Power Electronics Thermal Management

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National Renewable Energy Laboratory
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Project ID ELT078

NREL/PR-5400-71209

Overview

Timeline

- Project start date: 2017
- Project end date: 2019
- Percent complete: 60%

Barriers

- Size and weight
- Cost
- Performance and lifetime

Budget

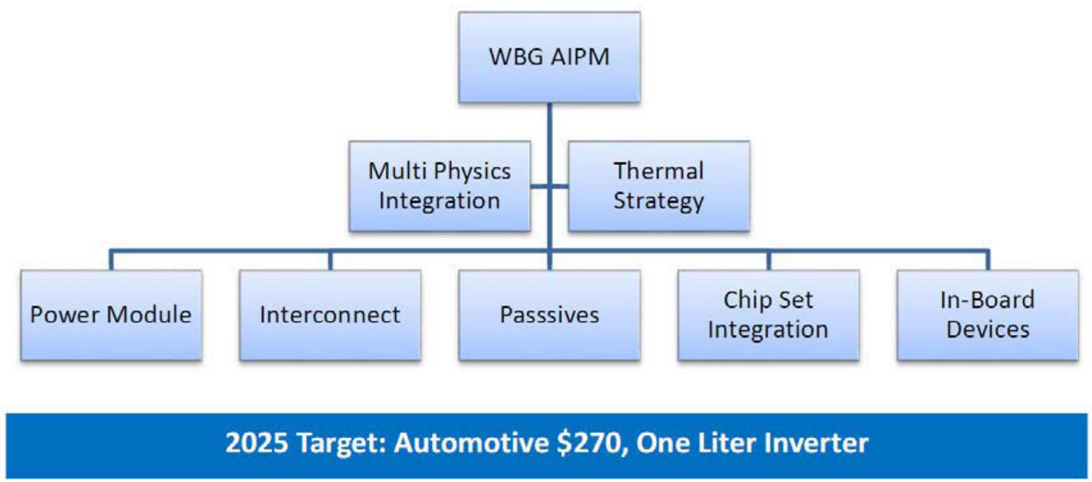
- Total project funding: $968K
  - DOE share: $968K
- Funding for FY 2017: $493K
- Funding for FY 2018: $475K

Partners

- John Deere
- Elementum3D
- Dielectric fluid manufacturers
- Oak Ridge National Laboratory (ORNL)
- Project Lead– National Renewable Energy Laboratory

Relevance

- Thermal management is essential to increase reliability and power density
- **Objective:** Develop thermal management techniques to enable achieving the DOE power density target of 100 kW/L
  - Challenge is to create a thermal solution that allows for packaging high temperature (250°C) wide-bandgap (WBG) devices next to capacitors that typically cannot exceed 85°C



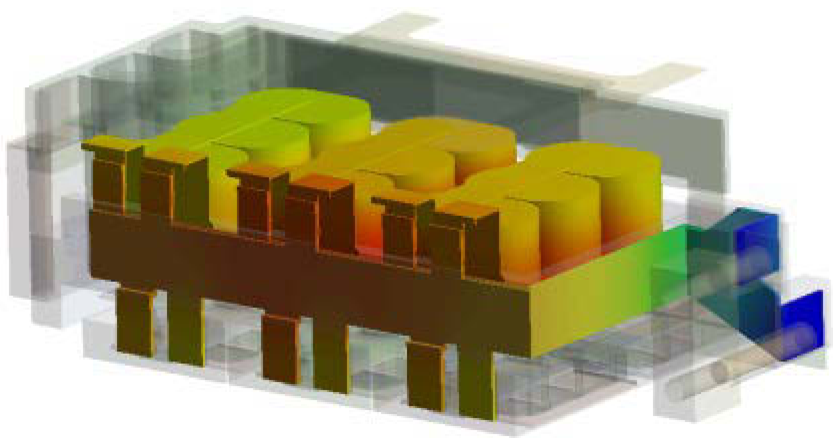
From 2017 EETT Roadmap

AIPM: advanced integrated power module

Approach

Power Electronics Thermal Management

Thermal Management Technologies to Enable 100-kW/L Power Density Target



Two-Phase Cooling for High Packaging Density Planar Inverter (Cooperative Research And Development Agreement [CRADA])

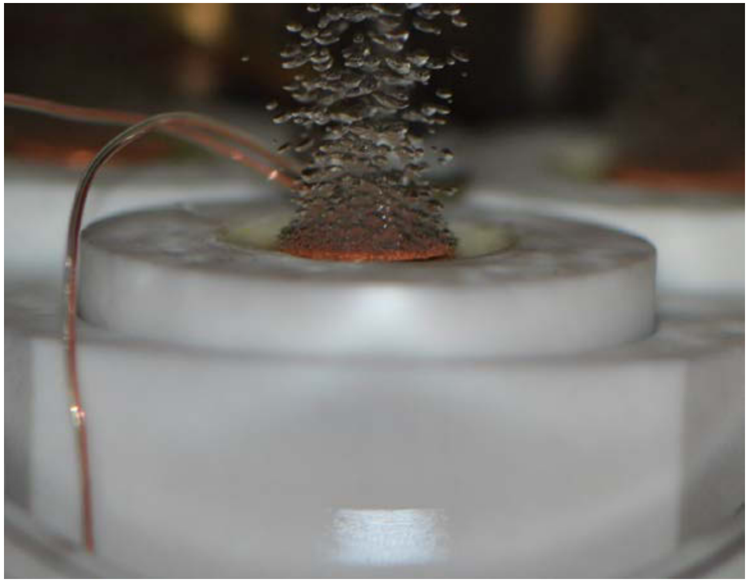


Photo Credit: Gilbert Moreno (NREL)

Approach

Define the thermal target required to achieve 100 kW/L → Compare potential cooling strategies → Design the cooling system via modeling

Component	Volume used for 100 kW/L inverter estimate [L]	Source
Gate driver (includes current sensors)	0.28	*2015 BMWi3 (125 kW)*
Control board	0.23	*2012 Nissan LEAF (80 kW)*
Capacitor	0.25	*2015 BMWi3 (125 kW): Assumption: capacitor volume decreased by 50% to account for a decrease in capacitor requirements for WBG devices*
Remaining volume for power module and cold plate	**0.24**	

Toyota Engineer Speaks on Advantages, Disadvantages of Silicon Carbide (SiC) Power Devices

*"…if switching frequency is improved by eight times by replacing a Si power device with a SiC power device, the **volumes of capacitors and reactors can be reduced by 70-80%...** "*

http://tech.nikkeibp.co.jp/dm/english/NEWS_EN/20120207/204483/

Approach

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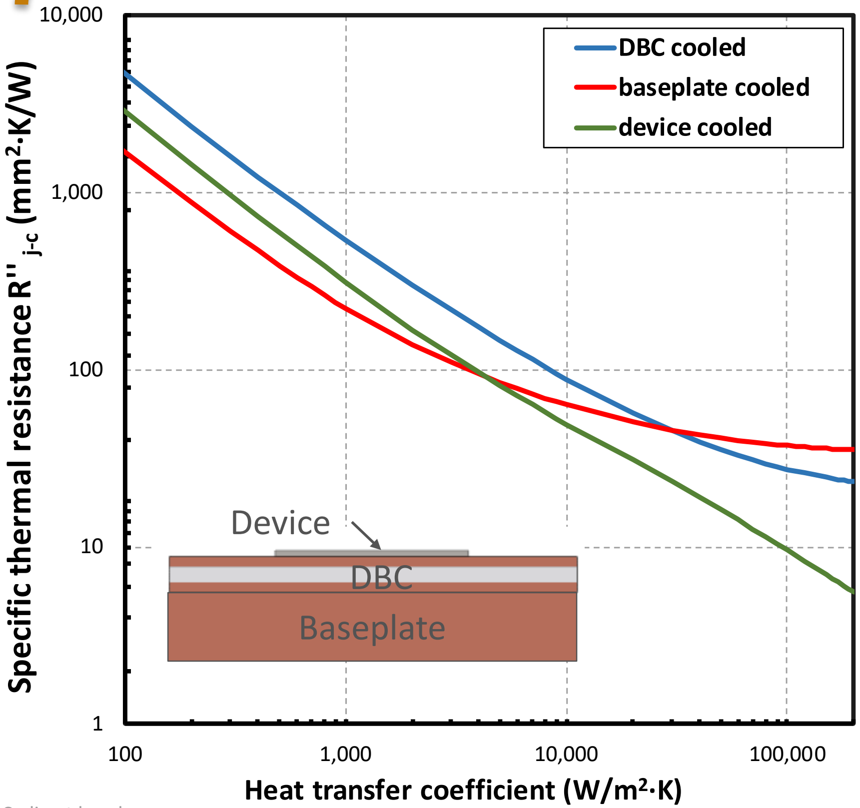
- Heat dissipation requirements: **2,150 W** (*assuming 100 kW system, 98% WBG inverter efficiency, and 95% motor efficiency*)
- Assuming $T_{j,\ maximum}$ = 250°C and $T_{coolant}$ = 65°C, **volumetric thermal resistance target is 21 cm^3-K/W**

Approach

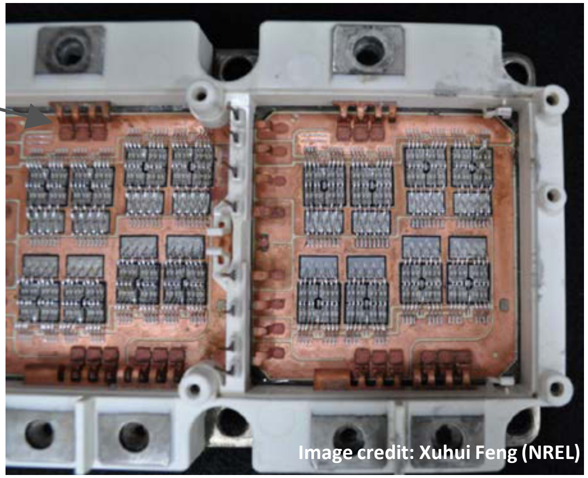
Define the thermal target required to achieve 100 kW/L → **Compare potential cooling strategies** → Design the cooling system via modeling



Device cooling

- Provides the lowest thermal resistance
- Enables cooling the electrical leads (decrease capacitors and board temperatures)

Electrical leads in the 2015 BMWi3 power module



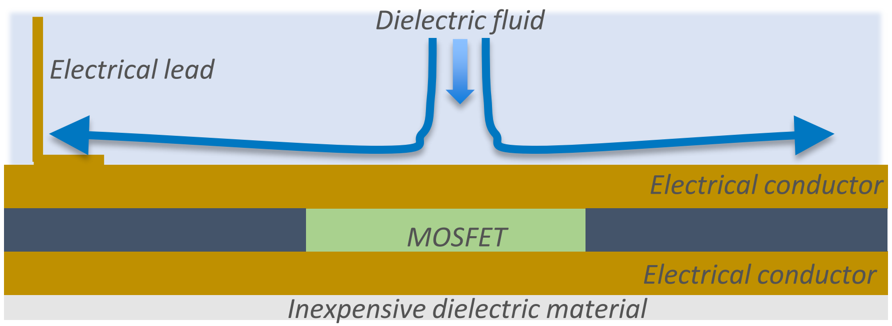
DBC: direct bond copper

Approach

Define the thermal target required to achieve 100 kW/L

Compare potential cooling strategies

Design the cooling system via modeling



Dielectric cooling of planar package

- Propose a single-phase cooling approach
  - ✓ Easier to seal (compared to two-phase system)
  - ✓ Potential to use automatic transmission fluid (ATF) (decrease cost)
  - x Low heat transfer. Propose to use jet impingement to improve performance
- Cool the electrical interconnects
- Replace expensive ceramic dielectric material with cost-effective alternatives

MOSFET: metal–oxide–semiconductor field-effect transistor

Approach/Milestones

Date	Description of Milestone or Go/No-Go Decision
December 2017 (complete)	**Milestone:** Conduct two-phase modeling of the cooling system using computational fluid dynamics multiphase modeling tools to support the research and analysis of an advanced compact power module
March 2018 (complete)	**Go/No-Go:** Research thermal management strategies for a planar, compact inverter capable of high-temperature operation
September 2018 (in-progress)	**Milestone:** Create a report to summarize the research results

Dielectric Coolant Selection

- Selected synthetic hydrocarbons that are used in electronics cooling (single-phase) applications
  - ElectroCool EC-140: Engineered Fluids (*used this fluid for the thermal analysis*)
  - Alpha 6: DSI Ventures (other possible option)
- **Ultimate goal is to develop a system that uses ATF as the dielectric to decrease cost, use fluid already qualified for automotive use, enable motor – inverter integration**

ElectroCool EC-140 properties at 70°C temperature (used for thermal modeling)

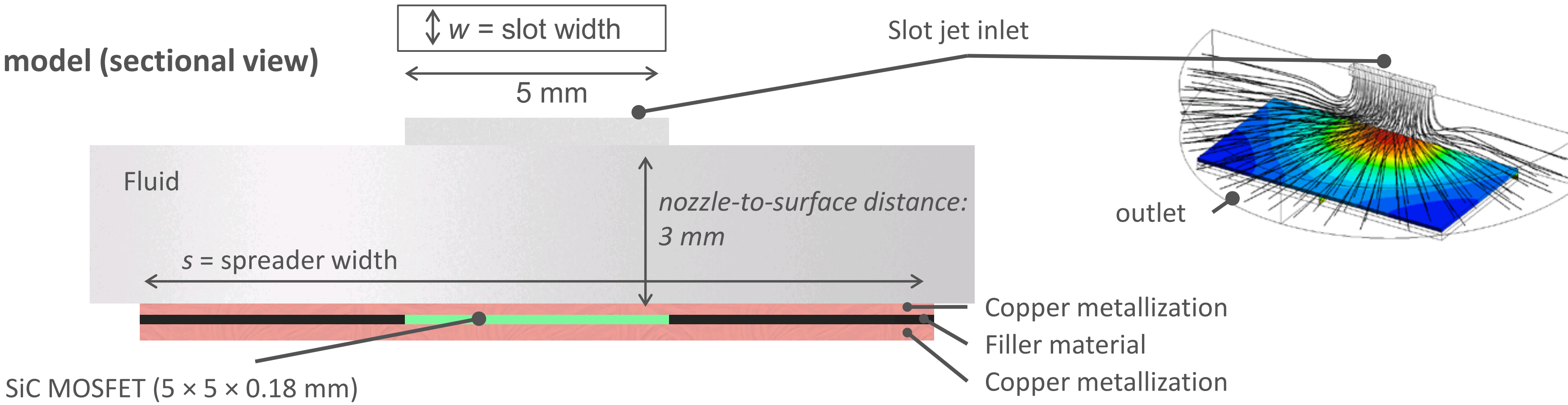
Thermal conductivity [W/m-K]	Specific heat [J/kg-K]	Density [kg/m^3]	Viscosity [Pa-s]	Flash point [°C]	Pour point [°C]
0.16	2,300	797	0.017	280	-52

Water/ethylene glycol (50 /50) properties at 70°C (provided for comparison)

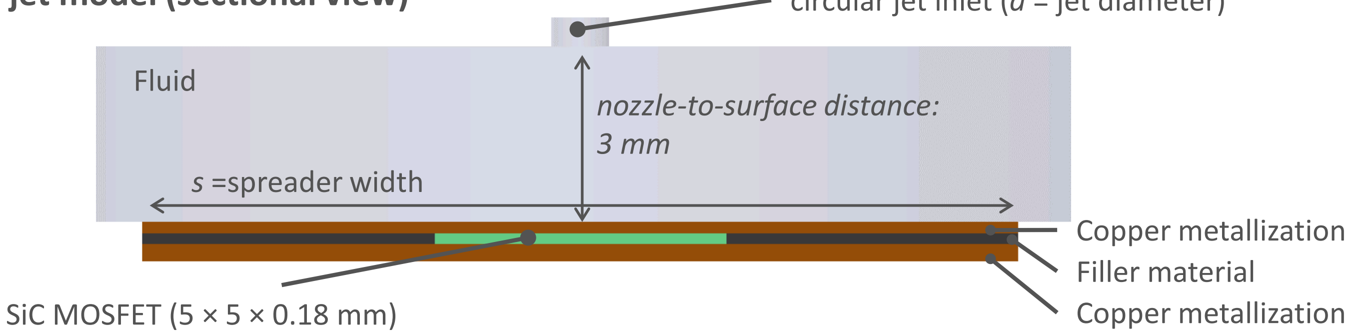
Thermal conductivity [W/m-K]	Specific heat [J/kg-K]	Density [kg/m^3]	Viscosity [Pa-s]
0.42	3,494	1,038	0.00126

CFD Jet Impingement Model Description

Slot jet model (sectional view)



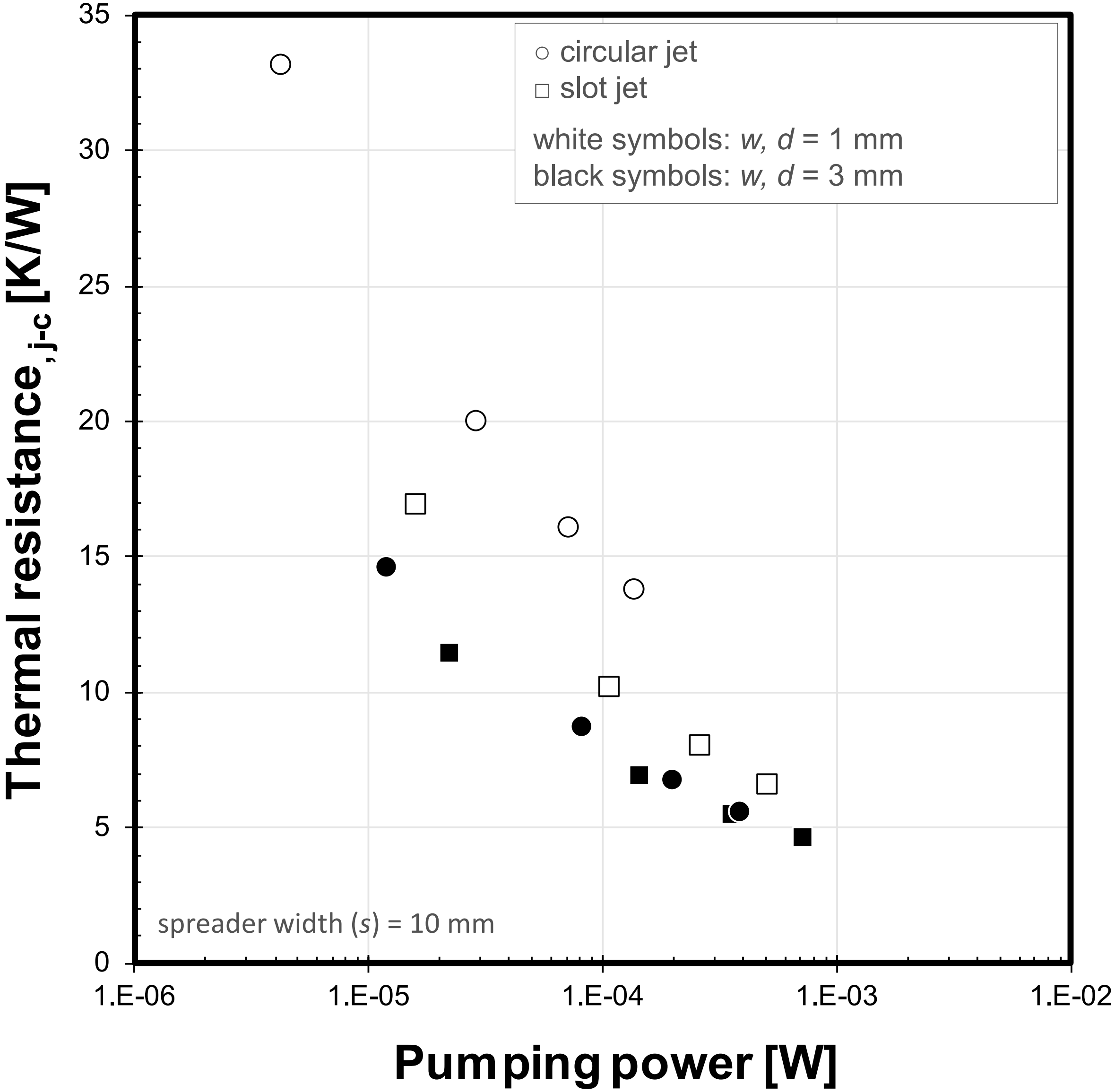
Circular jet model (sectional view)



- **Evaluated effect of jet velocity (1 m/s maximum), heat spreader size, nozzle characteristic length (*w, d*)**
- **T_{inlet} = 65°C, used laminar flow since Reynolds numbers < 300**

CFD: computational fluid dynamics

Circular Versus Slot Jet Performance Comparison



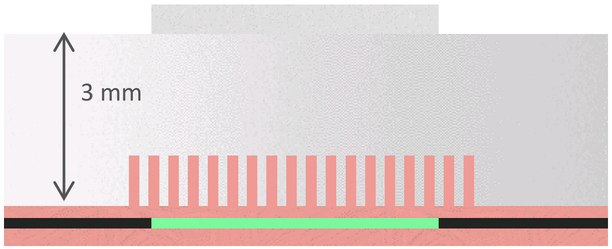
- Predict circular and slot jet to have similar performance for *w, d* = 3 mm
- Best performance yields a dismal thermal resistance of 4.7 K/W. Would require 60 devices to dissipate 2.2 kW
- Need to improve thermal performance. Evaluated using finned surface to improve performance.

Subscripts j-c: junction-to-coolant

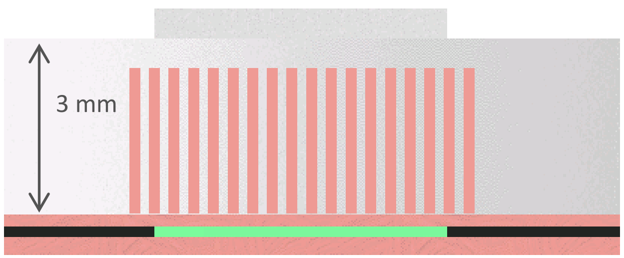
Finned Heat Spreader Concept

side views

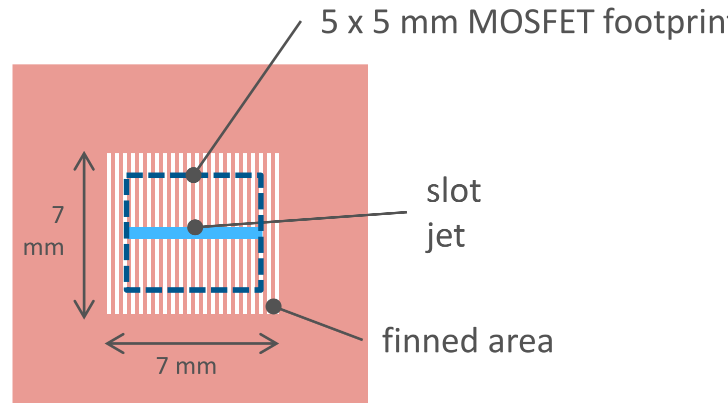
1-mm-tall fins



2.5-mm-tall fins

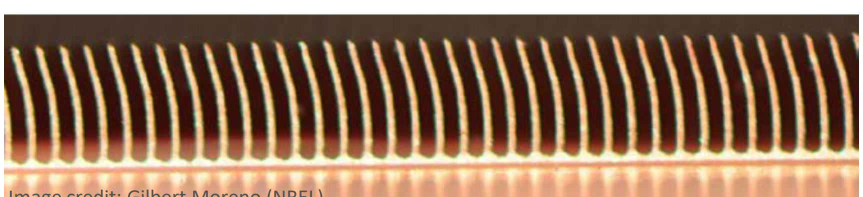


top view

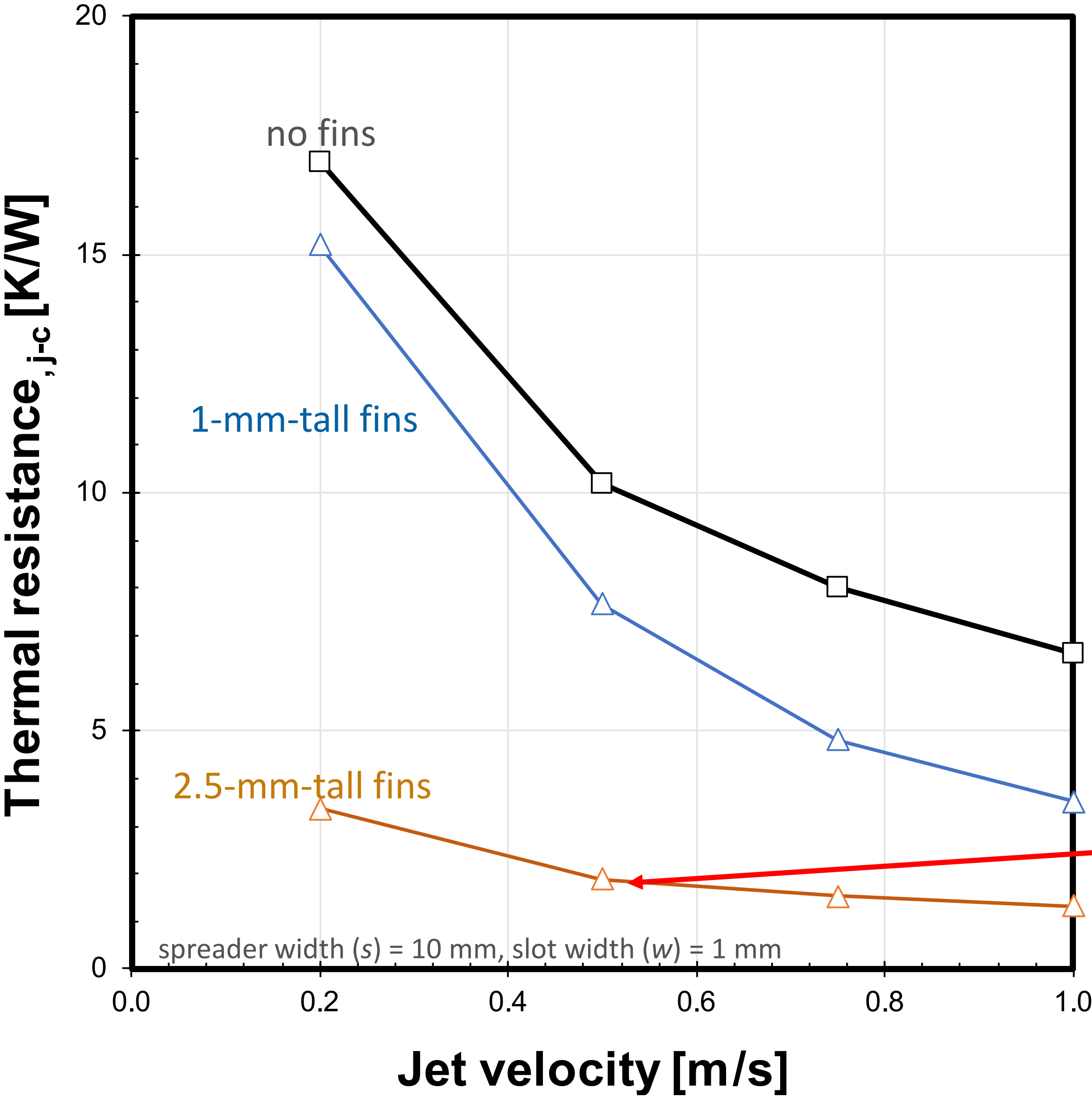


- Fin thickness, channel spacing = 0.2 mm
- Finned area extended 1 mm beyond 5 x 5 mm perimeter of the MOSFET area
- Fins only modeled for the slot jet case. Future work will model effect of fins on circular jet cases.

Fins can be fabricated using a skiving process. Image fin dimensions: fin thickness = 0.09 mm, channel width = 0.18 mm, fin height = 1 mm



Effect of Fins: Slot Jet



- Reduced thermal resistance by ~80% using finned surfaces
  - 50% lower thermal resistance (per device area) compare to the 2014 Accord
- Finned surfaces increase pumping power requirements

At 0.5 m/s, 24 devices can dissipate 2,150 W of heat. Each device would dissipate ~90 W at T_j < 250°C.

Initial Thermal Design

Initial results

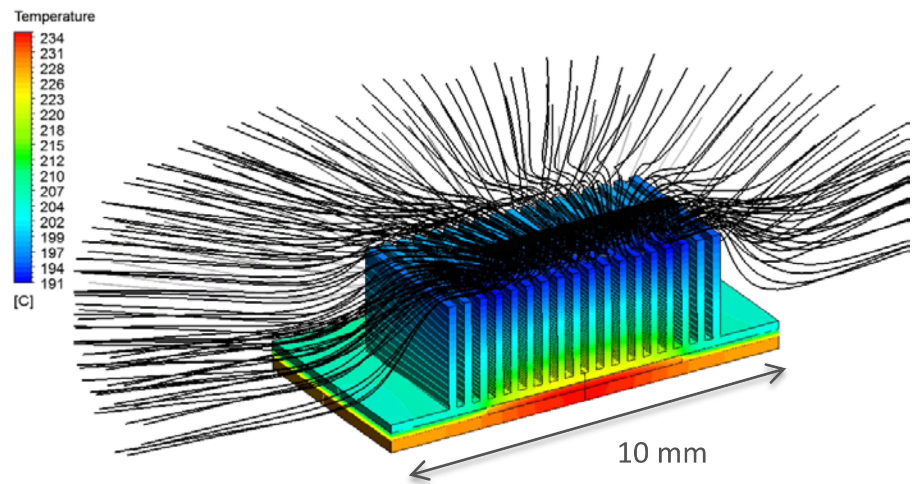
- Maximum T_j = 234°C
- Each device dissipates ~90 W
- 24 devices can dissipate 2,150 W
- Heat flux = 358 W/cm^2

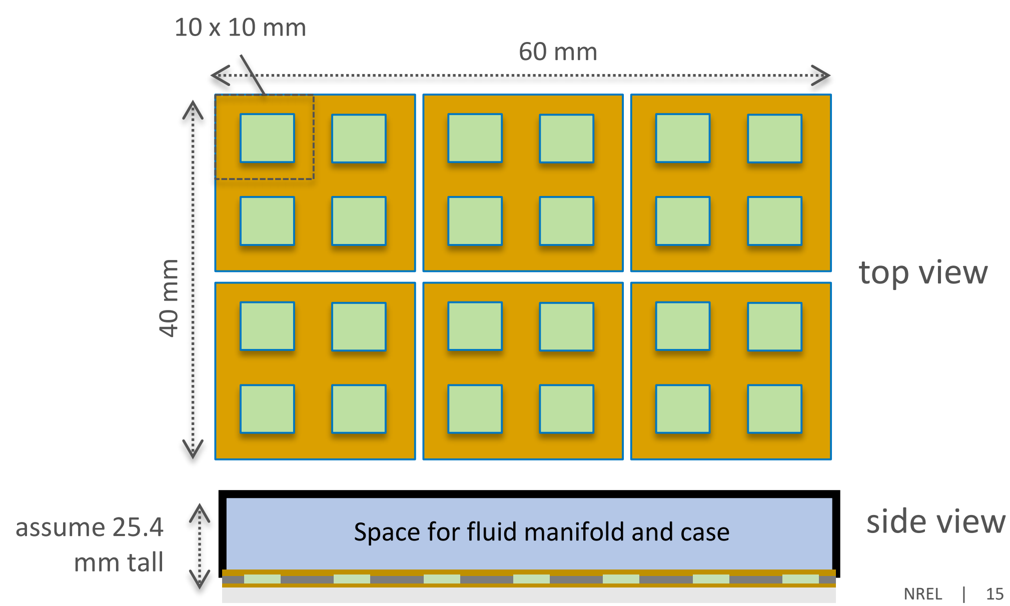
✓ Volume: 0.06 liters ($^1/_4$ of the volume available for the power module and cold plate)

✓ Flow rate requirements: 3.6 LPM (at this flow rate, the outlet fluid temperature is predicted to be 82.4°C)

CFD temperature contours (sectional view)

Slot jet: 2.5-mm-tall fins, *w* = 1 mm, jet velocity = 0.5 m/s





Responses to Previous Year Reviewers' Comments

- **Reviewer comment:** "*The reviewer commented the project is not specifically advancing the present state-of-the art: capacitor heating by power module, thermal interface material (TIM) degradation, capacitor active thermal management, eliminating the TIM layer, bus bar cooling, etc. are all known industry solutions*."
- **Response:** For 2018 and future years we are focusing our research efforts on the use of more novel power electronics cooling strategies (e.g., device cooling with dielectric fluids) that are typically not used or considered by industry.

- **Reviewer comment:** "*The reviewer said that this work is directed towards capacitor cooling. Computed capacitor temperatures were given but they were not verified by experimental measurements.*"
- **Response:** We plan to experimentally validate the concept through fabrication and testing after the model design work is completed. The validation work should be completed in 2018.

Collaboration and Coordination with Other Institutions

- John Deere (industry): Two-phase cooling for high packaging density planar inverter (CRADA)
- Elementum3D (industry): Provide 3D-printed metal parts to evaluate new heat exchanger concepts
- ORNL (national laboratory): Interactions related to ORNL's power electronics characterization research
- Interactions with other industry contacts
  - Dielectric fluid manufacturers

Remaining Challenges and Barriers

- **Creating a reliable, leak free cooling system**: main challenge is sealing the electrical leads that penetrate through the power module
- **Decreasing cost:** ultimate goal is to use transmission fluid as the dielectric coolant in an effort to decrease cost
- **Fluid compatibility with power electronics materials:** selected fluids should be compatible with electronics materials but tests should be conducted to verify compatibility
- **Pumping power requirements** at low temperatures due to higher fluid viscosity

Proposed Future Research

- Optimize jet impingement cooling with dielectric coolants
- Conduct module-scale simulations to evaluate cooling multiple devices and the electrical interconnects
- Evaluate cooling solution for transient conditions (effect of switching frequency and short-circuit heating)
- Experimental validation
- Evaluate using ATF as the dielectric coolant
- Evaluate phase-change cooling to enable greater power density

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

Summary

Relevance

- Effective thermal management is essential to achieve the 2025 DOE 100-kW/L power density target

Approach/Strategy

- Define a thermal target required to achieve the 100 kW/L power density
- Design a dielectric fluid-based device cooling system to meet the thermal target

Technical Accomplishments

- Developed thermal models to evaluate the performance of jet impingement cooling (single-phase) using dielectric fluids
- Computed the effects of slot versus circular jets, varying the nozzle size, adding finned features, varying the jet velocity, and increasing the spreader/electrical conductor size on jet- impingement thermal performance
- Developed a cooling concept that can meet the volumetric thermal targets and thus enable achieving the 100 kW/L power density target
- Collaborating with John Deere to develop a two-phase cooling strategy for their inverter

Collaborations

- John Deere
- Elementum3D
- Dielectric coolant manufacturers
- Oak Ridge National Laboratory

Acknowledgments

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Thank You

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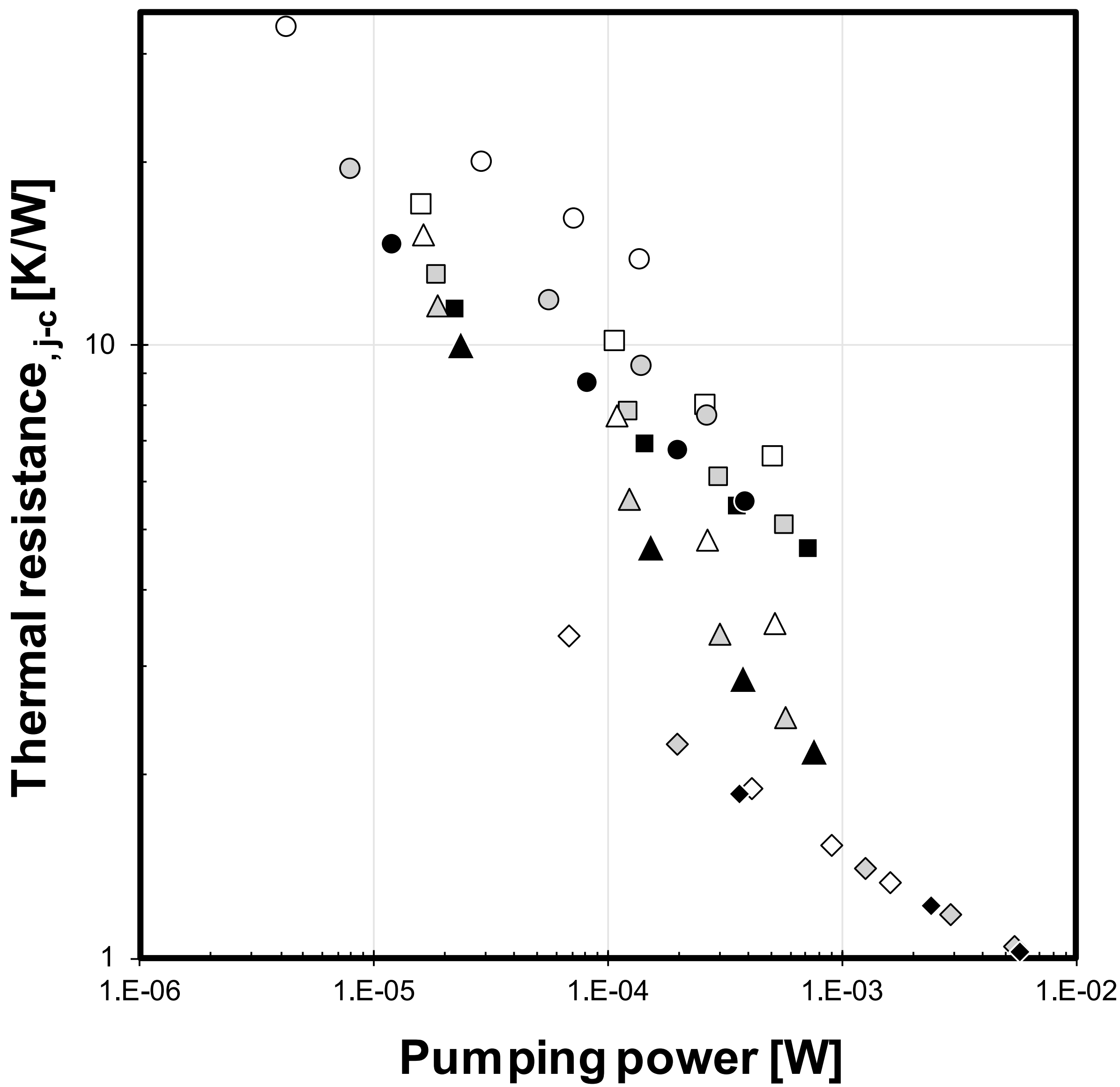
Technical Back-Up Slides

Other Candidate Dielectric Coolants

- ElectroCool EC-100: Engineered fluids
- Opticool-MIL Fluid: DSI Ventures
- Automatic transmission fluid: Afton
- Xceltherm 600: Radco
- Silicone oils: ClearCo
- Fluorocarbons: 3M

Thermal Resistance versus Pumping Power for All Cases Evaluated



Legend:

○ circular jet
□ slot jet
Δ slot jet with 1-mm-tall fins
◊ slot jet with 2.5-mm-tall fins

white symbols: *w*, *d* = 1 mm
gray symbols: *w*, *d* = 2 mm
black symbols: *w*, *d* = 3 mm