Power Electronics Thermal Management

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DOE Vehicle Technologies Program
2020 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT211

Overview

Timeline

- Project start date: FY 2019
- Project end date: FY 2023
- Percent complete: 30%

Budget

- Total project funding
  - DOE share: $700K
- Funding for FY 2019: $350K
- Funding for FY 2020: $350K

Barriers

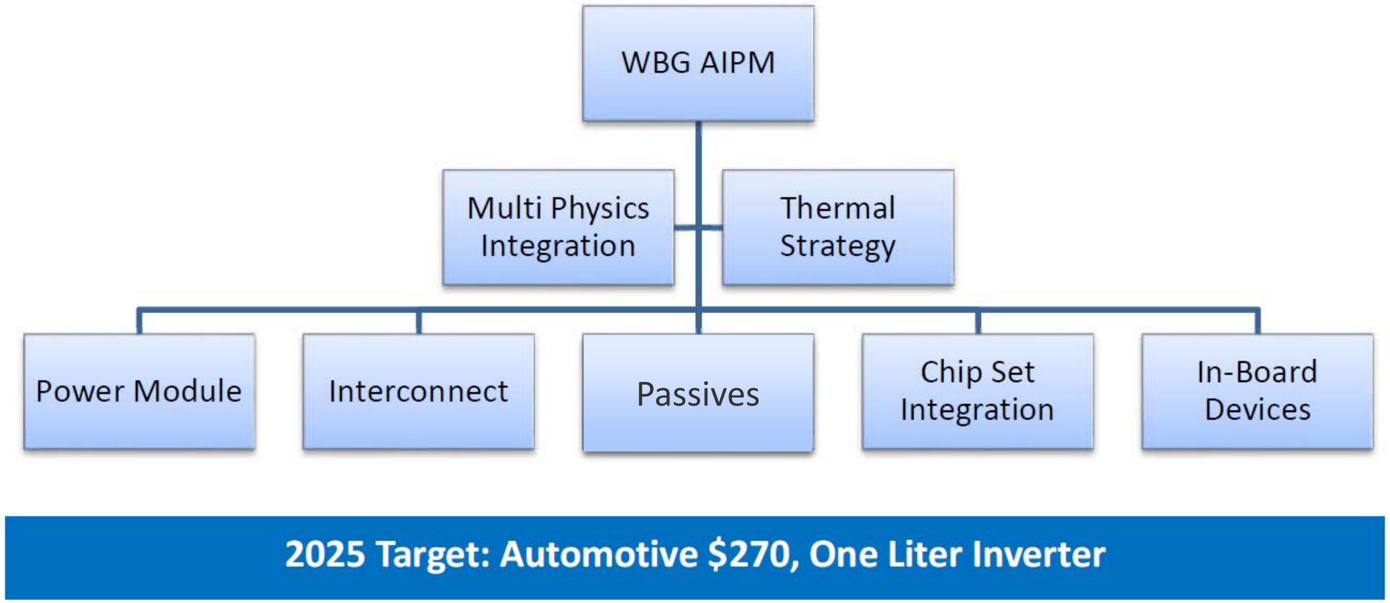
- Size and weight
- Cost
- Performance and lifetime

Partners

- John Deere
- Dielectric fluid manufacturers
- Oak Ridge National Laboratory (ORNL)
- Georgia Tech University (GT)
- Project Lead – National Renewable Energy Laboratory (NREL)

Relevance

- Thermal management is essential to increase power density and reliability.
- **Objective:** Develop thermal management techniques to enable achieving the (year 2025) DOE 100 kW/L power density target.
    - Challenge is to create a thermal solution that allows for packaging high temperature (250°C) and high heat flux wide-bandgap (WBG) devices next to capacitors that typically cannot exceed 100°C.



From 2017 Electrical and Electronics Technical Team Roadmap

AIPM: advanced integrated power module

Milestones/Approach

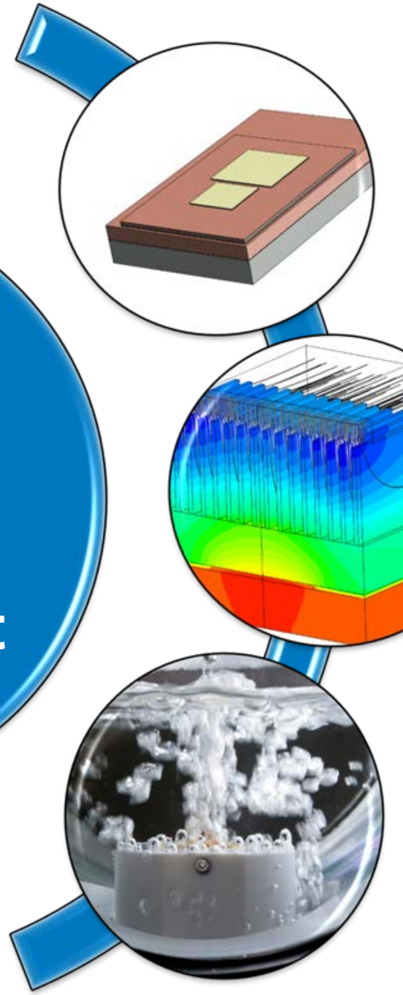
Date	Description of Milestone or Go/No-Go Decision
March 2020 (*complete*)	**Milestone:** Completed experiments to characterize the thermal performance of the dielectric-fluid-based heat exchangers (single-side cooled). Evaluated the effects of the dielectric fluid temperature and flow rate on thermal performance and pumping power.
June 2020 (*in progress*)	Design a double-side cooled, dielectric fluid heat exchanger to improve performance (beyond the single-side cooled design).
September 2020 (*in progress*)	Conduct experiments to measure the thermal performance and pumping power of the dielectric fluid heat exchanger using other dielectric fluids (AC-100) and automatic transmission fluids (ATFs) at various fluid temperatures and flow rates.

Overall Approach

Thermal strategy to reach a power density of 100 kW/L

Define the thermal target to achieve 100 kW/L

Design the cooling strategies to achieve the thermal target



Device packaging

Convective cooling

Fluid selection

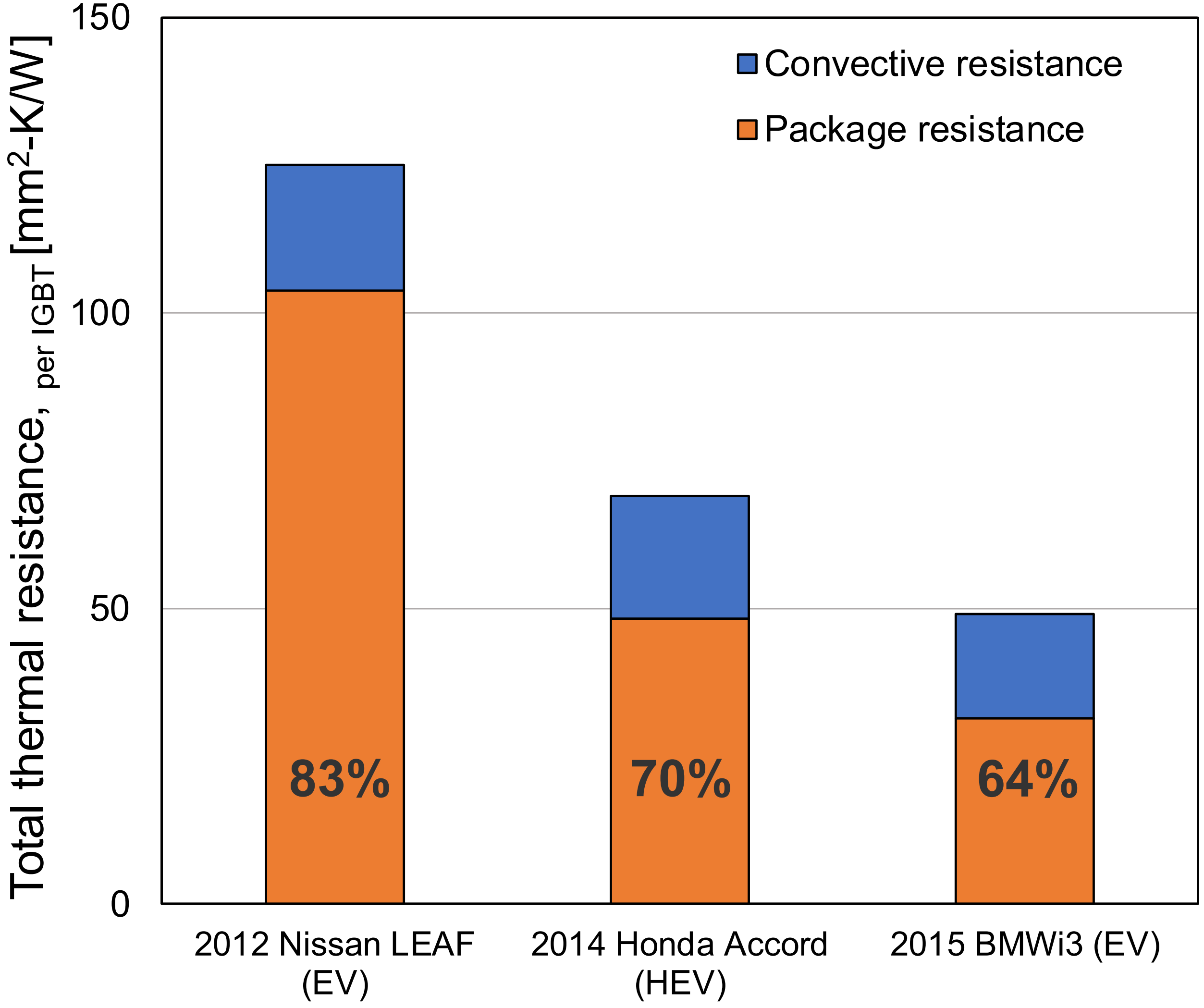
Photo Credit: Gilbert Moreno (NREL)

Estimated heat load (100 kW WBG inverter): 2,150 W
Maximum device temperature: 250°C
Module and cold plate volume: <240 mL

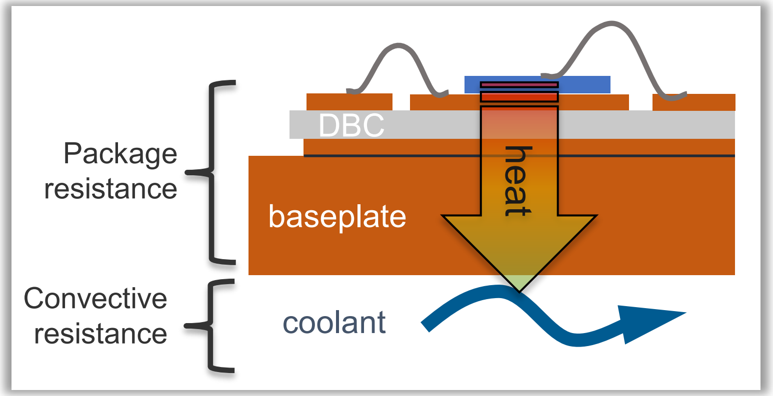
Volumetric thermal resistance target: <21 $cm^3 \cdot K/W$

Dielectric-fluid cooling (single-phase heat transfer) planar package concept

Thermal Design Approach



- Reduce the total thermal resistance by reducing the package thermal resistance. Package resistance (~60% to 80% of total) in conventional modules.
- Dielectric fluids enable a package **redesign to decrease the package resistance** (the dominant thermal resistance).
- **Potential to use ATF or other new driveline fluids** as the coolants.

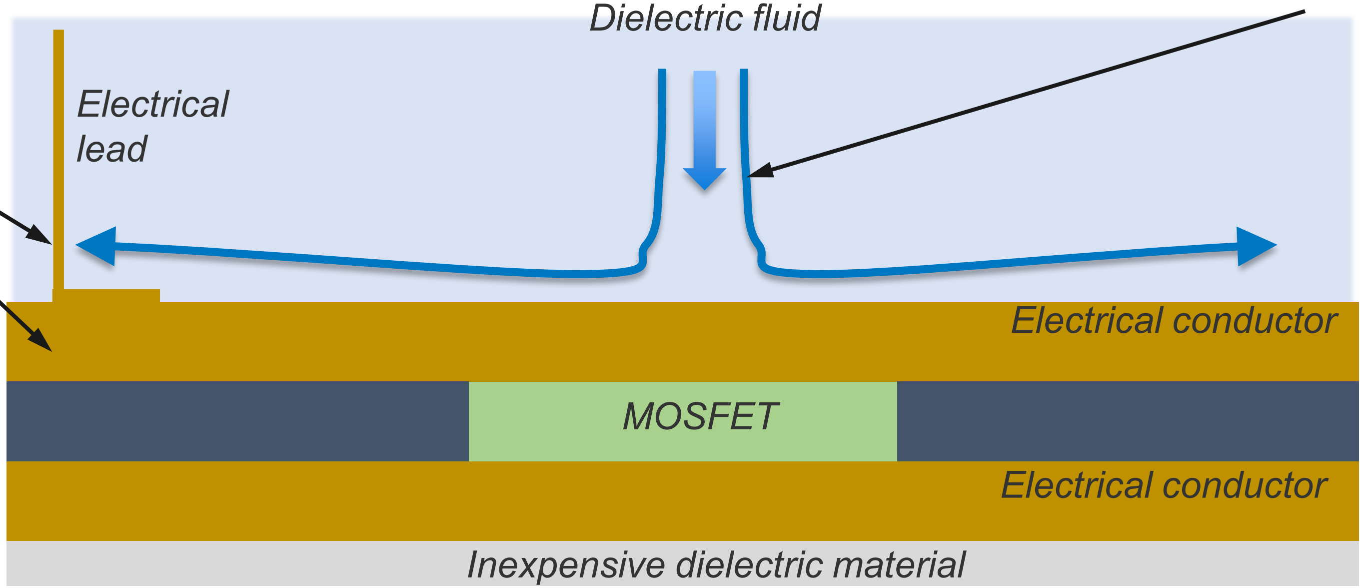


HEV: hybrid electric vehicle; EV: electric vehicle; DBC: direct-bond copper

Thermal Design Approach: Dielectric-Fluid Cooling Concept

Allows for cooling of the bus bars/electrical interconnects to lower capacitor and gate driver temperatures

Improved cooling (single-phase heat transfer) via jet impingement and finned surfaces



Eliminates expensive ceramic materials

Improves thermal performance over conventional DBC-based designs

- Reduced package/conduction resistance to 33% of total thermal resistance using a relatively high convection coefficient (17,300 W/[m^2·K])
- Designed single-side and double-side dielectric-fluid cooling concepts.

MOSFET*:* metal–oxide–semiconductor field-effect transistor

Thermal Design Approach: Project Tasks

1. Identified potential dielectric fluids (single-phase heat transfer)

Alpha 6, AC-100, and ATF fluid properties provided in Technical Back-Up Slide Section

2. Designed a jet impingement, dielectric fluid, single-side cooling system

3. Conducted experiments and validated model (single-side cooled system)

4. Modeled different fluids to compare performance at different temperatures

5. Designing a double-side cooled, dielectric-fluid cooling system

High heat flux heat exchanger

Enable reaching 100 kW/L power density

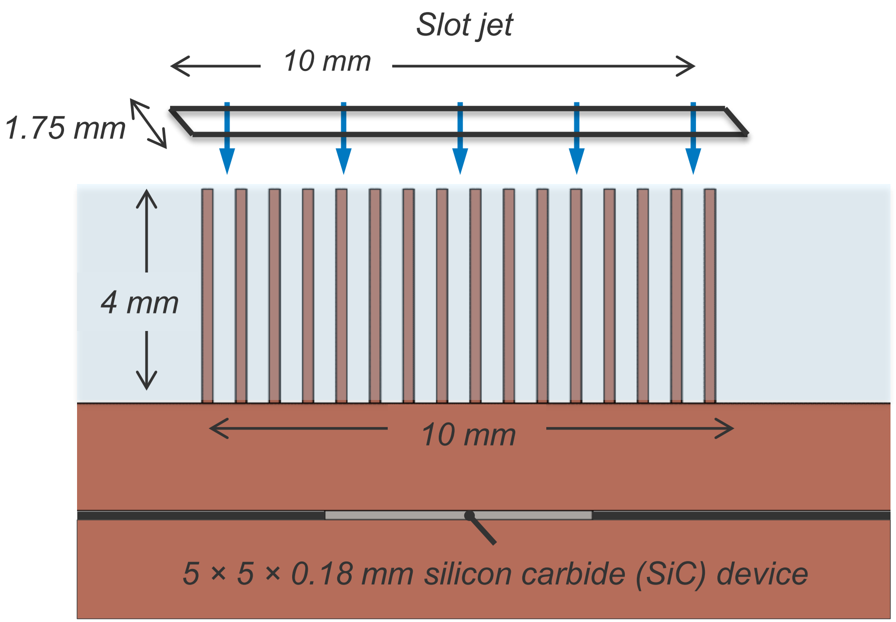
Work presented 2019 AMR

Current work

Conceptual Dielectric Fluid Cooling System (Single-Side Cooled Version)

Achieved high thermal performance

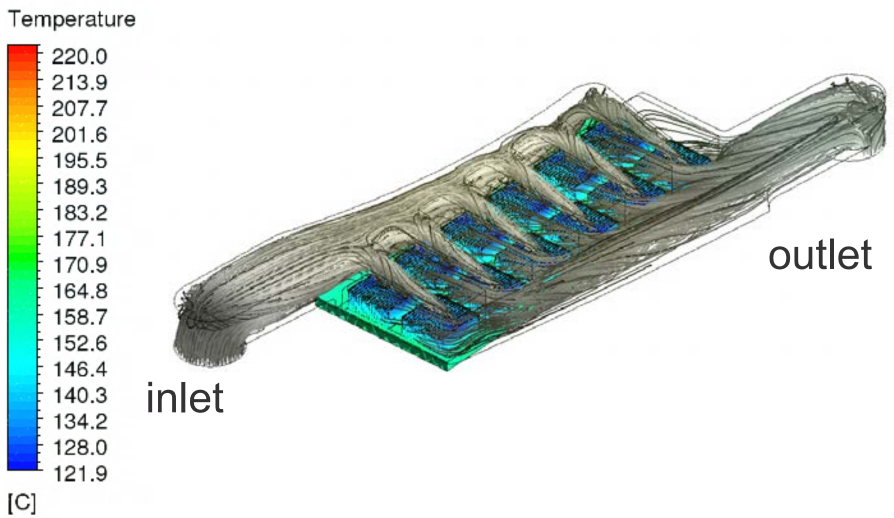
- Heat transfer coefficient 17,300 W/(m^2·K) at a relatively low jet velocity of 0.3 m/s
- **22 mm^2·K/W junction-to-fluid thermal resistance (per device)**



Planar module, dielectric cooling concept

Compact size

- Achieved **120 mL total volume** for conceptual 12-device module and heat exchanger
- Requires 4.1 L/min total flow rate
- Predict we can dissipate 2.2 kW with 12 devices. Results in a $T_j \approx$ 220°C at a **heat flux ~716 W/cm²**
- Compute **9 cm^3·K/W total resistance**, outperforms/lower than resistance target of 21 cm^3·K/W



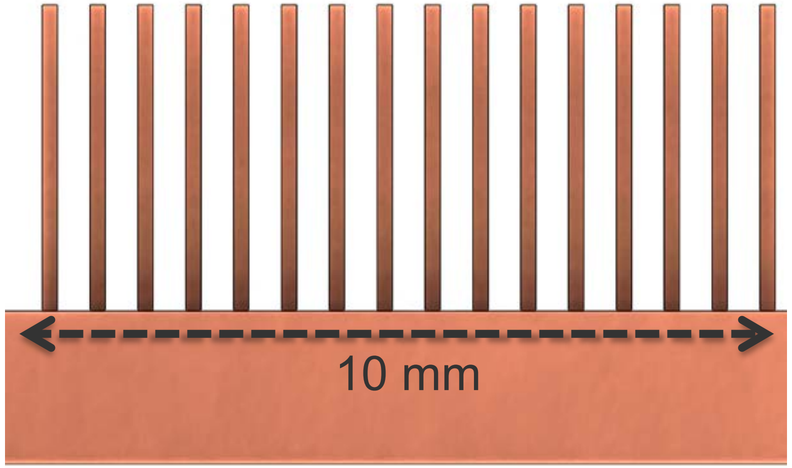
Conceptual power module with dielectric-fluid cooling system (PROV/19-69. Application No. 62/927,252). Results using Alpha 6 fluid at T_{inlet} = 65°C.

Moreno, G. et al., "High-Heat Flux, Dielectric-Fluid Cooling Method for Power Electronics." PROV/19-69. Application No. 62/927,252.

Experimental Validation: Fabricated the Finned Heat Spreaders

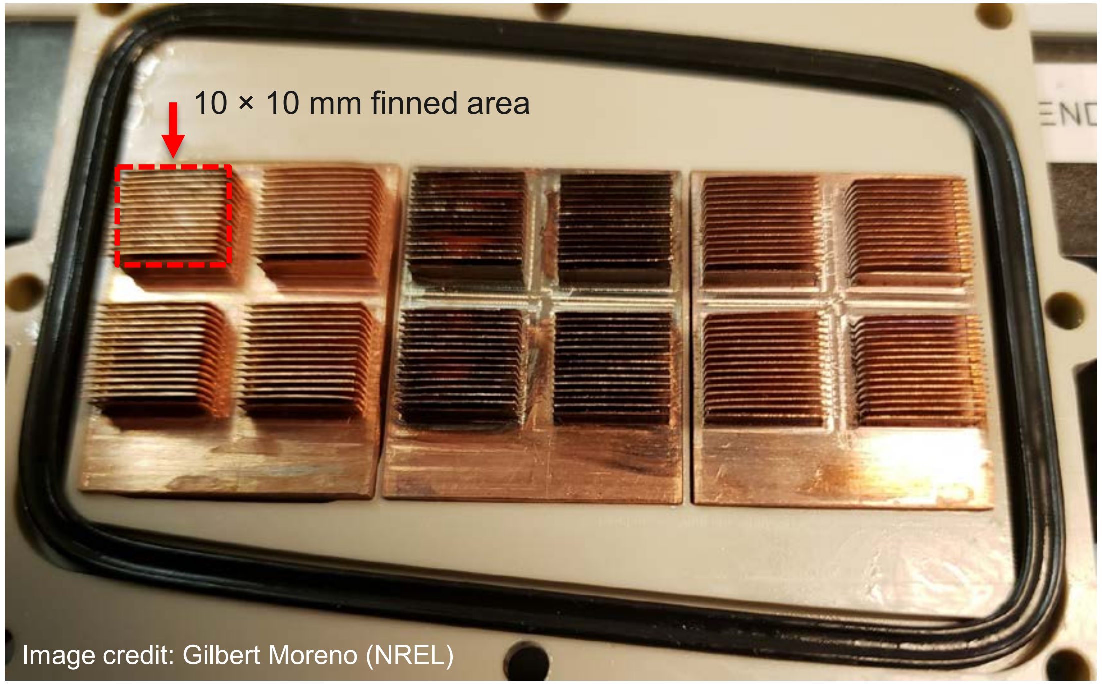
As modeled:
16 fins total (per device)
thickness = 0.2 mm
height = 4 mm
channels = 0.43 mm

Modeled



Measured:
15 fins total (per device)
thickness ≈ 0.25 mm
height ≈ 4 mm
channels ≈ 0.4 mm

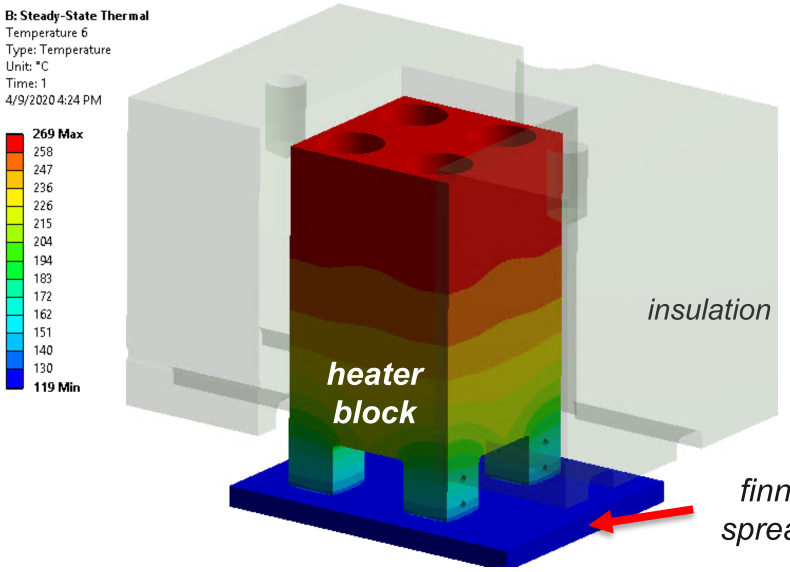
Actual

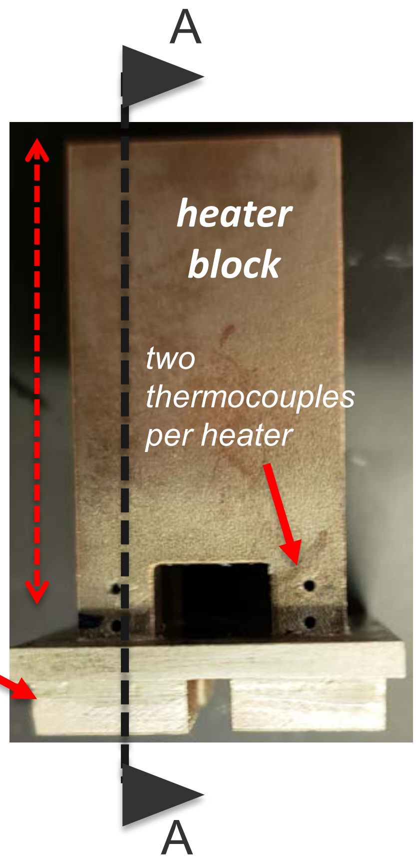


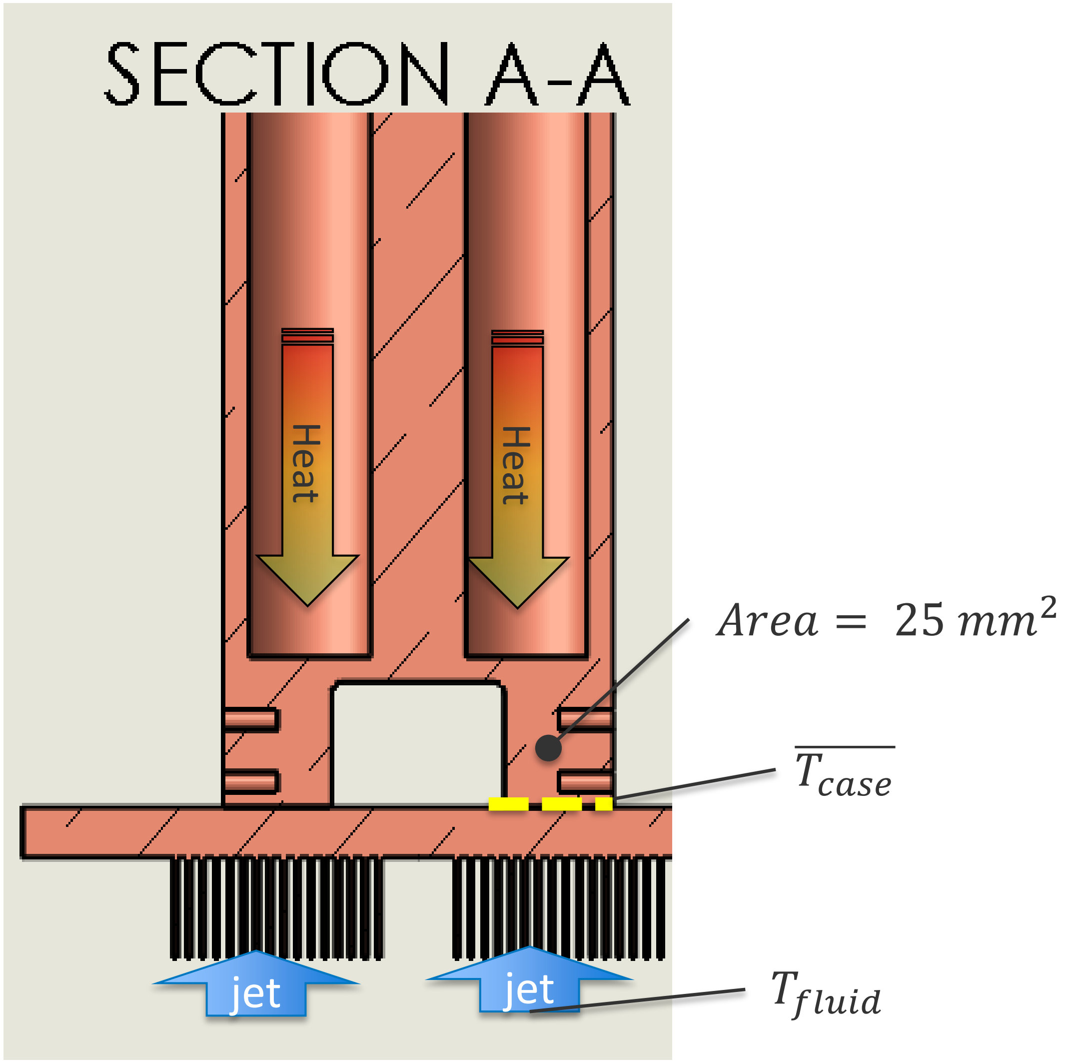
Finned heat spreaders mounted to plastic housing (PROV/19-69. Application No. 62/927,252). Twelve finned areas are directly above each device.

Moreno, G. et al., "High-Heat Flux, Dielectric-Fluid Cooling Method for Power Electronics." PROV/19-69. Application No. 62/927,252.

Experimental Validation: Completed the Heater Design





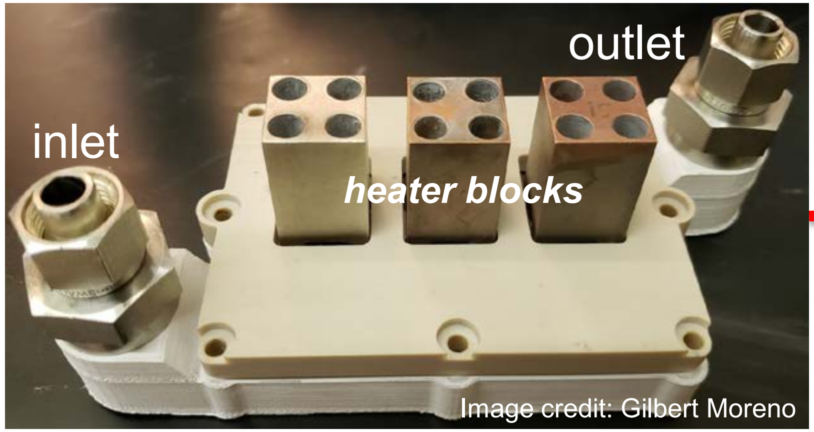


- Designed a cartridge heater system to simulate the 12 SiC devices.
- Heater blocks are soldered to finned heat spreaders.
- Measured the heat exchanger (case-to-fluid) thermal resistance.

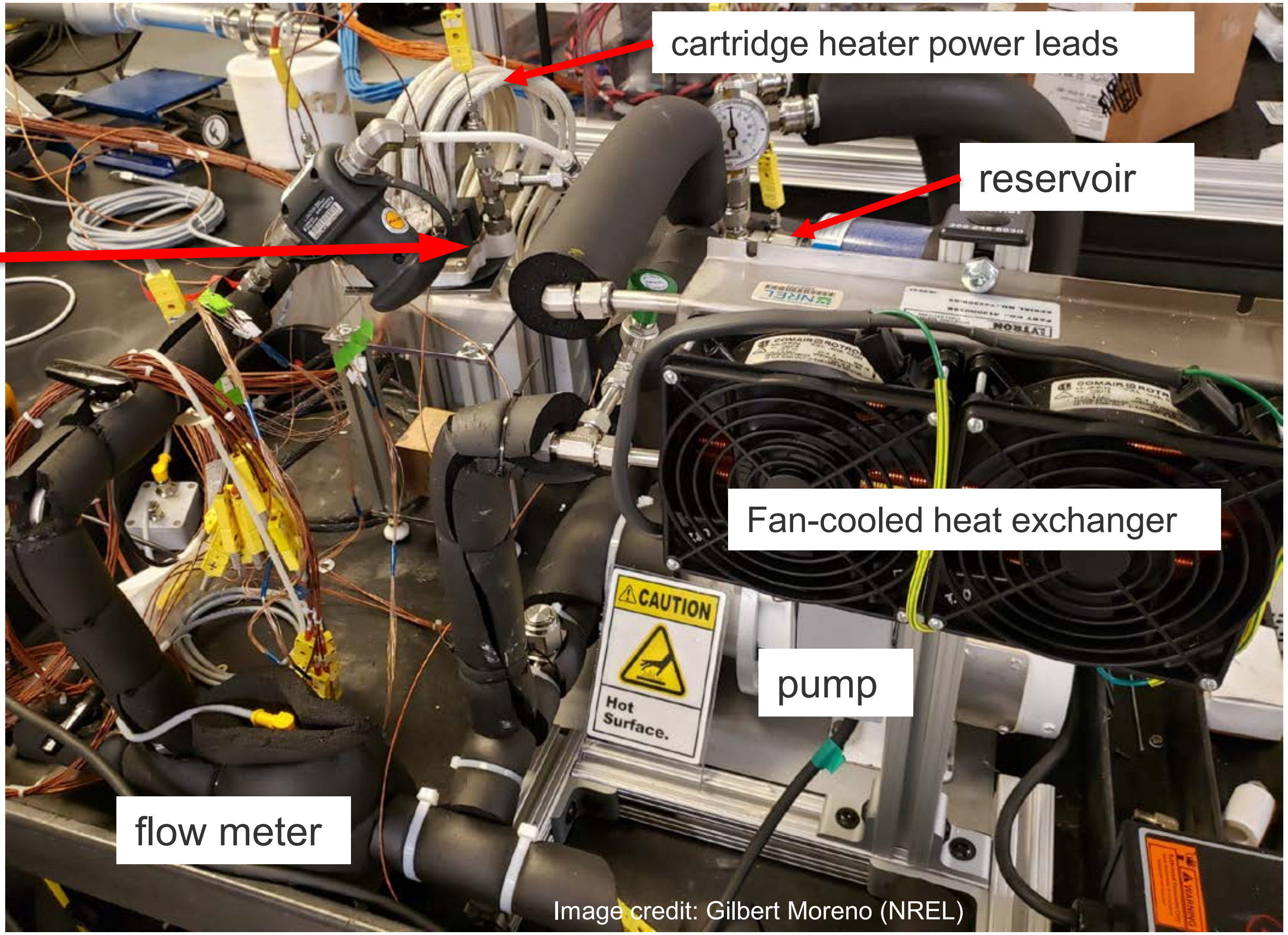
$$R''_{th,\,case-fluid} = \frac{Area\left(\overline{T_{case}} - T_{fluid}\right)}{Heat_{per\ heater,\,device}}$$

Experimental Validation: Fabricated the Dielectric Fluid Loop

Technical Accomplishments

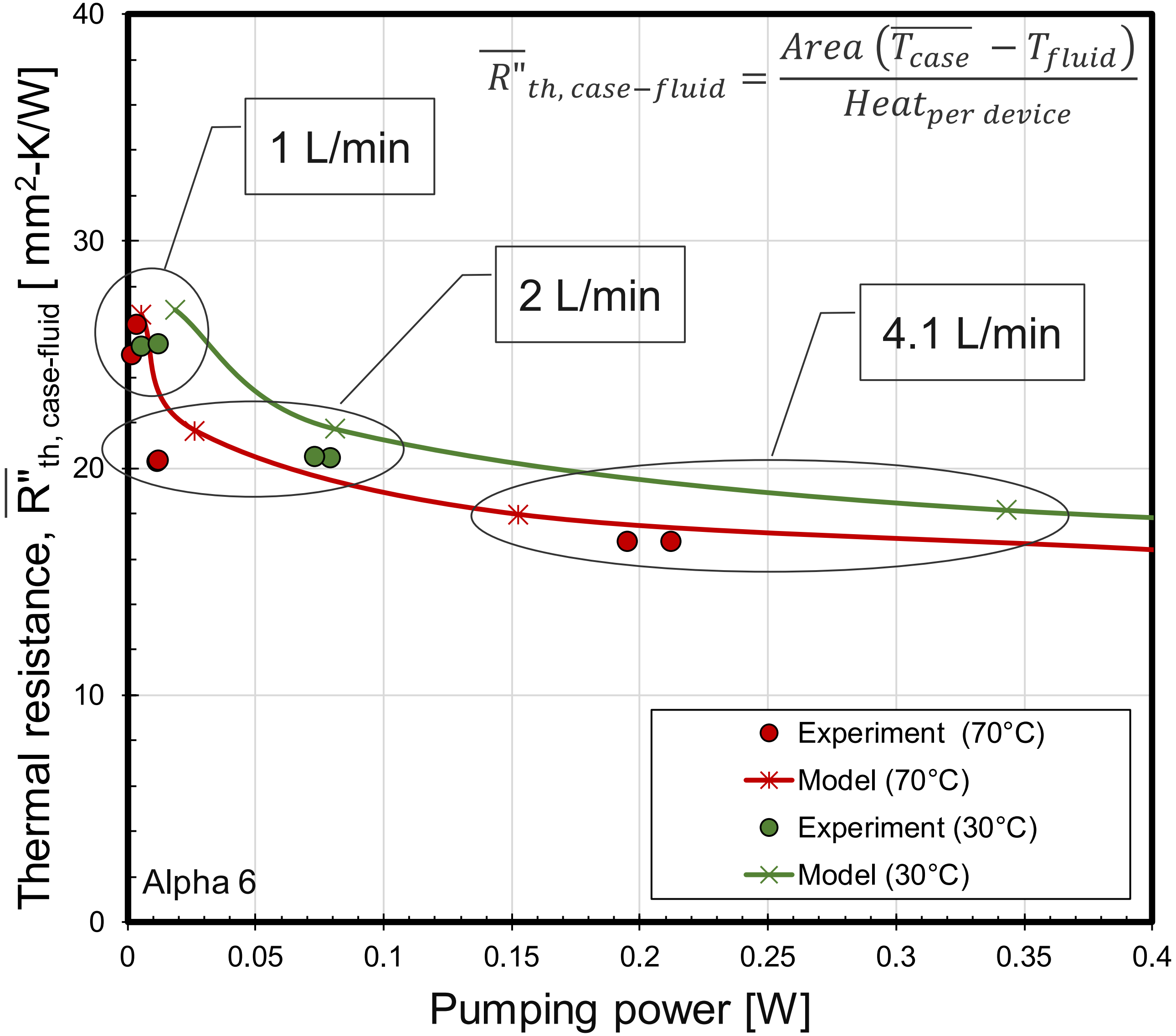


- Fabricated a polycarbonate prototype of the dielectric-fluid heat exchanger via 3D printing (cartridge heaters and insulation not shown).
- Completed fabrication of the dielectric fluid loop.
- Measured the heat exchanger (case-to-fluid) thermal resistance at various fluid flow rates and temperatures.



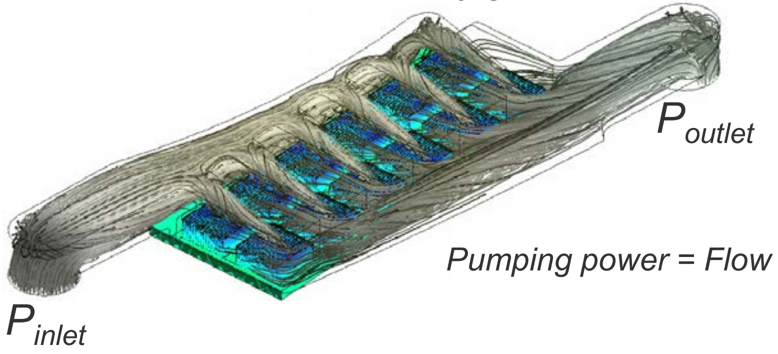
Dielectric fluid loop (schematic provided in Technical Back-Up Slides)

Experimental Results and Comparisons with Model



- Obtained a good match between experiments and model.
- Changing fluid temperature has minimal effect on thermal resistance but does affect pumping power.
- **Confirmed the heat exchanger low thermal resistance values. Provided confidence in model predictions.**

Model: inverter-scale, conjugate heat transfer CFD

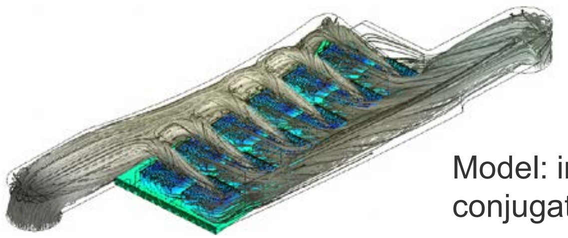


Pumping power = Flow rate × (P_{inlet} – P_{outlet})

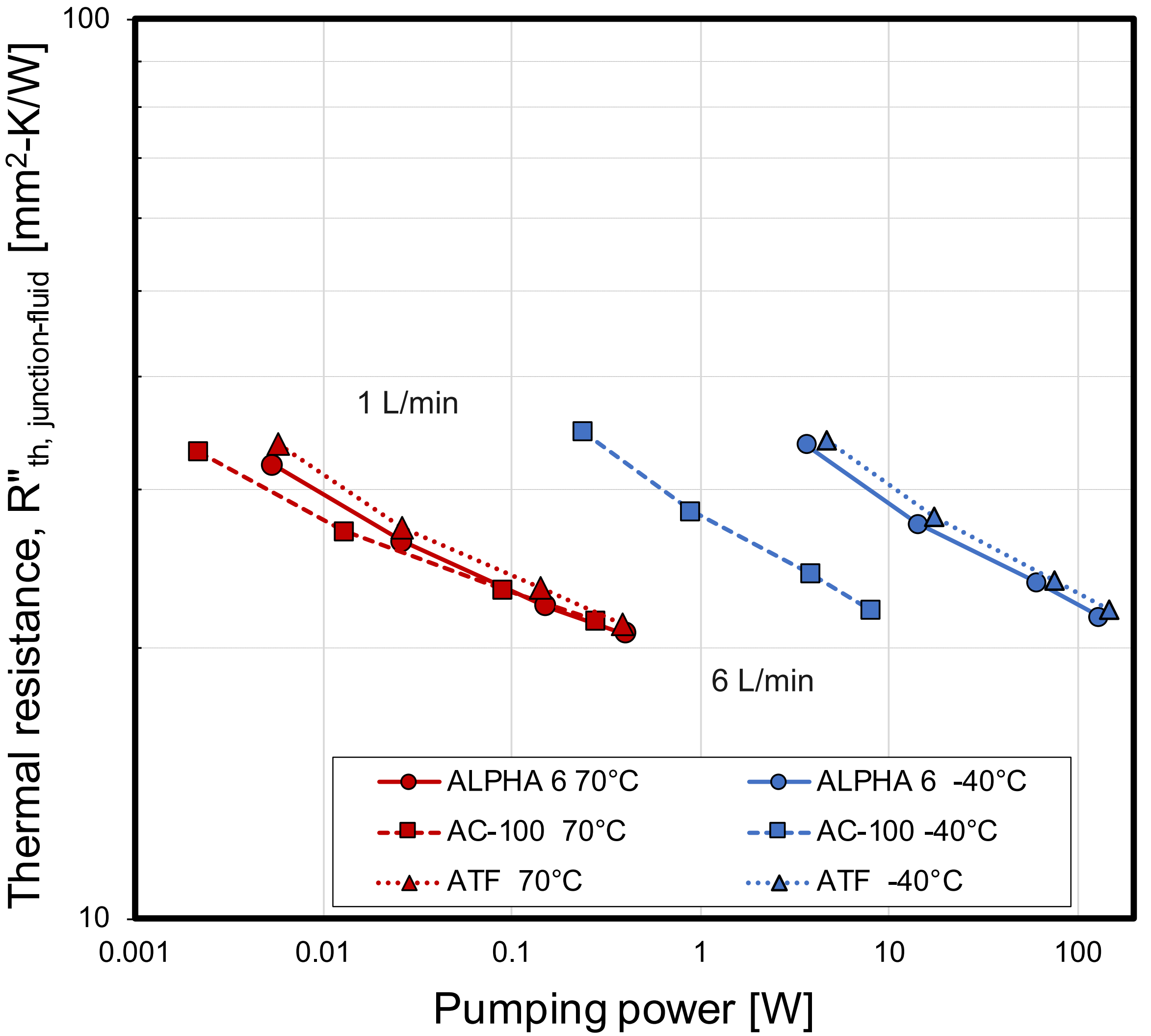
CFD: computation fluid dynamics

Compared Fluid Performance at Different Fluid Temperatures

- Modeled performance of Alpha 6, AC-100, and ATF at 70°C and −40°C fluid temperatures at different flow rates (1 L/min to 6 L/min).
- Changing fluids and varying temperatures has a minor effect on thermal resistance but has a big effect on pumping power when compared at the same flow rates.
- Predict ATF performance to be similar to Alpha 6 because they have similar properties.



Model: inverter-scale, conjugate heat transfer CFD

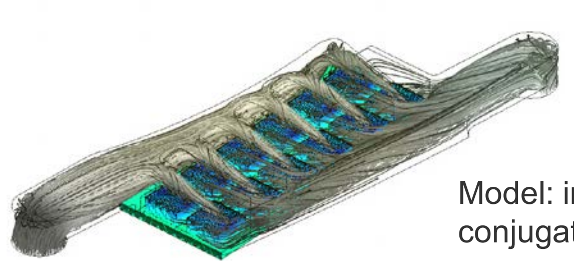


Data at all temperatures, including 30°C, are provided in Technical Back-Up Slides. The first data points correspond to 1 L/min, the last data points correspond to 6 L/min for all curves shown.

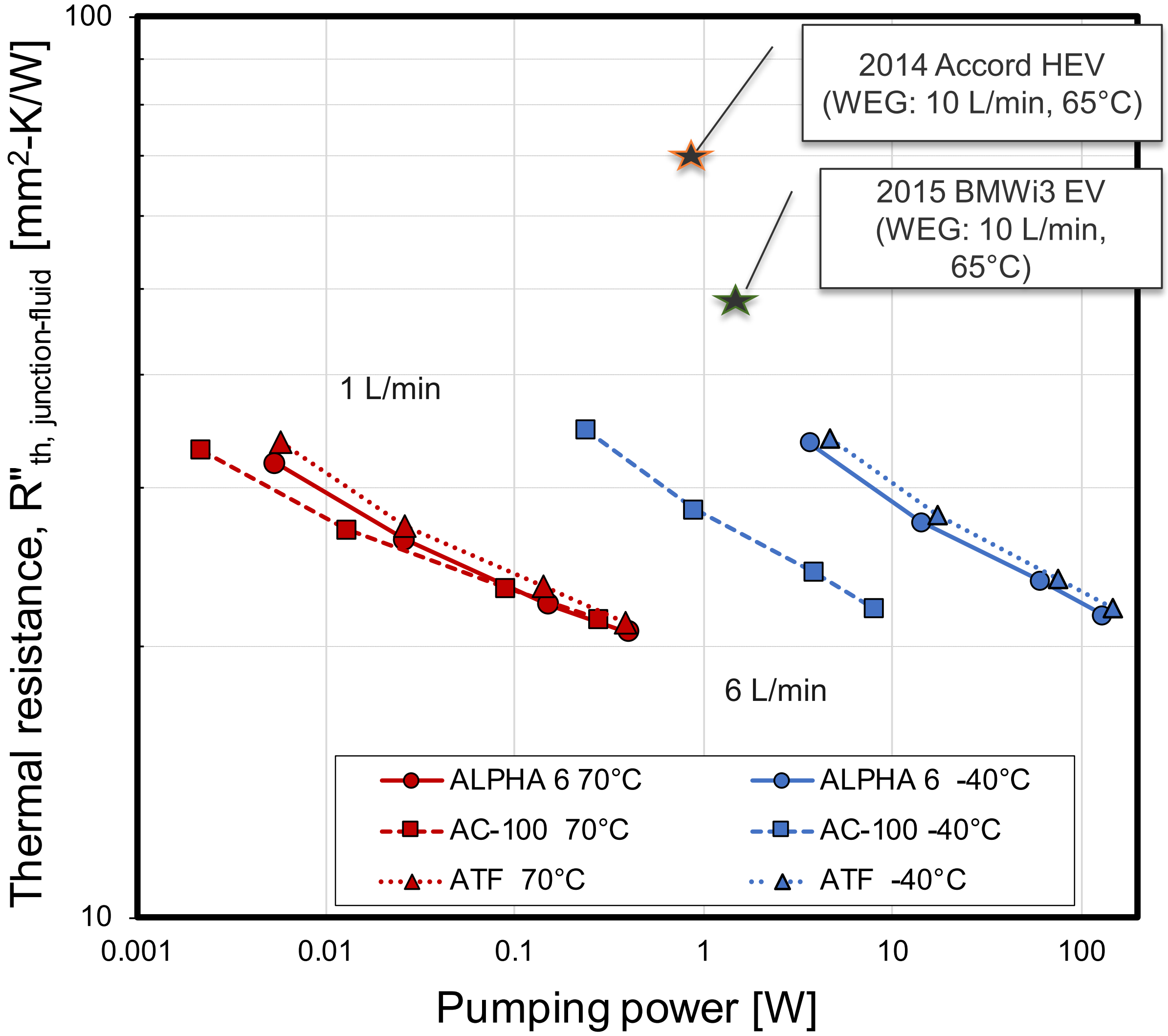
Compared Performance with Existing Automotive Systems

Technical Accomplishments

- Predict that all dielectric fluid cases provide lower thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV.
- AC-100 may be the best option due to its lower pumping power. **At −40°C, it's predicted to have a lower pumping power and thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV**.
- **Results indicate that higher viscosities at low temperatures may not be a problem if the correct fluid is chosen and coupled with a low pressure-drop system.**



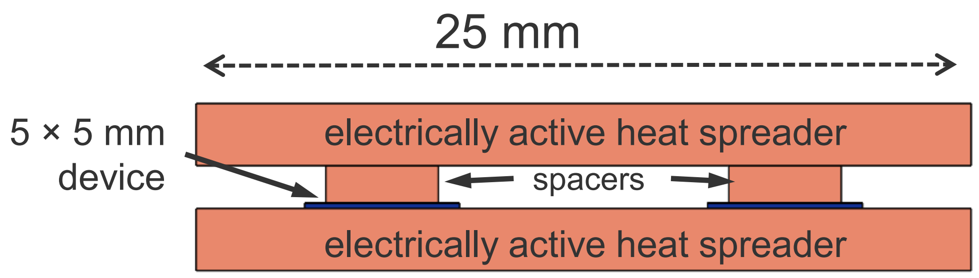
Model: inverter-scale, conjugate heat transfer CFD



Data at all temperatures, including 30°C, are provided in Technical Back-Up Slides. The first data points correspond to 1 L/min, the last data points correspond to 6 L/min for all curves shown.

Dielectric Fluid, Double-Side Cooled Module

Conceptual dielectric fluid, double-side cooled module



2013 Camry HEV module

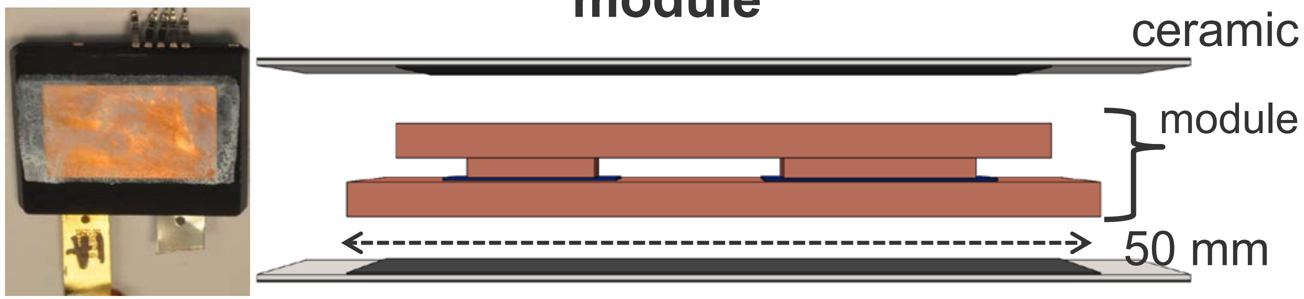
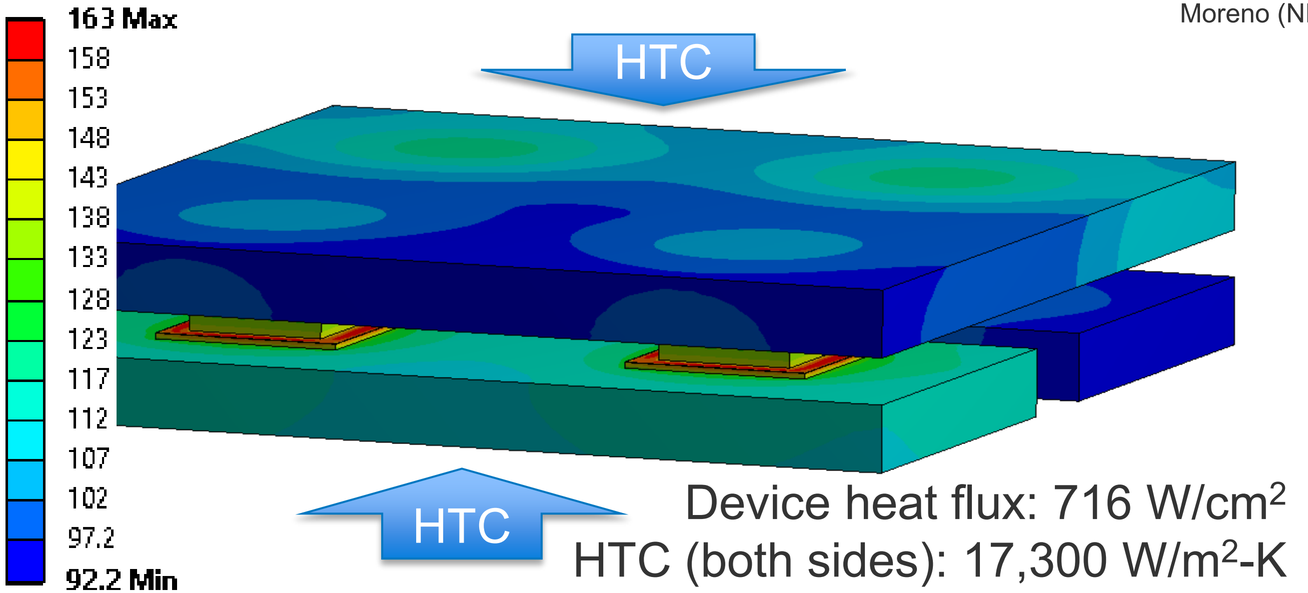


Image credit: Gilbert Moreno (NREL)



- Double-side cooled module design similar to 2013 Camry HEV module.
- **Predict 163°C maximum junction temperatures at 716 W/cm² heat flux** using HTCs from single-side concept; ~57°C temperature decrease compared to single-side concept.
- **Allows for $T_{max.\ junction}$ <175°C due to double-side cooled configuration.**

HTC: heat transfer coefficient

Summary of Results

	Single-side cooled, dielectric fluid concept	Double-side cooled, dielectric fluid concept	Target
Maximum junction temperature [°C]	220 [1]	163 [1]	<250 [2]
Total heat dissipated [W]	2,150	2,150	2,150
Heat flux per device [W/cm^2], maximum	716	716	N/A
Volumetric thermal resistance [cm^3·K/W]	9	11	21
Pumping power [W]	0.15 [1]	0.21 [1]	N/A

Developed dielectric fluid-based cooling strategies that we predict can enable reaching 100 kW/L power density.

[1] Computed/measured at 4 L/min and 70°C Alpha 6 inlet temperature.
[2] USDRIVE, 2017, *Electrical and Electronics Technical Team Roadmap*.

Responses to Previous Year Reviewers' Comments

- **Reviewer comment:** The reviewer said that the approach is fine, but the assumptions are not. 250 degrees Celsius (°C) for the die temperature is not feasible. The die may be able to handle this temp, but the bonding or other design parameters limit the temperature to only a few degrees above IGBT (insulated-gate bipolar transistor).
  - **Response:** We agree that the packaging of the high-temperature devices is the main issue. We have designed a double-side cooled approach that we predict limits the device temperatures <175°C while meeting the thermal target.
- **Reviewer comment:** The reviewer said the technical accomplishments to date are satisfactory. In the evaluation of the cooling concepts, considerations on the weight should be included. Also, comparison with state-of-the art solutions should be updated to more recent results.
  - **Response:** We agree with the reviewer comments. We have developed concepts that are significantly smaller than current systems (~¼ size of 2015 BMWi3 EV) and can be made using a lightweight (plastic) manifold, and thus the weight should also be reduced. We have also added thermal resistance and pumping power comparisons to a more recent automotive system (2015 BMWi3 EV).

Collaboration and Coordination

- John Deere (industry): Two-phase cooling for high-packaging-density planar inverter (CRADA)
- Georgia Tech University: Collaborate to evaluate and develop advanced cooling technologies (two-phase and inter-device cooling)
- Elementum3D (industry): Provide 3D-printed metal parts to evaluate new heat exchanger concepts
- ORNL
- Dielectric fluid manufacturers

CRADA: cooperative research and development agreement

Remaining Challenges and Barriers

- **Creating a reliable, leak-free cooling system:** main challenge is sealing the electrical leads that penetrate through the power module.
  - Developed a concept (ROI-20-72 Compact Dielectric Fluid Manifold for Multiple Double-Side Cooling Configurations) that may allow for sealing the modules and cooling of electrical interconnections.
- **Pumping power requirements** at low temperatures due to higher fluid viscosity.
  - Results indicate that higher viscosities at low temperatures may not be a problem if the correct fluid is chosen and coupled with a low pressure-drop system.
- **Fluid compatibility with power electronics materials:** selected fluids should be compatible with electronics materials, but experiments should be conducted to verify compatibility.
- **Long-term reliability** questions of the dielectric fluid under power electronics operating conditions.
- **Industry adoption** of new (nonconventional) technology.

Proposed Future Research

FY 2020

- Complete design of the double-side cooled, dielectric fluid concept.
- Conduct experiments with AC-100 and ATF at various fluid temperatures and flow rates.
- Collaborate with Georgia Tech to develop the advanced cooling technologies.

FY 2021 and beyond

- Fabricate a prototype of the double-side cooled concept.
- Experimental demonstration/validation of the double-side dielectric fluid concept.
- Evaluate the long-term reliability of the dielectric fluids.
- Collaborate with Georgia Tech to develop the advanced cooling technologies.

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

Summary

Relevance

- Effective thermal management is essential to achieve the year 2025 DOE power density (100 kW/L) and cost ($2.7/kW) targets.

Approach/Strategy

- Define a thermal target required to achieve the 100 kW/L power density.
- Design dielectric-fluid cooling strategies to meet the thermal target and enable high power density.

Technical Accomplishments

- Conducted experiments to measured the dielectric-fluid heat exchanger (case-to-fluid) thermal resistance at various fluid flow rates and temperatures. Obtained a good match between experiments and model. Results confirm that the single-side heat exchanger concept can meet the thermal target.
- Identified AC-100 as a good option due to its lower pumping power. At −40°C, it's predicted to have a lower pumping power and lower thermal resistance compared with 2014 Accord HEV and 2015 BMWi3 EV.
- Designing a double-side, dielectric fluid-cooled heat exchanger. Predict that this concept can dissipate heat fluxes >700 W/cm^2 (per device) while maintaining junction <175°C. This concept is also predicted to meet the thermal target.
- **Developed dielectric fluid-based cooling strategies that we predict can enable reaching 100 kW/L power density.**

Collaborations

- John Deere, Georgia Tech University, Elementum3D, dielectric coolant manufacturers, ORNL

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Thank You

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NREL Transforming ENERGY

Technical Back-Up Slides

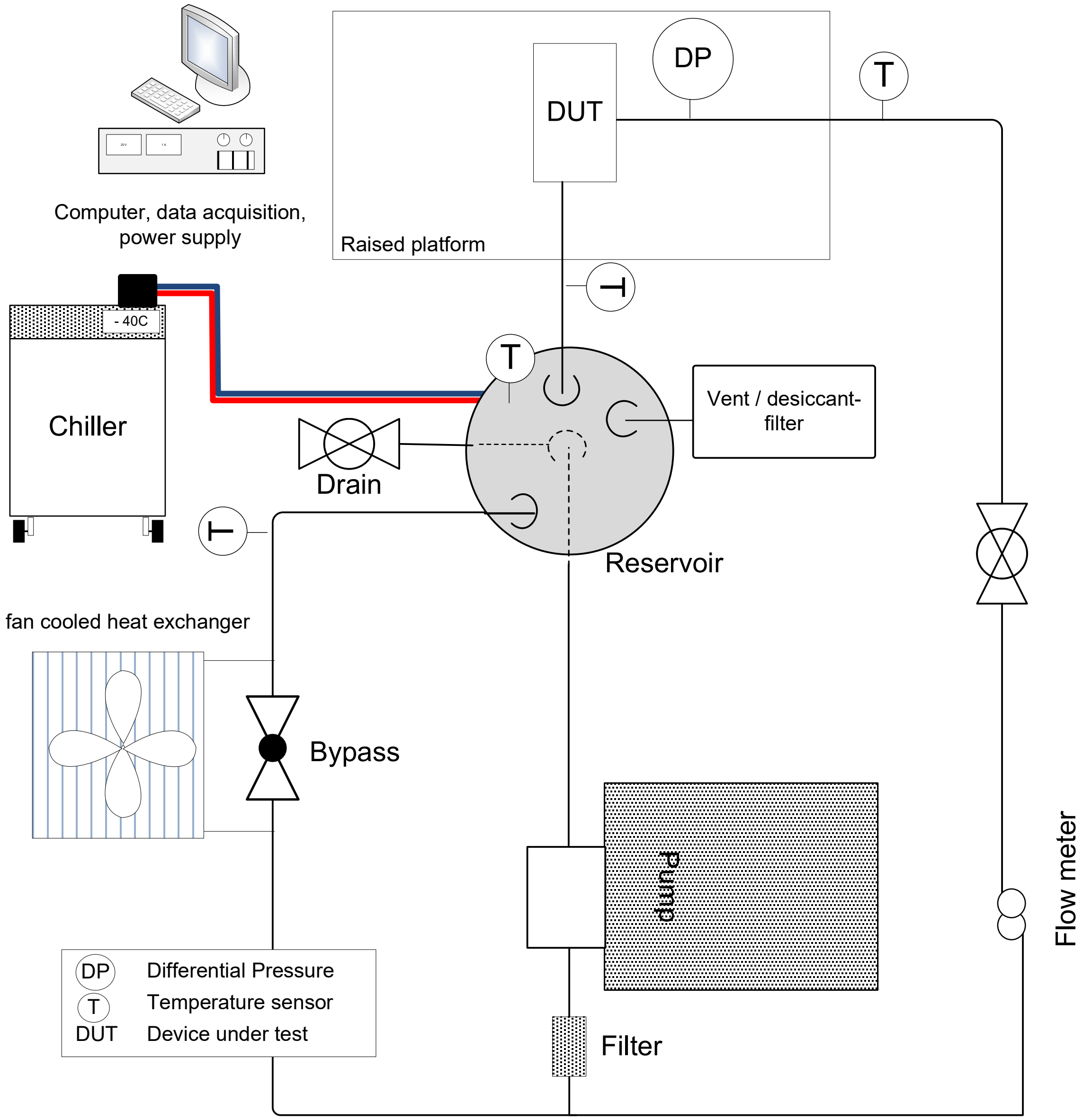
Dielectric Fluid Properties

- Selected synthetic hydrocarbons that are used in electronics cooling (single-phase) applications:
  - Alpha 6: DSI Ventures
  - AmpCool (AC)-100: Engineered Fluids
- Potential to use automatic transmission fluid (ATF) to decrease cost, use fluid already qualified for automotive use, enable motor–inverter integration.
- Challenge is to create a cooling system with high thermal performance using fluids with relatively inferior heat-transfer properties as compared to water-ethylene glycol (WEG).

Fluid *(properties at 70°C)*	**Thermal conductivity [W/(m·K)]**	**Specific heat [J/(kg·K)]**	**Density [kg/m^3]**	**Viscosity [Pa·s]**	**Flash point [°C]**	**Pour point [°C]**
Alpha 6 [1]	0.14	2,308	792	0.0091	246	−57
AC-100 [1]	0.13	2,326	761	0.0025	180	−55
ATF [2]	0.16	2,131	836	0.012	199	−45
WEG (50/50) [3]	*0.42*	*3,513*	*1,034*	*0.0013*	*>121* [4]	*−36* [5] *(freeze point)*

[1] Communications with vendor (DSI Ventures or Engineered Fluids)
[2] Kemp, Steven P. and James L. Linden. 1990. "Physical and Chemical Properties of a Typical Automatic Transmission Fluid." SAE Technical paper.
[3] Alshamani, Kaisar. 2003. "Equations for Physical Properties of Automotive Coolants." SAE Technical Paper.
[4] "Safety Data Sheet ZEREX HD Nitrile Free Extended Life 50/50 Antifreeze Coolant." Valvoline. Accessed April 1, 2019. https://sds.valvoline.com/valvoline-sds/sds/materialDocumentResults.faces.
[5] "Product Information: Valvoline ZEREX G05 Antifreeze Coolant." 2018. US_Val_ZXG05_AFC_HD_EN.Pdf. https://sharena21.springcm.com/Public/Document/18452/f93a8057-fe75-e711-9c10-ac162d889bd3/c264d227-0dbd-e711-9c12-ac162d889bd1.

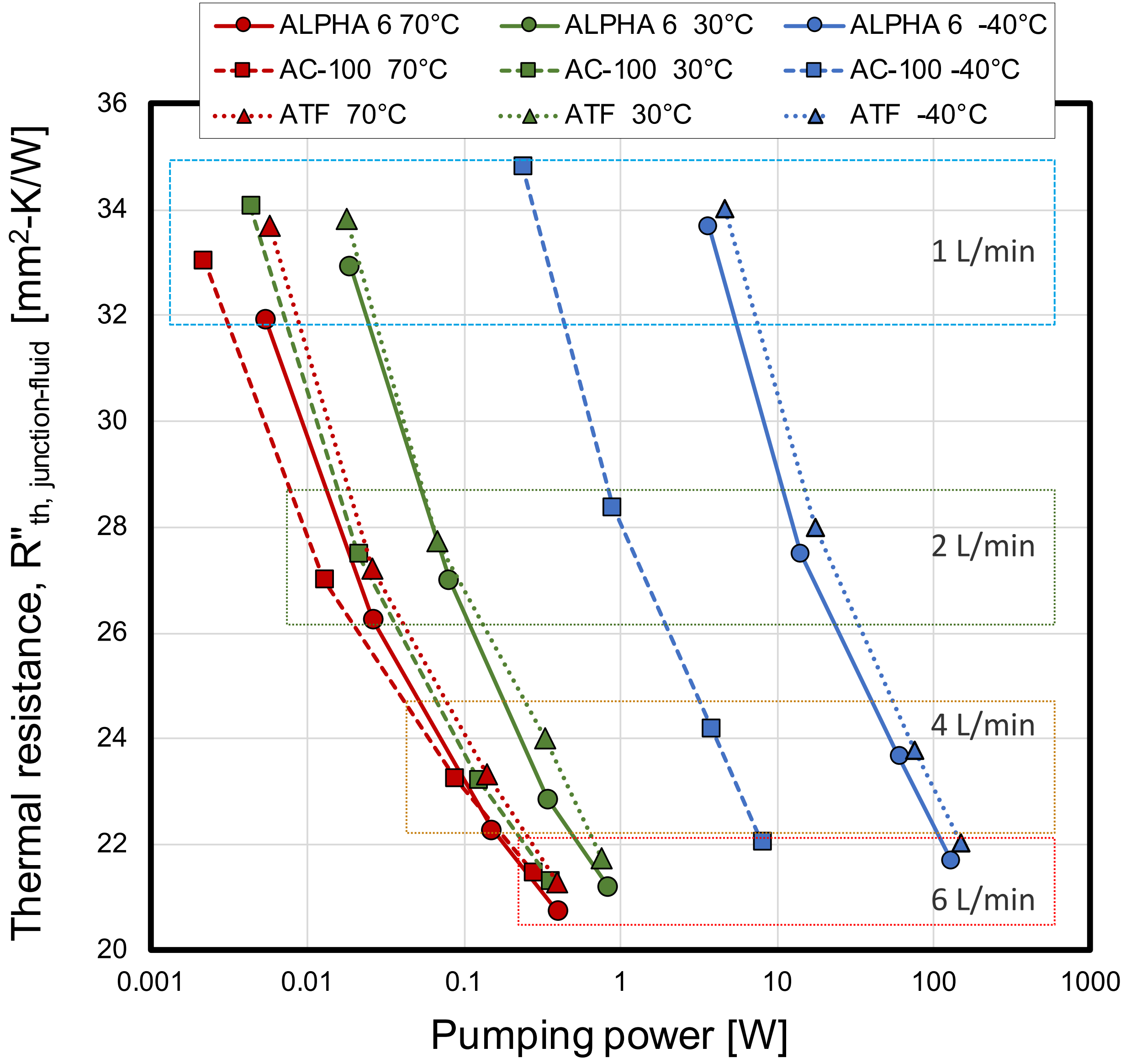
Dielectric Fluid Flow Loop



Effect of Fluid Temperature: CFD Model Results for Single-Side Cooled Concept

- Different fluids provide similar thermal resistance performance when compared at same flow rate.

- Changing fluid temperature has minimal effect on thermal resistance but has a big effect on pumping power.



Dielectric Fluid, Double-Side Cooled Heat Exchanger Pressure Drop versus Flow Rate Performance

- Total volume for the heat exchanger and conceptual modules is 240 mL.
- Computed pressure drop versus flow rate characteristics for series and parallel flow configurations. **Pressure drop is <2 psi** for all flow rates.