High Temperature Air-Cooled Power Electronics Thermal Design

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Project ID: APE019

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Overview

Timeline
Phase II Start Date: FY10
Project End Date: FY14
Phase II Complete: 80%

Budget
Total Project Phase II Funding: DOE Share: $1,700K
Funding Received in FY13: $450K
Funding for FY14: $450K

Barriers
• Cost – Eliminate need for secondary liquid coolant loop and associated cost and complexity
• Weight – Reduce unnecessary coolant, coolant lines, pump, and heat exchangers for lower system-level weight
• Performance – Maintain acceptable device temperatures while reducing complexity and system-level parasitic power

Partners
• Sapa Extrusions North America (aluminum extrusion/manufacturing)
• General Electric Global Research (previous air jet work)
• Oak Ridge National Laboratory (ORNL)
  – Madhu Chinthavali
All vehicles are air cooled

Just indirectly

Air cooling a goal for batteries:
- Simple
- Direct
State of the Art

Indirect Air Cooling via Liquid Cooling

Intermediate liquid cooling loop rejects heat to air

Direct Air Cooling

Has been done before

Honda Insight (12 kW)

AC Propulsion (150 kW)

Mitsubishi SiC Inverter
(50 kVA/L, 400 V output, 156 kVA)

Relevance

Low Power

Low Power Density

Prototype: not in vehicle

SiC = Silicon Carbide
**Project Objective**

Develop air-cooled thermal management system solution that contributes to:

- Accelerating electric drive vehicle adoption
- Eliminating intermediate cooling loops
- Meeting DOE’s APEEM 2015 technical targets (12 kW/kg, 12 kW/L)
- Supporting *EV Everywhere*

**FY14 Project-Specific Goals**

- Build and demonstrate module-level thermal (NREL) and electrical (ORNL) design (10 kW)
- Conduct detailed analysis and proof of concept at system level to show progress relative to DOE’s technical targets
Project Overview

**Advantages**

- Rejecting heat directly to air can **eliminate** intermediate liquid-air loops
- Attractive for high-temperature device (wide bandgap) applications
- Air is benign, is not carried, and does not need to be replaced
- Air is a dielectric and can contact the chip directly
- No global warming potential

**Challenges**

- Air is a poor heat-transfer fluid
  - Low specific heat
  - Low density
  - Low conductivity
- Potential parasitic power of fan
- Not yet used in high power production vehicles
- Filtering, fouling, fan noise
This collaborative research with ORNL is on track to demonstrate an air-cooled inverter for 30-kW continuous, 55-kW peak power.

Air-cooled inverter technology can meet 2015 DOE targets (12 kW/kg, 12 kW/L) and provides pathways to meet 2020 targets with acceptable parasitic loads.

Opens path to adoption by industry as an alternative to standard liquid-cooled system that lowers weight, volume, and cost.
Project Summary: FY11 – FY14

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<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
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<td>Q1</td>
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<td>Q3</td>
<td>Heat Transfer Feasibility</td>
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**Milestones**

- **FY12 M0**: Proof of principle and synthetic jet vs. steady jet
- **FY13 M1**: Heat transfer feasibility study
- **FY13 M2**: Build and test thermal module and initial balance of system
- **FY13 M3**: Demonstrate operating module and thermal system

**Deliverable/Milestone**

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<tr>
<th>Deliverable/Milestone</th>
<th>Go/No-Go</th>
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<tr>
<td>M1 (NREL): Heat transfer feasibility study</td>
<td>Heat transfer accomplished with reasonable flow and pressure loss?</td>
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<td>M1 (ORNL): Device-level evaluation</td>
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<tr>
<td>M2: Build and test thermal module and initial balance of system</td>
<td>Demonstrated design on track to meet targets?</td>
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<td>M2: Module electrical design</td>
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<td>M3: Demonstrate operating module and thermal system</td>
<td>Met targets for module level (10 kW)?</td>
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<td>M3: Electrical inverter design and module build</td>
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FY14 Tasks to Achieve Key Deliverable

**Go/No-Go 1:** Down selection of optimized design meets targets?

**Go/No-Go 2:** Module thermal/electrical design on track to meet targets?

**Go/No-Go 3:** Balance-of-system design on track to meet air flow requirements?

**Key Deliverable, M3:** Demonstrate operating 10-kW module and deliver system metrics (inverter power density, specific power, parasitic power)
System Level Analysis

Approach/Strategy

- Cooling Technology
  - Maximum Temperatures
  - Device Efficiency

- Packaging
  - Inverter Components
  - Under-hood Location

- Balance of System
  - Parasitic Power (Fan)
  - Air Source
High-Temperature Air-Cooled Inverter

- **Electrical Design**: Device type and location; electrical duty cycles; temperature-dependent losses, efficiency
- **Thermal Constraints**: Maximum junction temperature; heat generation; coolant temperature
- **Feasibility / Trade-Off**: Modeling; extrapolate to inverter scale
- **Thermal Design**: Sub-module testing and model validation; fan/ducting testing; optimization
- **Thermal System Design**: Balance-of-system analysis; full system models
- **Hardware**: Module prototype, improve design; balance-of-system testing
Heat dissipation for 55-kW peak power
*From conservative analytical analysis* ~ 2.7 kW heat (95% efficient)

- Fixed device heat generation and temperature (175°C)
- Parametrically optimized geometry by varying air flow rate using computational fluid dynamics (CFD) – ANSYS Fluent
- Extrapolated sub-module modeling and testing results to module level
- Added in balance-of-inverter components†

†Casing volume adjusted for fin geometry
†Capacitor ~1.13 L*, ~1.62 kg*
†Gate driver + control board ~0.88 L*, ~0.42 kg**

* Assumption provided by ORNL; ** NREL assumption based on similar device measurement
Parametric Channel Geometry Optimization

9 Modules, DBA, 175°C Junction Temperature

DBA = direct-bond-aluminum

Each geometry represents one CFD simulation

Accomplishments

- FY14
- AC blower or condenser fan power draw

Low parasitic power, but only most aggressive geometries barely meet 2015 targets

2015 Target:
- 12.0 kW/kg

2020 Target:
- 14.1 kW/kg

Baseline
Parametric Channel Geometry Optimization

6 Modules, DBA, 175°C Junction Temperature

Accomplishments

FY14

Selection of geometries meets targets with acceptable parasitic power.

Each geometry represents one CFD simulation.

AC blower or condenser fan power draw.

Go/No-Go 2

Baseline

Fan Parasitic Power [W]

12.0 kW/kg

14.1 kW/kg

2015 Target

2020 Target

Specific Power (kW/kg)
Parametric Channel Geometry Optimization

6 Modules, DBA, 175°C Junction Temperature

Accomplishments

Selection of geometries meets targets with acceptable parasitic power.

Go/No-Go

AC blower or condenser fan power draw

Fan Parasitic Power [W]

Power Density (kW/L)

2015 Target
12.0 kW/L

2020 Target
13.4 kW/L

Each geometry represents one CFD simulation.
Heat Exchanger Experiments

Baseline

Optimized

Prototypes provided by Sapa
Heat Dissipation for **Baseline** Case (9 modules)

- Specific Power: 9.4 kW/kg
- Power Density: 10.1 kW/L

**Fan sized to satisfy flow rate and pressure drop**

**Heat dissipation: 2.7 kW target**

- ~55 CFM
- 4 W Fluid Power

9 modules, $T_{\text{inlet}} \sim 42.5^\circ C$
Specific power and power density projected to meet 2020 targets, with tradeoff of higher parasitic power.
<table>
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<tr>
<th>Feedback</th>
<th>Response</th>
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<tr>
<td>The reviewer indicated that this is a good team, but felt that a vehicle manufacturer should be added to the team to get industry input. This reviewer suggested that this would help the project to become easier to manufacture and get industry acceptance.</td>
<td>We have a strong collaboration with ORNL. NREL is addressing thermal issues, and ORNL is focused on the electrical design. On the thermal work, NREL is collaborating with Sapa Extrusions North America to aid in manufacturing concerns regarding extruded aluminum, a potential method for simple and inexpensive cooling channels. ORNL is working with device manufacturers and other partners on the electrical design. We have met with OEMs and first-tier suppliers through on site visit presentations to get feedback on the direction of the research and to address the advantages, challenges, and potential applications for vehicle platform adoption. We are addressing the barriers and constraints that they have brought up in these meetings.</td>
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<td>The reviewer suggested that future work should produce a proof-of-concept of a working prototype and address practical application issues.</td>
<td>This fiscal year, the focus has been shifted from modeling and analysis to direct experimentation and proof-of-concept. Baseline and optimized sub-modules have been tested with data extrapolated to module and inverter level. An optimized module has also been manufactured and will be tested this fiscal year. One module heat sink will be tested for thermal performance at NREL, while another was sent to ORNL so they could mount the electrical topology and test the electrical design.</td>
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<tr>
<td>The reviewer observed that this project is very relevant to future wide-band applications because cooling requires significant energy that reduces the EV drive efficiency.</td>
<td>We agree that air cooling is better used on high-temperature application, where the large temperature difference helps overcome the shortcomings of air properties. Wide-band-gap devices provide an emerging opportunity for air cooling as they can be run at higher temperatures. They are more efficient, but with smaller areas, the heat flux is still a challenge. We believe air cooling will be a potential effective alternative to traditional cooling strategies.</td>
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Collaboration and Coordination

Collaborations

• **Industry:** Sapa Extrusions North America
  - Provided aluminum channel heat exchanger prototypes
  - Offered guidance on manufacturability for various designs and direction on reducing material and manufacturing costs

• **Federal Laboratory:** Oak Ridge National Laboratory (Madhu Chinthavali)
  - Building and testing electrical topology
  - Provided device information, estimated heat loads, balance-of-inverter component sizing, and design constraints

• **University/Industry:** WBG Institute (outside Vehicle Technology Office)
  - Developing relationships with industry and university partners for potential application of technology

Coordination

• **Industry:** Domestic OEMs and inverter suppliers
  - Contributed feedback on research and potential applications through direct one-on-one meetings

OEM = original equipment manufacturer
Remaining Challenges and Barriers

**Cooling Technology**

- Demonstrating prototype that meets technical targets

**Packaging**

- Showing how balance-of-inverter components complete efficient inverter packaging
- Under-hood location considerations for vehicle platforms

**Balance of System**

- Parasitic power requirements
- Comparison of weight, volume, and cost of necessary components (i.e. ducting, fans) compared to liquid-cooled loop
Electrical and Thermal Module (10 kW)

Future Work

Build 10-kW module
Demonstrate 10-kW module (thermal performance)

Build 10-kW module
Demonstrate 10-kW module (electrical performance)

Photo courtesy of ORNL (Madhu Chintavali)
System Test Platform

Build and test sample system to measure and characterize parasitic load

M3

Jim Snyder, NREL Image Gallery 15165
Summary

DOE Mission Support
• Overcome barriers to accelerate adoption of low-cost air-cooled heat exchangers for power electronics, especially for high-temperature (i.e. WBG) devices; air remains the ultimate sink

Approach
• Create system-level understanding and designs addressing advanced cooling technology, packaging, and balance of system
• Develop solutions from fundamental heat transfer, then system-level design, to application – culminating in demonstration of concept

Collaborations
• ORNL developed electrical topology and is testing with NREL air-cooled heat exchanger and provided balance-of-inverter component sizing and characterization and device loss (heat dissipation) direction
• Sapa Extrusions North America provided aluminum heat exchanger prototypes and guidance on manufacturing constraints to control cost
• Met with OEMs and 1st tier suppliers to obtain feedback on air-cooling applications and overcoming barriers and constraints for adoption
Summary

Technical Accomplishments

• Optimized thermal design showing candidate designs that meet DOE power density and specific power technical targets with acceptable parasitic loads

• Demonstrated baseline and optimized module design thermal performance and, using balance-of-system assumptions, projected to meet 2015 DOE technical targets

• Built module-level (10-kW) heat exchanger that will be tested in FY14

<table>
<thead>
<tr>
<th>Maximum Junction Temperature – 175°C</th>
<th>2015 Target</th>
<th>2020 Target</th>
<th>Baseline (9 modules)</th>
<th>Baseline (6 modules)</th>
<th>Optimized (9 modules)</th>
<th>Optimized (6 modules)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Density [kW/L]</td>
<td>12.0</td>
<td>13.4</td>
<td>10.1</td>
<td>12.8</td>
<td>11.8</td>
<td>14.5</td>
</tr>
<tr>
<td>Specific Power [kW/kg]</td>
<td>12.0</td>
<td>14.1</td>
<td>9.4</td>
<td>12.7</td>
<td>11.1</td>
<td>14.6</td>
</tr>
<tr>
<td>Fluid Power [W]</td>
<td>N/A</td>
<td>N/A</td>
<td>4</td>
<td>34</td>
<td>70</td>
<td>110</td>
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Acknowledgments and Contact

Acknowledgments:

• Susan Rogers and Steven Boyd
  U.S. Department of Energy

• Andrew Wereszczak
  Oak Ridge National Laboratory

Team Members:

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Charlie King
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Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)
Optimized Geometries Improve Specific Power

*On track to meet DOE 2015 technical target*

FY13 – Go/No-Go 1

9 modules, DBC

9 modules, DBC
Component Contributions to Inverter Weight

Other components need optimization.
System Level Test Bench

- Meets Fan Test Standard
  - ANSI/AMCA 210-07
  - ANSI/ASHRAE 51-07
- Range: 5–500 CFM
- $U_{95}$ Flow: ±1.5 CFM
- $U_{95}$ Pressure: ±1.6 Pa

- Fan or duct test subject

![Blower](image)

- Fan pressure curves
- Fan efficiency curves
Air Outlet Temperature for **Baseline** Case

**Accomplishments**

- FY14

- Outlet Temperature: ~100°C
- Volumetric Flow Rate: ~55 CFM
- $T_{j,max}$: 200°C
- $T_{j,max}$: 175°C
- $T_{j,max}$: 150°C

9 modules, $T_{\text{inlet}} \sim$ 42.5°C
Heat Dissipation for **Optimized** Case (9 modules)

**Accomplishments**

- **Specific Power:** 11.1 kW/kg
- **Power Density:** 11.8 kW/L
- **Heat dissipation:** 2.7 kW target

FY14

**Similar thermal performance to baseline, but higher specific power and power density, and parasitic power**

- ~70 CFM
- 70 W Fluid Power

9 modules, $T_{\text{inlet}} \sim 45^\circ\text{C}$