# Advanced Low-Cost SiC and GaN Wide Bandgap Inverters for Under-the-Hood Electric Vehicle Traction Drives

APEI

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APEI
June 10, 2015

Project ID: EDT058

# Overview

## Timeline

**Project Start Date:** October 1, 2013
**Project End Date:** September 30, 2015
**Percent Complete:** ~75%

## Budget

**Total Project Funding:** $3.8M
**Federal/DOE Share:** $1.8M
**Funding in FY14:** $677,626
**Funding in FY15:** $256,714; through 12/31/14

## Barriers and Targets

- Cost ≤ $182 unit cost / 100,000
- Ambient operating temperature ∈ [-40 to +140 °C]
- Weight ≤ 3.9 kg;
  Specific Power ≥ 14.1 kW/kg

## Partners

- Toyota - TRINA
- GaN Systems, Inc.
- National Renewable Energy Laboratory
- University of Arkansas National Center for Reliable Electric Power Transmission



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# Project Objectives

- Develop two independent 55 kW peak traction inverter designs (one SiC based and one GaN based) to showcase the performance capabilities of WBG power devices – namely high efficiency, increased gravimetric and volumetric density through high operating junction temperature capability.
- Demonstrate a substantial cost reduction from the die level to the system level.
- Optimize proven productized high temperature WBG power modules for increased manufacturability and reduced cost.
- Integrate existing APEI high temperature silicon on insulator (HTSOI) application specific integrated circuit (ASIC) designs as a means to low-cost, high-reliability, high-temperature circuitry.

# Project Objectives & Relevance

- Application of advanced system-level packaging techniques to completely eliminate a vehicle's secondary cooling loop system, utilize 85°C rated capacitors, reduce interconnects, and enable increased system reliability.
- Demonstrate design robustness and reliability through extended testing of subsystems and systems under realistic application operating conditions.
- Complete cost and manufacturing analysis to aid commercialization effort.

The goal of this research is to **reduce traction inverter size** (≥ 13.4 kW/L), **weight** (≥ 14.1 kW/kg), and **cost** (≤ $182 / 100,000) while maintaining 15 year reliability metrics.

# Relevance

**Current HEVs, PHEVs, and BEVs use inverters based on silicon IGBTs.**

**These devices and present-day packaging technology make it difficult to meet the VTO efficiency, cost, weight, and performance targets.**

| Requirement | Target |
| --- | --- |
| Continuous power output (kW) | 30 |
| Peak power output for 18 seconds (kW) | 55 |
| Weight (kg) | ≤3.9 |
| Volume (l) | ≤4.1 |
| Efficiency | > 93% |
| Unit Cost for quantities of 100,000 ($) | ≤182 |
| Operating voltage (Vdc) | 200 to 450; nominal: 325 |
| Power factor of load | >0.8 |
| Maximum current per phase (Arms) | 400 |
| Pre-charge time – 0 to 200 Vdc (sec) | 2 |
| Output current ripple – peak to peak (% of fundamental peak) | ≤3 |
| Maximum switching frequency (kHz) | 20 |
| Current loop bandwidth (kHz) | 2 |
| Maximum fundamental electrical frequency (Hz) | 1000 |
| Minimum isolation impedance-input and phase terminals to ground (MΩ) | 1 |
| Minimum motor input inductance (mH) | 0.5 |
| Ambient operating temperature ($^{o}$C) | -40 to +140 |

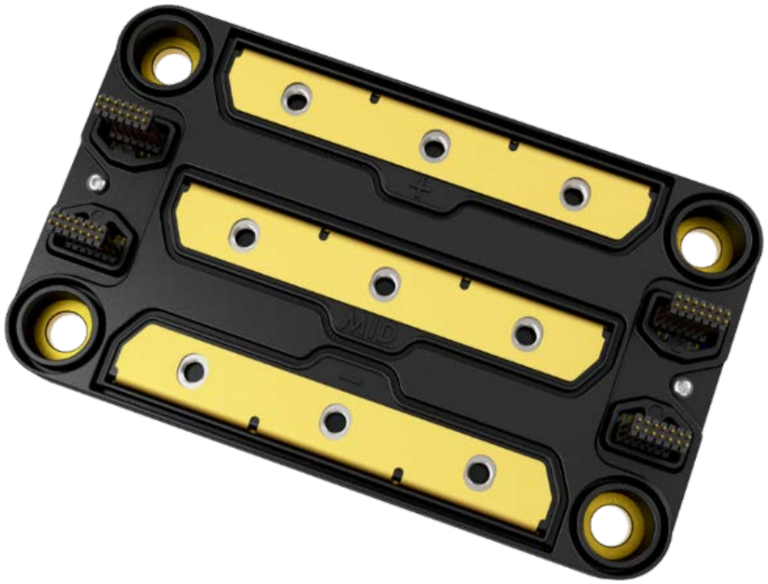
# Milestones & Go/No-Go

| Milestone | Type | Description |
|---|---|---|
| Control system design | Technical | • Control system design complete for SiC & GaN power |
| Power switch characterization | Technical | • Characterization of GaN power switches and commercial SiC power MOSFETs complete |
| Subcomponent Testing | Technical | • Subcomponent testing complete |
| Three-Phase Laboratory Testing | Go/No Go | • Three-phase laboratory testing to confirm WBG traction inverter design meets specifications |
| Build & test GaN and SiC traction inverters complete | Technical | • GaN and SiC traction inverters built for testing |
| Component Testing Complete | Technical | • Laboratory testing complete |
| Prototype testing complete | Technical | • Verification testing & prototype delivery |

# Technical Approach

- This program will develop two completely independent WBG traction inverters: one **SiC based and one GaN based.** This work will provide a unique, **direct comparison** between **inverter designs using SiC and GaN.** (APEI)
- This program will advance GaN HEMT power semiconductor device technology to **600 V, 100 A**. (GaN Systems)
- This program will utilize advanced **high performance power modules** to achieve high power density and efficiency. (APEI)
- This program will use **advanced packaging techniques** (APEI) and **active cooling technologies** (Toyota, NREL) to enable the use of low-cost, 85 °C-rated DC bus capacitors.
- **Custom, in-house HTSOI IC designs** will dramatically reduce the cost of high temperature capable support circuitry. (APEI)

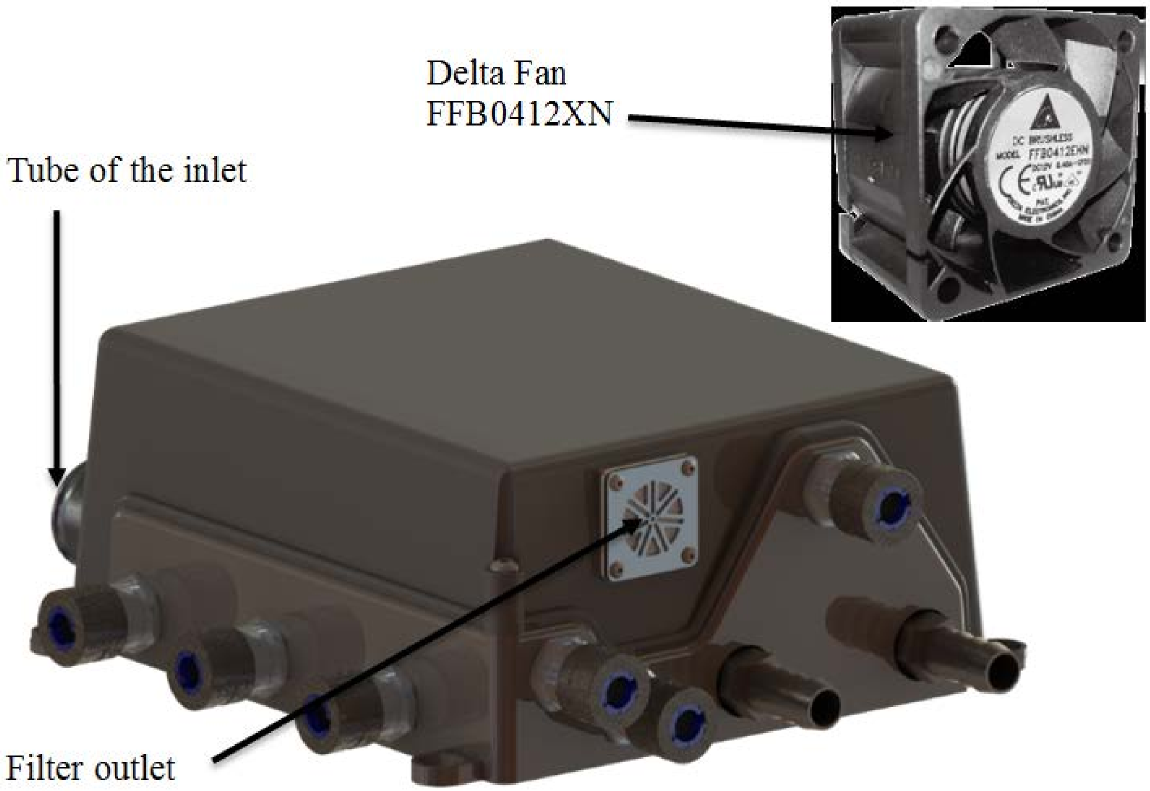
# Technical Approach



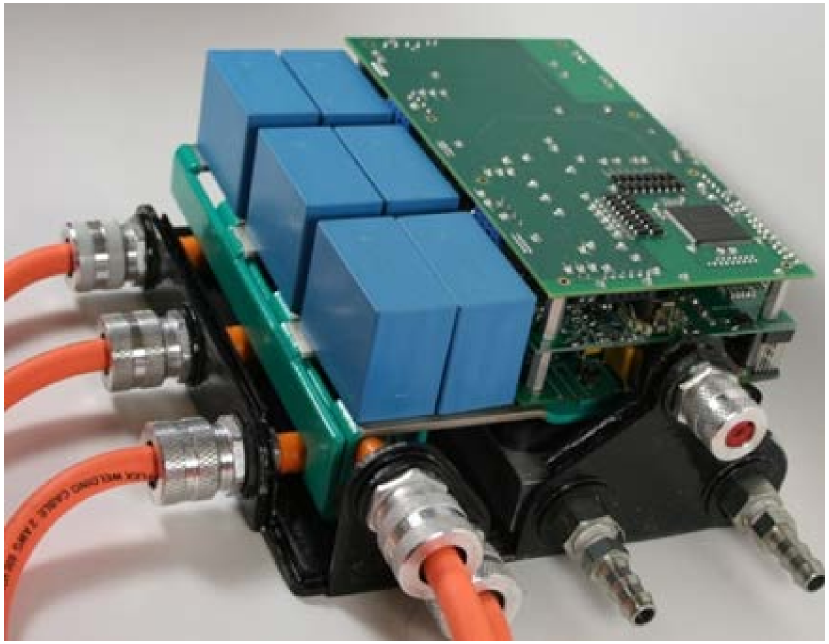
*APEI's 1200 V, HT-3000 WBG Device-Neutral Half-Bridge Power Module.*

- Work inside out. Optimize from the power devices to the outside world.
- Start with the smallest form factor, lightest weight, and highest performing WBG power module in the world
- Half-bridge power module capable of up to 1200 V and up to 1000 A (device dependent)
- High-temperature packaging materials (250 °C capable)
- WBG device neutral (SiC BJTs, JFETs, MOSFETs, GaN HEMTs, etc.)

# Accomplishments




# Accomplishments – Miscellaneous Challenges



- MNDA was fully executed on 4/7/15
- EMI considerations
- DC link resonance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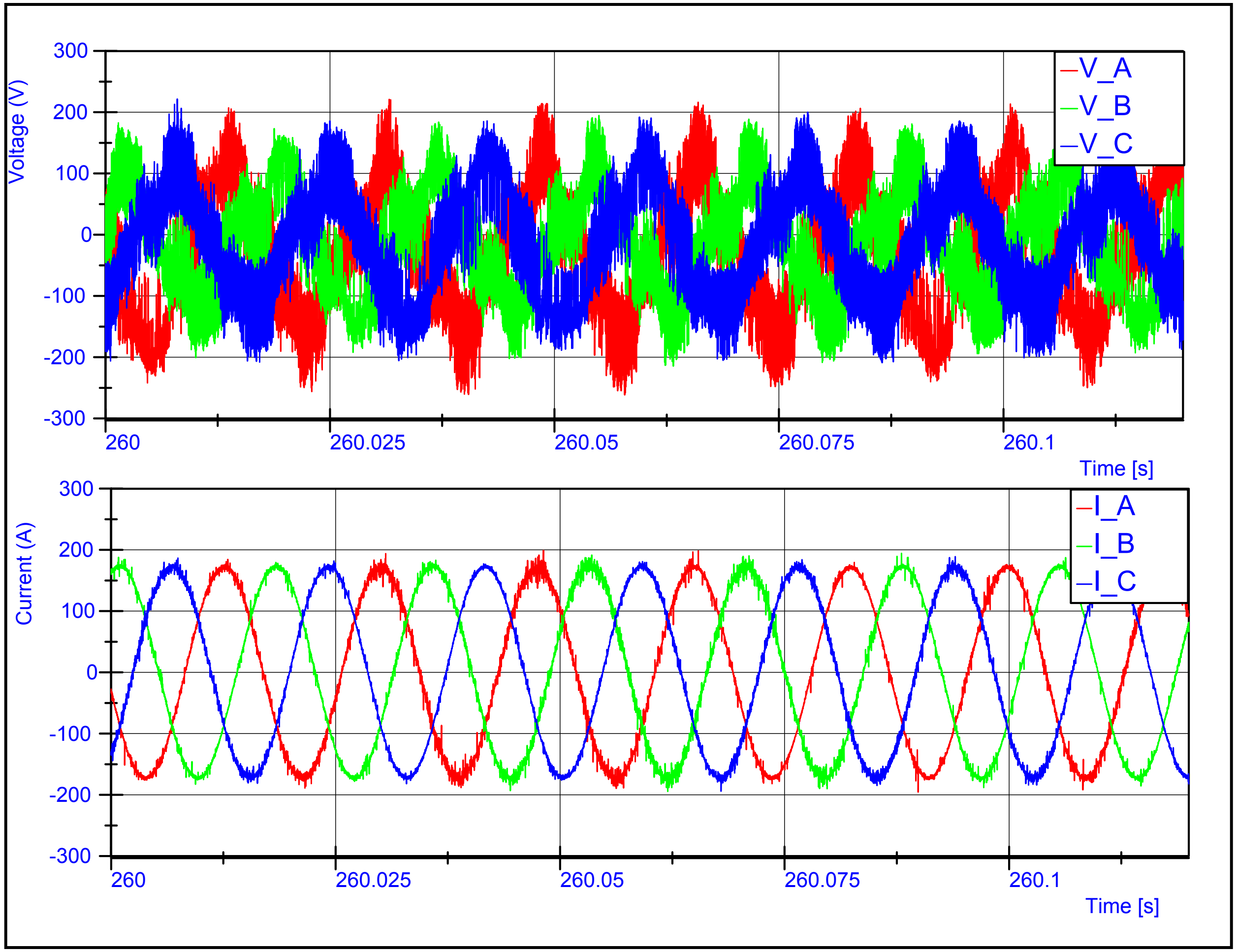
# Accomplishments – SiC Inverter Testing

*Test5_1750 RPM @ 30 kW using the SiC VTP inverter*

- *Phase Voltages and Line Currents*




*Efficiencies for the SiC VTP inverter operating at 1750 RPM with a 325 VDC bus (20 kHz).*

| Power (kW) | Efficiency, η (%) |
|---|---|
| **5** | 96.4 |
| **10** | 97.8 |
| **20** | 98.5 |
| **30** | 99.2 |



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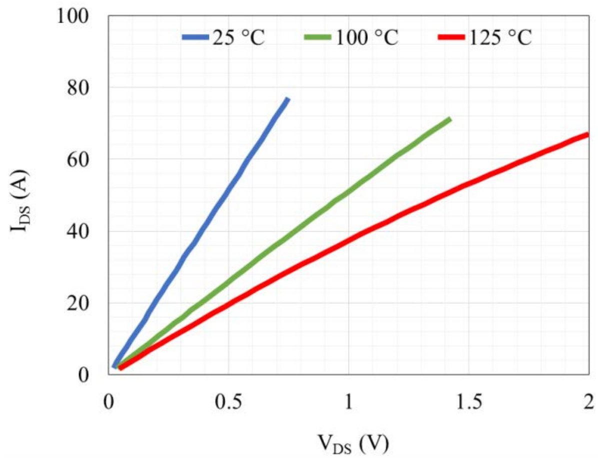
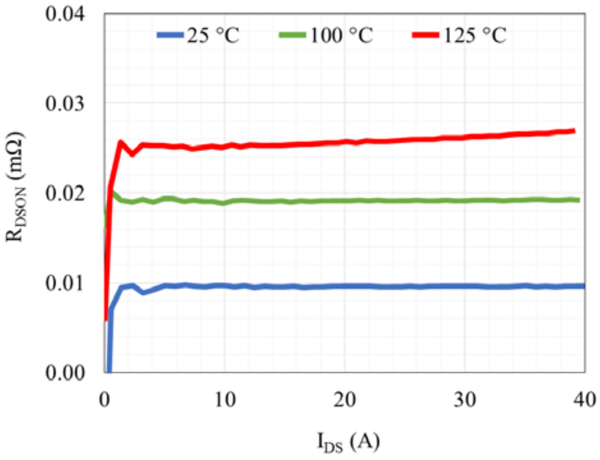
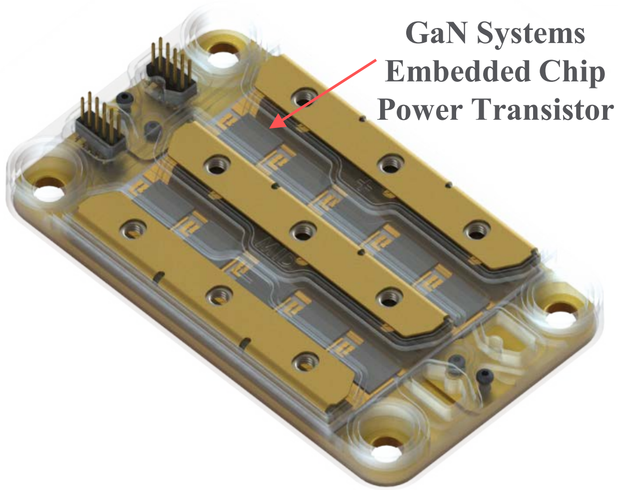
# Accomplishments – Power Modules

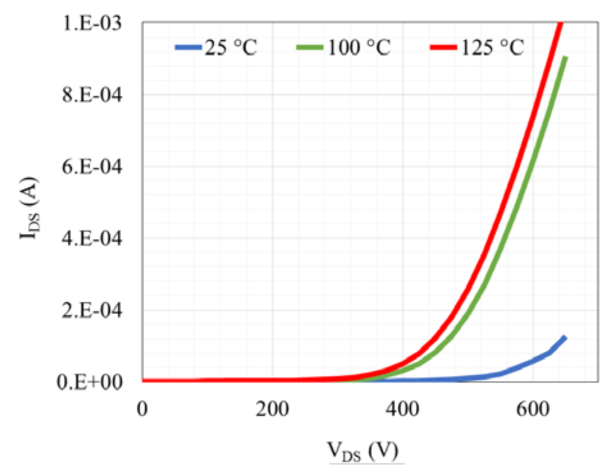
The on-state characteristics, on-resistance, and drain leakage as a function of temperature for a switch position in the GaN HT-3000 power module.




Clamped inductive load testing, power module burn-in, inverter build, LP dyno, HP dyno driving on the 75 HP Toyota-emulating PMSM







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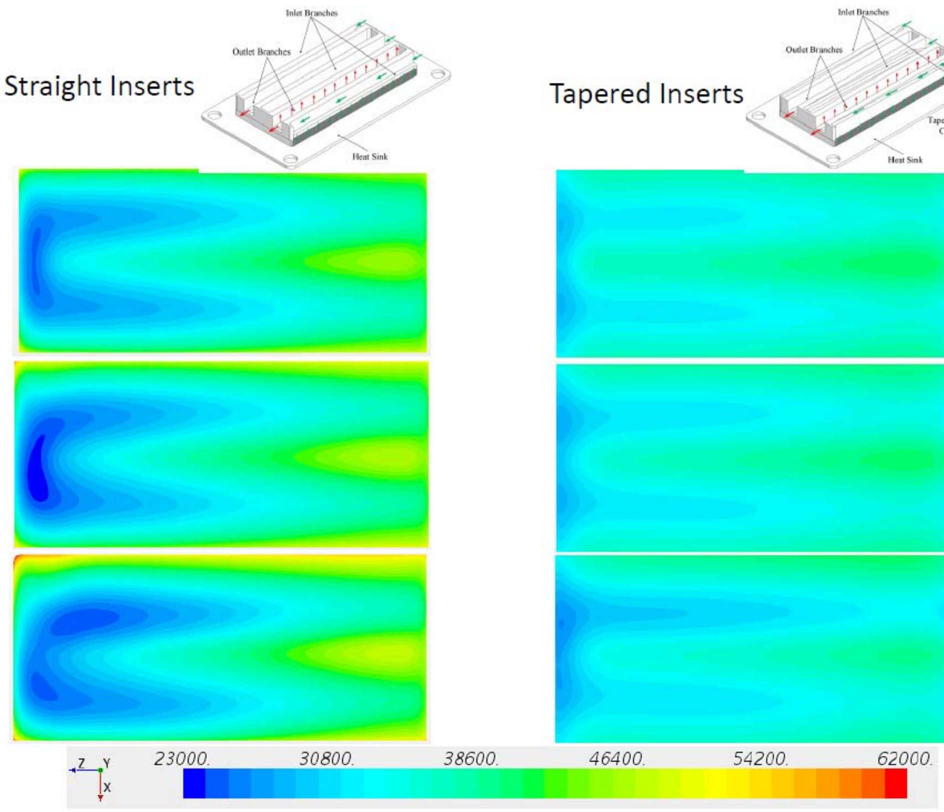
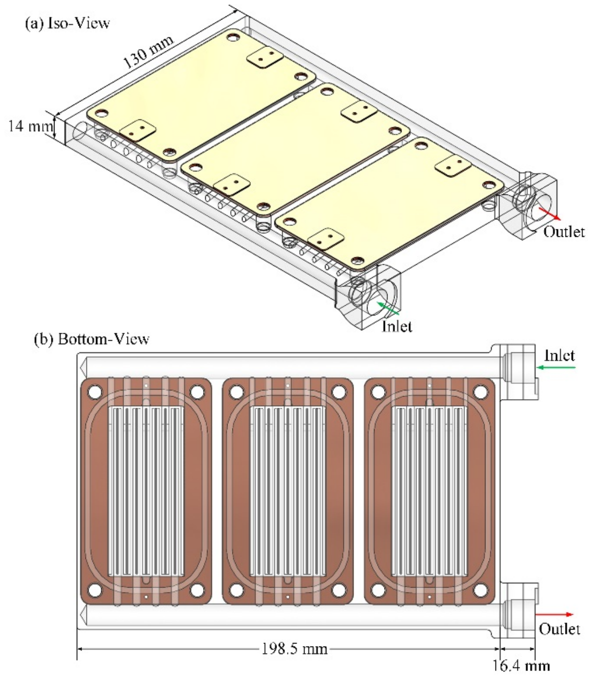
# Accomplishments – Cold Plates




- TRINA high-performance cold plate

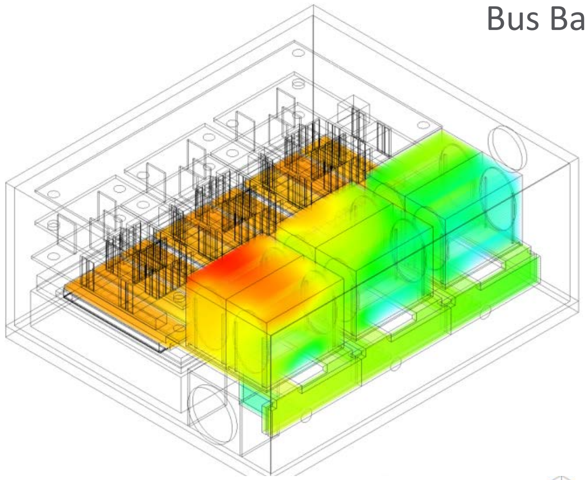


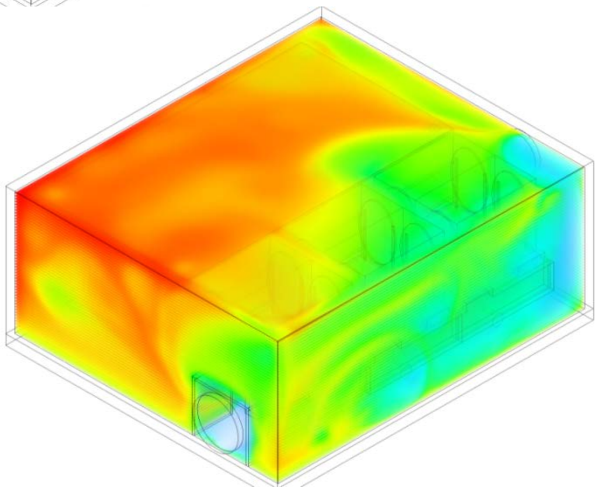
# Accomplishments - Thermal Analysis

- Power module thermal management
  - Evaluate passive and active thermal design choices
  - Determine performance targets for active convective cooling technologies

- Inverter system thermal modeling, analysis and design support
  - Performing finite element and computational fluid dynamics modeling
  - Evaluate impact of under hood temperatures
  - Quantify component temperatures such as bus bars, circuit boards, power modules, ceramic capacitors, DC link capacitors, and internal air temperature distribution
  - Identify thermal solutions to meet component temperature requirements

DC-Link Capacitor and Bus Bar Temperatures





Internal Air Temperatures



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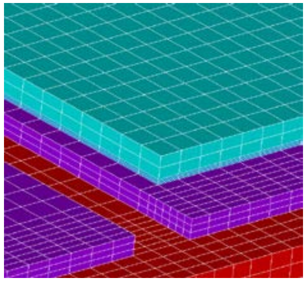
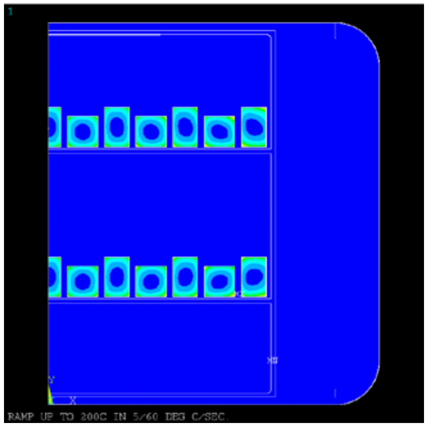
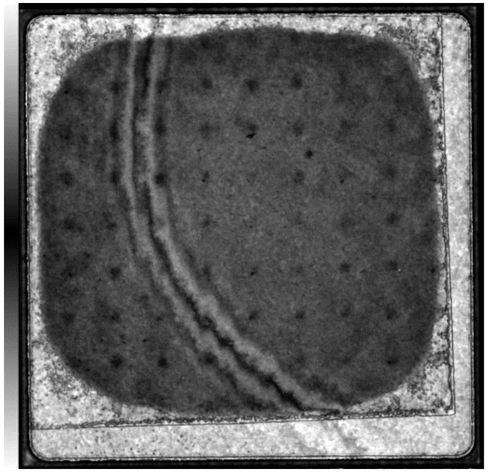
# Accomplishments - Reliability Evaluation

- Material effects on power module reliability from thermal temperature cycles
  - Compared creep strain energy density at device attach for selected range of material and packaging options
- Accelerated thermal testing of interface materials
  - Monitoring delamination rates through acoustic microscopy every 100 cycles from -40 °C to 170 °C
  - Monitoring thermal aging effects at 250°C through acoustic microscopy and by removing samples for cross-section examination at set intervals

Creep Strain Energy Density





Acoustic Image of One Sample Material after 100 Cycles

# Responses to Previous Year Reviewers' Comments

**Question 1**: Approach to performing the work – the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

Reviewer 1 Comments: "The reviewer suggested, however, that the work may have too much of a near-term focus on component selection and topology, given the somewhat speculative nature of the devices, but this would at least create a benchmark."

APEI: Near-term component selection is necessitated based on the need for accurate pricing information on components at quantities of 100,000. Speculative, research, or pre-production components will not enable the PI to obtain accurate pricing at quantities of 100,000. To do otherwise, the costing exercise needed to benchmark, track, and hit the $182 inverter target becomes moot.

# Responses to Previous Year Reviewers' Comments

**Question 1**: Approach to performing the work – the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

Reviewer 4 Comments: "The reviewer criticized…from project report."

APEI: It is obvious that the reviewer feels quite strongly that concurrently designing, building, and comparing a SiC- versus GaN-based inverter is **not** a good idea. Two "optimum" designs seem to be impossible according to this reviewer. The PI believes the definition of optimality of WBG inverters is neither defined nor mutually accepted throughout the industry. But two nearly optimum designs cannot be such a bad thing. The PI believes there are clever ways to carefully make "apples-to-apples" comparisons via testing at identical operating points.

The reviewer also opines that "…significant capture of business segment by SiC devices is questionable and doubtful for lower DC bus voltage inverters," However, Rohm thinks otherwise. Why does Rohm have a new 650 V N-channel SiC power MOSFET with listed applications of "Solar inverters" and "Motor drives?" (See the SCT2120AF datasheet Application section.)



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# Responses to Previous Year Reviewers' Comments

**Question 4**: Proposed future research – the degree to which the project has effectively planned its future work in a logical manner by incorporating appropriate decision points, considering barriers to the realization of the proposed technology, and, when sensible, mitigating risk by providing alternate development pathways.

Reviewer 2 Comments: "This reviewer suggested that if DOE granted an extension, then wider inclusion of WBG suppliers would be a nice future goal."

APEI: The PI is presently using Cree Gen2 25 mΩ SiC MOSFETs in the Design Cycle 1 SiC inverter. Design Cycle 2 power semiconductor devices will likely be the Cree Gen3 25 mΩ SiC MOSFETs. A second inverter build will be done with an HT-3000 loaded with GE12N45 SiC MOSFETs. These results will be shared with the DOE.

Rohm 650 V, 120 mΩ, 29 A drain current SiC MOSFETs (a new product since this project began on 10/1/2013) to package in the HT-3000 series power module for the inverter application. This would provide a direct comparison to 650 V GaN devices. To our knowledge, this is the only 650 V SiC MOSFET on the market worldwide. Rohm also has a 400 V, 120 mΩ, 20 A drain current SiC MOSFET as well (SCTMU001F).

# Responses to Previous Year Reviewers' Comments

**Question 6**: Resources: How sufficient are the resources for the project to achieve the stated milestones in a timely fashion?

Reviewer 1 Comments: "This reviewer said that this was not addressed directly, but was presumably sufficient."

APEI: The PI did state that insufficient time and budget would preclude delivering two inverter designs and evaluating novel circuit topologies that could take advantage of WBG device attributes and characteristics. The ubiquitous voltage-source inverter is the prevalent circuit topology of choice for inverters at the moment, and significant time and effort devoted to new topology adoption would have to happen before the VSI was displaced as such.

Reviewer 3 Comments: "It would have been interesting to this reviewer if the data were made available to see how the cost target of $182 unit cost was tracking."

APEI: The Reviewer is correct. APEI is NOT a production manufacturer of WBG inverters; APEI is a production manufacturer of WBG discrete devices and power modules. The PI appreciates this feedback and will seek to address this point in a future quarterly report at the appropriate time.



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# Collaborations and Coordination with Other Institutions

- OEM – Toyota. Toyota will collaborate on system-level **specifications** and on the design of the **thermal management system**.
- Device Manufacturer – GaN Systems, Inc. GaN Systems will fabricate and test ≥ 600 V, ≥ 50 A **GaN HEMTs**.
- Supporting Research Organizations
    1. National Renewable Energy Laboratory – NREL will perform **thermal and reliability analysis** as the module- and system-levels, respectively.
    2. University of Arkansas NCREPT – UA NCREPT will assist in the extensive **characterization and testing** of the traction inverter system using a custom-designed dynamometer test bed.

# Proposed Future Work

- Task 2.1 Design Cycle 2: Complete electrical, mechanical, and thermal refinement cycle to further meet or exceed all technical targets utilizing feedback from testing of Design Cycle 1 In process
- Task 2.2 Power Module Package Development Cycle 2: Iterate the high-temperature WBG power module capable of housing either SiC or GaN die. Explore cost reduction strategies and lifetime. Gen3 25 mΩ MOSFETs & newest generation of the GS66508P
- Task 2.3 Fabrication Cycle 2: Fabricate and assemble multiple hardware units of each updated WBG traction inverter design for internal testing. In progress.
- Task 2.4 Analysis of cost and manufacturability ROM based on Design Cycle 1
- Task 2.5 Testing of Design Cycle 2: Functional testing of all updated inverter subsystems SiC-based inverter in progress
- Task 2.6 Extended three-phase testing: Extended three-phase, high-power testing of the Cycle 2 traction inverter systems to further validate performance
- Task 2.7 Hardware Deliverables: Fabricate, validate, and deliver three (3) traction inverter hardware prototypes of each design (three SiC-based and three GaN-based).

# Project Summary


TOYOTA GaN Systems NREL NATIONAL RENEWABLE ENERGY LABORATORY UNIVERSITY OF ARKANSAS

# Questions?