Holistic Thermal Management

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Power Electronics and Electric Machines

Power electronics (inverters, converters, chargers) and electric machines (motors) are critical to controlling the power flow through electric-drive vehicles across a range of applications (hybrid, battery electric, fuel cell).

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Power Electronics and Electric Machines

Integrated Thermal Management

Reduced Components

Improved Power Density

Reduced System Cost

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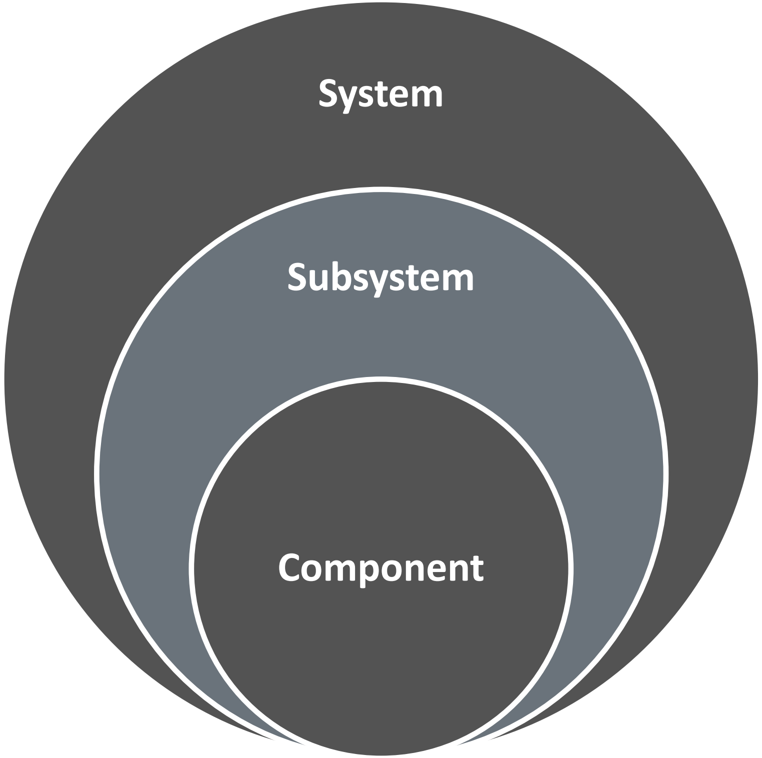
Holistic Thermal Management



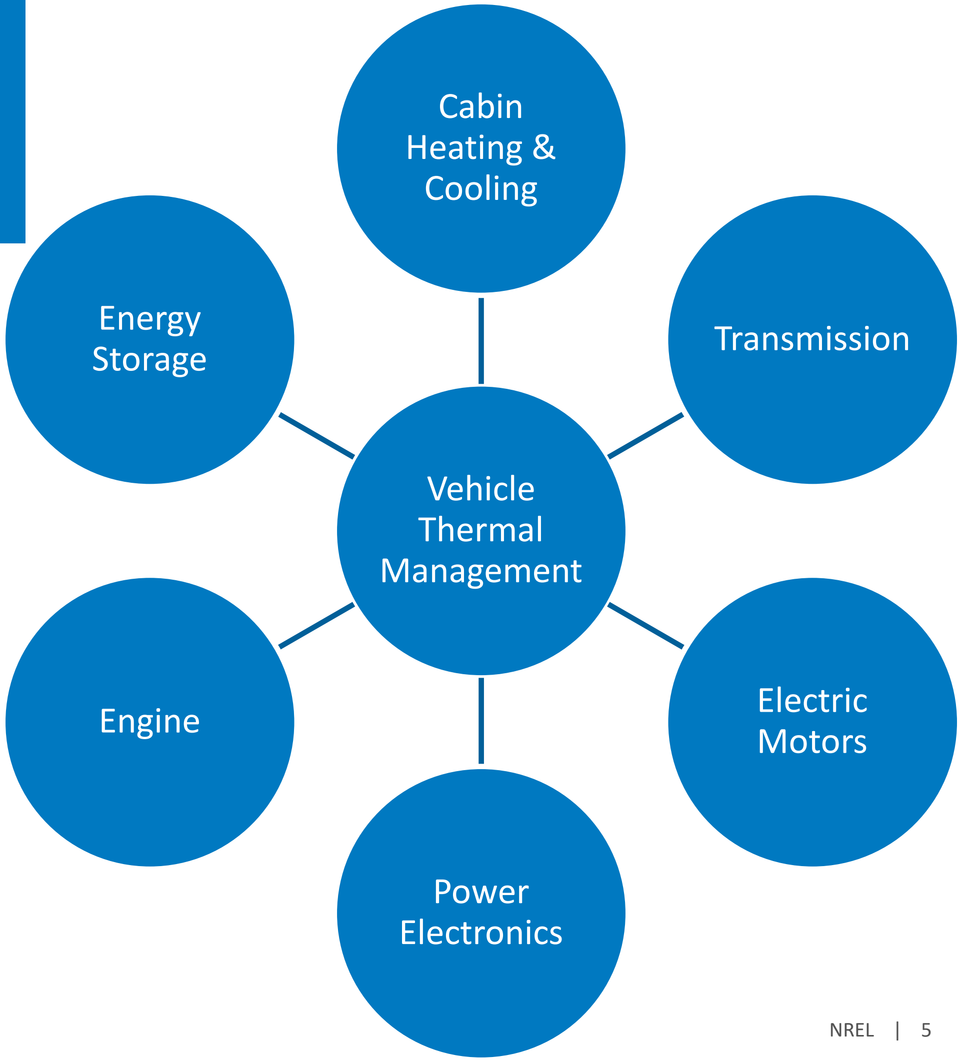
Vehicle Thermal System Integration
- Examples: Full electric vehicle, Hybrid electric vehicle

Subsystem Thermal Management
- Examples: Power electronics, Electric motors, Engine, Transmission

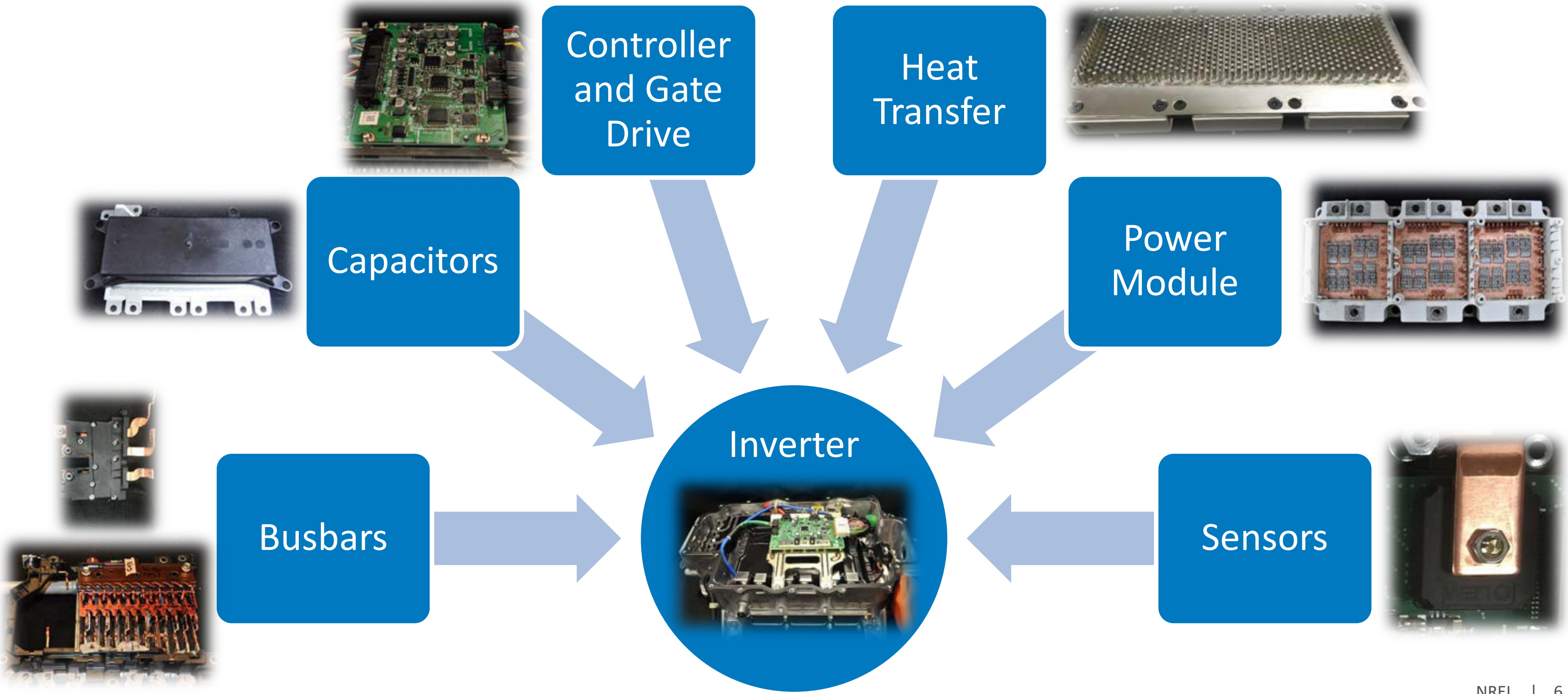
Component Thermal Management
- Examples: Transistors, capacitors, motor windings

Vehicle Thermal Systems

- Multiple separate thermal management systems to manage temperature constraints for a range of vehicle subsystems



Electrical, Mechanical, Thermal Integration



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Electrical, Mechanical, Thermal Integration


Insulation Systems

Stator Core

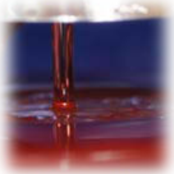
Winding Systems

Rotor Core

Sensors

Motor

Heat Transfer

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Contents

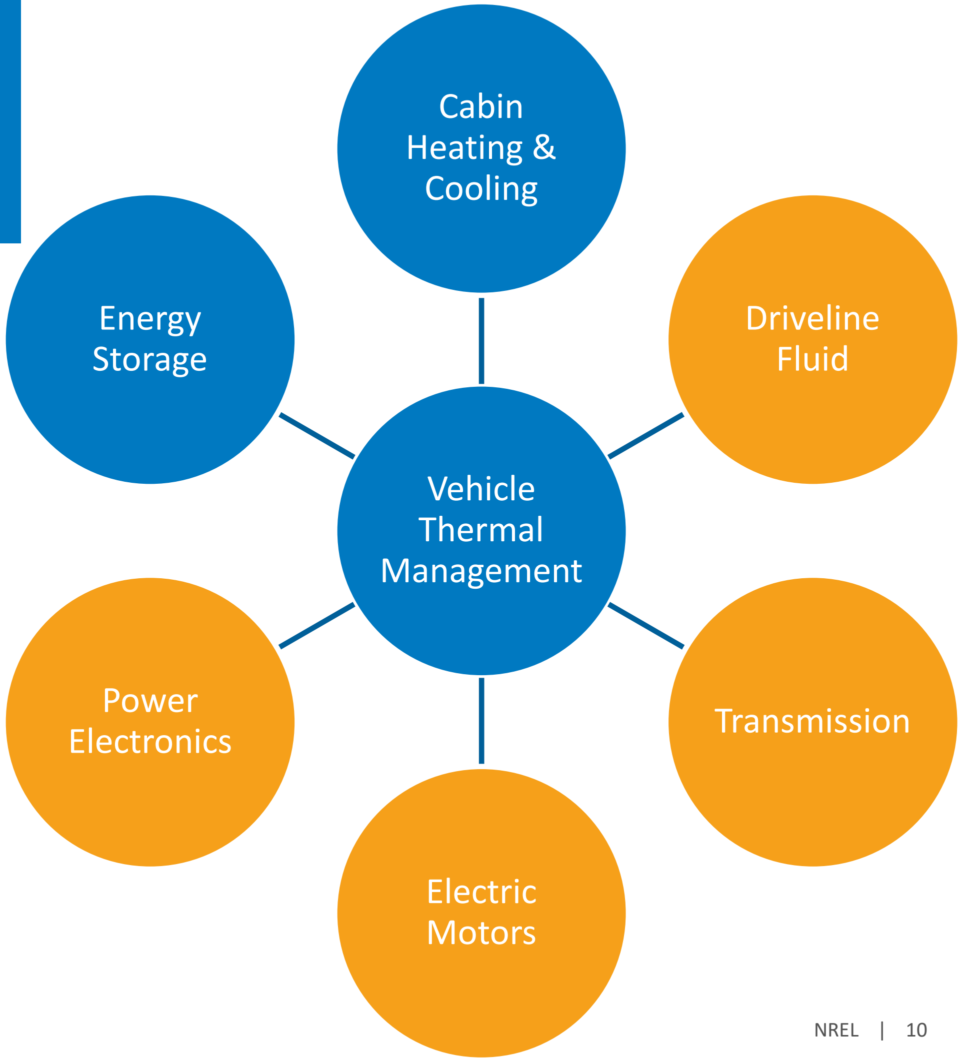
- Electric Machine/Motor, Power Electronics, and Driveline Thermal Integration
- Power Electronics and Engine Coolant Thermal Integration

Electric Machine/Motor, Power Electronics, and Driveline Thermal Integration

Driveline fluid cooling of motors and power electronics

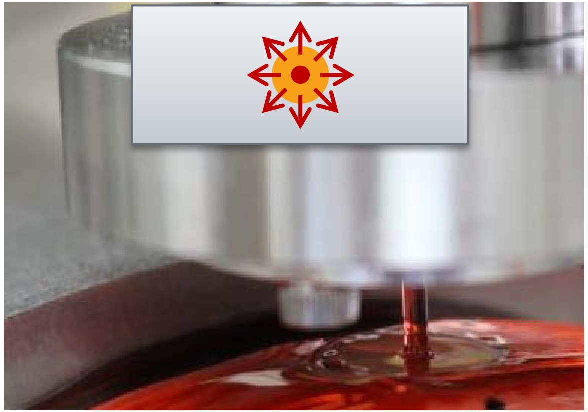
Full Electric System Example

- Integration of electric motor and power electronics thermal management with transmission and driveline fluids

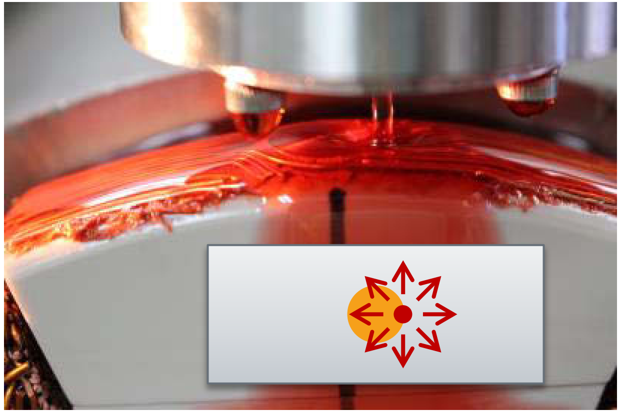


Automatic Transmission Fluid (ATF) Cooling of Windings

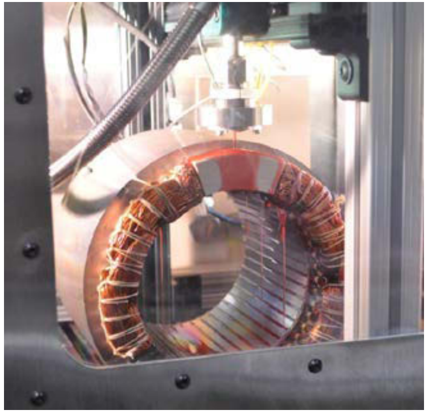
- Measuring heat transfer variation along winding
- Quantifying impact of new or alternative cooling approaches for ATF cooling of motors



Orifice Jet Center Impingement



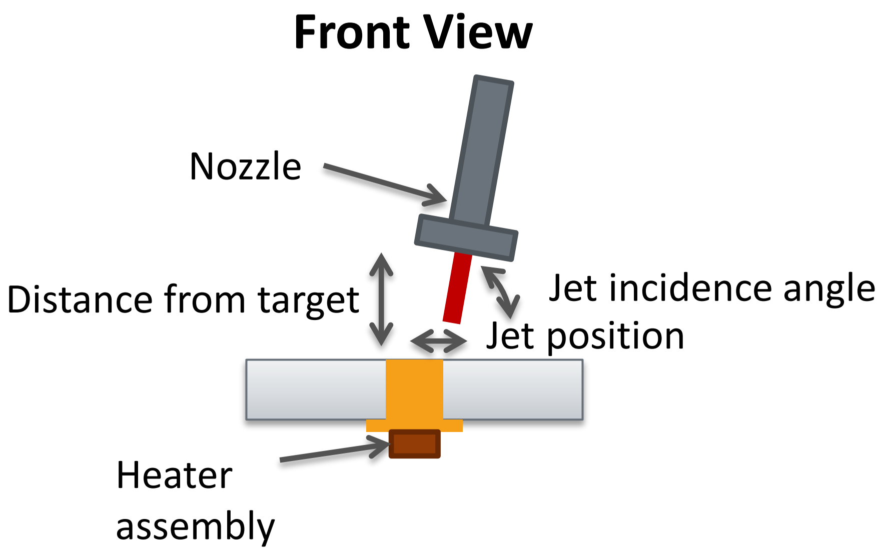
Orifice Jet Edge Impingement



Test Enclosure

Photo Credits: Bidzina Kekelia and Kevin Bennion, NREL

Measurement Method



$$h = \frac{q_s}{A_s(T_s - T_l)}$$

$h = heat\ transfer\ coefficient$

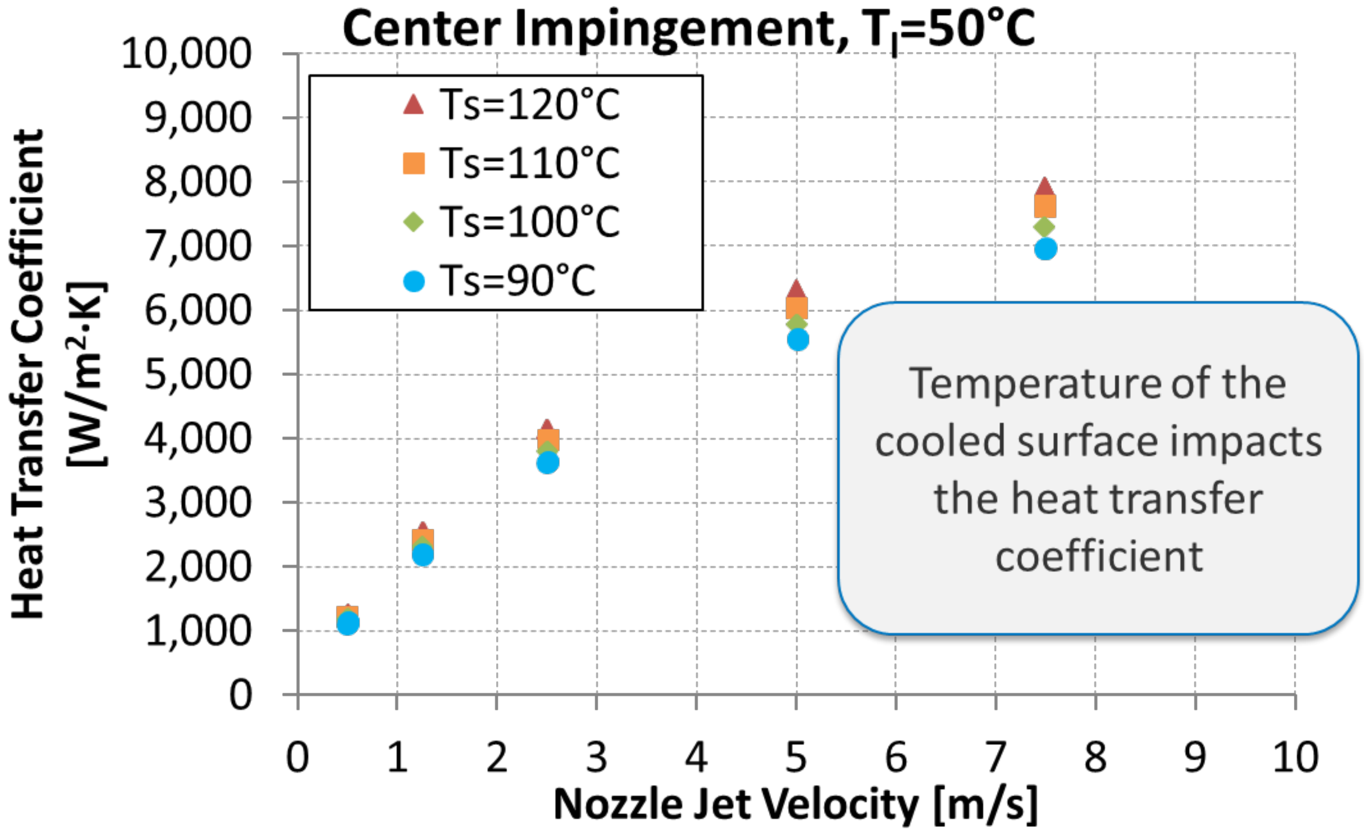
$q_s = heat\ removed\ from\ target\ surface$

$A_s = area\ of\ target\ surface$

$T_s = target\ surface\ temperature$

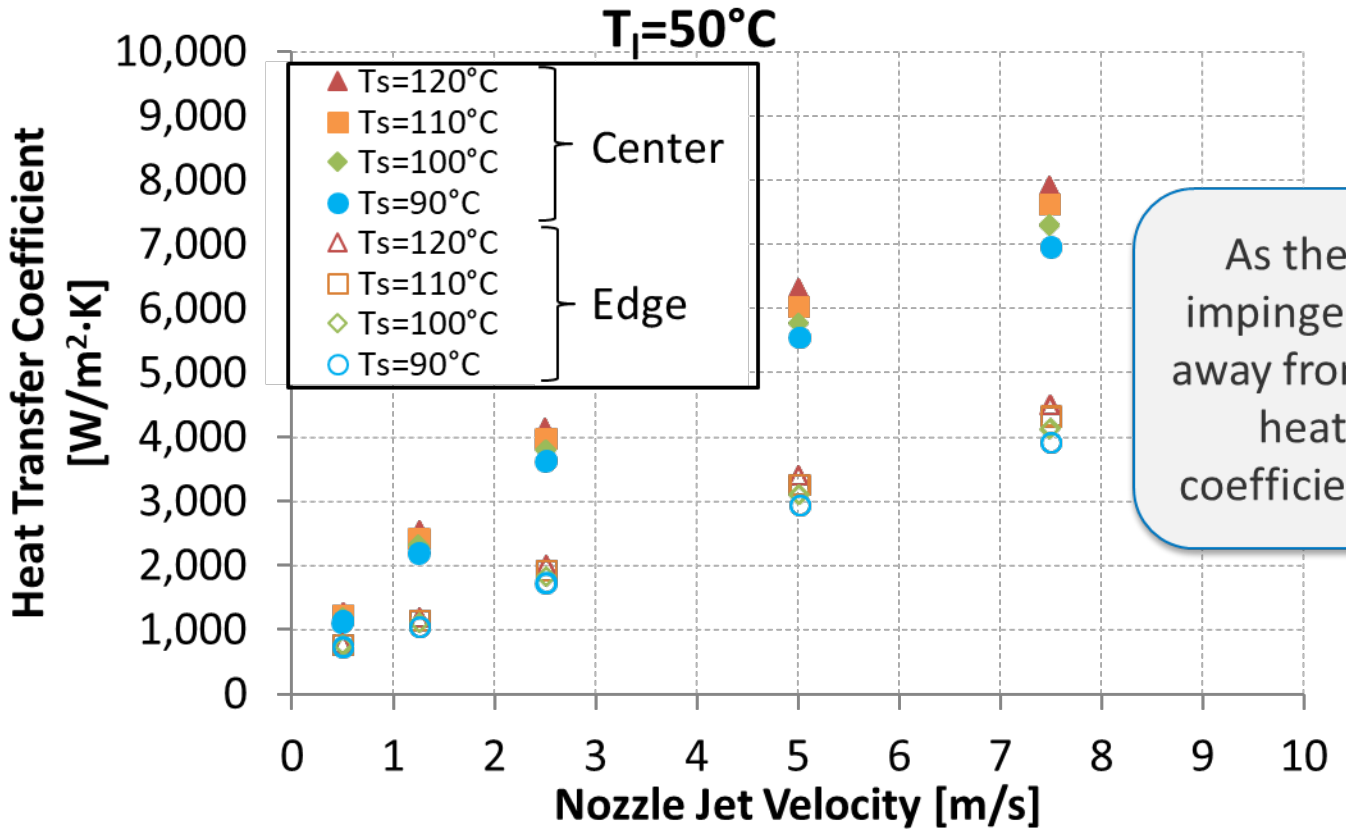
$T_l = fluid\ or\ liquid\ temperature$

Heat Transfer Comparison



Temperature of the cooled surface impacts the heat transfer coefficient

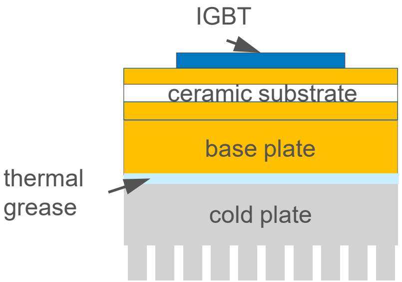
Heat Transfer Comparison



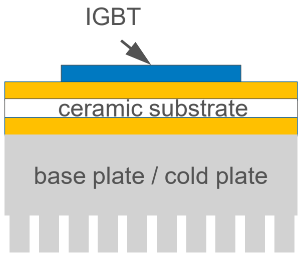
As the orifice jet impingement moves away from center, the heat transfer coefficient decreases

Automotive Power Electronics Cooling Trends

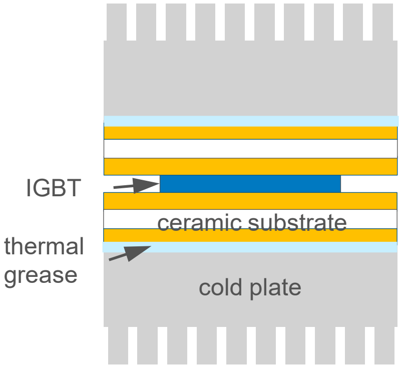
Cold-plate cooled



Base-plate cooled



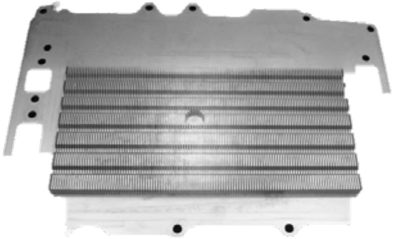
double-side cooled



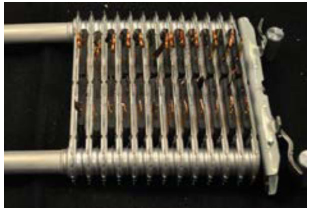
IGBT: insulated gate bipolar transistor

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

2012 Nissan LEAF



2014 Honda Accord Hybrid

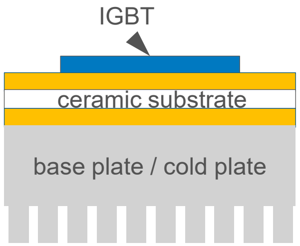


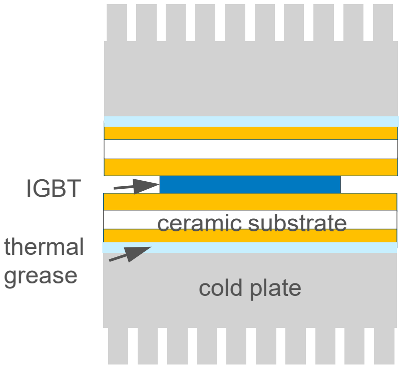
2012 Camry Hybrid (2016 Prius is similar)

Photo Credits: Gilbert Moreno, NREL

Integrated Electric Drive

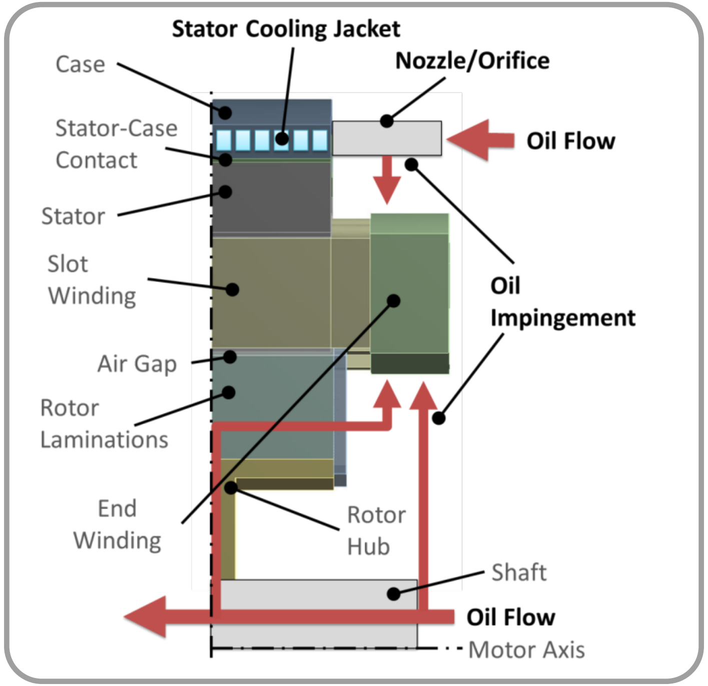
Power Electronics





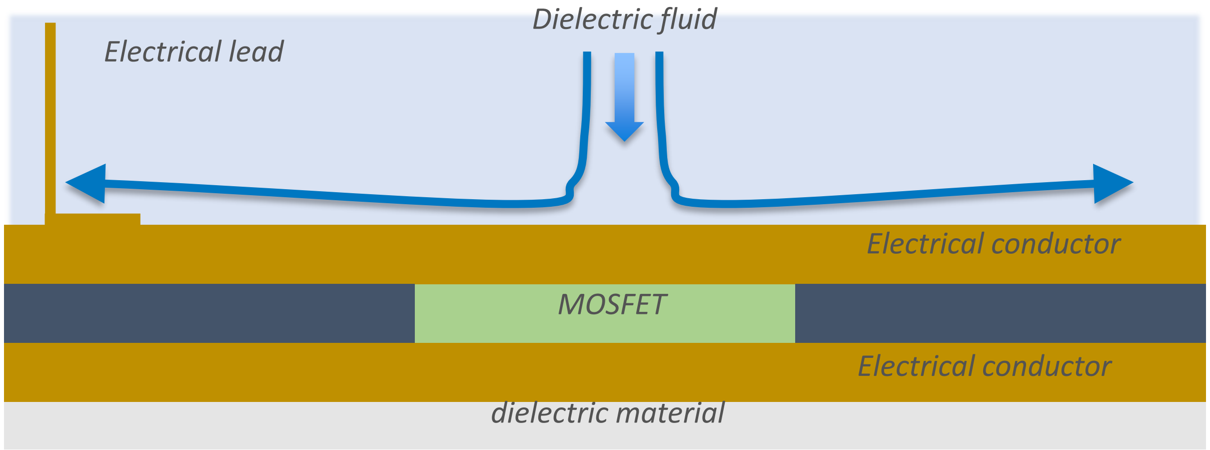
Integrated Drive System with Integrated Cooling

Electric Motor



Driveline Fluid Cooling of Power Electronics

- Potential to use driveline fluid such as ATF
  - Propose using jet impingement to improve performance
  - Cool the electrical interconnects



Dielectric cooling of planar package

MOSFET: metal–oxide–semiconductor field-effect transistor

Future Work

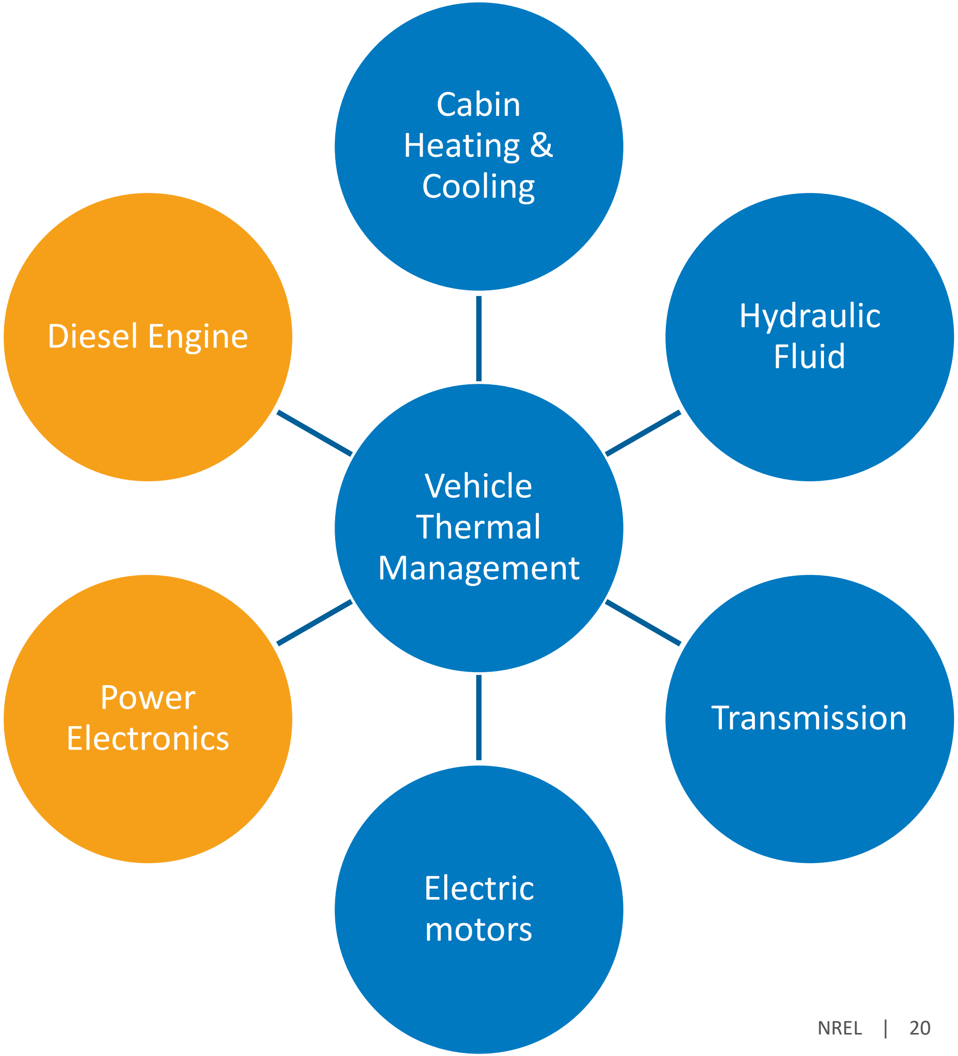
- Evaluate effect of high fluid viscosity at lower temperatures on thermal performance
- Understand the dielectric properties of ATF to evaluate its use as a coolant for power electronics
- Evaluate approaches for integrating power electronics and motor with integrated cooling system

Power Electronics and Engine Coolant Thermal Integration

High-temperature engine coolant for
power electronics cooling

Hybrid Electric System Example

- Integration with Engine Coolant System
  - Reduce Components
  - Reduce system cost

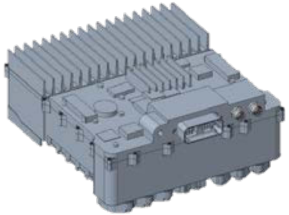


Project Objective

- The project, funded through Power America and led by John Deere Electronic Solutions (JDES), will design, manufacture, and commercialize a 200-kW 1,050 VDC silicon carbide (SiC) dual inverter
- NREL support to JDES project
  - Thermal management system integrated with engine coolant
  - NREL supporting JDES in thermal design optimization and thermo-mechanical analysis

Accomplishments

- Gen 1 SiC Dual Inverter
  - Integrated with engine cooling system
  - Compatible with engine coolant up to 105°C
  - Demonstrated and tested the SiC wide bandgap (WBG) inverter in a John Deere hybrid electric construction vehicle
  - Shown in APEC 2017 in John Deere booth



- Gen 2 SiC Dual Inverter
  - Integrated with engine cooling system
  - Compatible with engine coolant up to 115°C while achieving higher power density

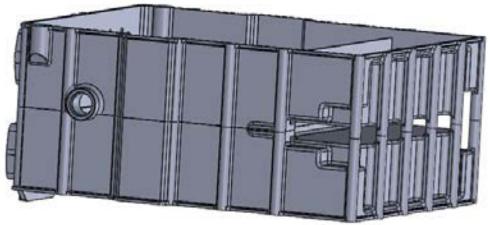
Photo Credits: JDES

Thermal Design Approach

Analysis at Multiple Scales

- Channel and Fin CFD
- Module Thermal FEA
- Module and Heat Exchanger CFD
- Inverter-Scale CFD
- Thermo-mechanical Analysis

Drawing of Gen 2 inverter six-pack module CAD geometry

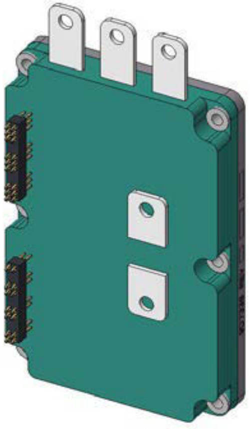


Gen 1 inverter system enclosure

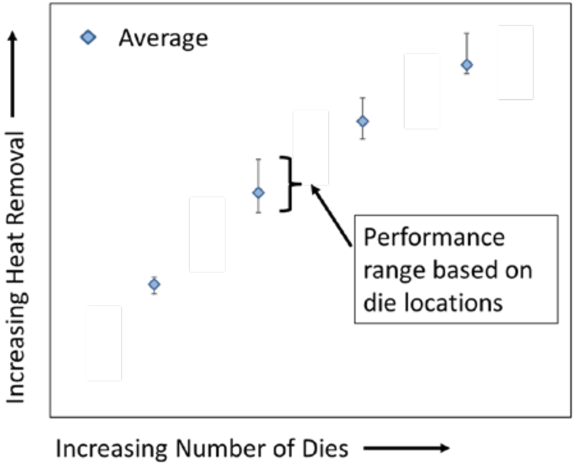
CFD: computational fluid dynamics
FEA: finite element analysis

Module Thermal FEA

- Developed thermal models for 6-pack module thermal FEA
  - Quantified material impacts on thermal resistance
  - Studied impacts of die placement within 6-pack power modules on heat rejection capability versus maximum temperature limit and coolant temperature
  - Studied impact of heat exchanger performance on device temperatures



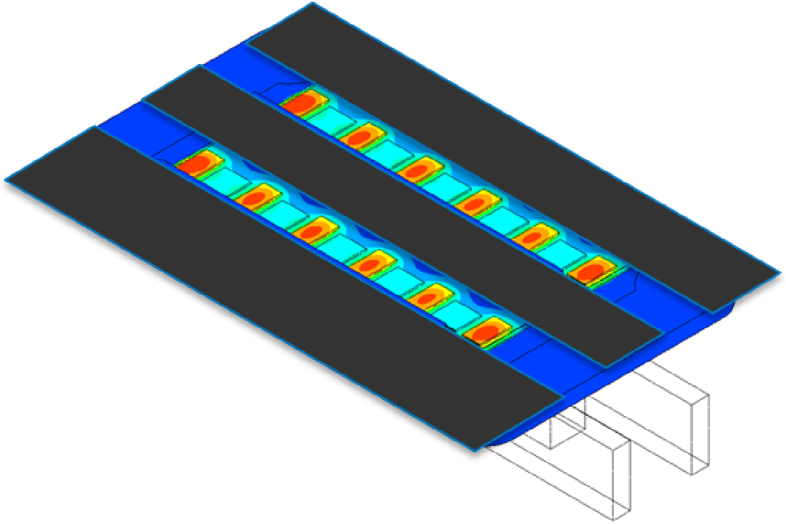
Drawing of Gen 2 inverter six-pack module CAD geometry



Example analysis of die number and die placement

Module and Heat Exchanger CFD

- Full module and heat exchanger conjugate heat transfer CFD preliminary results
  - 282 million element model
- Using advanced thermal management method we are able to keep identical junction temperature for all SiC die

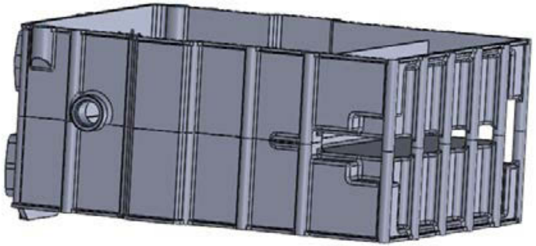


Thermal analysis of Gen 1 module

Thermo-Mechanical Analysis

- Thermo-mechanical analysis for power module and inverter-level reliability analysis
  - Power module die, package, and interface material analysis
  - Manufacturing process impacts versus thermal cycling impacts
  - Power module stress and deflection analysis for safety and coolant system sealing
  - Inverter enclosure stress and deflection analysis based on operating and JDES safety requirements

Magnified image of Gen 1 power module baseplate displacement analysis with pressurized coolant system



Gen 1 Inverter system enclosure for stress and deflection analysis

Summary

- Supports off-highway and on-highway heavy-duty vehicle inverter applications
- Integration leads to system cost advantages
- The project led by JDES will work to commercialize a modular SiC inverter for use across multiple vehicle platforms that are engine coolant capable.

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Thank You

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