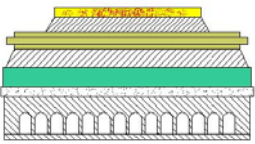


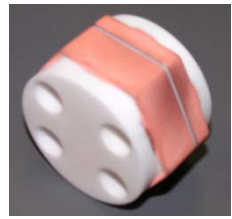
Direct Water-Cooled Power Electronics Substrate Packaging

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Project ID: APE001



Overview



Barriers

Timeline

- **Project start – Oct. 2007**
- **Project end – Sept. 2011**
- **Percent complete – 65%**

Budget

- **Total project funding**
 - DOE 100%
- **FY08 - \$349K**
- **FY09 - \$428K**
- **FY10 - \$388K**

- **Barriers**

- **Substrate metallization** – Thick copper metalized surfaces are difficult to bond with success.
 - This is critical to the thermal performance of the substrate modules.
- **Substrate plating** – Determining the proper plating combination for chip sintering and satisfactory wire bond strength.
- **Buss structures** – Optimization and placement of the Buss structures in and around the capacitor interconnects will be critical to inverter performance.

- **Vehicle Technology Program Targets**

- DOE 2020 target: 13.4 kW/l
- DOE 2020 target: 14.1 kW/kg

Partners

- CoorsTek – Ceramic Fabrication
- Stellar Ind. – Substrate Metallization
- Orthodyne Electronics – Ribbon Bonds
- NBE Tech., LLC. – Plating and Chip Sintering

Objectives

- Achieve a reduction in both the size and weight of the heat sink for power electronic inverter technologies while operating with a high temperature coolant.
 - Volume Reduction – ORNL structure allows for the maximum surface area to be utilized within the smallest geometrical volume.
 - Weight Savings – Weight reduction of approximately 17% as compared to the Camry by the removal of the traditional base plate and heat sink.
- Achieve system cost reductions through:
 - The elimination of auxiliary cooling loop.
 - Removal of the base plate and heat sink.
 - Use of Silicon switches and high temperature coolant.
- Achieving a reliable substrate design while utilizing 105°C Water-Ethylene Glycol (WEG) coolant.

Milestones

FY09

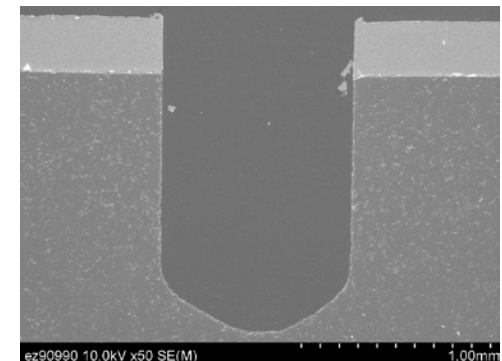
- Ceramic substrates were fabricated, metalized, and chips were soldered into place.
- Pressure drops in the coolant channels containing the thermal enhancement material were evaluated.
- Single module testing completed.
- **Go / No-Go decision** was favorable after comparison of testing results and FEA results show agreement to 10-15%.



Al_2O_3 material plated with 10-25 microns of Molybdenum/Manganese followed by Nickel and 0.3mm copper plating.

FY10

- Metallization of the second generation ceramic substrate was completed. Metallization is being evaluated to determine bond strength.
- **Go / No-Go decision:** If bond strength is deemed acceptable proceed to metalize remaining components.
- Flow header FEA has been completed to obtain a balanced coolant flow design to supply the substrates.
- Buss structures within the design have been optimized for inverter performance.

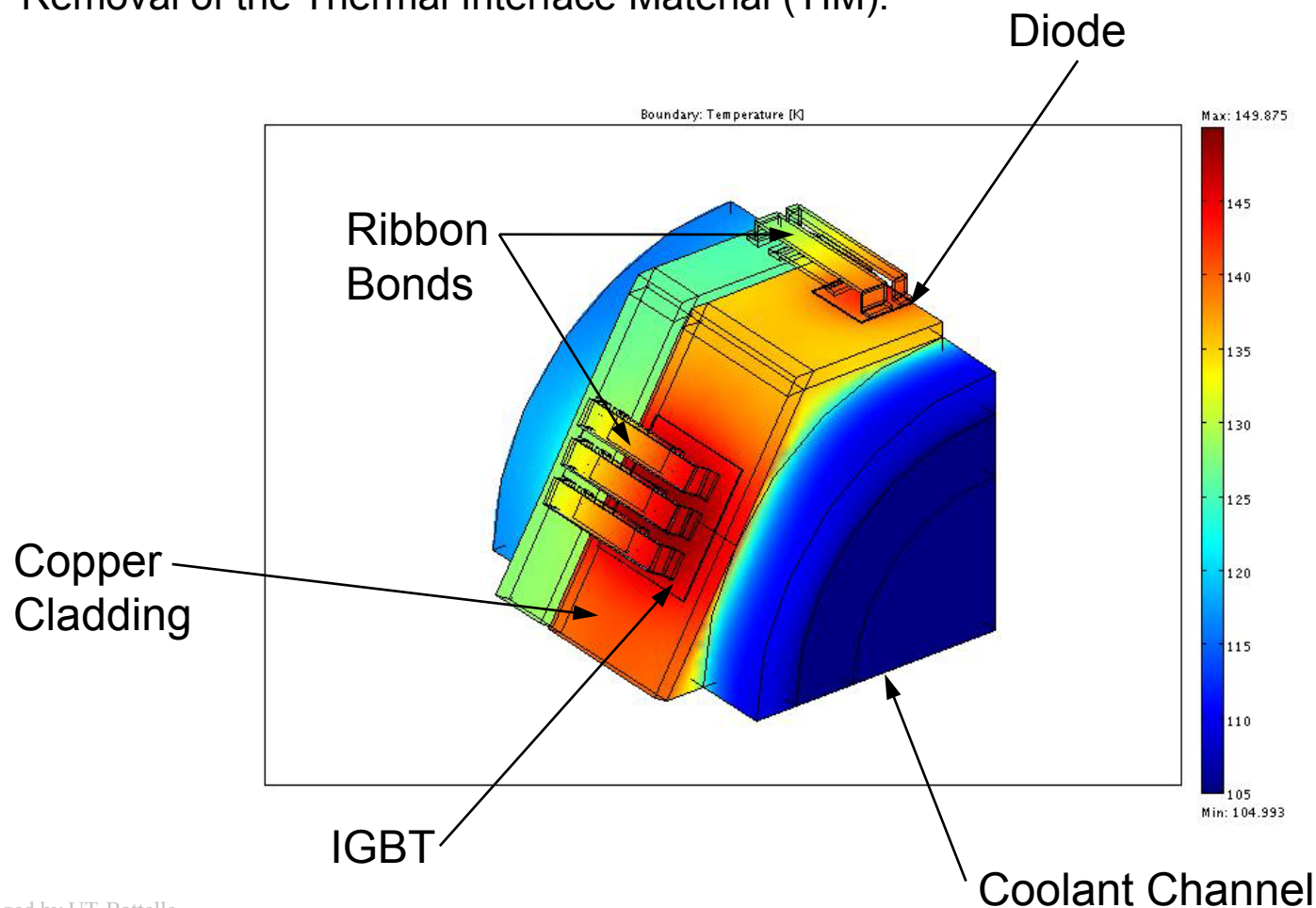


Al_2O_3 plating magnified. Results indicate an excellent bond strength.

Technical Approach

The strategy of this research effort was to reduce the size and weight of the heat sink for power electronic inverter technologies. This objective will be met by:

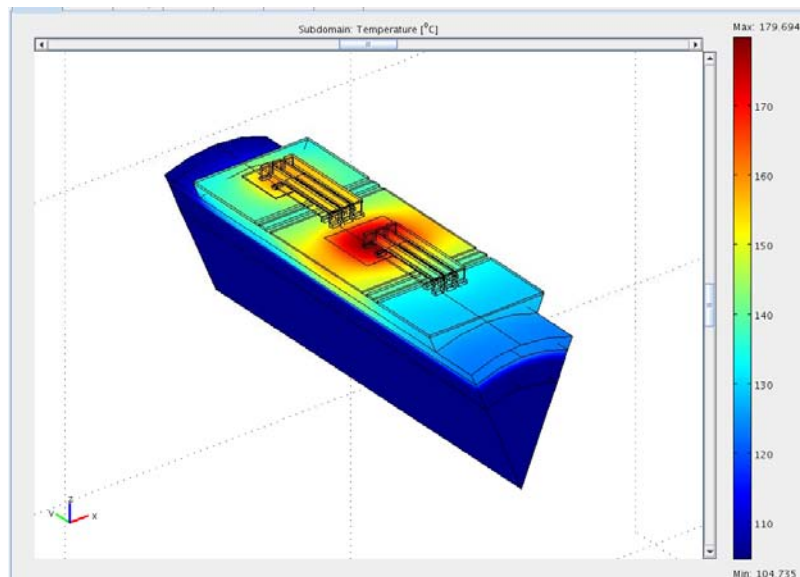
- Directly cooling the substrate package.
- Elimination of the cold plate and the heat spreader.
- Removal of the Thermal Interface Material (TIM).



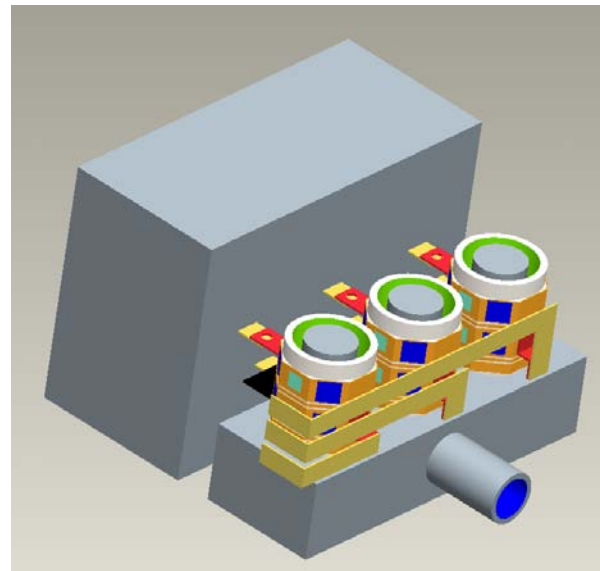
Technical Accomplishments FY09

Two Chip Deep Annulus Design

- Volume of inverter design is 4.1 Liters.
- Coolant is 105°C Water/Ethylene Glycol.
- Copper cladding thickness is 0.012”.
- Design achieves 13.4 kW/L, which meets the 2020 FreedomCAR target.
- Maximum steady state temperatures for 30 kW continuous loads:
 - IGBT – 166.3°C
 - Diode – 151°C
 - Coolant fluid – 143°C



FEA results of annulus design.

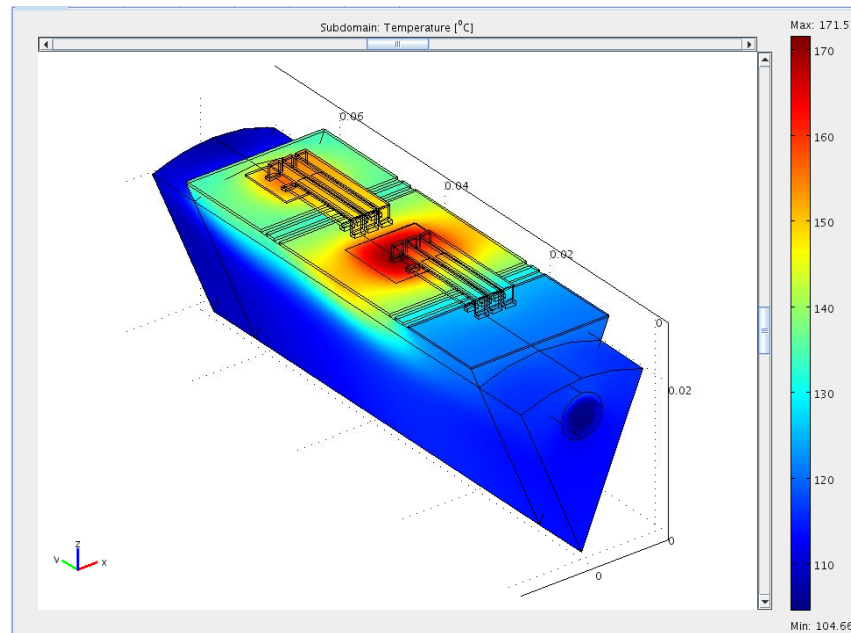


Annulus design component assembly.

Technical Accomplishments FY10

Two chip deep octagonal design containing eight (8) coolant channels.

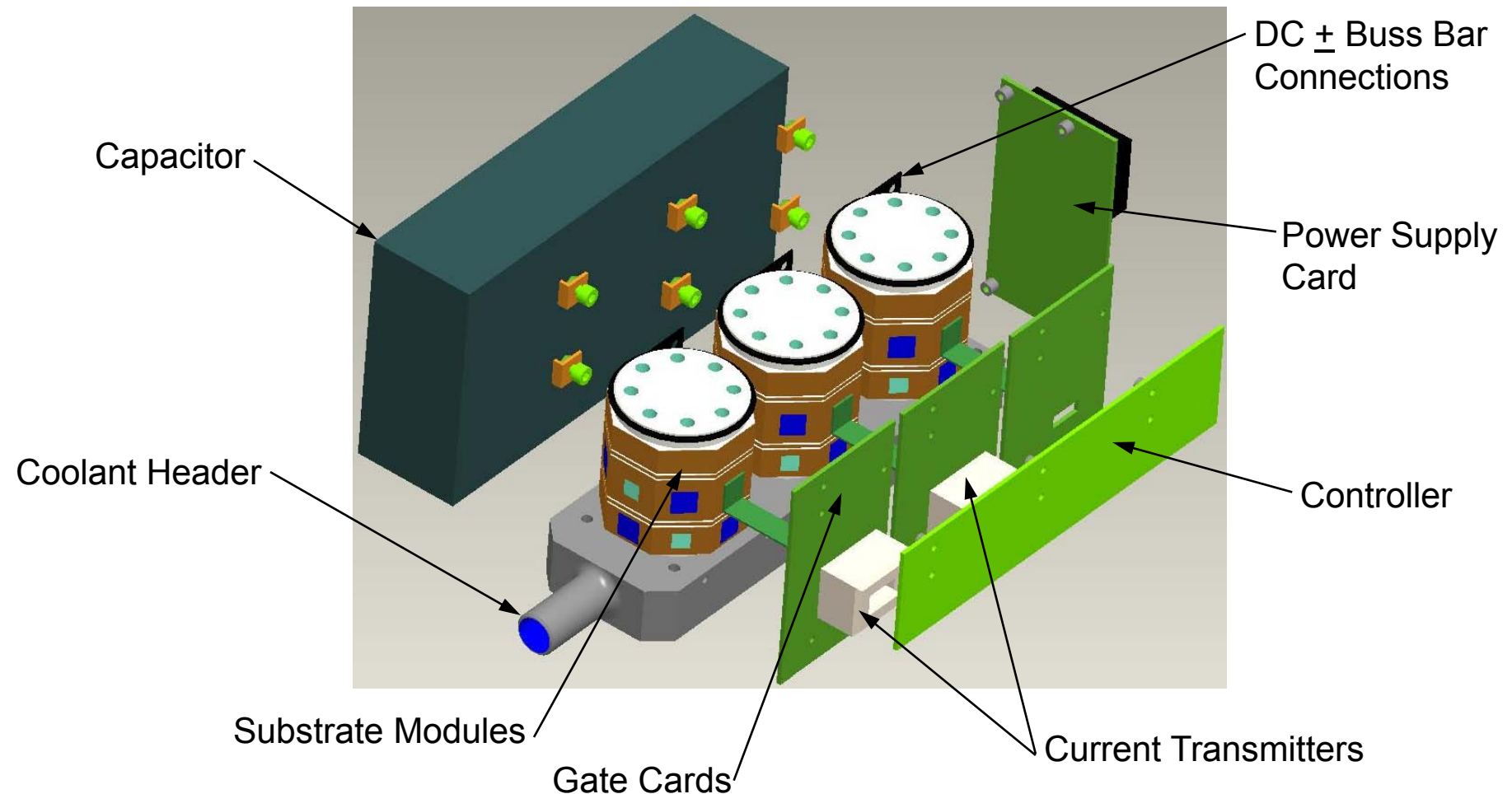
- Volume of inverter design is 3.6 Liters.
- Coolant is 105°C WEG.
- Copper cladding thickness is 0.012”.
- Design achieves 15 kW/L, which meets the 2020 FreedomCAR target.
- Maximum Steady State Temperatures for 30 kW continuous loads:
 - IGBT – 164.5°C
 - Diode – 154.2°C
 - Coolant fluid – 127.8°C



FEA results of octagonal design.

Technical Accomplishments FY10

Two Chip Deep Octagonal Design Assembly Exploded View



Collaborations

Industry Partners

- CoorsTek – Ceramic substrate fabrication.
- Stellar Industries – Metallization of substrates.
- NBE Technologies – Metalized plating and chip sintering.
- Orthodyne Electronics – Ribbon bonds.

Laboratory Partners

- Metals and Ceramics Division – ORNL
 - Andrew Wereszczak – Collaboration on ceramic materials, ceramic module strength, and fatigue issues.
- Power and Energy Systems Group – ORNL
 - Madhu Chinthavali – Gate card and control card design.
- Center for Transportation Technologies and Systems – NREL
 - Kevin Bennion – Thermal package analysis.

Future Work

FY10

- Complete fabrication and initiate assembly of inverter components:
 - Complete fabrication of gate card and control card.
 - Metalize ceramic substrates.
 - Plate the metalized substrates, sinter chips into position, and wire bond.
 - Purchase capacitor with specified DC interconnect positions.
 - Initiate the assembly of the fabricated components.

FY11

- Complete assembly of inverter.
- Test assembled inverter:
 - Complete testing at low power for initial system check-outs. If any technical issues are found, correct the issues and resume initial low power testing.
 - Complete the testing at the full 55 kW test level.
- Prepare design report:
 - Include results in the Vehicle Technologies Annual Report as well as ORNL-TM Report.

Summary

The Direct Water-Cooled Power Electronics Substrate Packaging concept developed at ORNL substantially improves upon the established packaging concepts used today:

- Elimination of the auxiliary cooling loop resulting in a system cost savings of \$175, removal of the base plate and heat sink, and the use of Silicon switches with high temperature (105°C) coolant.

Improvements over the standard inverter packaging include:

- Removal of the TIM or thermal grease which vastly improves waste heat removal in the system.
- The copper base plate and the aluminum heat exchanger are eliminated resulting in additional weight, volume, and cost savings.
- Flowing coolant directly through the ceramic substrate delivers cooling more directly to the semiconductor dies.
- Results indicate a 175°C rated silicon IGBT could work using 105°C WEG coolant.
- This innovative design and thermal stack reduction is expected to achieve higher inverter power densities and significantly reduce system costs.
- Current design allows ORNL to meet the 2020 FreedomCAR target of 14.1 kW/kg with the use of 105°C coolant.