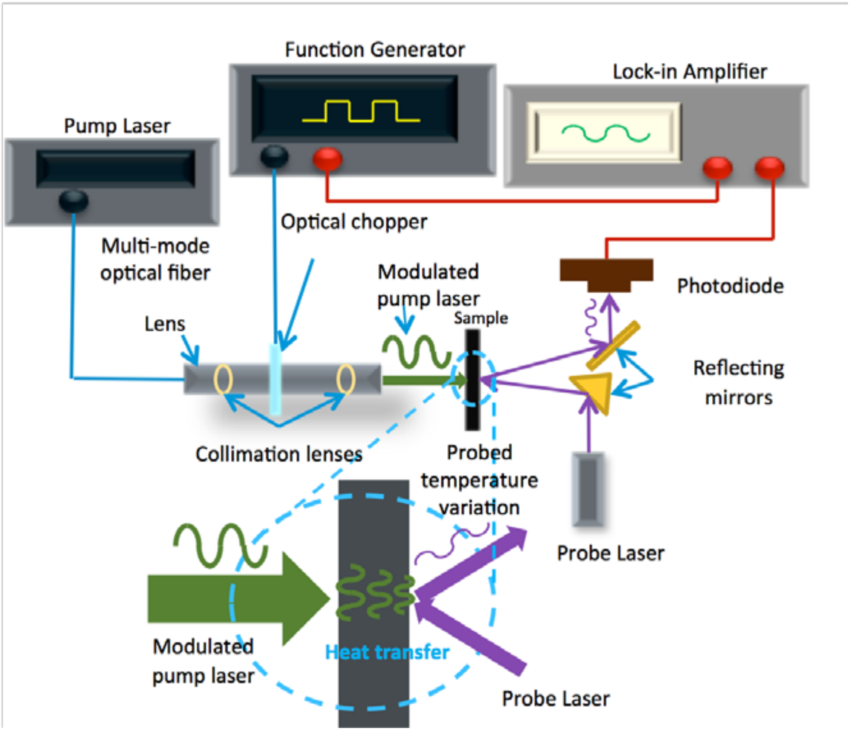


Si-Si Bonded Samples

- Prior Si/Al samples were bonded via small section on Si side
  - Si-Si samples will attempt to minimize CTE mismatch and delamination
  - Thermal resistance will be measured via the phase-sensitive transient thermoreflectance (TTR) technique



Partial Si to Sintered-Silver Bond



TTR Technique

Responses to Previous Year Reviewers' Comments

The reviewer considered the future work to well defined, but recommended that when looking at bond pad geometries to reduce stress, the project team should also add to the geometries how they may affect the thermal performance.

It is desirable to optimize the CTE mismatch with the package thermal resistance.

This reviewer relayed that modeling updates are progressing, but wondered if a biased humidity test could be included with the thermal cycle tests to determine if the silver material will survive in a typical automotive environment (e.g., no dendrite).

Additional testing procedures will be considered.

Collaboration and Coordination

- **ORNL:** technical partner on sintered-silver samples

Remaining Challenges and Barriers

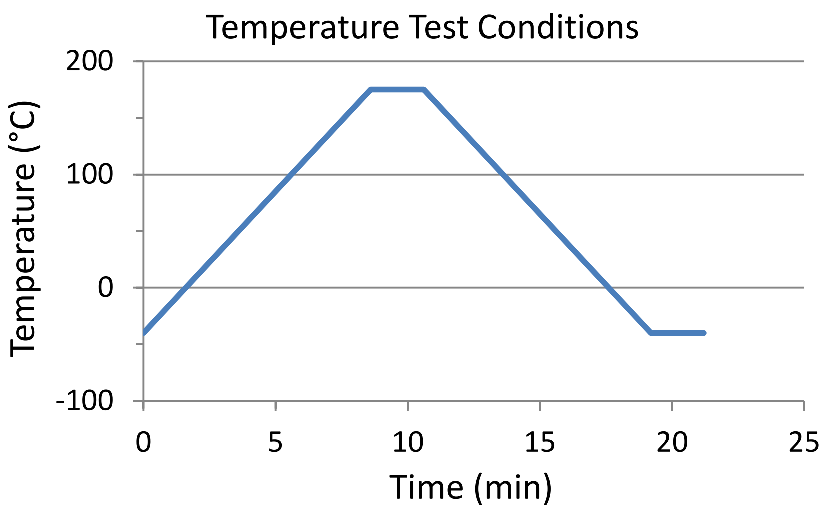
- Quality of sintered-silver joints is dependent on many parameters (temperature, pressure, time of synthesis, and plating quality)
- Obtaining accurate material properties for sintered-silver is critical for crack analysis modeling
- Fracture-mechanics–based crack modeling must replicate sintered-silver failure mechanism

Proposed Future Work (FY16)

- Subject additional round samples to accelerated temperature testing:
  - –40°C to 175°C thermal cycle
- Monitor delamination rates through acoustic microscopy

- Synthesize and shear test additional samples for mechanical characterization of sintered-silver
  - Establish lifetime estimation model for sintered-silver

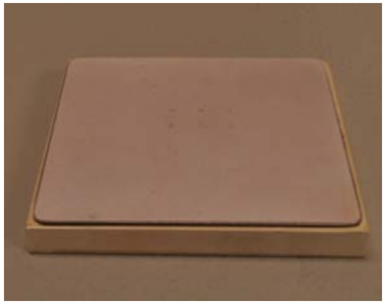
- Synthesize Si-Si bonded sintered-silver samples for characterization of thermal resistance via the TTR technique

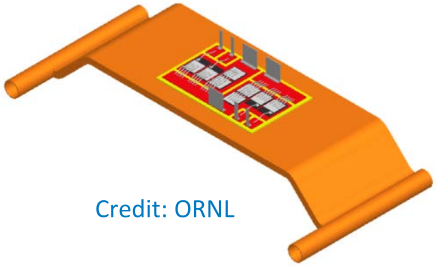


Shear Test Fixture and Sample

Proposed Future Work (FY17)

- **Additional Shear Testing**
  - Additional coupons will be needed for evaluating properties under various temperatures and strain rates
- **Large Area Attach**
  - Previous substrate-attach evaluations with solders, thermoplastics, and sintered-silvers have utilized 50 mm x 50 mm Si_3N_4 substrates attached to 50 mm x 50 mm x 5 mm Cu baseplates
  - Additional samples will evaluate variations in stencil patterns and plating options
- **Package Integration**
  - Demonstration of an ORNL double-sided planar package utilizing sintered-silver at die-and substrate-attach layers will be a key milestone for this project





Credit: ORNL

Summary

- **DOE Mission Support:**
  - Bonded interface materials are a key enabling technology for compact, lightweight, low-cost, reliable packaging, and for high-temperature coolant and air-cooling technical pathways
- **Approach:**
  - Synthesis of sintered-silver bonds, accelerated temperature cycling, bond inspection (acoustic microscope), and stress field versus cycles-to-failure models
- **Accomplishments:**
  - Characterized the degradation of sintered-silver interfaces
- **Collaborations**
  - ORNL

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Acknowledgments:

Susan Rogers and Steven Boyd
U.S. Department of Energy

For more information, contact:

Principal Investigator
Douglas DeVoto
Douglas.DeVoto@nrel.gov
Phone: (303) 275-4256

Team Members:

Paul Paret
Andrew Wereszczak* (ORNL)

EDT Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: (303) 275-4062

* Jointly funded by the OVT EDT and
OVT Propulsion Materials Programs