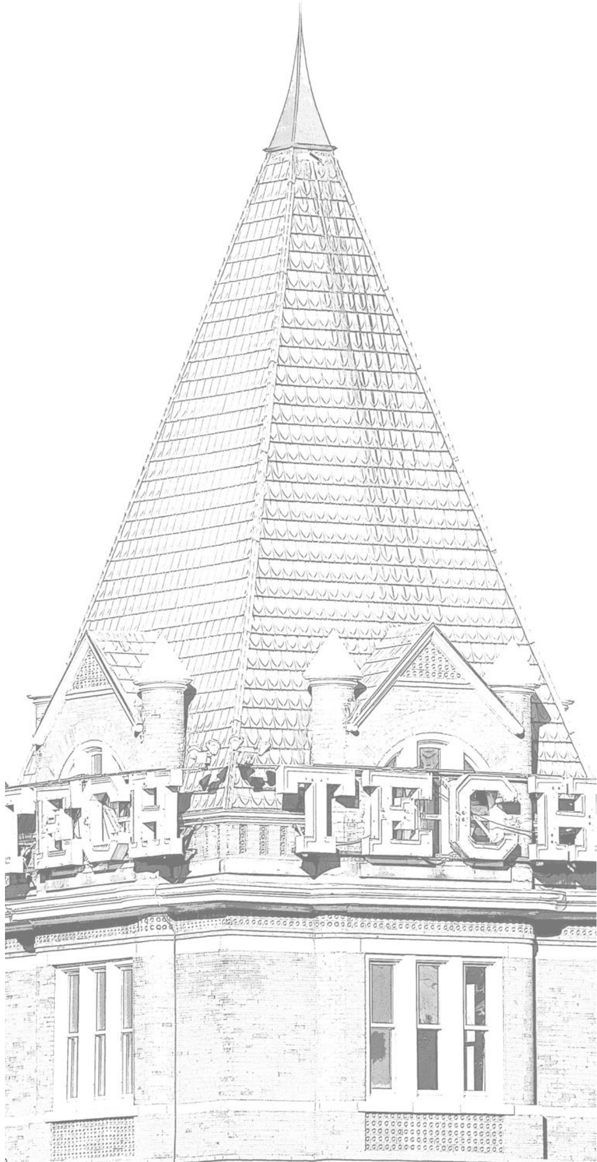


Device- and System-Level Thermal Packaging for Electric-Drive Technologies

Yogendra Joshi, Samuel Graham, Satish Kumar
Georgia Institute of Technology
June 2, 2020

Project ID# elt251

DOE Vehicle Technologies Office
2020 Annual Merit Review

This presentation does not contain any proprietary, confidential, or otherwise restricted information

Georgia Tech

Timeline

- Project start date: April 2019
- Project end date: March 2024
- Percent: 20%

Budget

- Total project funding: $1.5M
  - DOE share: $1.5M
  - Contractor share: $0
- Funding for FY 2019: $300K
- Funding for FY 2020: $300K

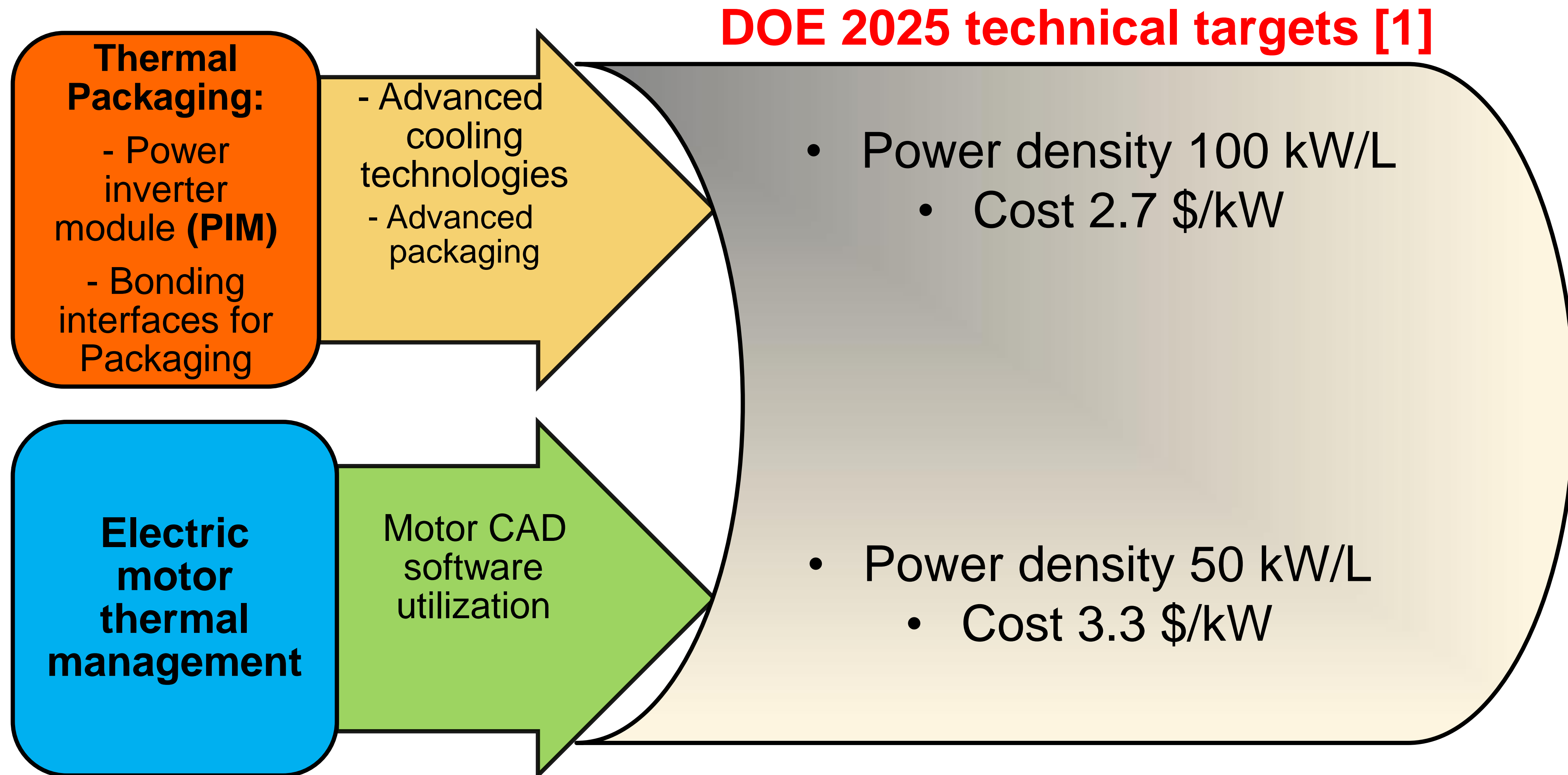
Barriers

- Cost, power density and reliability challenges in vehicle electrification using WBG devices
- Thermal management techniques required to achieve targeted power densities in power inverter module and electronic motors
- New packaging concept to enable transition to WBG devices.

Partners

- National Renewable Energy Laboratory (NREL)
- Oak Ridge National Laboratory (ORNL)
- SUNY Polytechnic Institute

RELEVANCE-SUMMARY



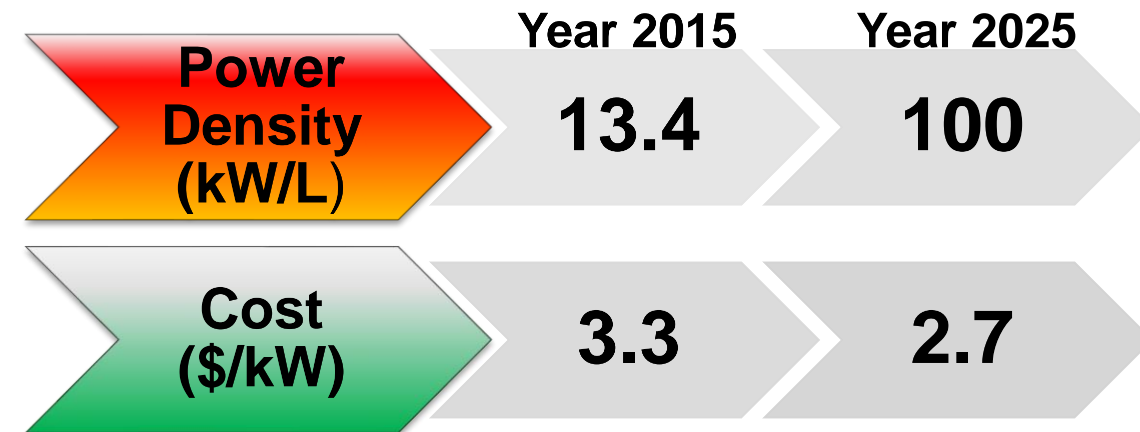
[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017

RELEVANCE –THERMAL PACKAGING

- Effective thermal management is essential for high power density and reliable Power Inverter Modules (PIM).

- Objective 1: Identify and demonstrate thermal management techniques to meet DOE target of 100 kW/L power density by 2025 [1].

- Objective 2: Design a compact and reliable packaging module to increase power density, and reduce cost by enhancing thermal performance with minimized CTE mismatch



DOE high voltage PIM technical target, adopted from [1]

[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017

RELEVANCE-ELECTRIC MOTOR THERMAL MANAGEMENT

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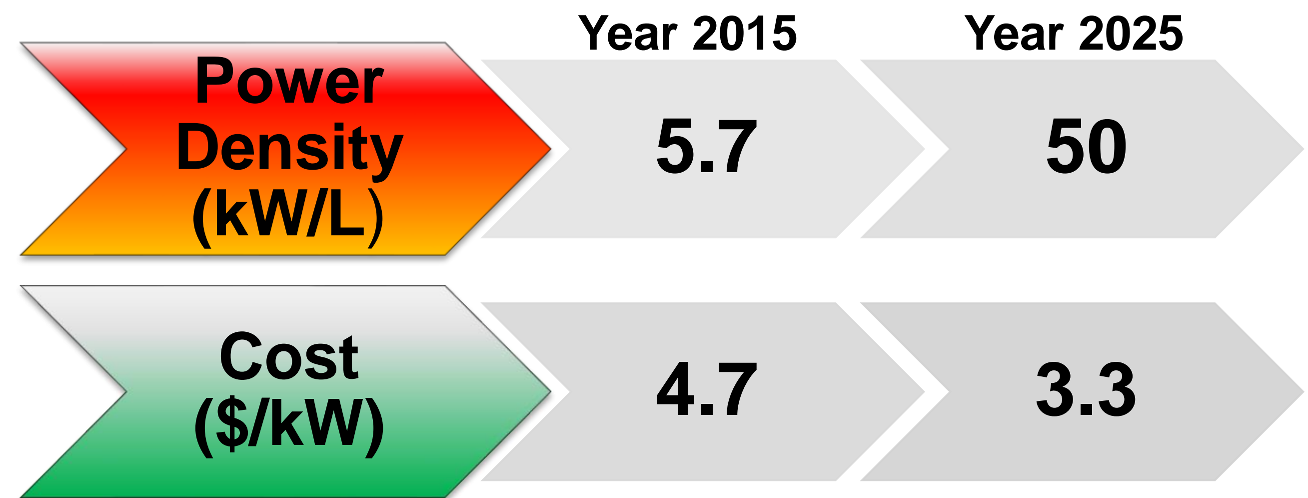
- Electric motor thermal modeling is essential to enhance reliability and reduce size.
- Objective: Validate thermal modeling of electric motor in Motor CAD software and propose cooling technologies to meet DOE 2025 technical targets [1].



DOE electric traction motor technical target, adopted from [1]

[1] U.S. DRIVE Electrical and Electronics Technical Team Roadmap, 2017

- Georgia Tech cleanroom facility
- Georgia Tech machine shop
- ANSYS numerical modeling software
- IR thermal camera
- Zeiss Metrotom 800 for x-ray
- Single and two phase flow loops with flow and temperature measurement components
- Zeiss Ultra 60 SEM
- High Temperature Tube Furnace
- Graphite rig
- Polishing machine

MILESTONES

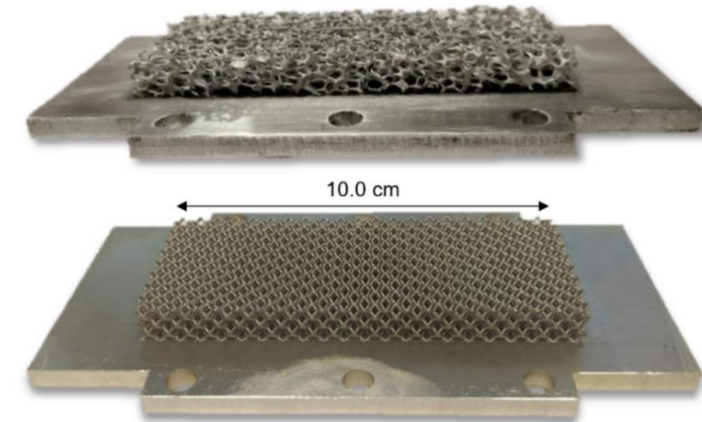
Milestone	Type	Description	Status
Establishment of baseline TM performance and improvement targets	Technical	Using the most promising present and future power electronics packaging topologies and materials we will establish baseline performance, and targets for the budget period.	Completed
Device and package level thermal and electro-thermal modeling approach established	Technical	The multi-scale modeling approach for device and package level thermal/electro-thermal modeling will be defined.	Completed
Bonded interfaces characterization intermediate results	Technical	Approach for bonded interface characterization established.	Completed
Demonstration of improved TM performance	Technical	Establish performance improvements using vapor chamber and cold plate technologies	Completed
Go/No Go Decision Title Demonstrate thermal packaging approach for 500 W/cm^2 for power components	Go/No Go	Thermal packaging approach for device heat flux of 500 W/cm^2 established.	Completed

TM: Thermal Management

APPROACH- THERMAL PACKAGING

Inverter thermal management:

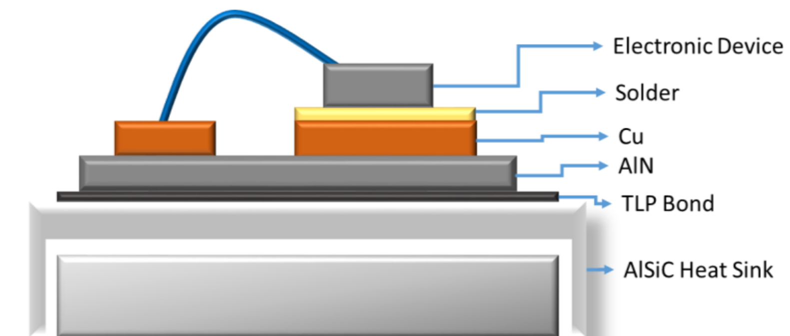
- Improved liquid cooling using additively manufactured (AM) foam-type structures
  - Direct printing to eliminate thermal interface materials and contact resistance
  - Local control of parameters such as pores per inch (PPI), porosity (ε), elongation, etc.
  - Enabling localized hotspot cooling, thermal gradient management, vapor pathways
- Utilized microscale pin fin array to achieve superior single-phase heat removal capability
  - Removed maximum 580 W/cm^2 heat flux at sub-100 °C temperatures



Stochastic ERG foam with visible thermal epoxy layer (top) and designed foam (bottom)

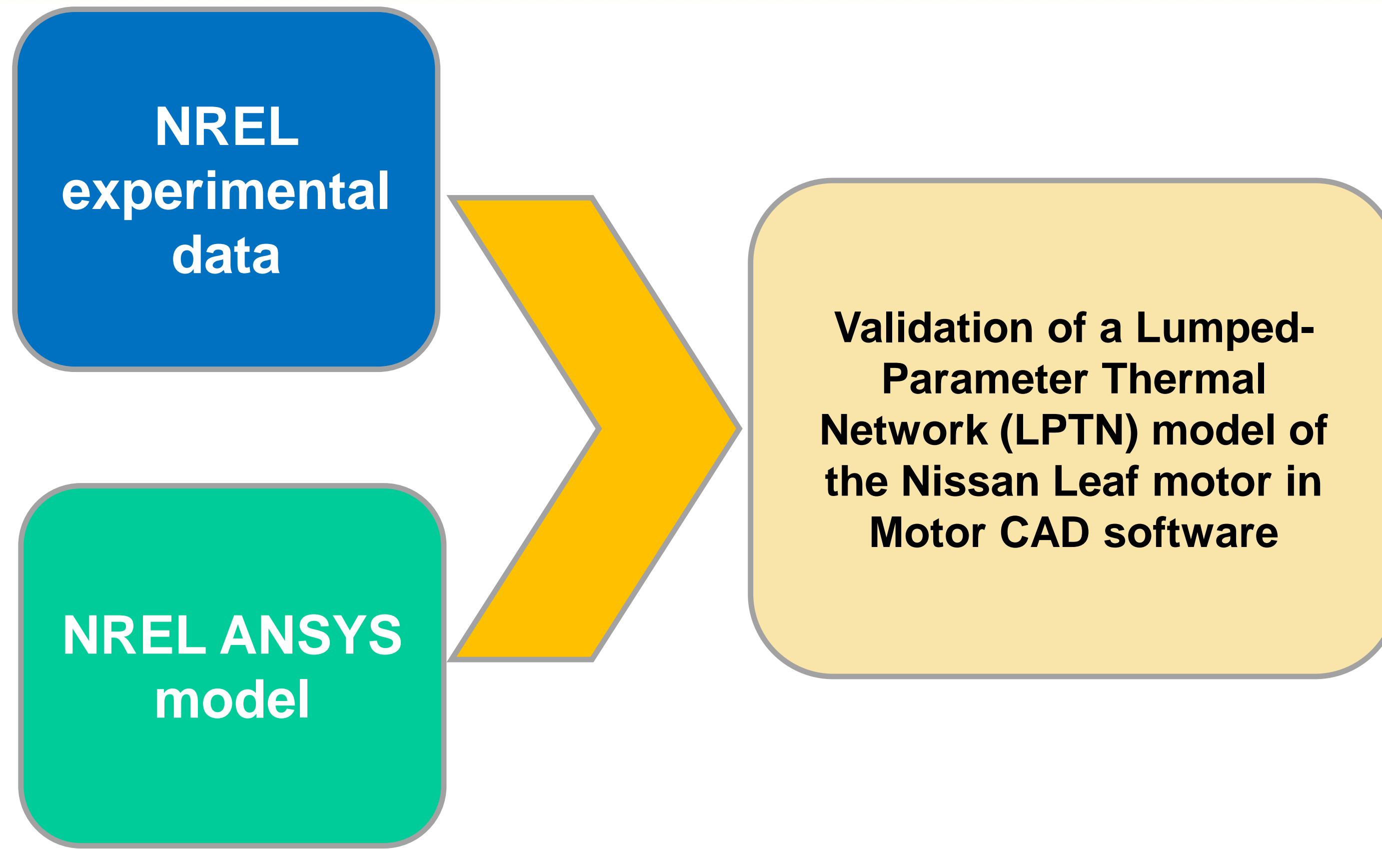
Packaging

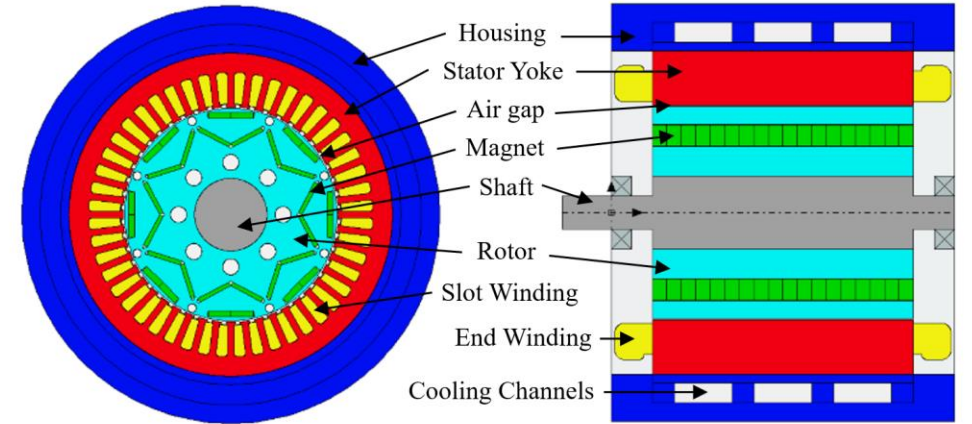
- Utilized Transient Liquid Phase Bonding (TLP) to construct a novel compact packaging concept with minimized CTE mismatch and better thermal performance
  - Cu diffuses into Al
  - Al-Cu mixture fully melts at held temperature, and re-solidifies. Bond is cooled back to ambient
  - Bonding Temperature down to 565°C from 1070°C (DBC)
  - Low cost – no deposition – no gases



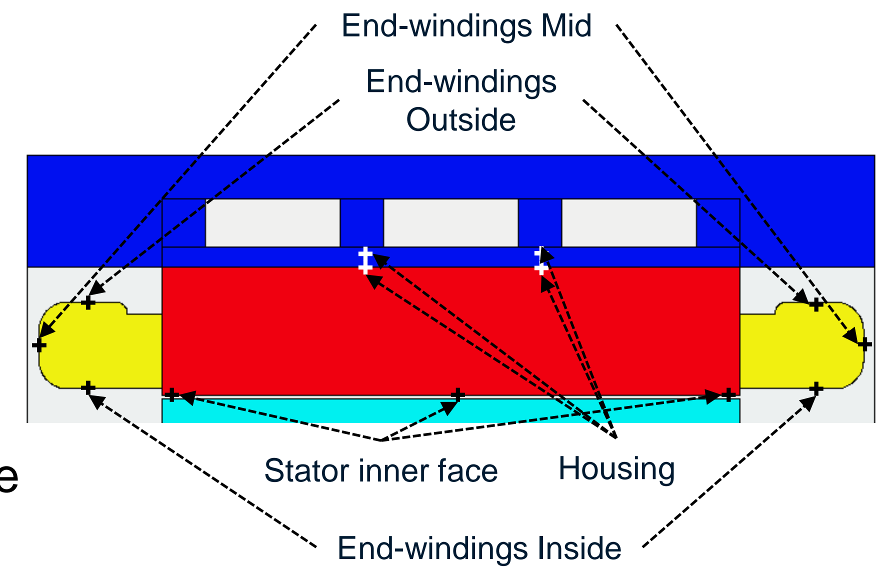
Proposed packaging

APPROACH-ELECTRIC MOTOR THERMAL MANAGEMENT





Nissan Leaf Motor Geometry within Motor-CAD Environment



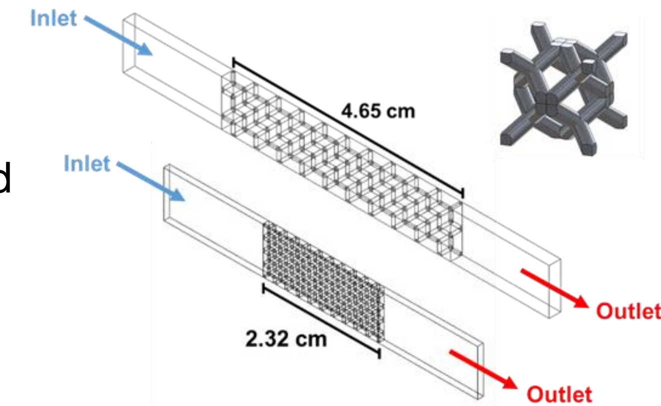
Temperature measurements points from NREL experiments used for the LPTN validation

- Validation based on steady-state thermal analysis
- Study is focused on the stator of the motor
- All other losses (AC losses, eddy losses) where not considered since we had DC currents
- Thermal convection and radiation with ambient air are not considered

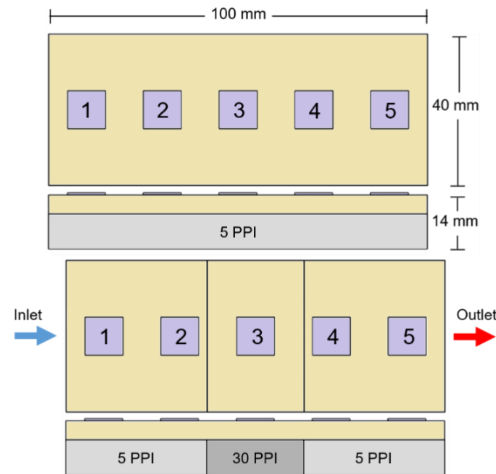
PIM Thermal management-Metal foams

➢ CFD/HT modeling of cold plates with additive manufactured metal foam

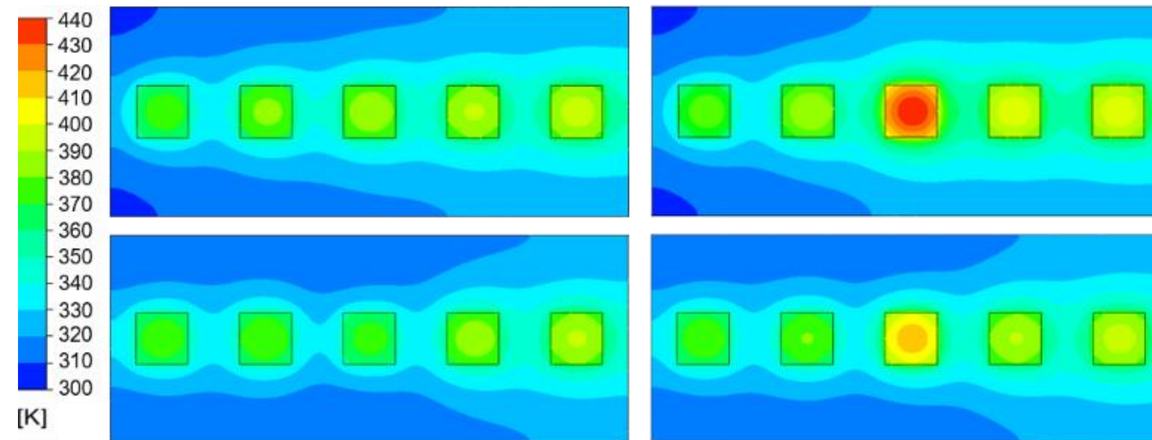
- Pore-scale models used to obtain closure thermohydraulic closure terms for volume-averaged simulations
- Two geometries with discrete heaters tested – 1) uniform structure and 2) hotspot mitigating structure with spanwise densification at middle
- Noticeable decrease in maximum temperature (~14%).
- Hotspot mitigation performance bottlenecked by other thermal resistances.



5 PPI pore-scale model (top) and 30 PPI pore-scale model (bottom) with unit cell shown



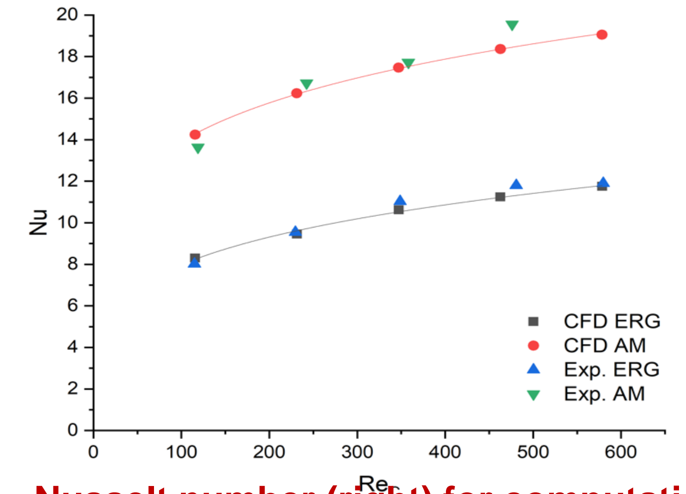
Assembled geometries with uniform foam PPI (top) and hotspot mitigating structure (bottom)



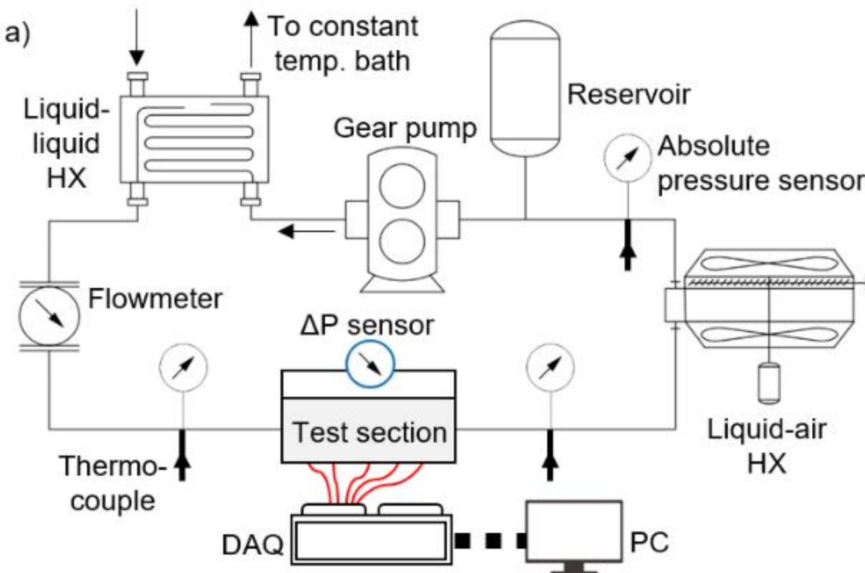
Temperature contours for uniform geometry without hotspot (top) and with hotspot mitigating structure (bottom) at u = 10 cm/s

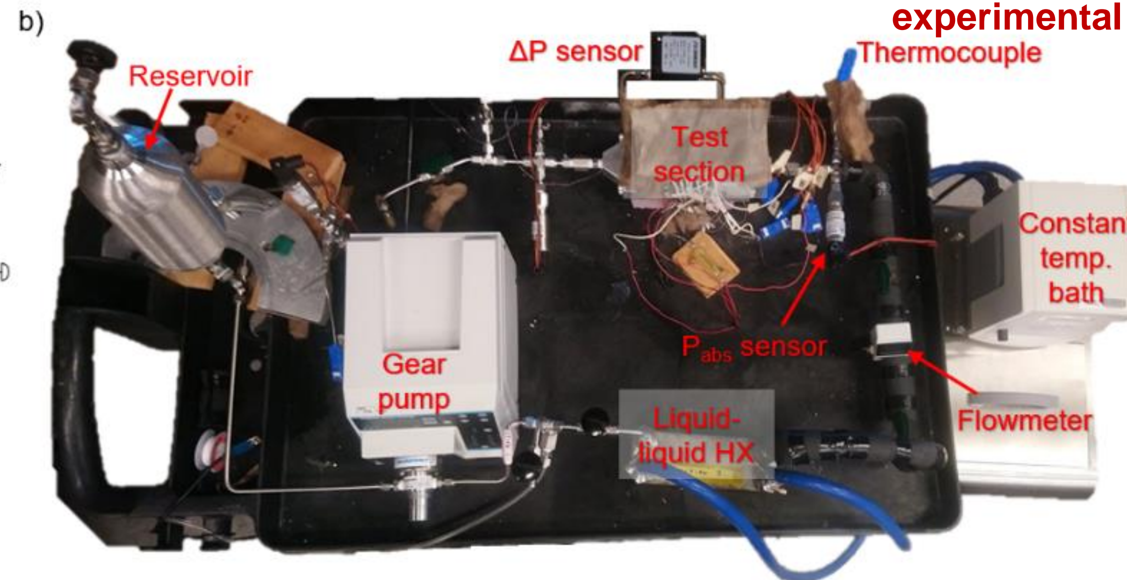
PIM Thermal management-Metal foams

- **Demonstrated the advantages of traditionally manufactured and AM metal foams for thermal management w/ experimentally validated CFD-HT models**
- Thermal performance of the AM sample was significantly higher than that of the traditional metal foam



Nusselt number (right) for computational and experimental data of both the ERG and AM samples

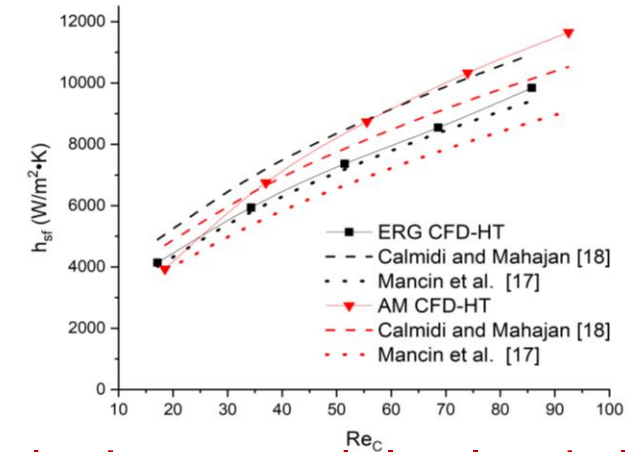




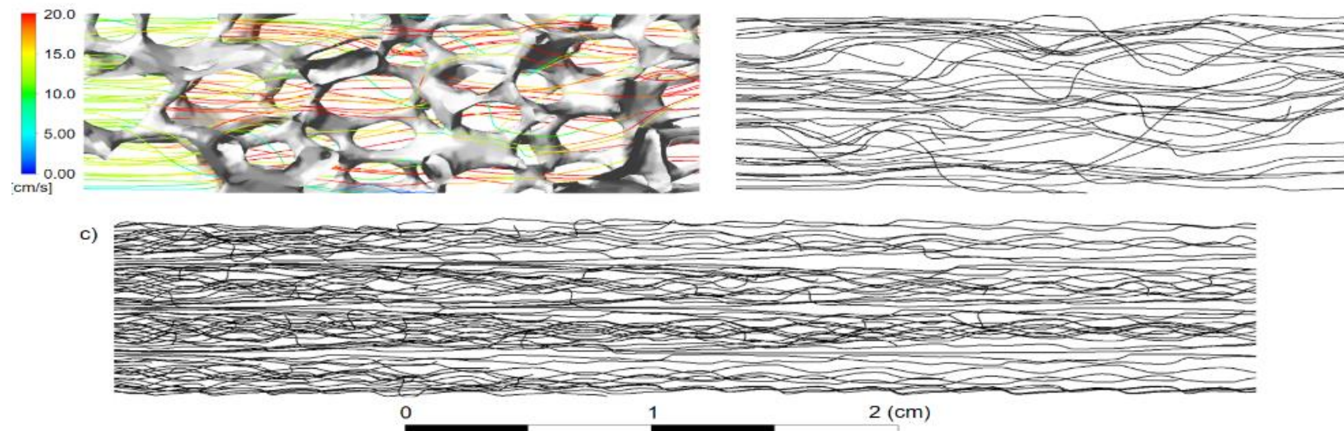
a) Schematic and b) image of closed flow loop and data acquisition setup

PIM Thermal management-Metal foams

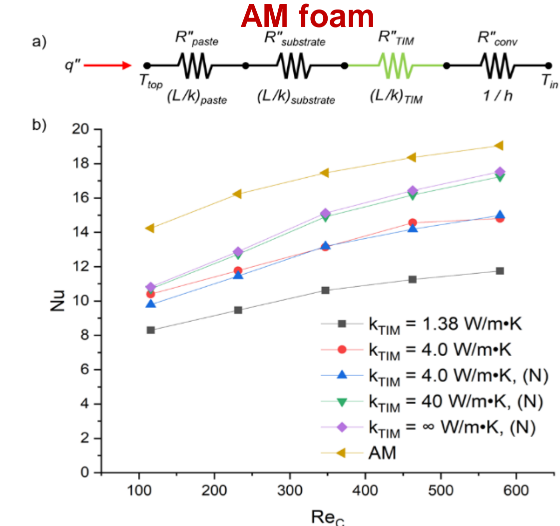
- **Tortuosity, TIM thermal conductivity, and interfacial heat transfer coefficients were examined for the traditional vs. AM structures.**
  - Tortuosity in ERG foam was shown to be ~2.45x greater
  - Validated 1D resistor network showed diminishing benefits with improved TIM thermal conductivity
  - Interfacial heat transfer coefficient agrees with the correlations



Comparison between numerical results and calculated results using correlations for the ERG Inc. foam and the AM foam



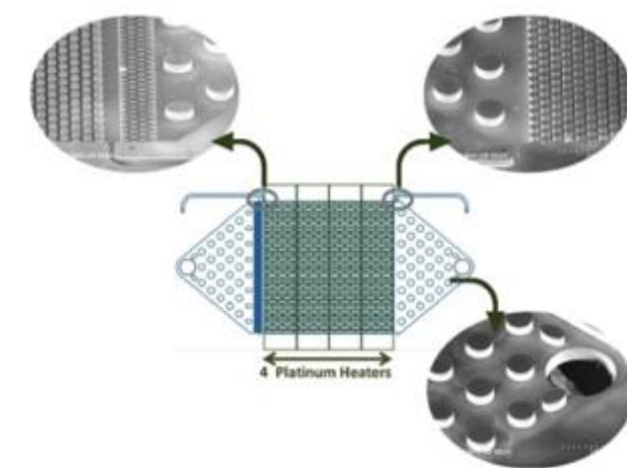
Streamlines visualized for stochastic geometry with u = 10 cm/s, and streamlines for the additive manufactured sample with u = 10 cm/s



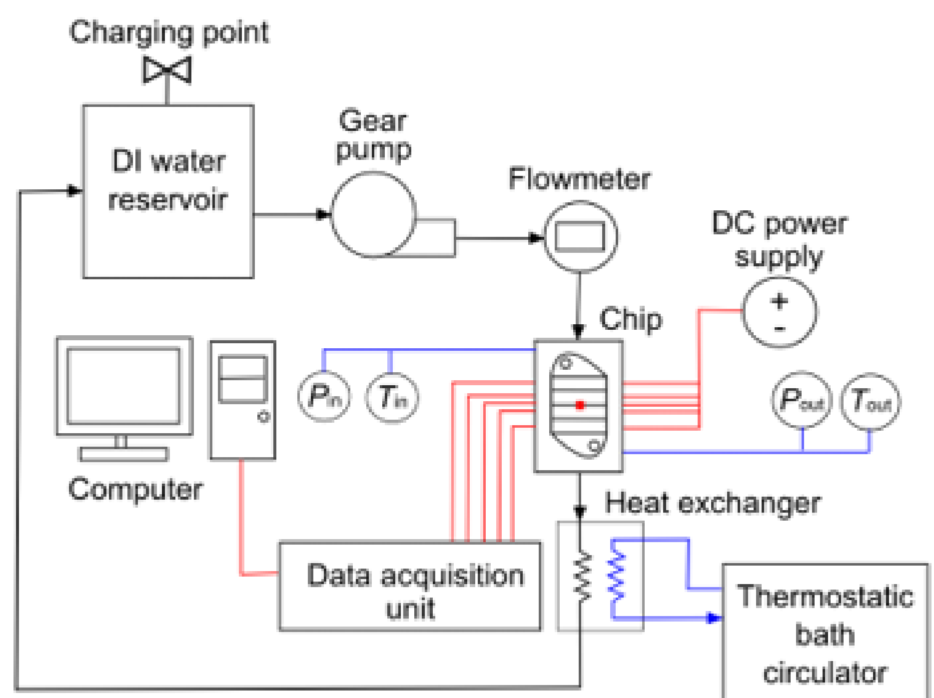
Non-dimensional heat transfer performance for AM foam and ERG Inc. foam with varying kTIM values – (N) denotes values found using a resistance network approach

PIM Thermal management-Micro pin fin array

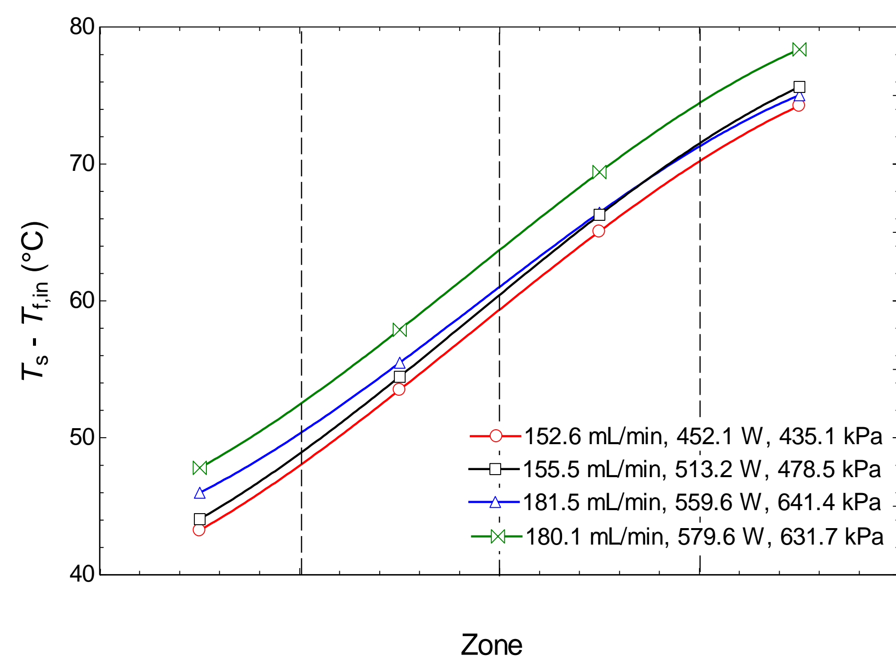
- **Demonstrated heat flux removal of 580 W/cm² at below 100 °C with a 1 cm² pin fin array silicon chip.**
- DI water is used as the coolant, with an inlet temperature of $T_{f,in}$ = 18.5 °C.
- Heating is provided through embedded platinum RTDs across four zones in the chip (uniform).



Silicon chip used for thermal testing. 1 cm² active heated area with cylindrical pin fins of 150 um diameter.

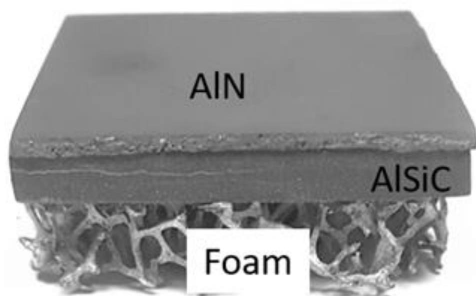


Experimental loop

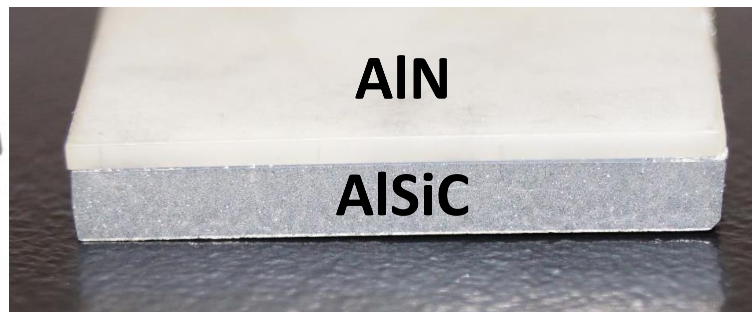


Surface temperature at different flow rates, power inputs and pressure drops.

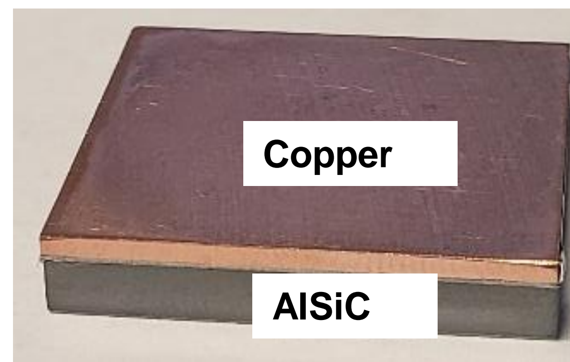
Bonding interfaces



AlN – AlSiC – Al foam stack after bonding



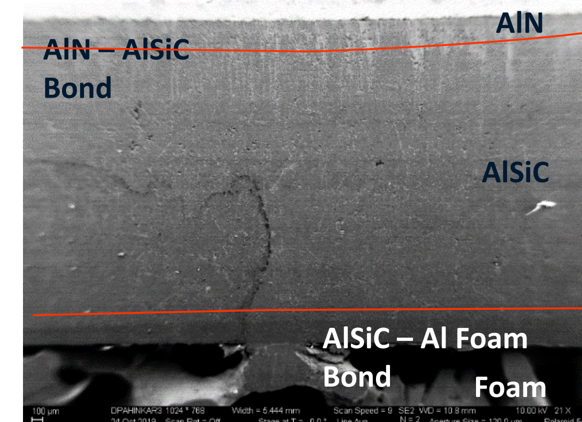
AlN – AlSiC coupons bonded using Cu-Al alloy

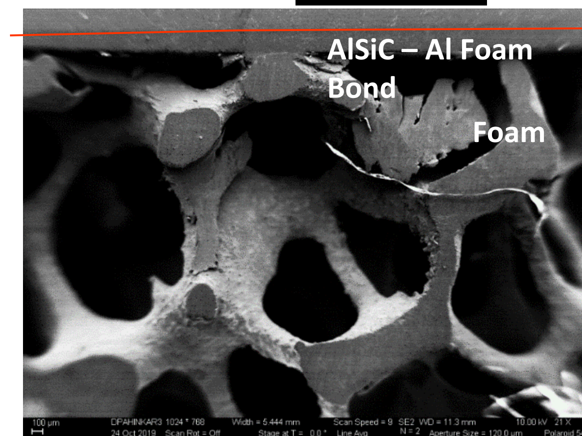


Cu-AlSiC coupons bonded using Cu-Al alloy

Thermal Management of Al Foam

- Although AlSiC has been demonstrated to improve the durability of electronic packages, it is extremely difficult to machine
- Hence, additional cooling features must be integrated to improve the heat transfer performance of the package
- Successfully bonded Aluminum foams to AlSiC using TLP Bonding Technique
- Diffusion zone thicker than interlayer thickness
- Cu diffusion as deep as 1 mm into AlSiC and Al foam





Aluminum foam bonded to AlSiC

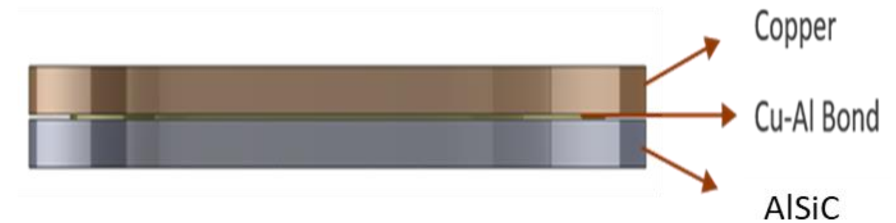
Bonding interfaces

Applications of TLP Bond

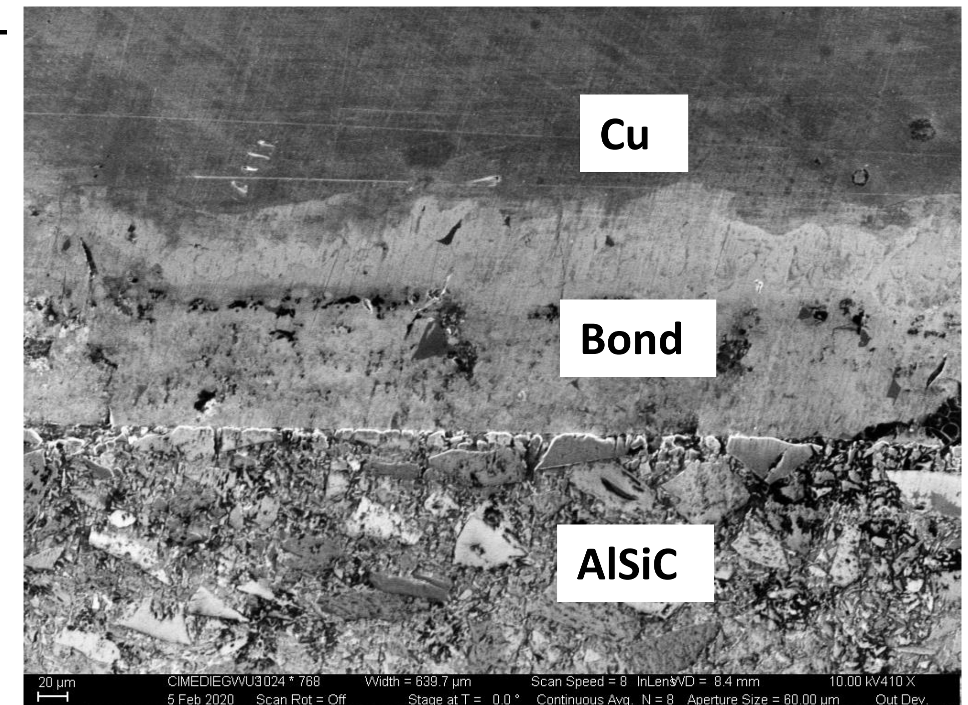
- Demonstrated effectiveness of TLP bond with alternate materials of varying CTE mismatch – results shown for Cu and AlSiC coupons
- Assessed bond properties and microstructure using SEM and X-ray EDS
- Modified bond parameters to lower void composition within
- AlN-AlSiC TLP bond – C-SAM results

Cu-AlSiC results

- SEM images of the Cu-AlSiC sample show that the TLP alloy melted uniformly under applied pressure, creating a crack-free bond across the cross-section and successfully bonding Cu and AlSiC.

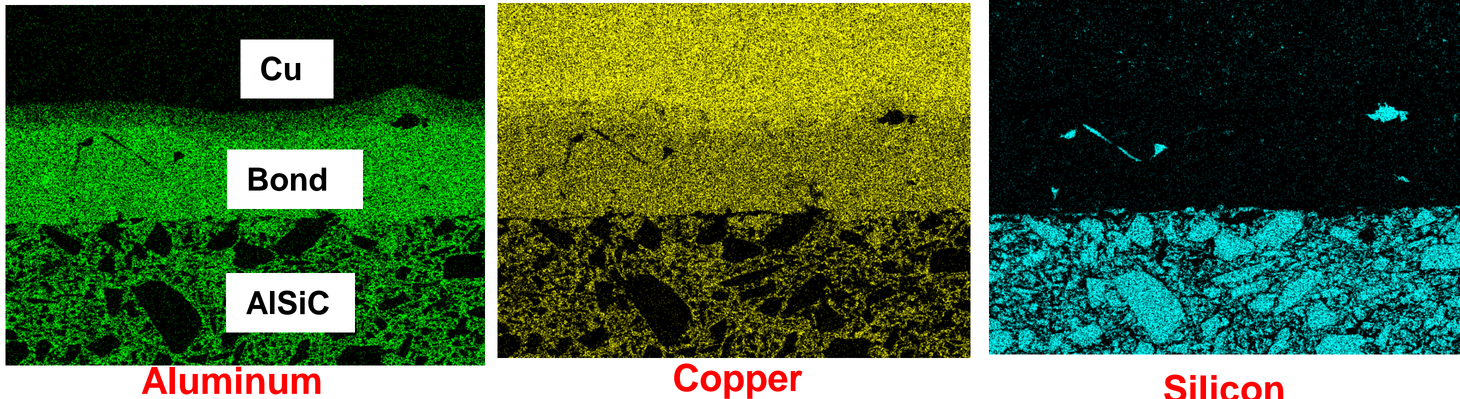


Cu and AlSiC coupons bonded using Cu-Al



SEM Image Cu-AlSiC

Bonding interfaces

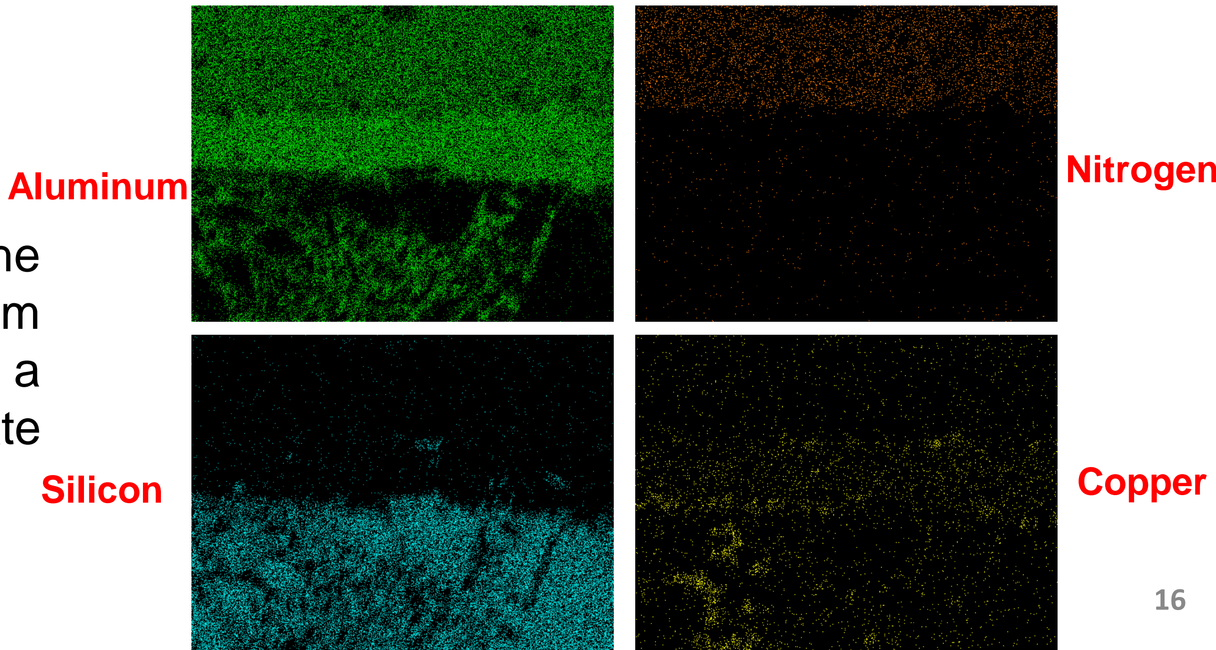


EDC results – Cu-AlSiC

- X-ray EDS results reveal copper diffusing into the AlSiC coupons which causes Aluminum in the AlSiC to melt and Silicon particles to migrate into the Cu-Al bond reinforcing the TLP bond.

EDS results – AlN-AlSiC

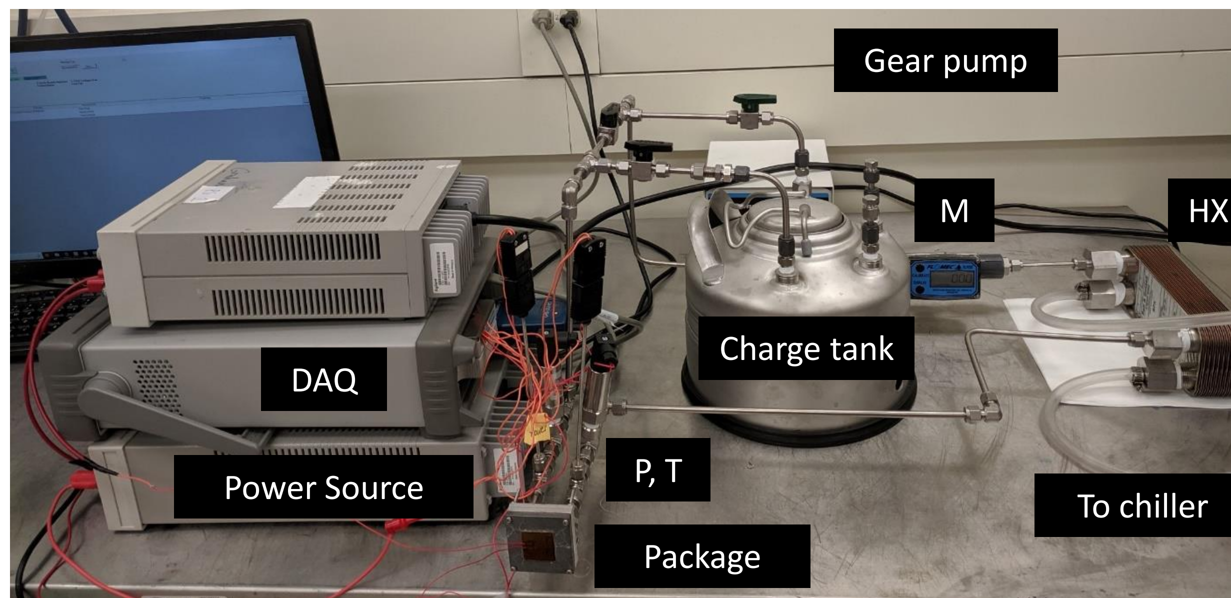
- X-ray EDS results for the AlN-AlSiC assembly shows the composition of the elements within the sample. Cu from the Cu-Al bond (1:5) causes the Aluminum to melt at a temperature lower than it's T_m , bonding the AlN substrate to the AlSiC heatsink.



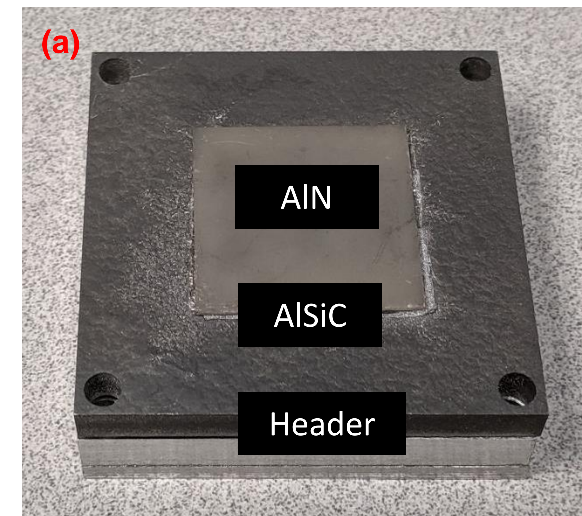
Bonding interfaces

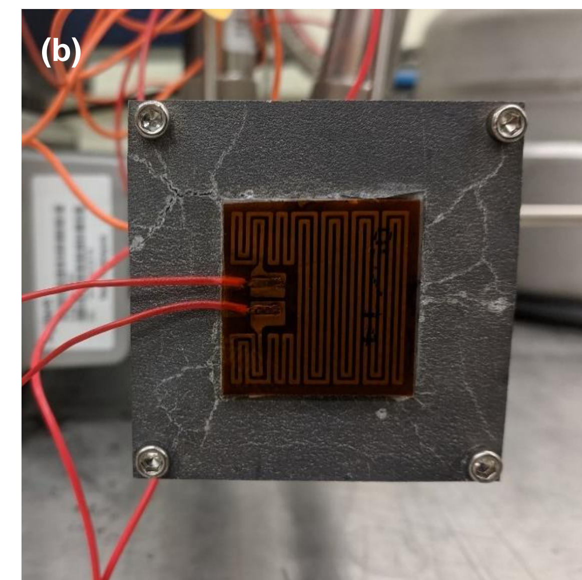
Thermal Management Prototyping

- Analysis of thermal effectiveness of adding foam to the stack
- Design and fabrication of the liquid coolant loop
  - Analysis of pressure drop and HTC offered by foam w.r.t mass flow rate and foam density
  - Estimation of HTR for AlSiC – Foam bonds



Liquid coolant loop for AlSiC-Foam bonds tests





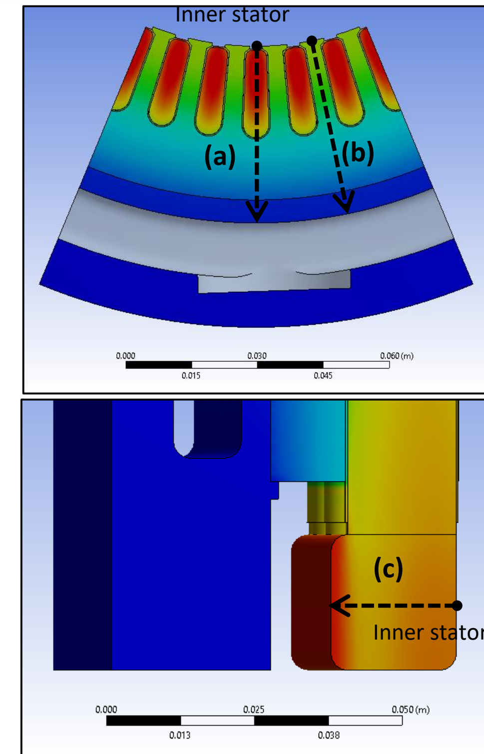
(a) AlN-AlSiC header top view (b) Complete assembly with film heater

TECHNICAL ACCOMPLISHMENTS- ELECTRIC MOTOR THERMAL MANAGEMENT

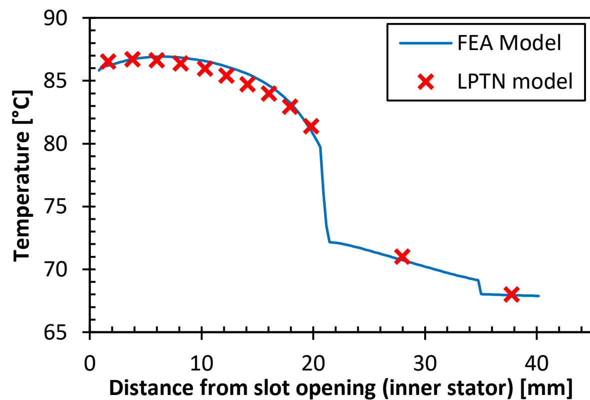
Georgia Tech

- **LPTN model can be used for the thermal design of an electric motor**
- **The liner represents the main thermal resistance within the slots**
- **The maximum temperature is located at end-windings location**

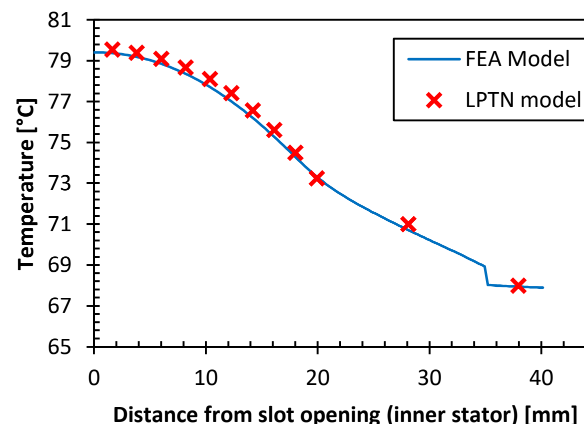
- Maximum deviation between LPTN and FEA temperatures along each path:
  - Path (a): 0.5%
  - Path (b): 0.9%
  - Path (c): 2.1%
- Zone with the highest thermal resistance at liner location where $\Delta T \approx 13°C$ with length < 1mm



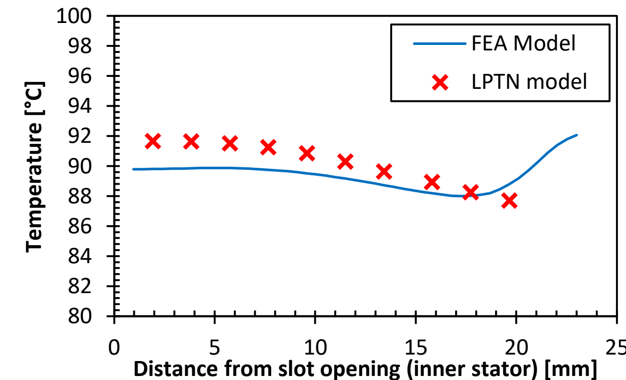
Cross section views from FEA model



Temperature profile along path (a) for FEA model from NREL and LPTN model using Motor-CAD



Temperature profile along path (b) for FEA model from NREL and LPTN model using Motor-CAD

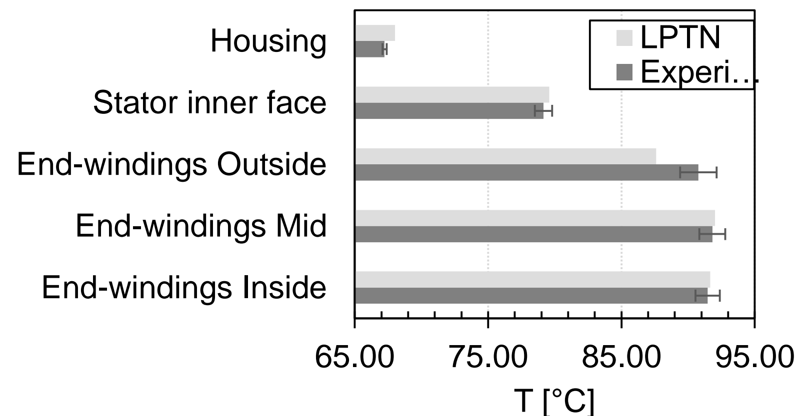


Temperature profile along path (c) for FEA model from NREL and LPTN model using Motor-CAD

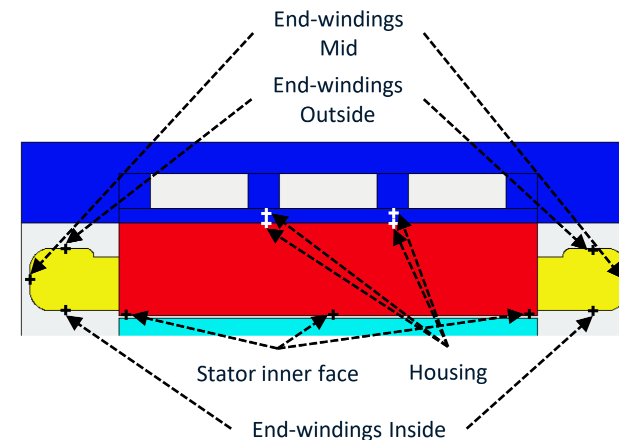
Validation of the LPTN model compared to Experimental data

- Temperature measurements points are averaged according to assumed symmetries in the LPTN
- Maximum deviation between LPTN and experimental data: **3.6%** ⇒ LPTN model is validated for steady state analysis

- **LPTN model is validated for steady-state analysis**
- **Few temperature points has been considered, hence the need for a comparison of the LPTN with the FEA model**



Temperatures measured at 5 different points [4] compared to the LPTN output temperatures at the same points



Temperature measurements points from NREL experiments used for the LPTN validation

[4] NREL measurement, EDT Motor Thermal Management Project

Sensitivity analysis of thermal resistances

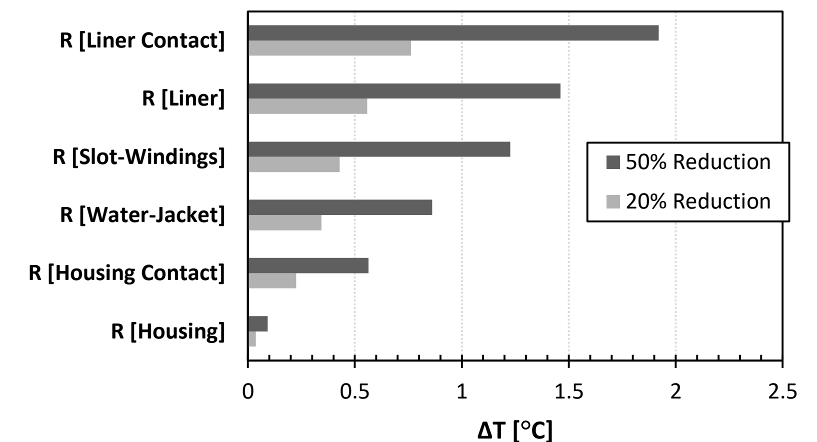
DESCRIPTION

- A sensitivity analysis (using LPTN model) of main thermal resistances
    - **R [Liner]**
    - **R [Slot-Windings]** (radial and tangential directions only considered)
    - **R [Housing]**
    - **R [Liner Contact]**
    - **R [Housing Contact]**
    - **R [Water-Jacket]** (related to the water-jacket heat transfer coefficient)
- Each resistance is individually reduced by 20% and 50% from its initial value in the model
- Temperature difference ΔT = difference between windings maximum temperature with initial resistances and windings maximum temperature with the new reduced resistant

RESULTS

- Highest sensitivity for liner contact resistance
- Housing contact resistance has significantly less impact
- No non-linear effect from 50% to 20% resistance reduction

- **Reduction of thermal resistance within the stator should focus on liner area**
- **Improving Water-Jacket heat transfer coefficient may have no significant impact on decreasing maximum windings temperature**



Sensitivity analysis of thermal resistances involved in motor midplane heat flow

TECHNICAL ACCOMPLISHMENTS – ELECTRIC MOTOR THERMAL MANAGEMENT

Georgia Tech

Sensitivity analysis of thermal resistances

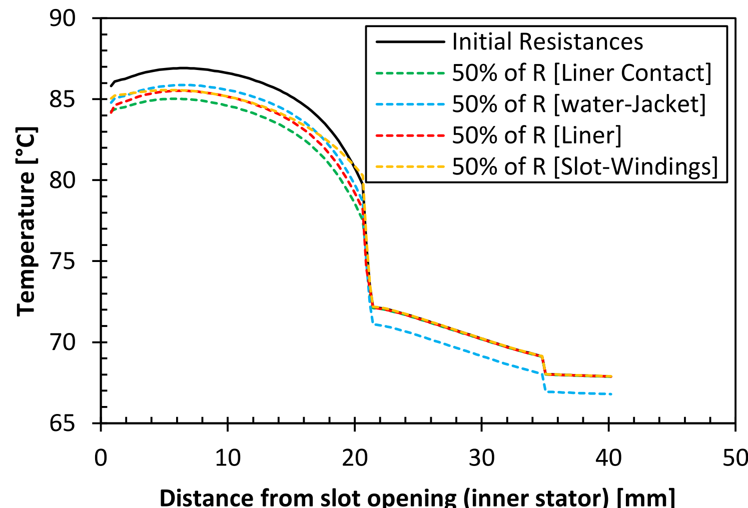
DESCRIPTION

- Influence of the reduction of thermal resistances on the temperature profile along slot-windings path (a), and end-windings path (b) using FEA model

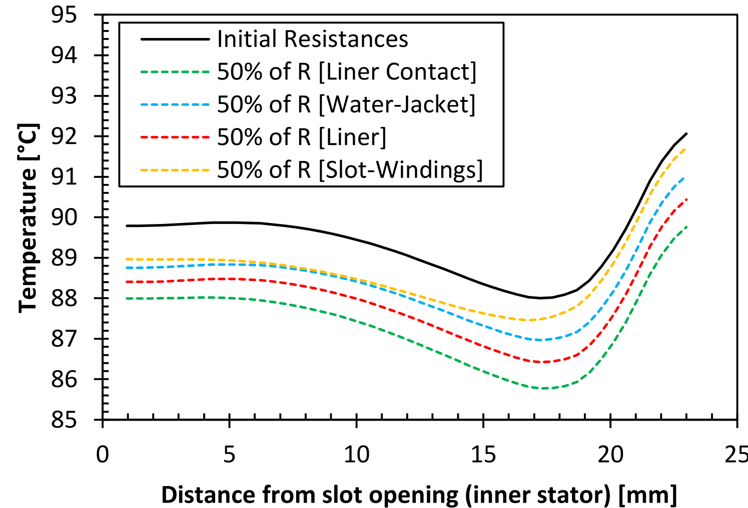
RESULTS

- No particular change in the temperature profile shape by reducing the thermal resistances (linear behavior is predominant)
- Same most sensitive parameters order as for the LPTN model results

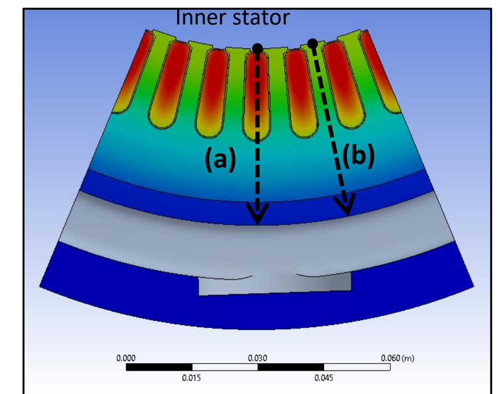
- **50% reduction of R [Liner Contact] causes a 2% temperature decrease in slot-windings and end-windings**
- **50% reduction of R [Liner Contact] causes a temperature decrease twice that cause by 50% reduction of R [Water-Jacket]**



Temperature along Slot-Winding for thermal resistance reduction by 50% of Liner Contact, Water-Jacket, Liner and Slot-Windings



Temperature along End-winding for thermal resistance reduction by 50% of Liner Contact, Water-Jacket, Liner and Slot-Windings



Path (a) and (b)

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RESPONSE TO PREVIOUS YEAR REVIEWERS' COMMENTS

- This is a new project with no reviewers' comments.

COLLABORATION AND COORDINATION

Georgia Tech

NREL:

- *Thermal packaging:*
  - Received materials for bonding for the project
  - Exchanged acoustic microscopy images on bonded interface to compare with Georgia Tech SEM results
  - Received dielectric fluids data form power electronic thermal management
- *Electric motor thermal management*
  - Received numerical modeling and experimental data to compare with Georgia Tech Motor-CAD results

ORNL:

- *Electric motor thermal management:*
  - Received torque and current measurements for the 2012 Nissan Leaf Motor

SUNY Poly Institute:

- *Thermal packaging:*
  - Received feedback on SiC MOSFETs to develop thermal management strategies

REMAINING CHALLENGES AND BARRIERS

Georgia Tech

➢ Thermal Packaging:

- Heater resistance is found to be very high – Ongoing design of low resistance heater concept
- Improved models for flow boiling simulation by using CLSVOF instead of VOF
- High heat flux removal capability of 1 kW/cm^2 required with operating temperature of 200°C.
- Higher volume of copper present in pure Cu coupon lowers melting point of AlSiC, initiating micro-cracks within bonded structure - future study to be conducted on alternate bond composition
- High thermal mass of AlSiC baseplate limits heat transfer to Al foam in cooling experiment - parametric study ongoing to determine appropriate thickness of baseplate for effective thermal management
- Thermal interface impedance between heater and AlN substrate insurmountable - high conductivity TIM required

➢ Electric motor thermal management

- Validate the LPTN Network for the rotor at different speed
- Compare FEA model and LPTN model for transient thermal analysis instead of steady-state
- Explore a more accurate way of modeling end-windings to have a better temperature prediction in end-windings

FUTURE PROPOSED RESEARCH –THERMAL PACKAGING

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FY2020:

➢ Thermal Packaging:

- Validate cold plate models with experimental data – requires heaters with low resistance
- Perform flow boiling experiments and simulations with dielectric fluids with a AM foam
- Preform Jet impingement cooling of SiC MOSFET to achieve 1 kW/cm^2 heat flux removal with 200 °C operating temperature.
- Develop sub mm vapor chambers for heat spreading
- Perform mechanical characterization of bond (in progress)
- Compare AlN-AlSiC assembly to conventional DBC stack without cooling enhancement features
- Evaluate heat transfer properties of bonded assembly with and without porous medium

➢ Electric motor thermal management

- Create an ANSYS Fluent Model of the new cooling system for a steady state study
- Assess the windings temperature drop with our end-winding cooling system
- Investigate the influence of different type of pipe materials on the heat transfer within the end-windings
- Infer equivalent heat transfer coefficient from the Fluent simulation
- Include the new heat transfer coefficient to the LPTN model in Motor-CAD and assess the new performance of the motor

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

FUTURE PROPOSED RESEARCH –THERMAL PACKAGING

Beyond FY2021:

- Thermal Management Technologies for Heterogeneous Integrated (HI) Power Electronics:
  - Passive thermal technologies for 2.5D and 3D HI
  - Active thermal technologies for 2.5D and 3D HI
- Modeling and co-Design of HI Power Electronics:
  - Multi-physics modeling for HI
  - Compact models, and co-design for HI

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

SUMMARY

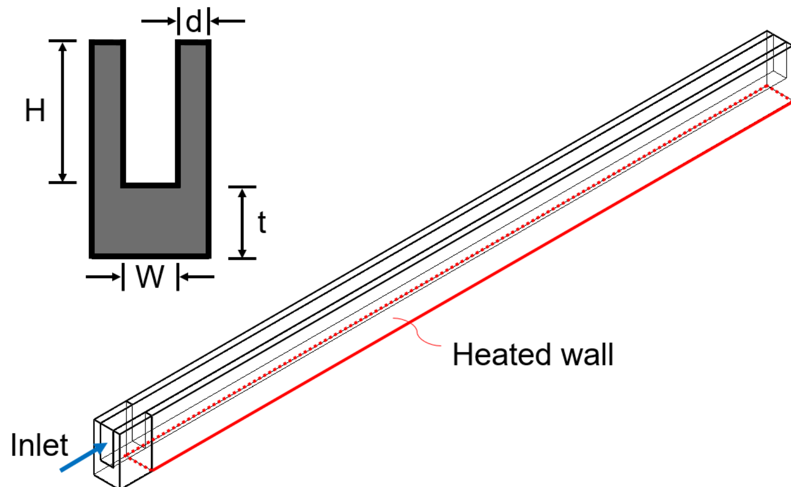
- **Relevance**:
  - High performance thermal management strategies for power inverters
  - Fast and precise modeling for thermal management of electric motor
  - Advanced low cost, compact, highly conductive packaging

- **Approach:**
  - Metal foam single/two phase experimental measurements and numerical simulations
  - Micro pin fin array single phase experimental measurements
  - Motor-CAD software validation against ANSYS modeling and measurement results
  - Transient Liquid Bonding (TLP) to test a novel packaging concept
- **Technical accomplishments:**
  - CFD heat transfer (CFD/HT) modeling of cold plates with additive manufactured metal foam was performed. Hotspot mitigation potential with single phase cooling demonstrated.
  - Demonstrated above 500 W/cm^2 heat flux removal using single phase micro pin fin array.
  - Validated Motor-CAD LPN model against ANSYS and experimental data to further use of LPN modeling for electric motors.
  - Explored various bonding materials via TLP.
- **Collaboration:**
  - NREL
  - ORNL
  - SUNY POLY

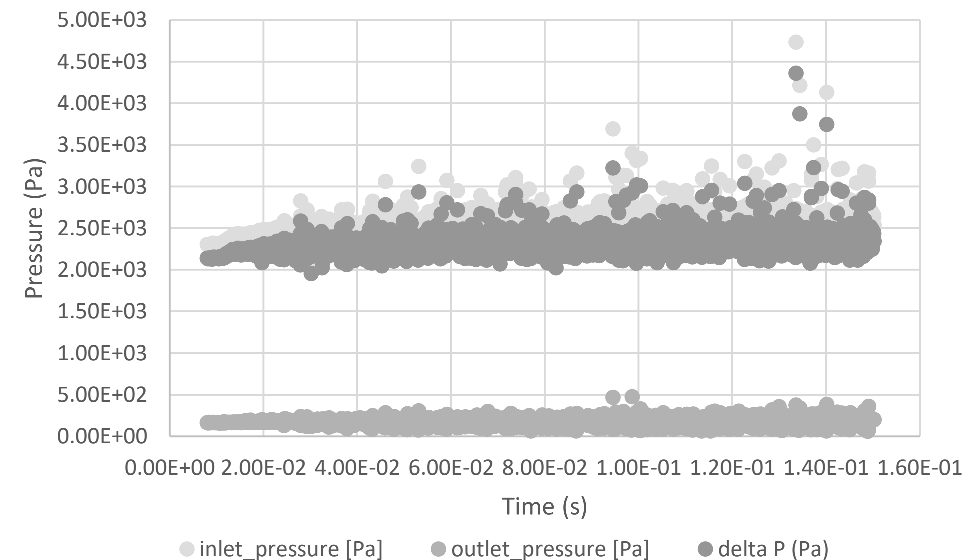
Back-Up Slides

Two-phase flow simulation capability

- **Initial transient simulations for comparing microchannel geometries were performed.**
- Following investigation will investigate single microchannels (as opposed to parallel microchannel or loop-based effects)
- Four geometries selected for pressure oscillation control – baseline straight, constricted inlet, diverging, and merging microchannels
- Laminar flow solution for initialization, heat flux of 100 W/cm^2, inlet mass flux of 500 kg/m^{2}s



Baseline straight microchannel geometry



Pressure as a function of time for the straight microchannel (mesh size 199k elements)

A ROBUST PROCESS FLOW FOR ATTACHING HEATERS

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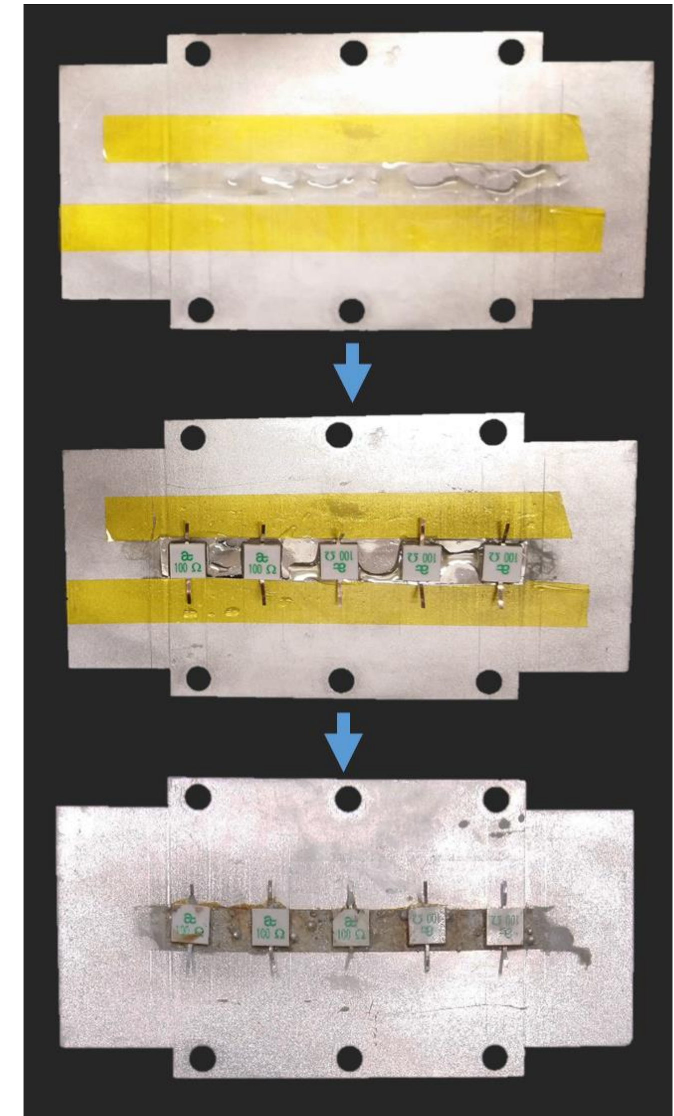
- Thin-film heaters enclosed in ceramic w/ backside metallization
  - Representative of power module heating elements
- Flux 3 (specifically for soldering to aluminum) and 96.5Sn/3.5Ag solder ribbon (T_m = 220 ˚C) used to solder heaters to aluminum substrate
- Process flow shown to the right
  - Kapton tape w/ flux applied
  - Solder ribbon, additional flux, then test chips placed
  - Substrate heated until solder melts, and then high temperatures sustained for 5-10 minutes for intermetallic formation
- 5 thermocouples attached to the topside of each heater

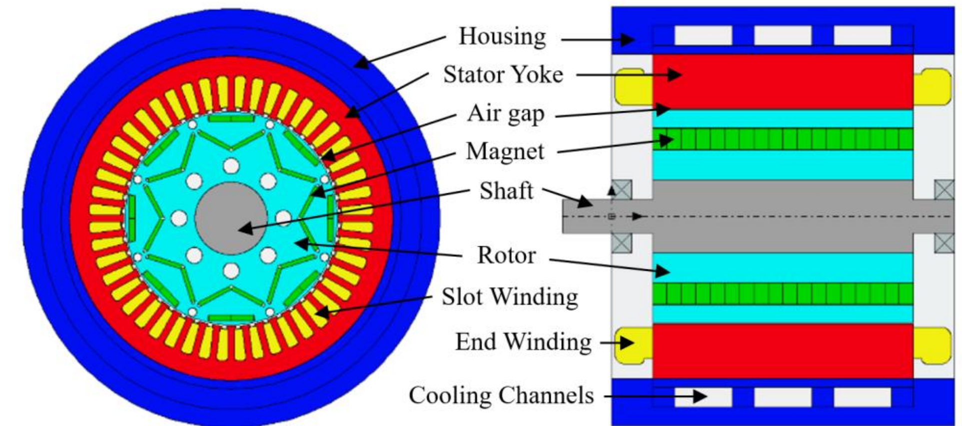


Process flow for soldering test chips

Validation of a Lumped-Parameter Thermal Network (LPTN) model of the Nissan Leaf motor

DESCRIPTION

- Heat source: copper losses generated by a DC current in each phase of the motor: $P_{losses} = 567W$
- Flow rate inside the water-jacket: 10 L/min
- Fluid temperature: 65°C



Nissan Leaf Motor Geometry within Motor-CAD Environment

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DETAILS OF MOTOR-CAD SOFTWARE SIMULATIONS

Validation of a Lumped-Parameter Thermal Network (LPTN) model of the Nissan Leaf motor in Motor CAD software

Experimental data

- slot-windings
- The FEA model which has been validated by NREL will provide these missing temperatures sensors for a complete validation of the LPTN

FEA Model

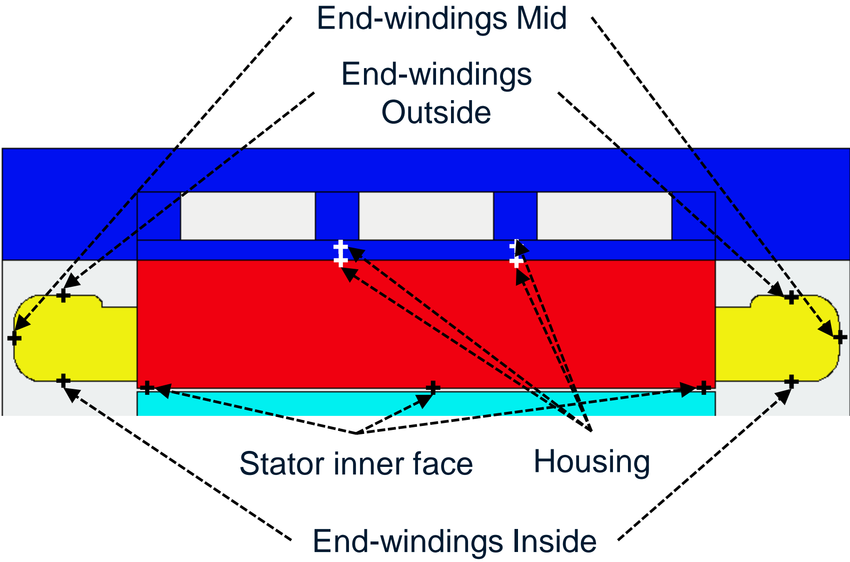
- Thermal resistances from the FEA model have been adapted to the LPTN within Motor-CAD environment in order to have the same thermal parameters for the two models
- Each of main resistance value is deducted from experimental results provided in [1], [2], [3] and [5]

Thermal conductivity $[W.m^{-1}.°C^{-1}]$	Radial	Tangential	Axial
Stator Laminations	21.9	21.9	1.68
Slot-Windings	0.986	0.986	292
End-Windings	0.764	201.7	101.2
Slot liner	0.175	0.175	0.175
Aluminum	167	167	167

Table 1: Thermal conductivities of each part of the stator [1]-[4]

Thermal contact conductance $[W.m^{-2}.°C^{-1}]$	
Slot-Windings | Liner	556
Liner | Laminations	1645
Laminations | Housing	5555
Heat transfer coefficient $[W.m^{-2}.°C^{-1}]$	
Water-Jacket	1428

Table 2: Thermal contact conductance and heat transfer coefficient from [4]



Temperature measurements points from NREL experiments used for the LPTN validation

[1] Emily, C. Bennion, K., DeVoto, D., Mihalic, M., Narumanchi, S., 2015 “Characterization of Contact and Bulk Thermal Resistance of Laminations for Electric Machines” NREL Technical Report NREL
[2] NREL calculation based on copper fill-factor measurement
[3] Bennion, K., and Cousineau, J., “Sensitivity Analysis of Traction Drive Motor Cooling.” Paper presented at the IEEE Transportation Electrification Conference and expo, Dearborn, Michigan, 2012.
[4] NREL measurement, EDT Motor Thermal Management Project

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PROPOSAL FOR A NEW TYPE OF END-WINDING COOLING SYSTEM

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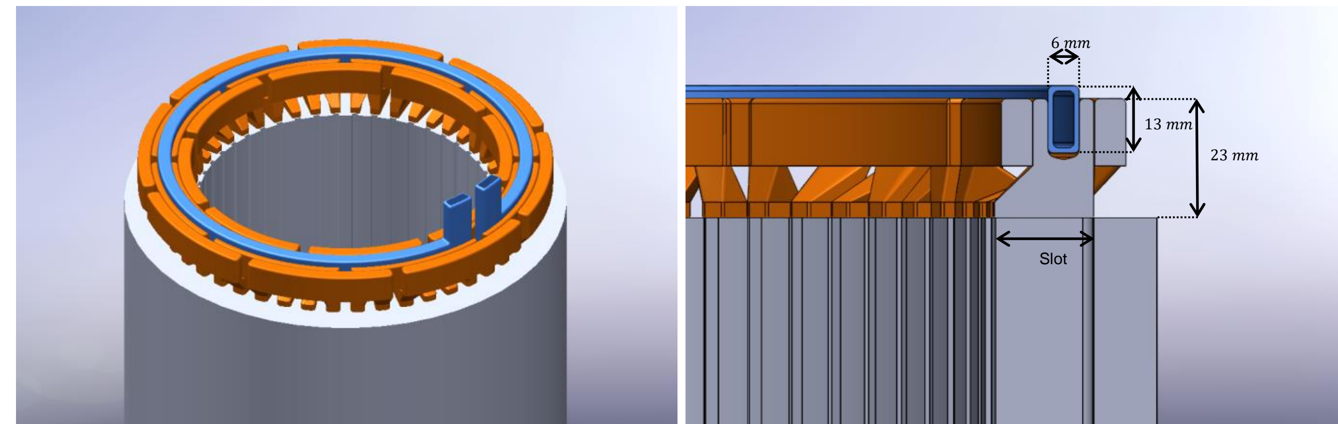
MOTIVATION

- End-winding is the hot-spot of current internal permanent magnet electric motors
- Most proposed cooling systems for end-windings [1]-[3] are designed for concentrated windings where automotive industry uses distributed windings

PROPOSED DESIGN

- Double or single circular channel passing through the end-windings
- Pipe materials constraint: low electric conductivity, high thermal conductivity, high-temperature operating range (>150°C)
- Form a single loop with the water-jacket
- Fluid: Water Ethylene Glycerol as a first approach
- End-windings modeling: separate end-turns instead
- of a single block



On the left: 3D view of a single channel end-winding cooling system. On the right: Cross-section view of the same system with its dimensions

[1] W. Sixel, M. Liu, G. Nellis and B. Sarlioglu, "Ceramic 3D Printed Direct Winding Heat Exchangers for Improving Electric Machine Thermal Management“, 2019 IEEE Energy Conversion Congress and Exposition (ECCE), Baltimore, MD, USA, 2019

[2] H. Vansompel and P. Sergeant, "Extended End-Winding Cooling Insert for High Power Density Electric Machines with Concentrated Windings“, IEEE Transactions on Energy Conversion, 2019

[3] Madonna, Vincenzo & Walker, Adam & Giangrande, Paolo & Gerada, Chris & Serra, Giovanni & Galea, Mikiel., “Improved thermal management and analysis for stator end-windings of electrical machines” IEEE Transactions on Industrial Electronics, 2019

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