Advanced Packaging Designs

(Keystone Project 1)

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National Renewable Energy Laboratory
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DOE Vehicle Technologies Program
2024 Annual Merit Review and Peer Evaluation Meeting

ELT218

Overview

Timeline

- Project start date: 10/01/18
- Project end date: 09/30/24
- Percent complete: 90%

Budget

- Total project funding: $1,000,000
  - DOE share: $1,000,000
- Funding for FY 2023: $150,000
- Funding for FY 2024: $150,000

Barriers

- Barriers addressed:
  - Cost reduction
  - High-temperature capability
  - Multiphysics integration.

Partners

- Interactions/collaborations:
  - Oak Ridge National Laboratory (ORNL)
  - DuPont
- Project lead:
  - National Renewable Energy Laboratory (NREL).

Relevance

- Wide-bandgap (WBG) packaging designs must thermally allow for:
  - Higher operating temperatures
  - Higher heat fluxes/power densities
  - Hot spots.
- Coefficient of thermal expansion (CTE) mismatch between layers of the module will impose stresses that can initiate and propagate defects:
  - Attach layer fatigue
  - Interconnect fatigue.
- New package designs must address thermal and reliability concerns and be evaluated under accelerated conditions that approximate real-world conditions.

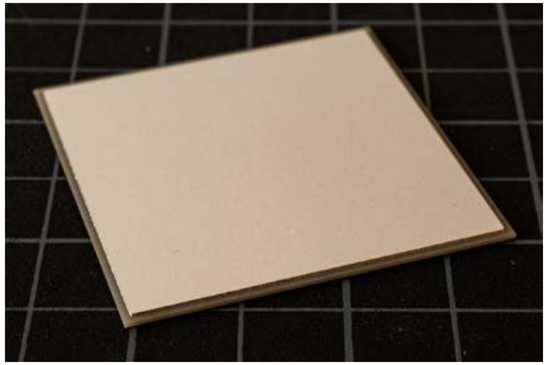
Approach

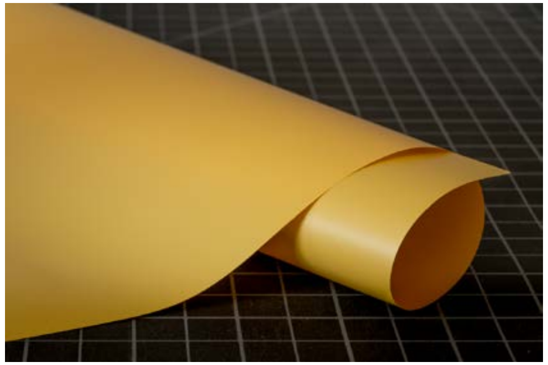
- Design path must show an improvement in performance over a baseline module while allowing for co-design of electrical, thermal, mechanical, and cost constraints (instead of a traditional linear design workflow).
- NREL is working closely with ORNL and industry partners to evaluate new packaging materials and manufacturing techniques for WBG-based traction inverters.
  - A polyimide material from DuPont (Temprion electrically insulating film) has been evaluated in the form of an organic direct-bond copper (ODBC) substrate as a replacement for ceramic substrates that can operate at higher temperatures.

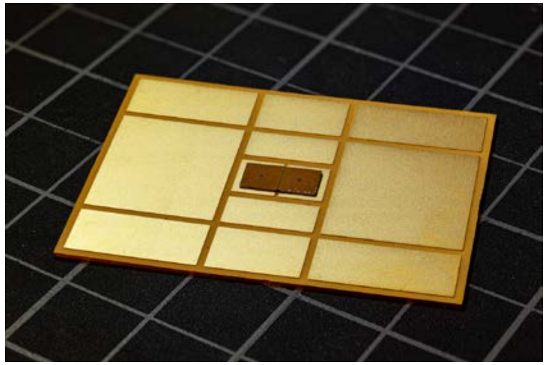
Milestone End Date	**Milestone Description**
September 2024 *(in progress)*	• Demonstrate an optimized power module design, with a ceramic-free electrically insulating substrate, through the development of a rapid multiphysics optimization workflow.

Approach

- Traditional metalized ceramic substrate technologies:
  - Direct-bond copper (DBC)
    - Oxidation of copper (Cu) foils during bonding lowers melt temperature from 1,083°C to 1,065°C.
    - Maximum metallization thickness of 1 mm.
    - Must have metallization layers on both sides of the ceramic.
    - Examples include aluminum oxide (Al_2O_3), aluminum nitride (AlN), and zirconia (ZrO_2)-doped high-performance substrates (HPS).
  - Active metal bonding (AMB)
    - Brazing process with silver-copper (Ag-Cu) alloy between Cu and ceramic at 850°C in vacuum.
    - Requires more processing steps and is more expensive than DBC.
    - Silicon nitride (Si_3N_4) and AlN substrates are examples.
- ODBC
  - A polyimide dielectric is bonded with metal at elevated temperature (300°C) and pressure (2.41 MPa) under vacuum or inert atmosphere.
  - No limitations in metal material or metallization thickness.
  - Maintains electrical and thermal performance after 5,000 thermal shock cycles (−40°C to 200°C, 5-minute dwells).

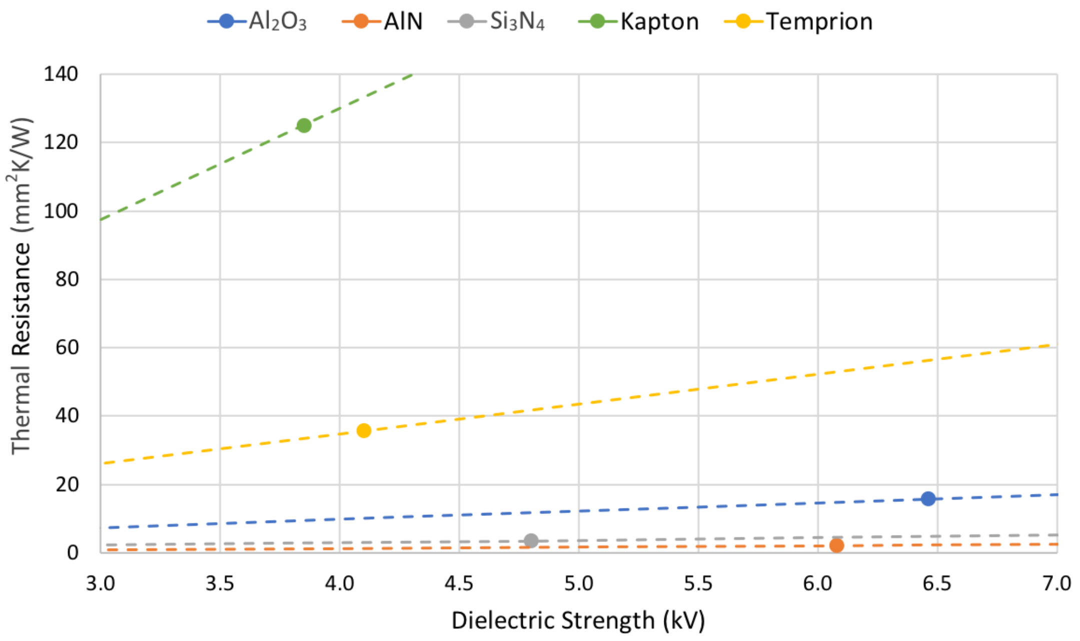

Traditional substrate

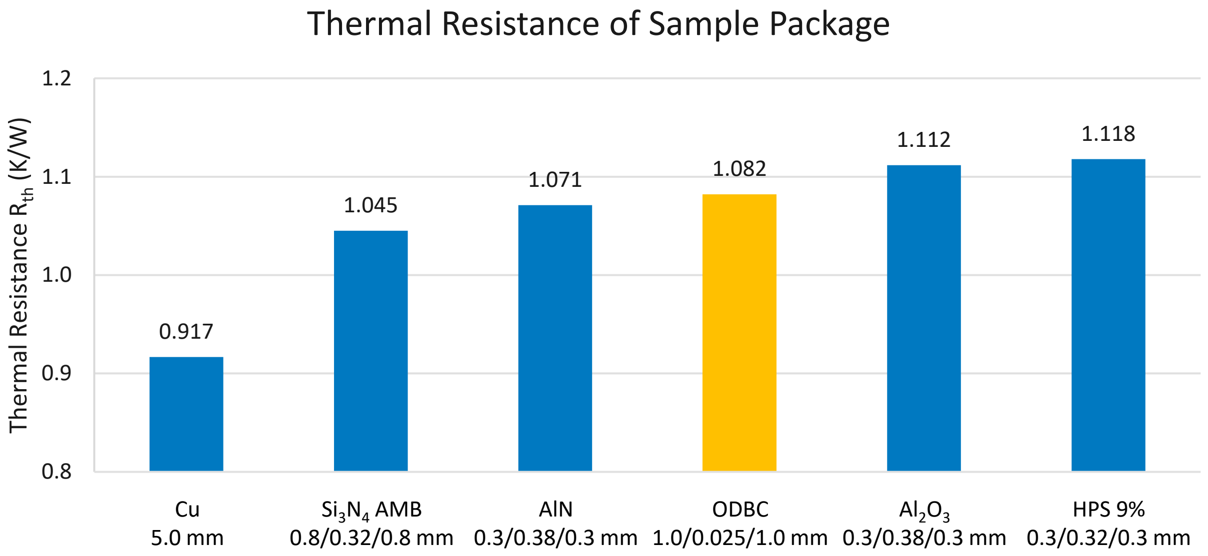

DuPont Temprion polyimide film


DuPont ODBC substrate

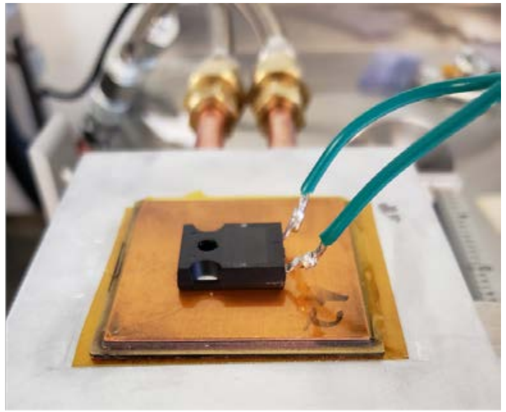
Approach

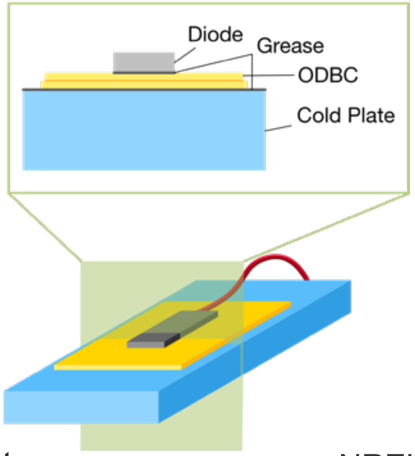
- Lower thermal conductivity of Temprion is offset by thicker topside metallization.





Insulator	Thickness (µm)	Dielectric Strength (kV/mm)	Dielectric Strength (kV)	Thermal Conductivity (W/[m·K])	Thermal Resistance (mm^2K/W)
Al_2O_3	380	17	6.5	24	16
AlN	380	16	6.1	180	2
Si_3N_4	320	15	4.8	90	4
Kapton	25	154	3.9	0.2	125
Temprion	25	164	4.1	0.7	36





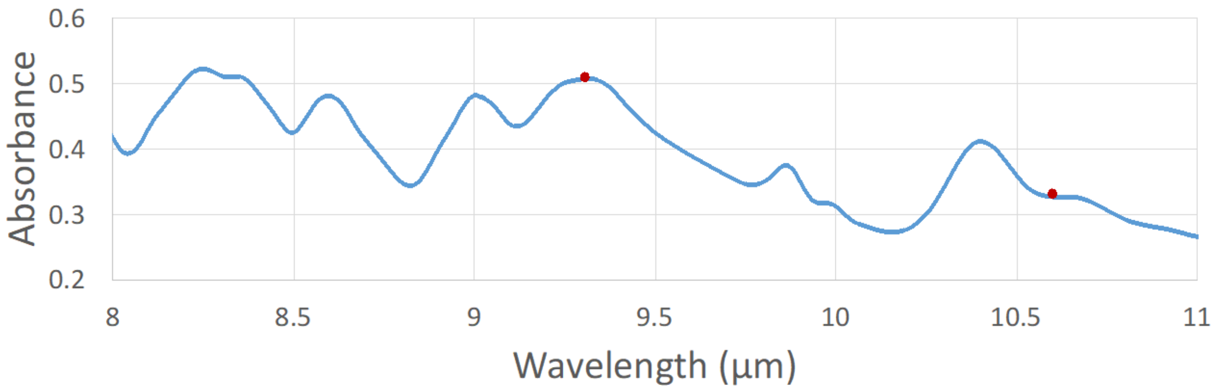
T3ster test setup

Technical Accomplishments

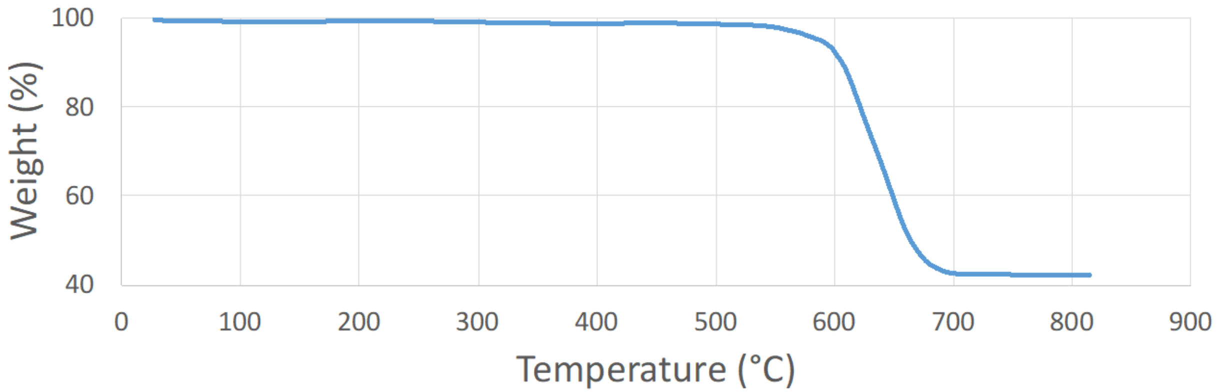
- Polyimide Material Analysis
- Power Electronics Module Fabrication
- Multiphysics Design Optimization

Polyimide Material Analysis

- In previous work, the polyimide was mechanically cut to shape with a sharp blade, but this manual process limited the complexity of shapes that could be patterned.
- NREL first evaluated the compatibility of Temprion for laser patterning and processing.
  - Fourier-transform infrared spectroscopy indicates that Temprion has higher absorption values at 9.3 μm than 10.6 μm, common CO_2 laser wavelengths.
  - Thermogravimetric analysis and dynamic mechanical analysis indicate very high thermal stability (>500°C) and wide processing window.



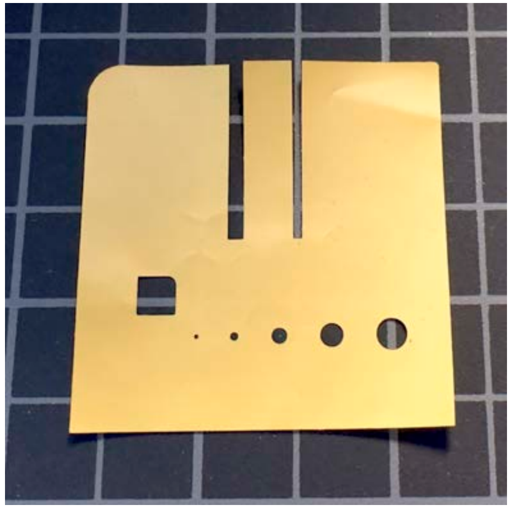
Temprion absorption analysis



Temprion thermal stability analysis

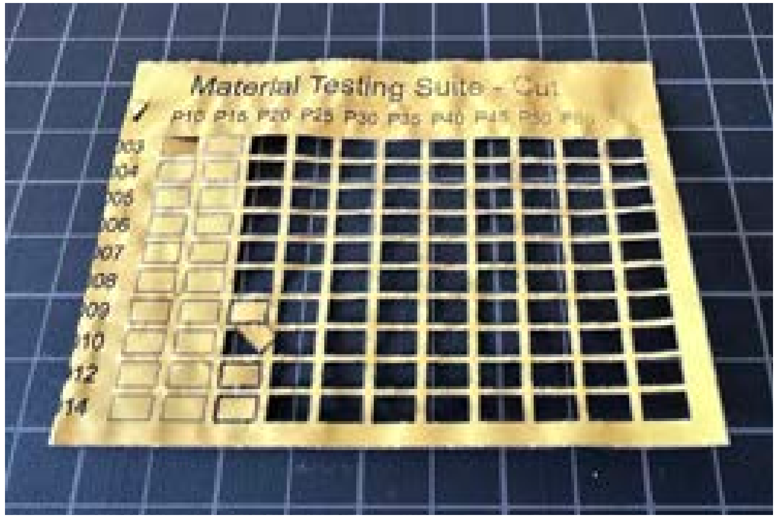
Polyimide Material Analysis

- The polyimide was patterned in two different laser cutters.
  - A commercial 30-W, 9.3-µm CO_2 laser platform.
  - A consumer 30-W,10.6-µm CO_2 desktop laser.
- The laser power and cutting speed were optimized for both systems.



Temprion commercial test pattern

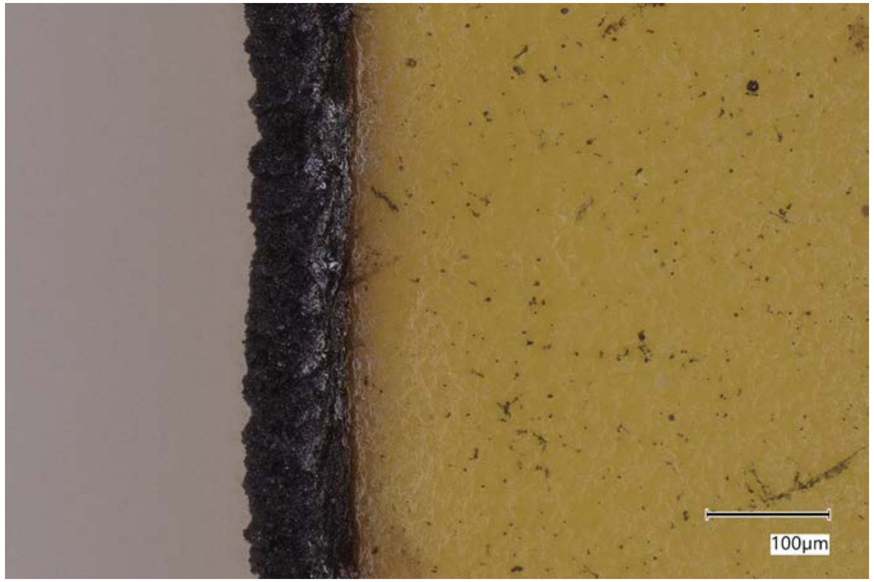
Temprion cutting process on consumer laser platform



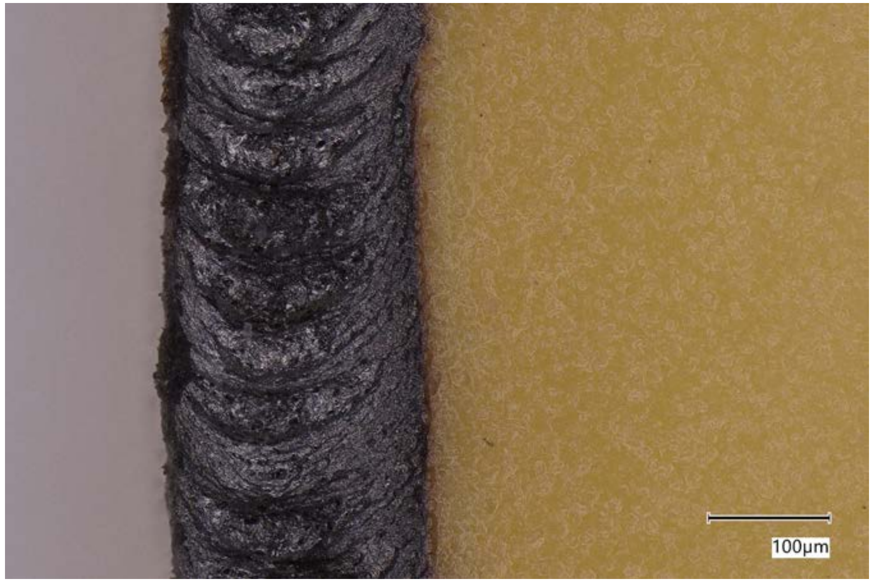
Completed optimization pattern

Polyimide Material Analysis

- The optimized laser wavelength and focusing optics of the commercial laser platform created a smaller heat-affected zone (HAZ) than the consumer laser.
- The HAZ was measured to be 85 μm and 200 μm for the commercial and consumer laser systems, respectively.



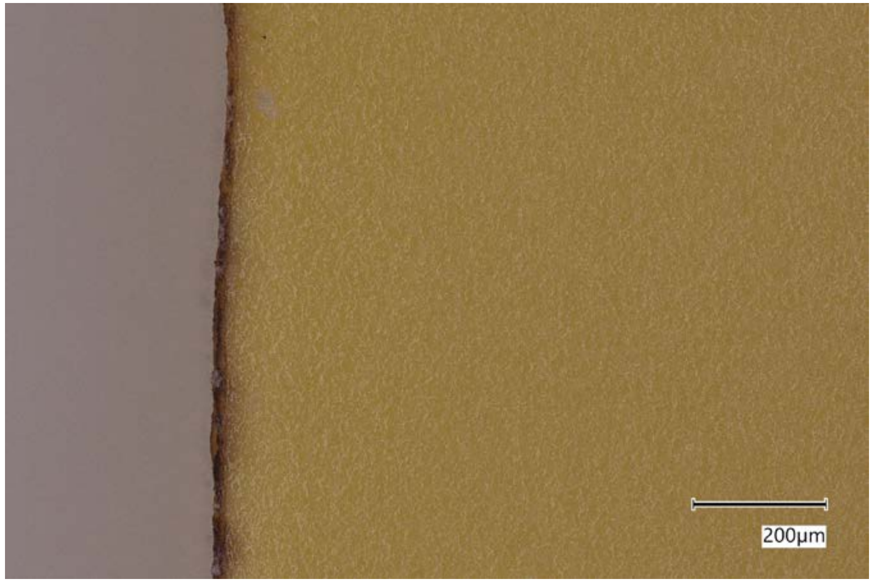
HAZ of 9.3-μm commercial CO_2 laser



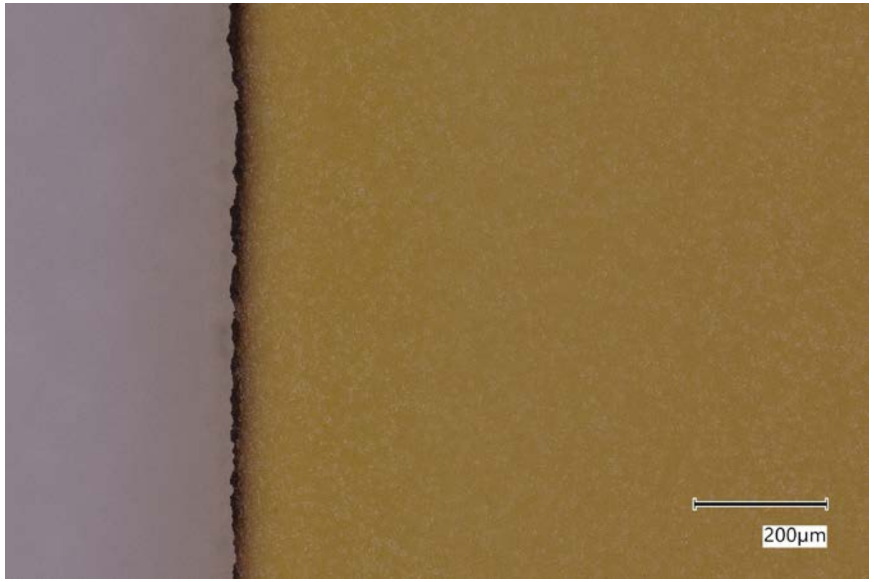
HAZ of 10.6-μm consumer CO_2 laser

Polyimide Material Analysis

- Samples from both systems were cleaned in an ultrasonic bath for 5 minutes. The edge quality after sonication is similar.
- For required tolerances of power module fabrication, the widths of the HAZs from either laser system can be compensated for by adding an offset to the desired dimensioned drawings.



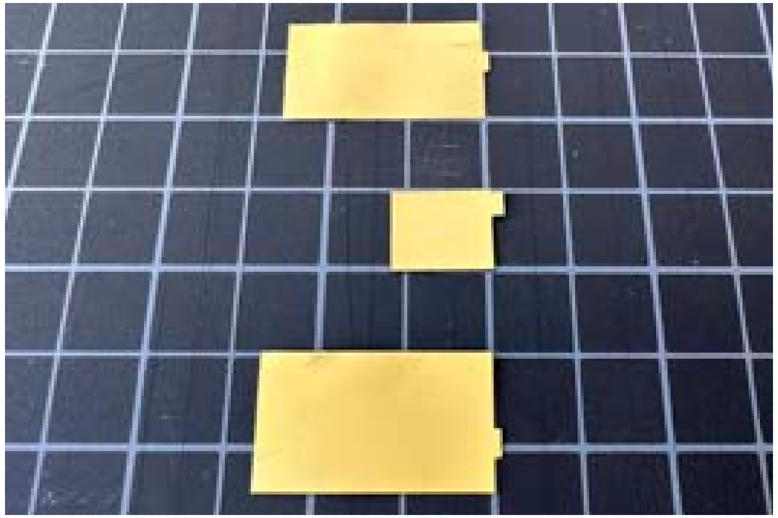
Cleaned edge of 9.3-µm commercial CO_2 laser



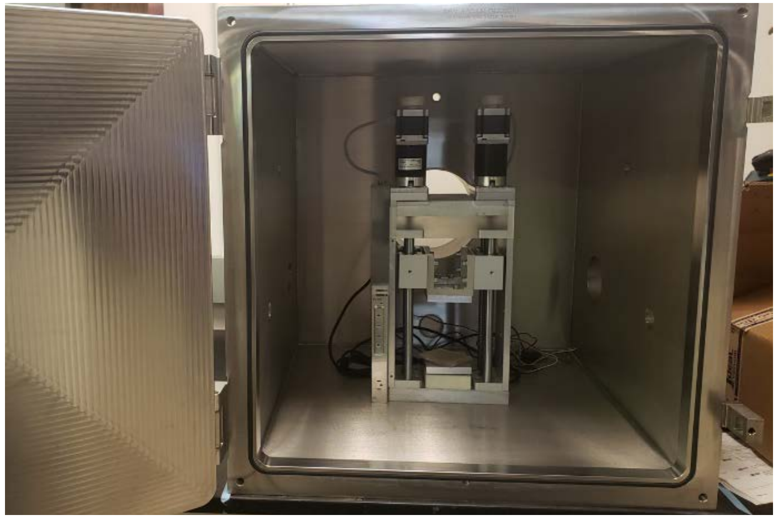
Cleaned edge of 10.6-µm consumer CO_2 laser

Power Electronics Module Fabrication

- Polyimide was cut using optimized laser settings on the 10.6-μm CO_2 desktop laser cutter to obtain substrate patterns for a power module design.
- One significant improvement in the bonding process has been made by installing the high-temperature press into a vacuum chamber.
  - Bonding in a vacuum or an inert environment eliminates detrimental oxidation on Cu surfaces during the bonding process.



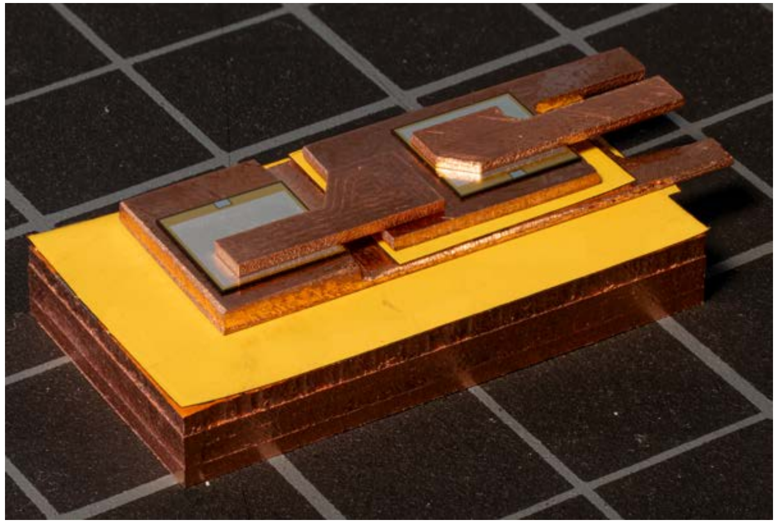
Polyimide layers for module fabrication



Vacuum high-temperature press

Power Electronics Module Fabrication

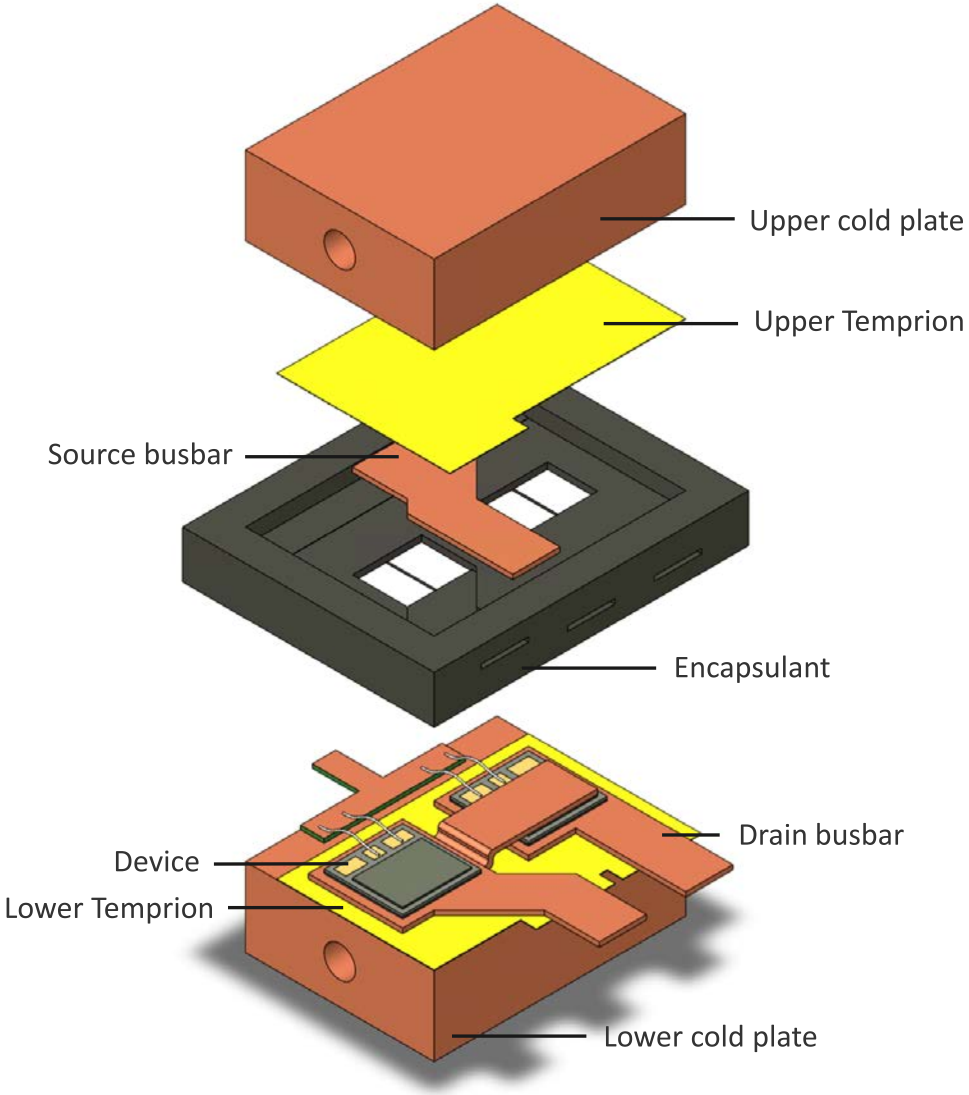
- Cu busbars and cold plates were machined on a computer numerical control router.
- In the future, additional fixtures will be machined to keep components aligned during the bonding process.
- Due to supply chain constraints, SiC metal–oxide–semiconductor field-effect transistors (MOSFETs) with topside metallization layers compatible with Ag sintering were not available to integrate into the module.
    - SiC junction-gate field-effect transistors (JFETs) with topside Al metallization were used instead.



Half-bridge power module assembly

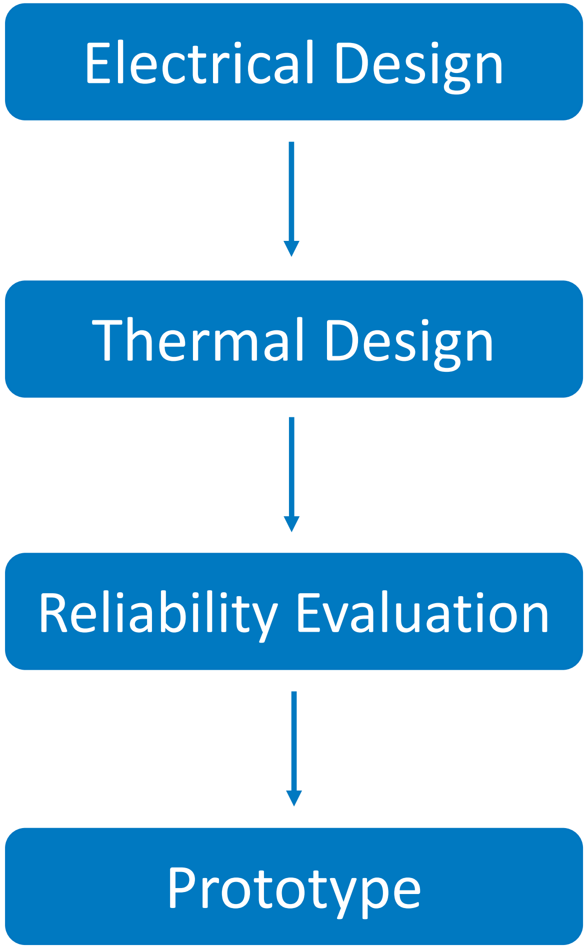
Multiphysics Design Optimization

- GeneSiC G4R12MT12-CAU MOSFETs were obtained with Au topside metallization.
- The polyimide half-bridge module was redesigned to take full advantage of the smaller die size.
- This package design is being used for multiphysics optimization.

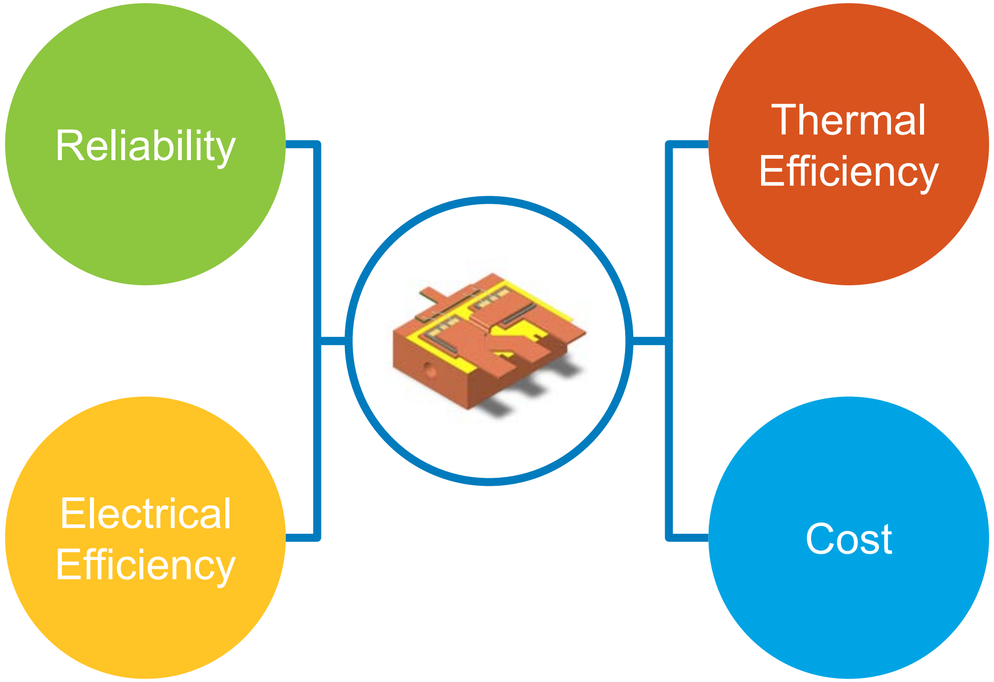


Multiphysics Design Optimization

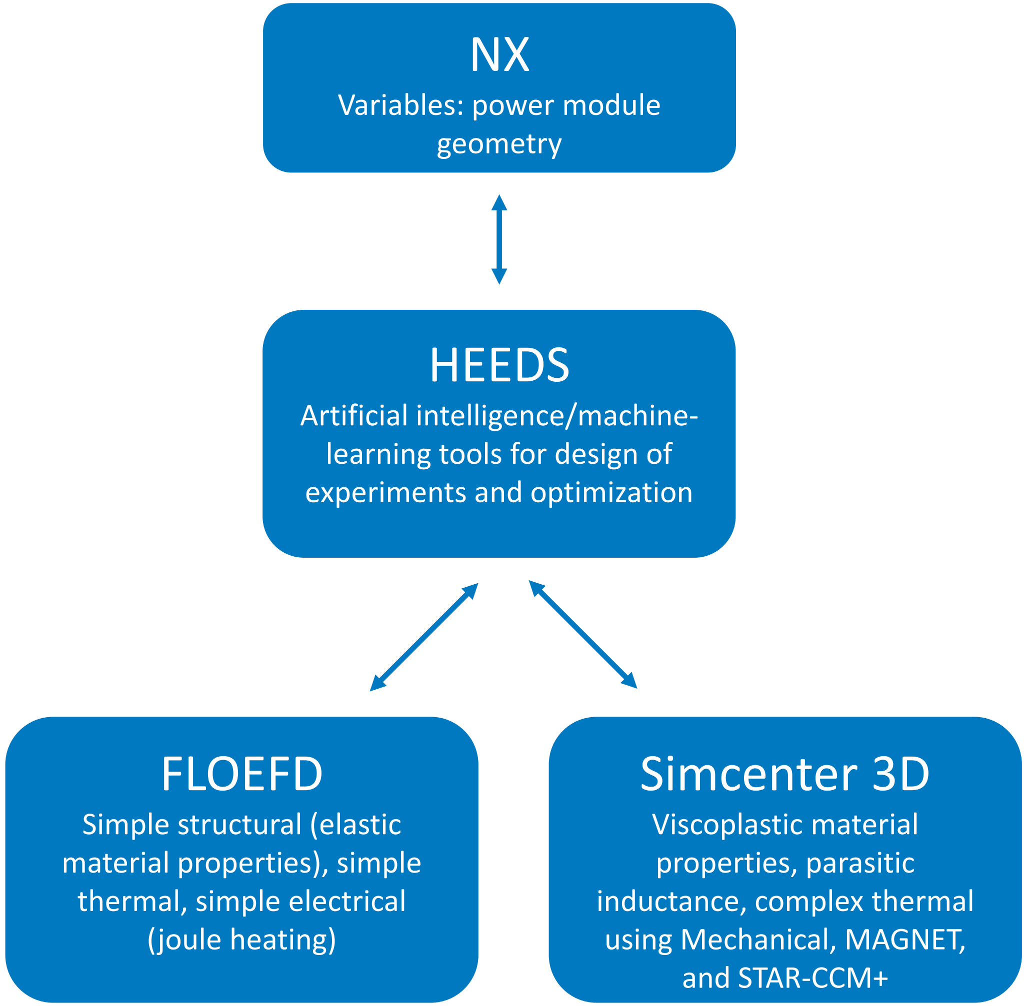
Linear Method



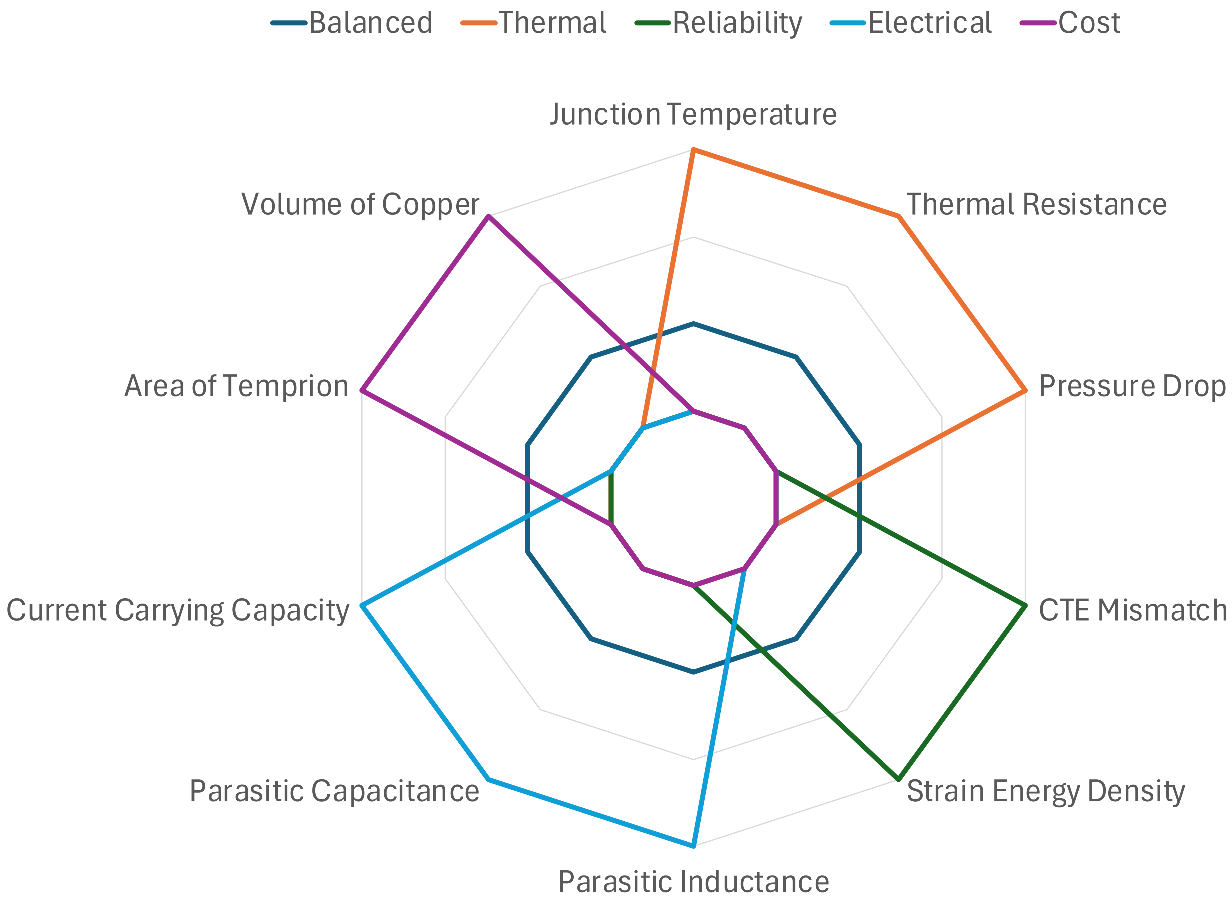
Multiphysics Method



Multiphysics Design Optimization

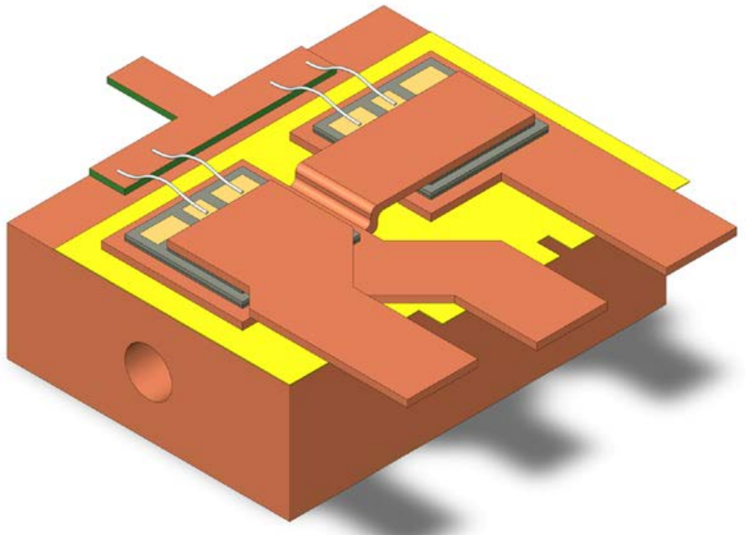


Optimization approach utilizing Siemens software

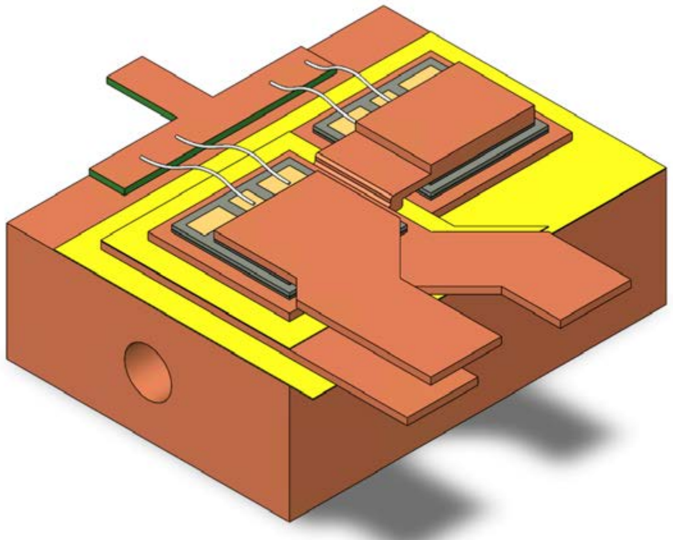


HEEDS: Hierarchical Evolutionary Engineering Design System

Multiphysics Design Optimization



Thermally driven design



Electrically driven design

Criteria	Thermally Driven Design	Electrically Driven Design
Junction Temperature (°C)	141	153
Parasitic Inductance (nH)	5.9	2.7
Area of Temprion (mm^2)	335	367
Volume of Copper Busbars (mm^3)	55	74

Collaboration and Coordination

- ORNL
  - Laboratory partner for multiphysics design approach of power electronics modules.
- DuPont
  - Industry partner for Temprion material and initial ODBC bonding guidance.

Remaining Challenges and Barriers

- Thermal and reliability concerns of new packaging technology must be experimentally evaluated.
  - Experimental characterization will be performed to evaluate module electrical and thermal performance.
- New substrate technologies may be susceptible to unforeseen failure mechanisms.
  - Past reliability evaluation of ODBC substrates has been promising, but full module assembly and evaluation in collaboration with industry is needed.

**Any proposed future work is subject to change based on funding levels.*

Proposed Future Research

- FY 2024
  - Complete milestone goal to demonstrate an optimized power module design, with a ceramic-free electrically insulating substrate, through the development of a rapid multiphysics optimization workflow.

**Any proposed future work is subject to change based on funding levels.*

Summary

Relevance

- New package designs must address thermal (i.e., higher operating temperatures) and reliability (i.e., CTE mismatch) concerns.

Approach

- Design path must show an improvement in performance over a baseline module while allowing for co-design of electrical, thermal, mechanical, and cost constraints (instead of a traditional linear design workflow).

Technical Accomplishments

- Completed patterning evaluation of polyimide.
- Updated manufacturing process for ODBC packages.
- Developed framework for multiphysics optimization.

Collaborations

- ORNL
- DuPont.

Acknowledgments

Susan Rogers, U.S. Department of Energy

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Thank You

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NREL Transforming ENERGY

Reviewer-Only Slides

Publications and Presentations

Publications

- DeVoto, D. 2023. “Advanced Power Electronics Designs – Reliability and Prognostics.” 2023 DOE VTO Annual Progress Report.

Presentations

- DeVoto, D. 2022. “Advanced Power Electronics Designs/Power Electronics Materials and Bonded Interfaces.” Presented to the DOE VTO Electrical and Electronics Technical Team, January 2022.

Critical Assumptions and Issues

- Working with private industry involves protection of their intellectual property and limits public disclosure of traction inverter designs.
  - Industry partners have presented directly to the U.S. Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) Electric Drive Technical Team (EDTT) and could be contacted for questions and additional information.
- The increase in power density from proposed packaging designs may require higher-performance cooling techniques.
  - Accurate thermal modeling and experimental testing of proposed designs will enable an informed selection of appropriate cooling techniques that balance cooling performance with cost, volume/weight, and reliability targets.