Thermal Management and Packaging of High Temperature Automotive Power Electronics

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Outline

- Motivation and objectives
- Describe the cooling systems currently used in automotive power electronics
- Discuss current research: cooling the power electronics using dielectric fluids
- Future work

Motivation

- Increase the market penetration of electric-drive vehicles (EDV)
  - Hybrid electric
  - Plug-in hybrid electric
  - Battery electric
  - Fuel-cell electric vehicles
- Requires reducing the cost and increasing power density of the electric traction drive system

Power Electronics Targets (100 kW peak power)		
Year	**On-road**	**2025**
Cost [$/kW]*	10	2.7
Power density [kW/L]*	18	100

**Source: Electrical and Electronics Technical Team Roadmap, October 2017*
https://www.energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

Wide-bandgap Technology (WBG)

WBG (silicon carbide, gallium nitride, gallium oxide)

Benefits:

- More efficient
- Higher temperatures
- Higher voltages
- Higher switching frequencies

Challenges:

- Higher heat flux
- Higher cost
- High device temperatures presents packaging issues

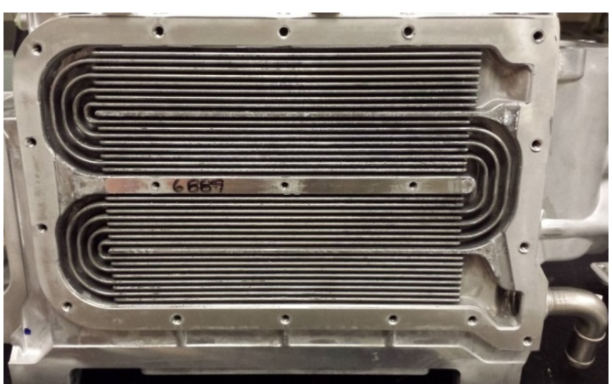
Objective

Develop thermal management techniques to enable achieving the DOE power density target of 100 kW/L

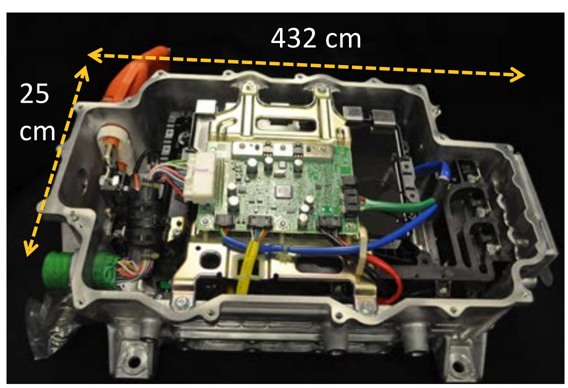
- Challenge is to create a thermal solution that allows for packaging high temperature (250°C) wide-bandgap (WBG) devices next to capacitors that typically cannot exceed 85°C

Current Automotive Power Electronics Cooling Strategies

- Use water-ethylene glycol (WEG) in channel-flow type heat exchangers
- Require a dedicated, low-temperature WEG cooling system for the power electronics and motor
- In most cases, the distance between components is large such that the capacitors and electrical boards do not require any cooling



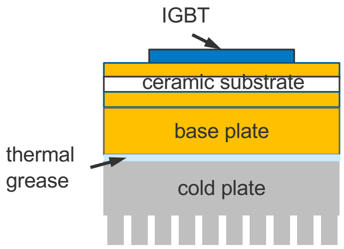
2012 Nissan LEAF cold plate



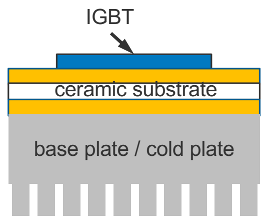
2012 Nissan LEAF power electronics

Automotive Power Electronics Cooling Trend

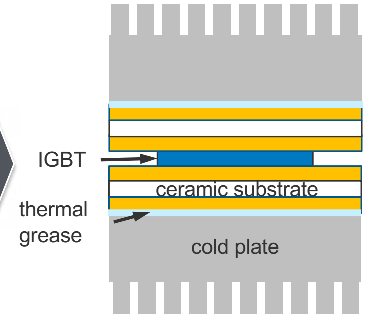
cold plate cooled



base plate cooled

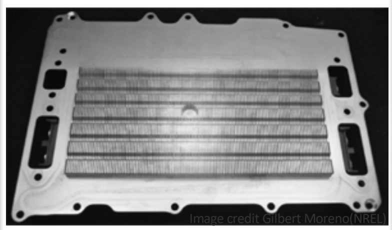


double-side cooled

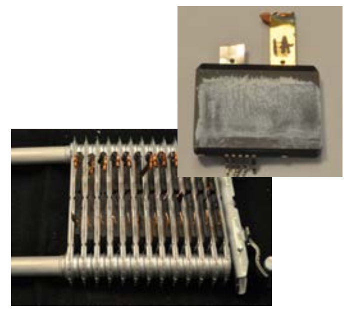


Note: the automotive modules below may be slightly different from the above schematics

2012 Nissan LEAF

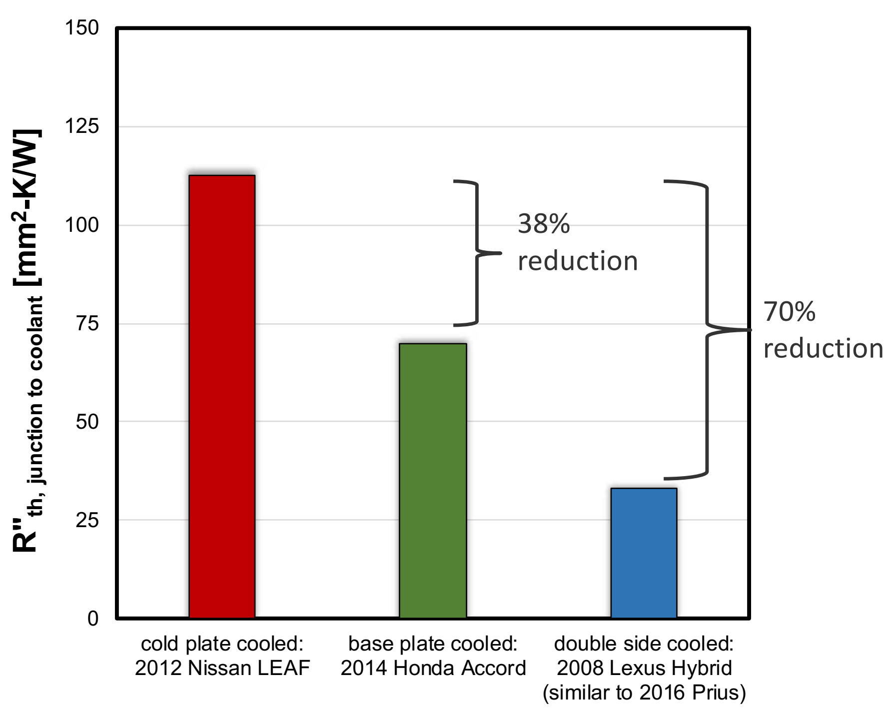


2014 Honda Accord Hybrid



2012 Camry Hybrid
(2016 Prius is similar)

Automotive Power Electronics Cooling Trend



Cooling configuration

Defining a Thermal Target

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/

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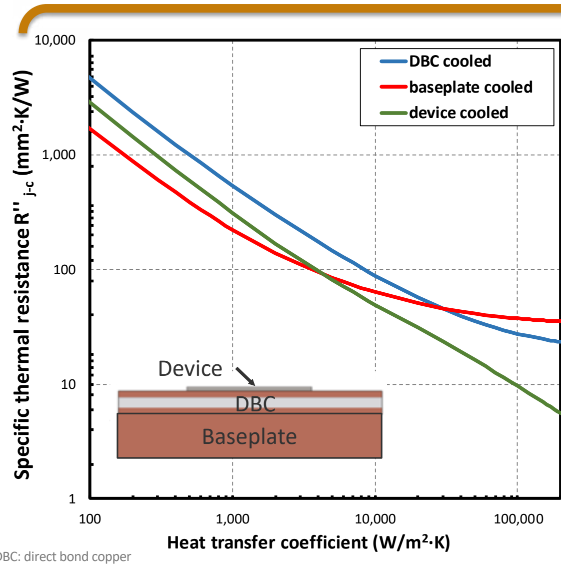
- Heat dissipation requirements: **2,150 W** (*assuming 100 kW system, 98% WBG inverter efficiency, and 95% motor efficiency*)
- Assuming $T_{j,\ maximum}$ = 250°C and $T_{coolant}$ = 65°C, **volumetric thermal resistance target is 21 cm^3-K/W**

Defining a Thermal Target

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

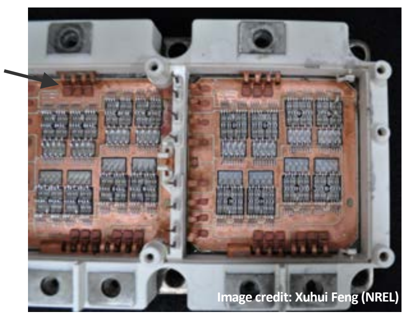


DBC: direct bond copper

Device cooling

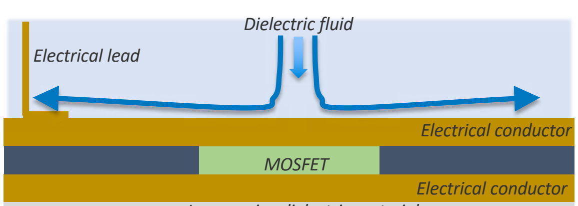
- Provides the lowest thermal resistance
- Enables cooling the electrical leads (decrease capacitors and board temperatures)

Electrical leads in the 2015 BMWi3 power module



Defining a Thermal Target

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

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)

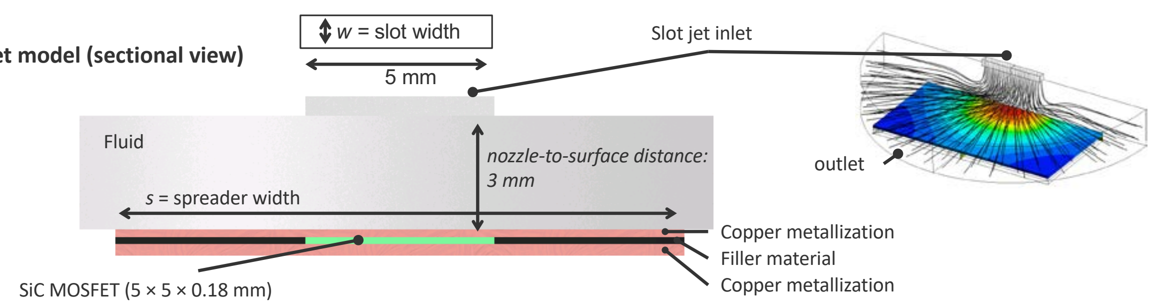
Thermal conductivity [W/m-K]	Specific heat [J/kg-K]	Density [kg/m³]	Viscosity [Pa-s]	Flash point [°C]	Pour point [°C]
0.16	2,300	797	0.017	280	-52

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

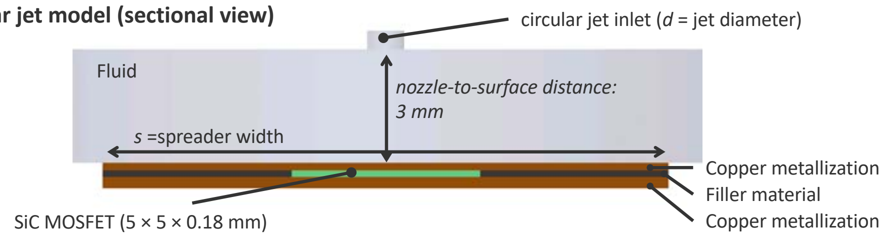
Thermal conductivity [W/m-K]	Specific heat [J/kg-K]	Density [kg/m³]	Viscosity [Pa-s]
0.42	3,494	1,038	0.00126

CFD Jet Impingement Model Description

Slot jet model (sectional view)



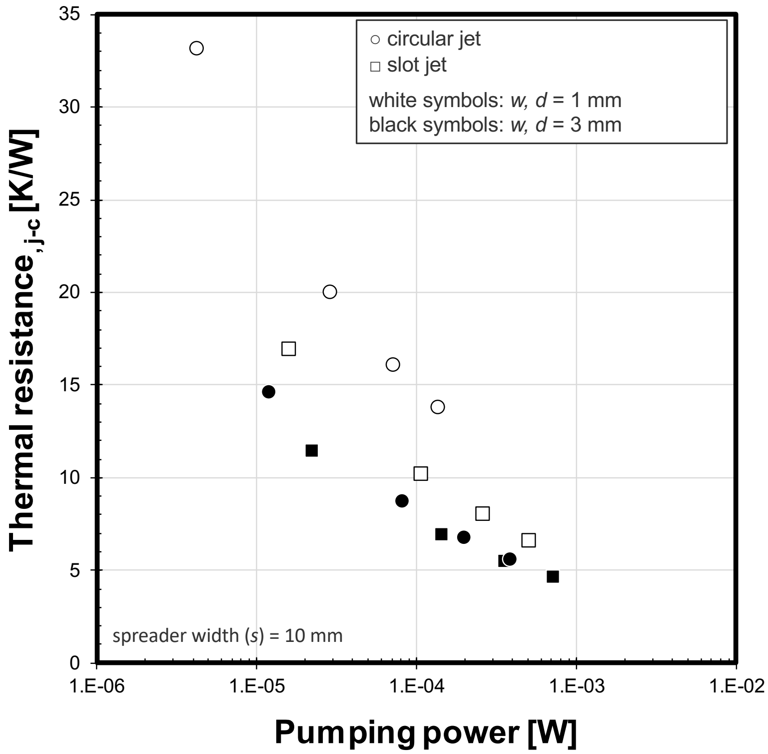
Circular jet model (sectional view)



- **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

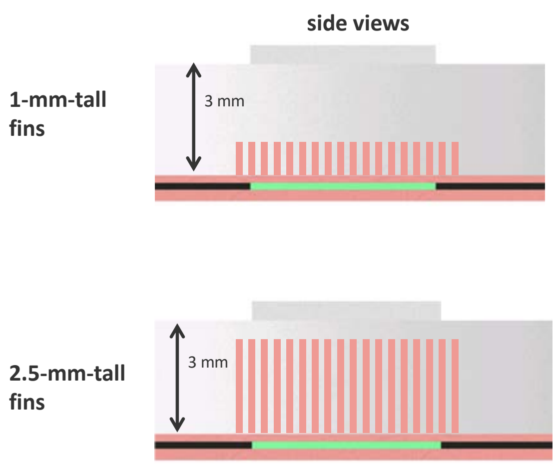
Circular Versus Slot Jet Performance Comparison

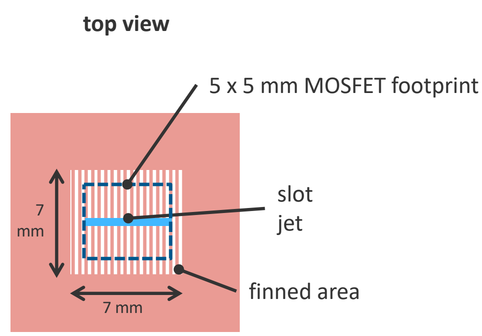


- Predict circular and slot jet to have similar performance for *w, d* = 3 mm
- Best performance yields a dismal thermal resistance of 4.7 K/W. Would require 60 devices to dissipate 2.2 kW
- Need to improve thermal performance. Evaluated using finned surface to improve performance.

Subscripts j-c: junction-to-coolant

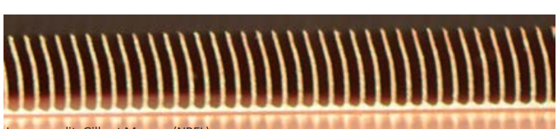
Finned Heat Spreader Concept



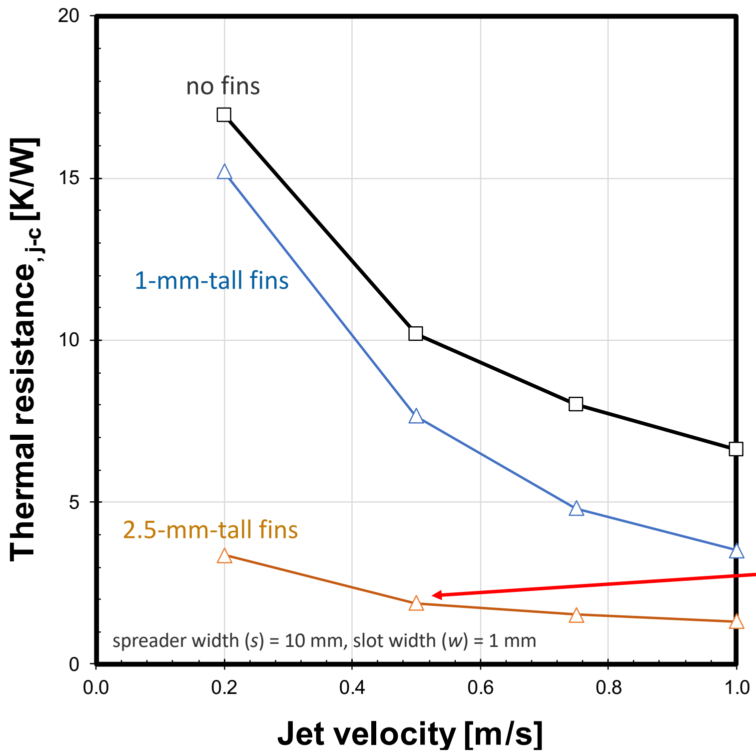


- Fin thickness, channel spacing = 0.2 mm
- Finned area extended 1 mm beyond 5 x 5 mm perimeter of the MOSFET area
- Fins only modeled for the slot jet case. Future work will model effect of fins on circular jet cases.

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



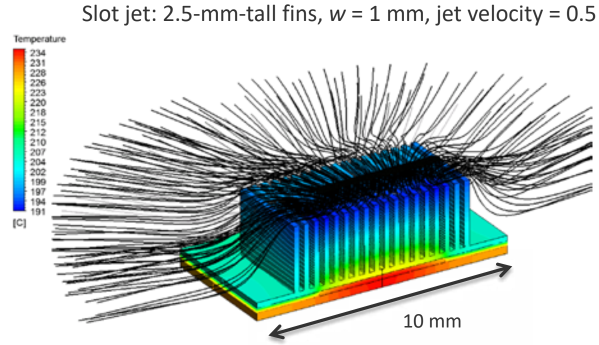
- Reduced thermal resistance by ~80% using finned surfaces
  - 50% lower thermal resistance (per device area) compare to the 2014 Accord
- Finned surfaces increase pumping power requirements

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

CFD temperature contours (sectional view)

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

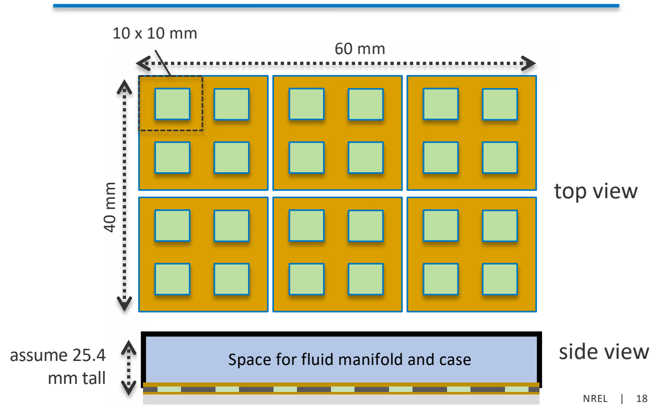


Initial results

- 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)



Future Work

- Evaluate effect of high fluid viscosity at lower temperatures on the thermal performance
- Understand the dielectric properties of ATF to evaluate their use as a coolant
- Develop methods to cool the electrical connections using dielectric fluid
- Design the entire cooling system and conduct an experimental validation of the cooling concept

Conclusions

- Evaluating using dielectric fluids in a jet impingement configuration to cool the power electronics
  - Modeled circular and slot jets and the effect of adding micrometer-sized fins
  - Ideal to use ATF as the dielectric fluids
- Developed a cooling concept that can meet the volumetric thermal targets and thus enable achieving the 100 kW/L power density target

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Thank You

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