Automotive Power Electronics and Electric Machine Thermal Management

Kevin Bennion
Senior Research Engineer
National Renewable Energy Laboratory
Bidzina Kekelia, Gilbert Moreno

September 19, 2018
Plymouth, Michigan

Contents



An energy revolution is sweeping the nation

Photo Credits: NREL Image Library 24693, 49115, 18891-C

Sustainable Transportation Systems

Early-stage research and engineering for the development and widespread adoption of affordable, high-performance, low-emission, energy-efficient strategies for passenger and freight transportation.

Photo Credits: NREL Image Library 47589, 22791

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).

Photo Credits: NREL Image Library 40146, 22791

Electrical, Mechanical, Thermal Integration

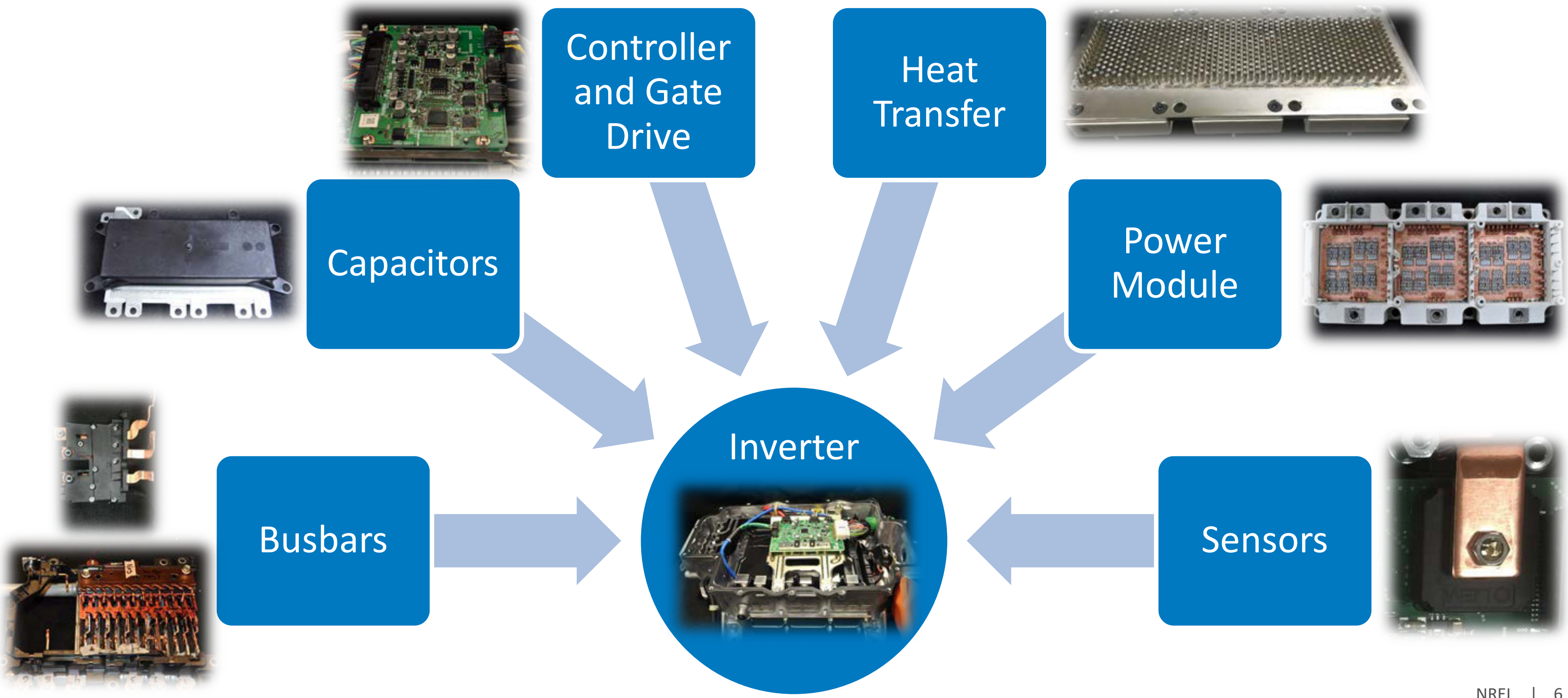


Photo Credits: Gilbert Moreno, Xuhui Feng, NREL

Electrical, Mechanical, Thermal Integration

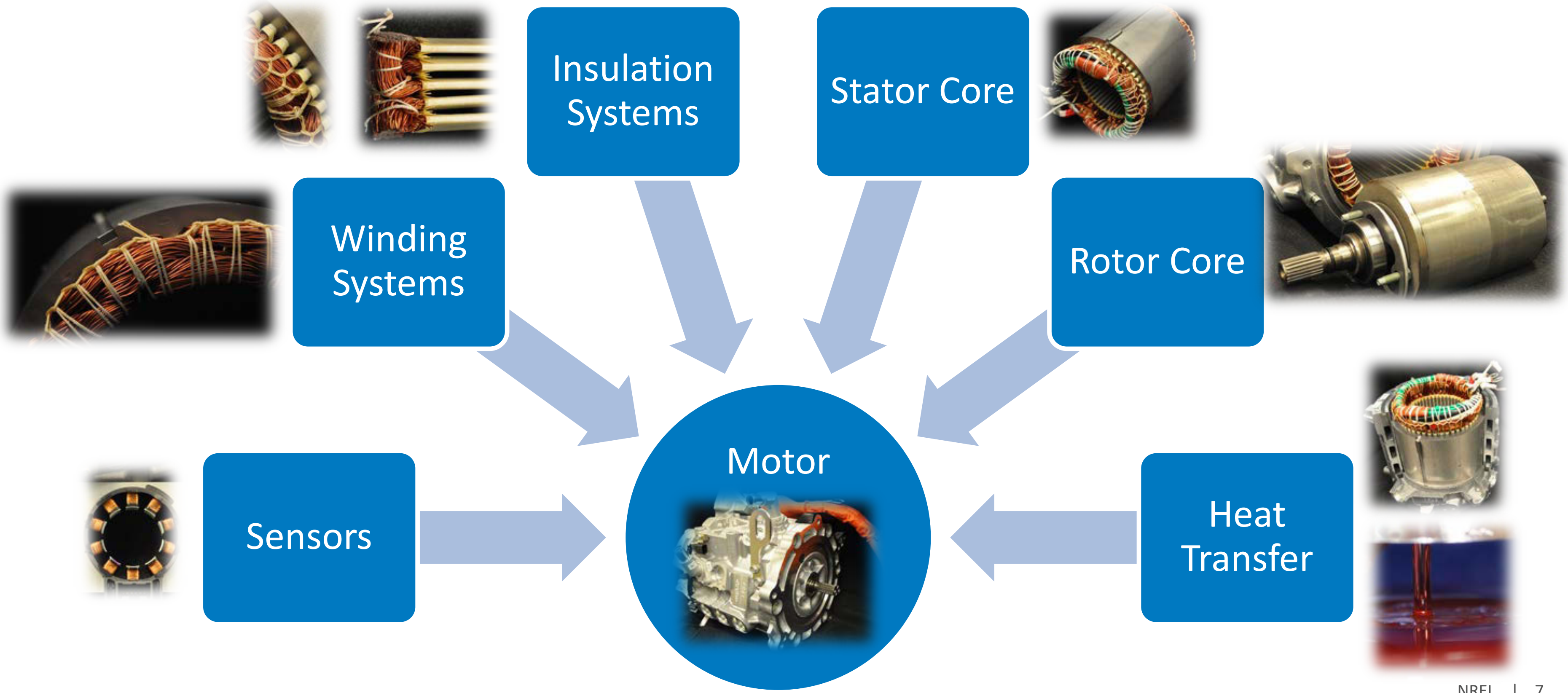
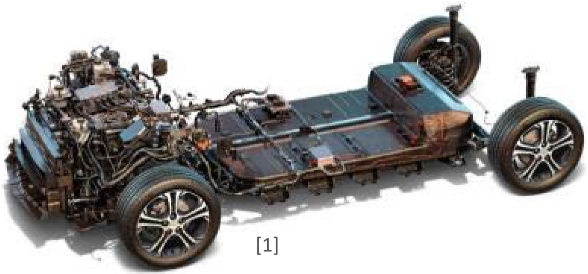


Photo Credits: Kevin Bennion, Bidzina Kekelia , NREL



[1]

[1]

[1] Image Source: "Electrical and Electronics Technical Team Roadmap." U.S. DRIVE, Oct-2017.
https://energy.gov/sites/prod/files/2017/11/f39/EETT%20Roadmap%2010-27-17.pdf

U.S. DRIVE Electrical and Electronics Roadmap

10 x Reduction in Volume at Half the Cost

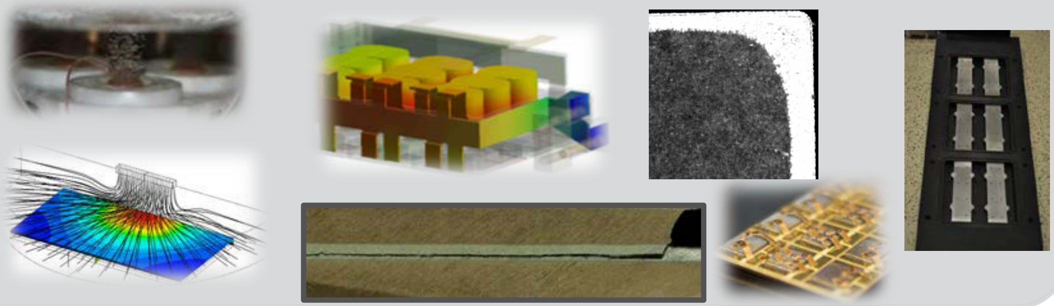
Trends and Challenges

Vehicle architecture change	Compact with least cost
Greater fleet applications of BEVs	Increased reliability (300K miles)
Long-range BEVs	High-power charging

BEV: battery electric vehicle

Thermal and Thermomechanical Research

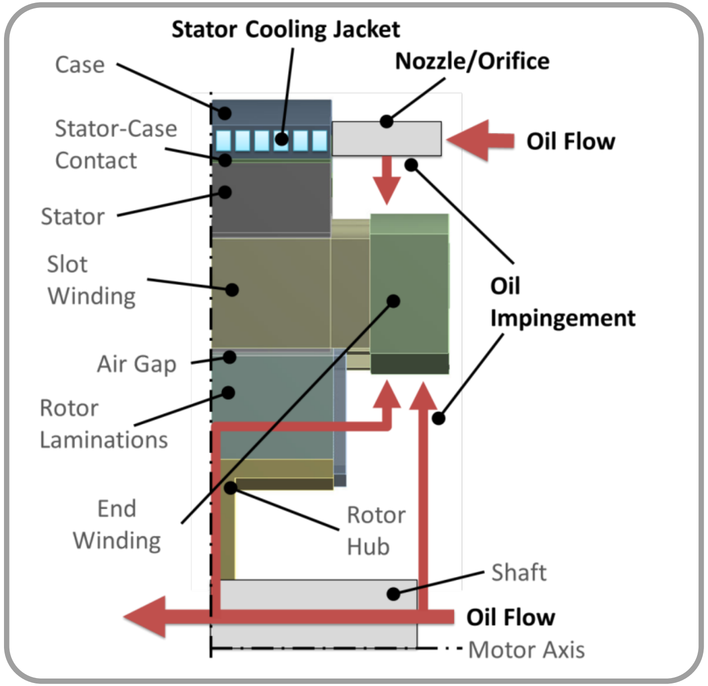
Power Electronics

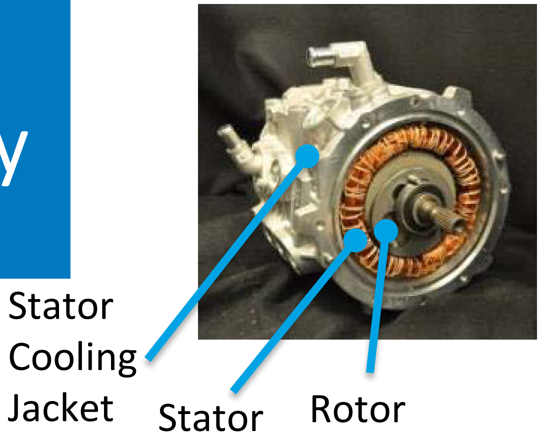


Electric Machines/Motors

Photo Credits: Gilbert Moreno, Doug DeVoto, Emily Cousineau, Kevin Bennion, Bidzina Kekelia , NREL

Motor Heat Transfer for Increased Motor Power Density and Reliability



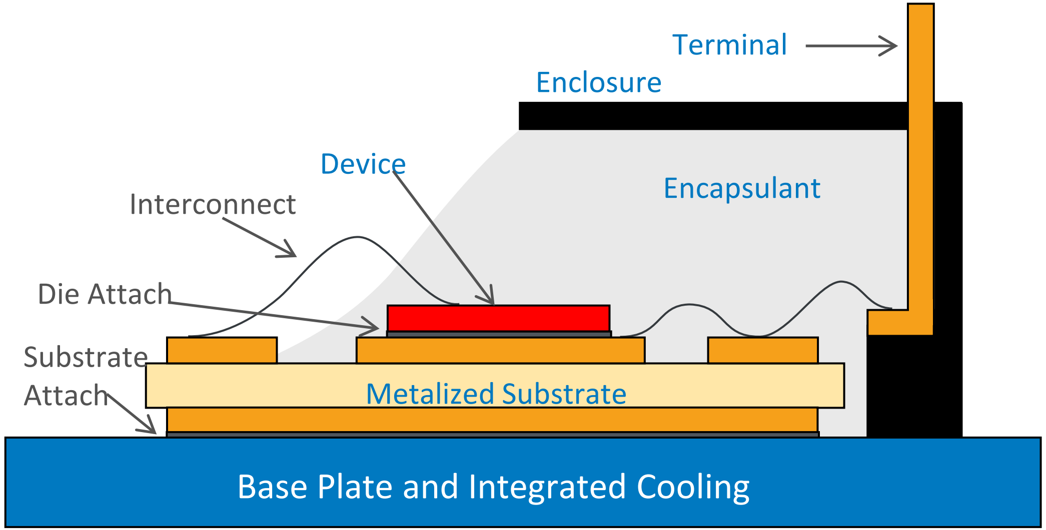


- Increase current density
- Understand material properties over temperature and life
- Research material impacts on advanced cooling
- Enable higher voltages and switching frequencies

Photo Credits: Kevin Bennion, NREL

Advanced Heat Transfer Enables Increased Power Density and Higher Operating Temperatures

- Higher-temperature rated components and advanced heat transfer
- High-temperature interface materials capable of joining dissimilar materials (different CTE)
- Predictive lifetime models



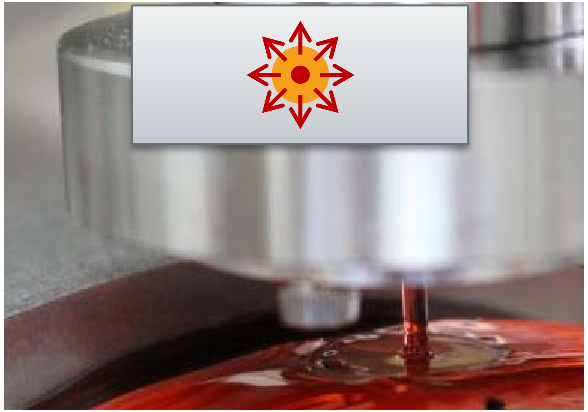
CTE: coefficient of thermal expansion

Electric Machine/Motor Example Research

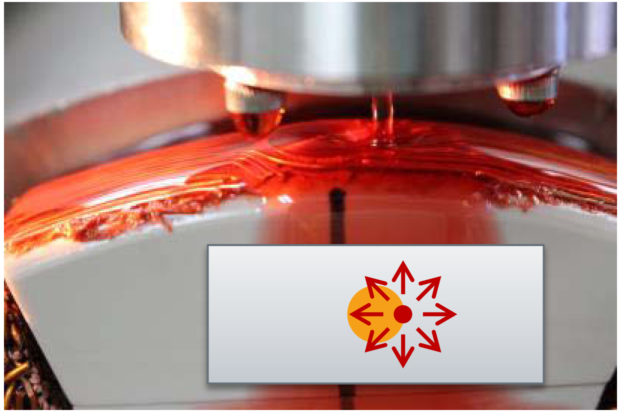
Transmission fluid cooling of motors

Direct Automatic Transmission Fluid (ATF) Cooling of Windings

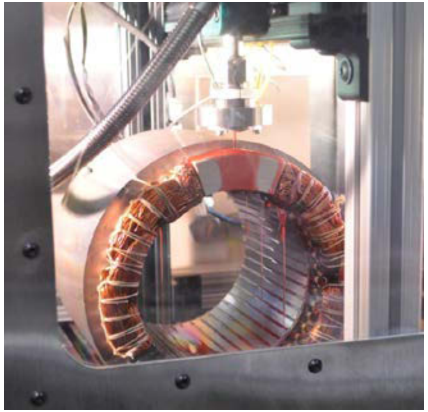
- Measuring heat transfer variation along winding
- Quantifying impact of new or alternative cooling approaches for ATF cooling of motors to take advantage of new motor materials



Orifice Jet Center Impingement



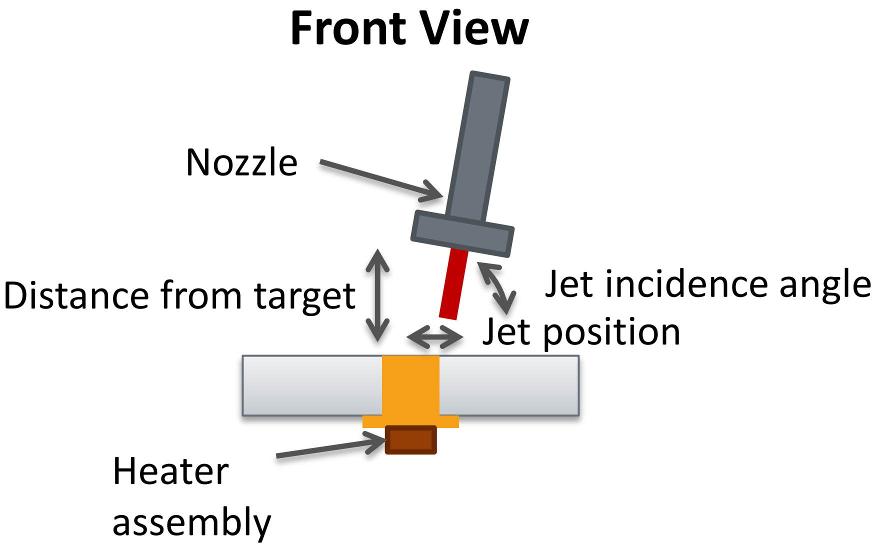
Orifice Jet Edge Impingement



Test Enclosure

Photo Credits: Bidzina Kekelia and Kevin Bennion, NREL

Measurement Method



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

$h = heat\ transfer\ coefficient$

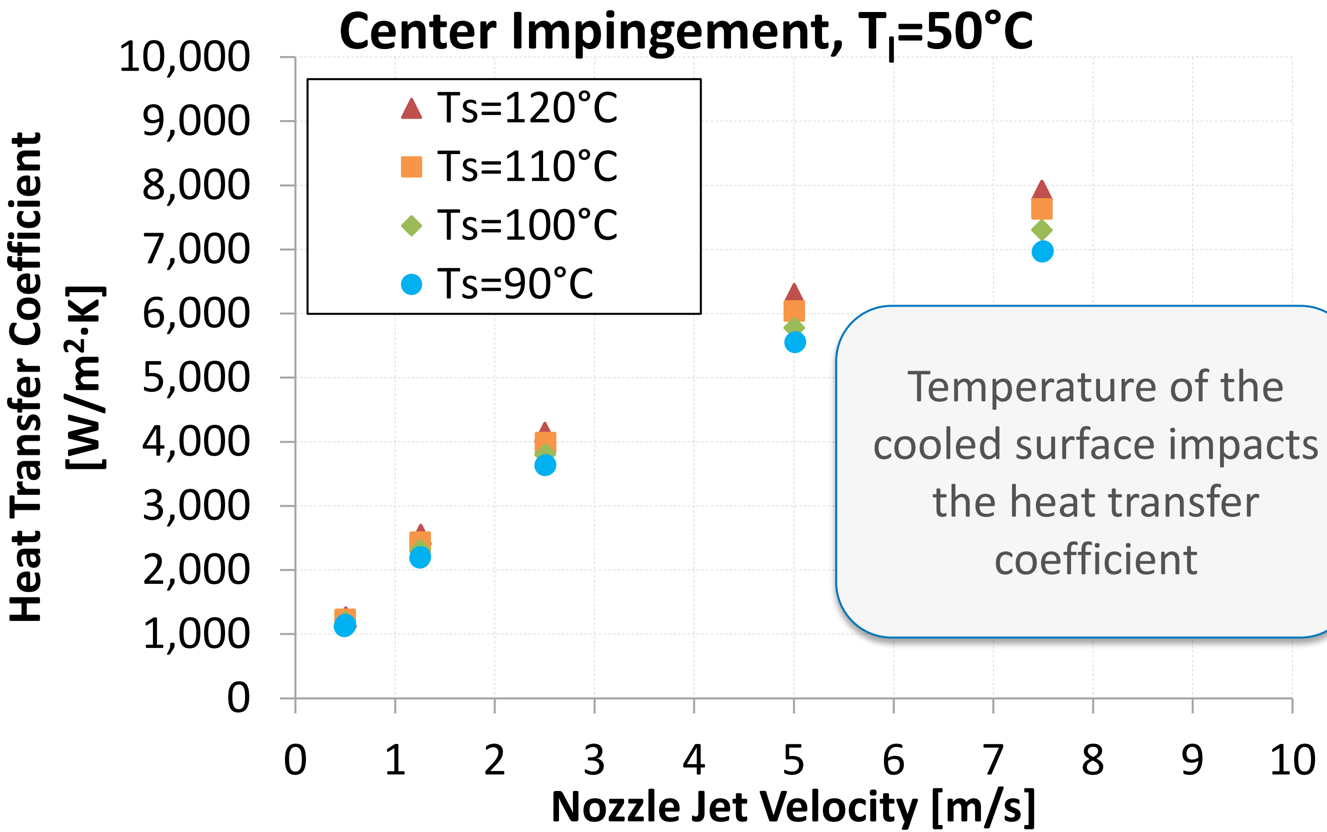
$q_s = heat\ removed\ from\ target\ surface$

$A_s = Area\ of\ target\ surface$

$T_s = Target\ surface\ temperature$

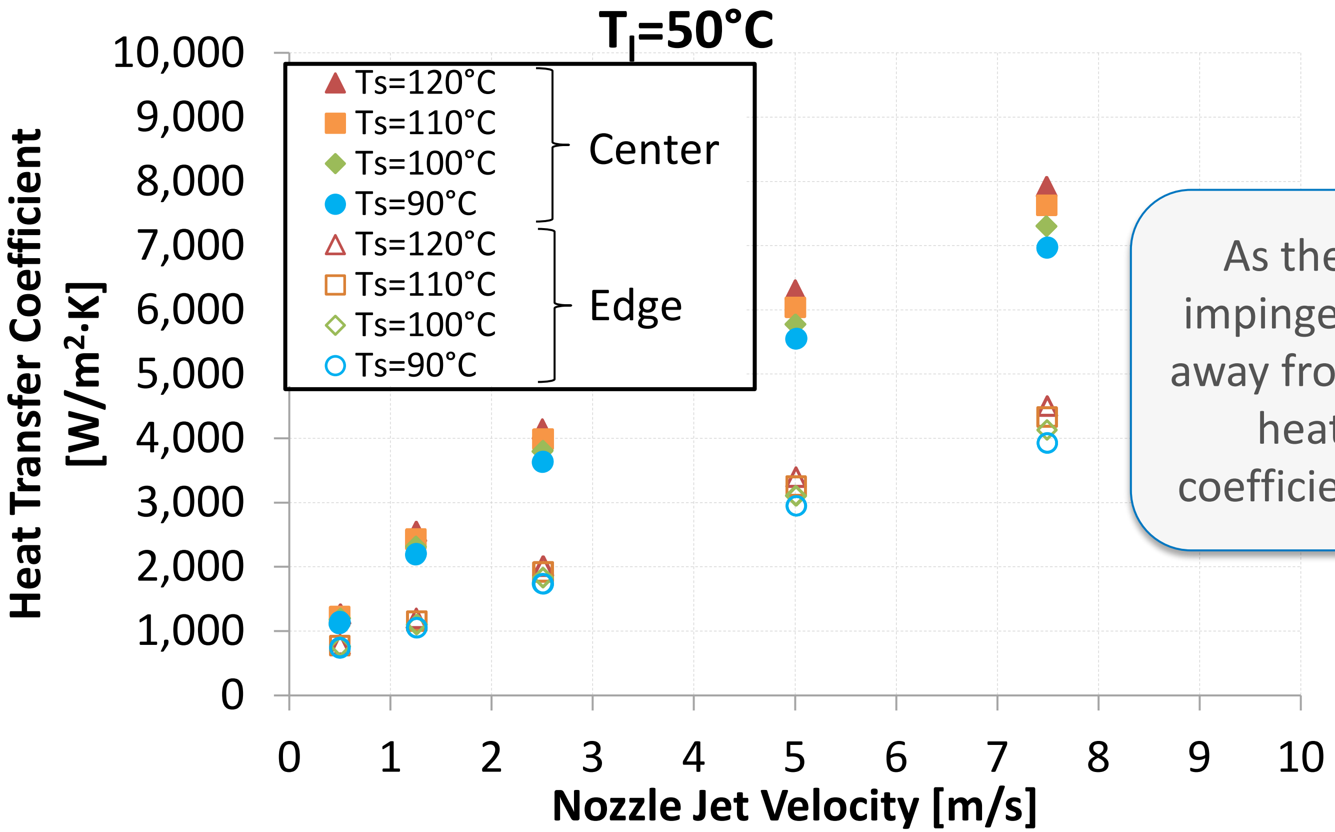
$T_l = Fluid\ or\ liquid\ temperature$

Heat Transfer Comparison



Temperature of the cooled surface impacts the heat transfer coefficient

Heat Transfer Comparison



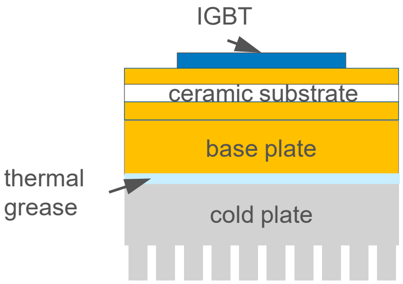
As the orifice jet impingement moves away from center, the heat transfer coefficient decreases

Power Electronics Example Research

Inverter oil cooling

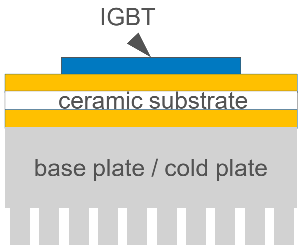
Automotive Power Electronics Cooling Trend

cold plate cooled

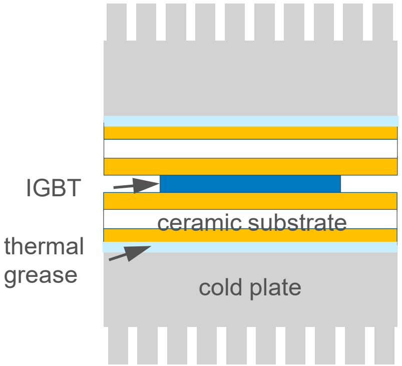


IGBT: insulated gate bipolar transistor

base plate cooled

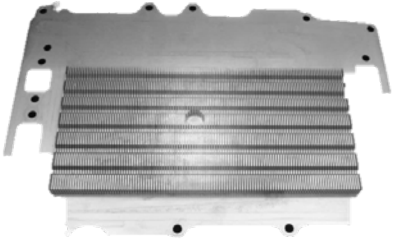


double-side cooled

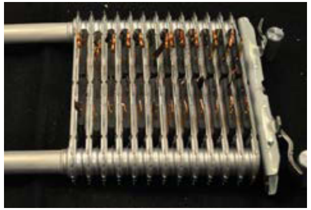


Note: the automotive modules below may be slightly different from the above schematics

2012 Nissan LEAF



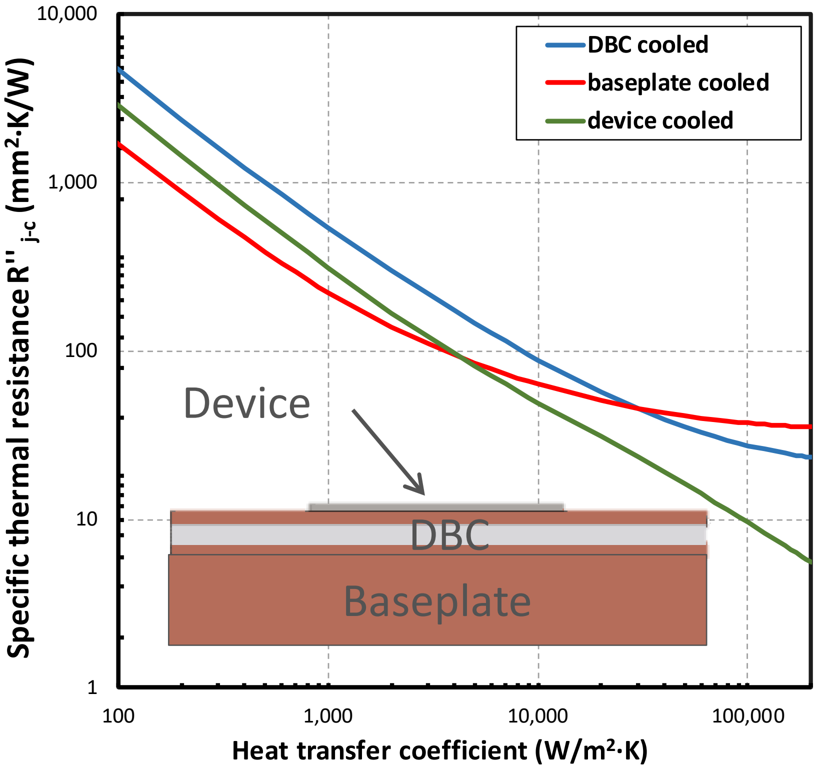
2014 Honda Accord Hybrid



2012 Camry Hybrid (2016 Prius is similar)

Photo Credits: Gilbert Moreno, NREL

Device Cooling



Device cooling

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

Electrical leads in the 2015 BMWi3 power module

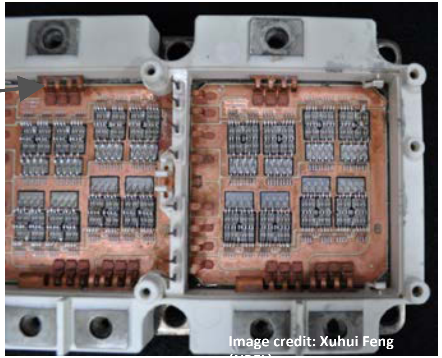
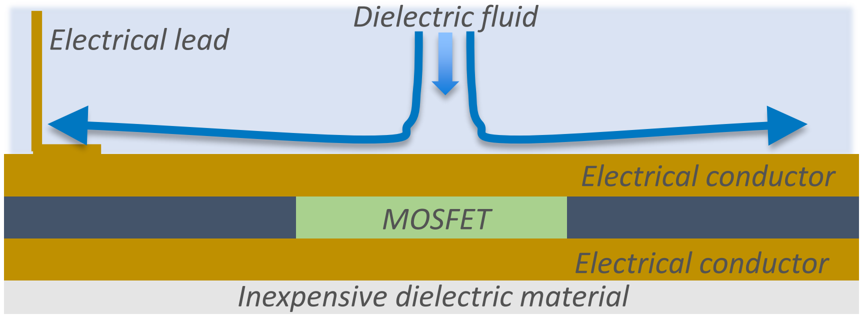


Photo Credits: Xuhui Feng, NREL

DBC: direct bond copper

Direct Cooling Approach



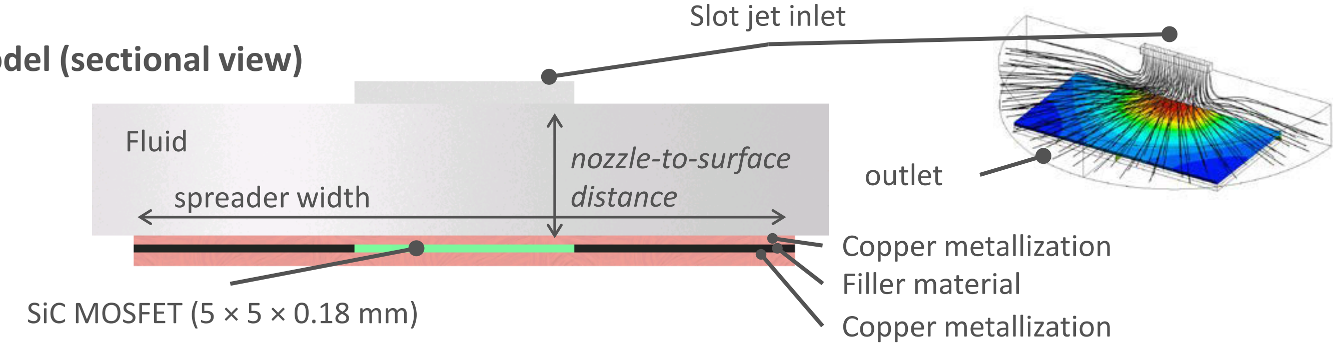
Dielectric cooling of planar package

- Propose a single-phase cooling approach
  - ✓ Easier to seal (compared to two-phase system)
  - ✓ Potential to use 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

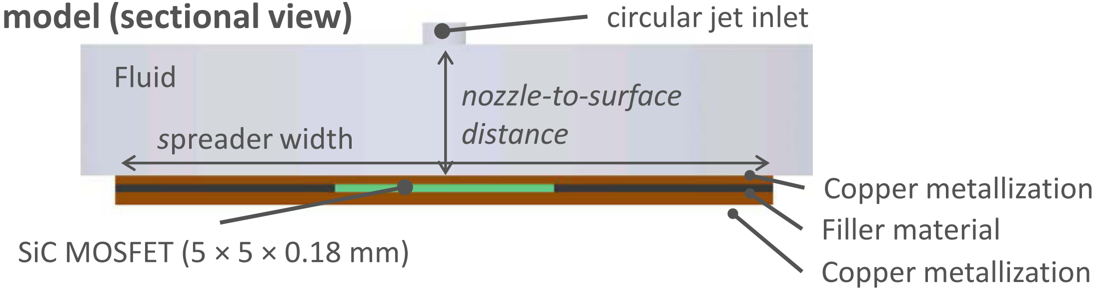
MOSFET: metal–oxide–semiconductor field-effect transistor

Jet Impingement Model

Slot jet model (sectional view)



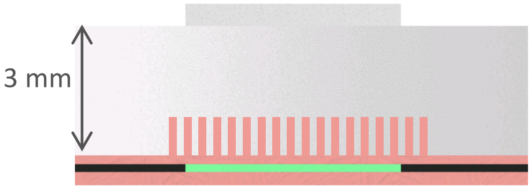
Circular jet model (sectional view)



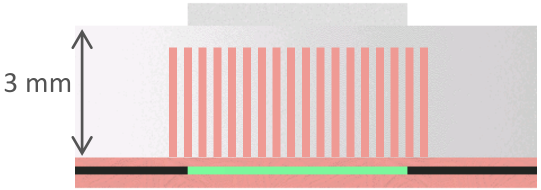
Finned Heat Spreader Concept

side views

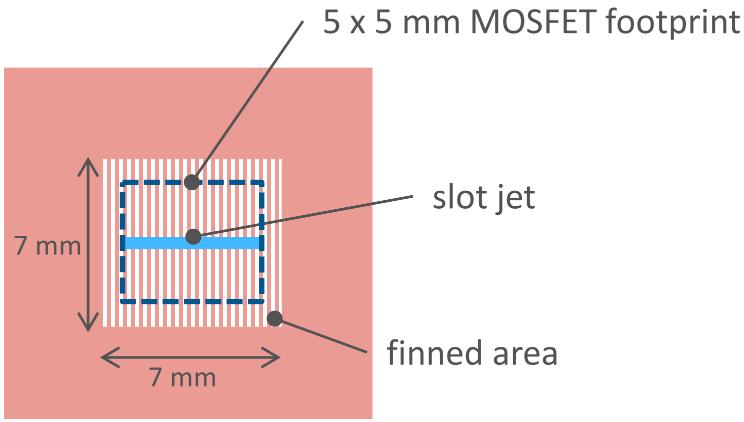
1-mm-tall fins



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

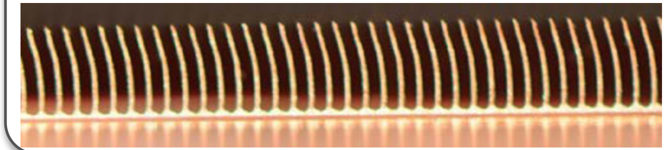
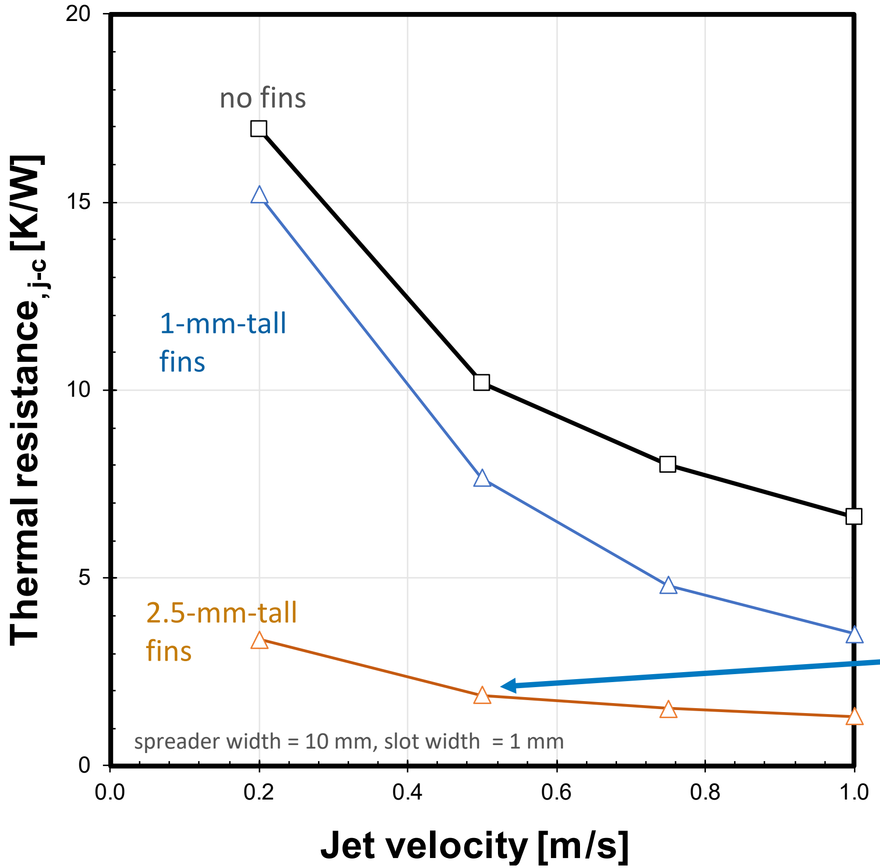


Photo Credits: Gilbert Moreno, NREL

Effect of Fins: Slot Jet



- Reduced thermal resistance by ~80% using finned surfaces
- 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.

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

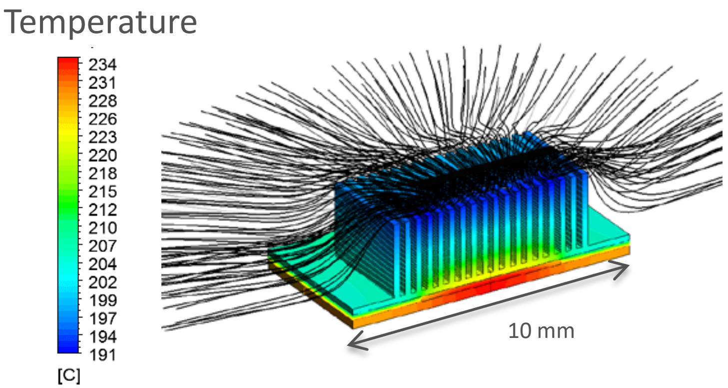
✓ Volume: 0.06 liters ($^1/_4$ of the volume available for the power module and cold plate)

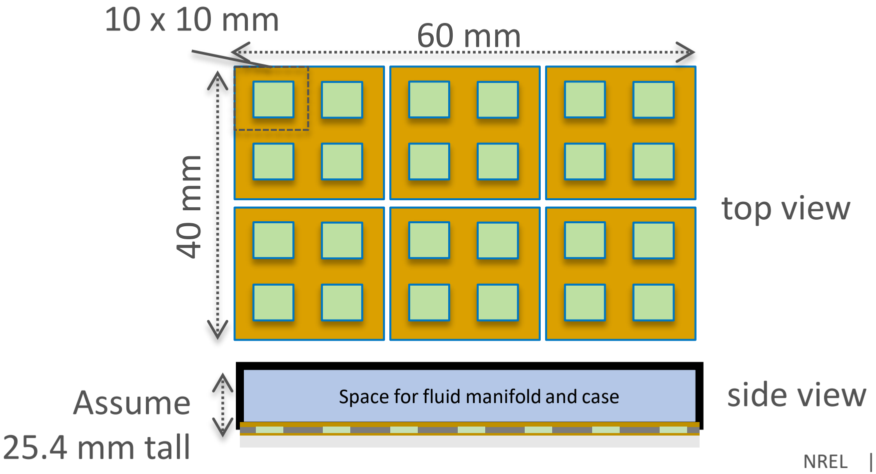
✓ Flow rate requirements: 3.6 LPM (at this flow rate, the outlet fluid temperature is predicted to be 82.4°C)

CFD: computational fluid dynamics

CFD temperature contours (sectional view)

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





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
- Develop methods to cool the electrical connections using dielectric fluid
- Evaluate approaches for integrating power electronics and motor with integrated cooling system

Acknowledgments

Susan Rogers, U.S. Department of Energy

NREL Team Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov

Phone: (303)-275-4062

Team Members

Kevin Bennion, Emily Cousineau,
Doug DeVoto, Xuhui Feng, Bidzina Kekelia,
Ramchandra Kotecha, Joshua Major,
Gilbert Moreno, Paul Paret, Jeff Tomerlin

Thank You

www.nrel.gov

NREL/PR-5400-72325

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

NREL Transforming ENERGY