Vehicle Electrification Thermal Management Challenges and Solutions Overview

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Contents

Purpose:

1. Describe market segments and trends in vehicle electrification
2. Describe trends in advanced power semiconductor modules and requirements:
   - Higher operating temperatures and SiC implementation
   - Improved reliability
3. Module design developments and thermal management solutions.
Introduction

DS&A LLC:

Consulting firm founded in 2003, for new business development in electronics thermal management and packaging, for materials, components, and systems.

David L. Saums, Principal

Thirty-two years of electronics thermal management business development, strategic planning, market assessment, product development management, and technical marketing.

General Chair, Program Chair, IEEE Semitherm Conference (2006, 2007)
General Chair, IMAPS Advanced Technology Workshop on Thermal Management (2000-2011)
Co-Chair, ECPE Thermal Interface Materials Workshop, Nürnberg, Germany (2010) and Keynote Co-Chair, IMAPS ATW Automotive (2010)
Co-Chair, ECPE Advanced Cooling Workshop, TU-Delft, The Netherlands (2008)
Co-Chair, ECPE Advanced Thermal Workshop, Nürnberg, Germany (2006) and Keynote Speaker Co-Chair, IMAPS ATW Power LED Packaging (2005, 2006)
Organizing Committee, Technical Session Chair, IMAPS France ATW Thermal (2006-2011)
IMAPS Fellow (2010)
Purpose and Motivation

Why are we pursuing increased electrification of ground vehicles?

- Decrease dependence on petroleum fuels
- Decrease emission and particulate air pollution and increase air quality
- Reduce production of ozone-depleting gases
- Increase vehicle powertrain efficiency and reduce overall losses
- Reduce vehicle powertrain weight
- Increase use of electricity, a significantly less expensive fuel than gasoline and diesel
- Increase electricity consumption with night-time charging, balancing total electric utility output capacity and total 24-hour cycle demand
- Increase use of electricity as a fuel, which is produced with solar, wind, hydro, nuclear, natural gas, coal, wave action, biofuel, and other types of fuels.
- Regenerative braking for energy recapture
- For specialty vehicles:
  - Increase capabilities for on-board power generation that is not dependent on PTO
  - Reduce vehicle thermal image (for military ground vehicles)
  - Develop silent-running capabilities (for military ground vehicles).

Source: Johnson Controls Inc.
## Terminology

Common terms:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEV</td>
<td>Hybrid electric vehicle</td>
</tr>
<tr>
<td>EREV</td>
<td>Extended-range electric vehicle</td>
</tr>
<tr>
<td>PHEV</td>
<td>Plug-in hybrid electric vehicle</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery electric vehicle (or, simply, electric vehicle)</td>
</tr>
<tr>
<td>FCEV</td>
<td>Fuel cell electric vehicle</td>
</tr>
<tr>
<td>ICE</td>
<td>Internal combustion engine</td>
</tr>
<tr>
<td>PEEM</td>
<td>Power electronics and electrical machine</td>
</tr>
<tr>
<td>IGBT</td>
<td>Isolated gate bipolar transistor</td>
</tr>
<tr>
<td>SiC</td>
<td>Silicon carbide</td>
</tr>
<tr>
<td>GaN</td>
<td>Gallium nitride</td>
</tr>
</tbody>
</table>
Powertrain Electrification Topologies

A simple scheme for categorizing powertrain technologies, illustrating the transition from thermal power vehicle (TV) to electric power vehicle (EV):

Power ratio classification:

Global demand for rapid improvements in energy efficiency in every form is driving rapid development in the power semiconductor market:

- All forms of energy generation, transmission, storage, application.
- Power semiconductor fabrication: transition from silicon to silicon carbide:
  - Higher temperature capability with smaller semiconductor footprint
  - Reduced device size, reduced losses
  - Higher reliability, improved life
- Power semiconductor packaging development requirements:
  - Packaging and thermal materials
  - Components
  - Power delivery, storage, and thermal management components and systems
- Higher temperature capability for semiconductor devices:
  - SiC may be used at current operating temperatures to achieve higher system reliability.
  - SiC may be used at higher future operating temperatures, with accompanying demand for higher system reliability.
- Summary: Higher operating temperatures, heat fluxes, requiring new packaging materials and improved thermal management solutions.
Vehicle Market Segments
HEV/PHEV/EV Market Forecasts

Electrification by passenger vehicle segment, North America:
- North American vehicle market is heavily focused on SUV/light truck/van/crossover segments:

![Diagram showing vehicle segments](chart.png)

Source: Johnson Controls Inc.
HEV, PHEV, and EV Vehicle Market Segments

Many differing passenger vehicle segments. Expected duty cycles vary across markets.

Source: C. Rudolph, STILL GmbH, Hamburg, Germany
HEV, PHEV, and EV Vehicle Market Segments

Increasing electrification with Chevrolet Volt EREV:

- Always operates on electric traction motors
- First 40 miles on electric drive (Charge-depleting, or CD mode) from battery
- Remaining driving on gasoline or electric drive from battery/ICE/generator (Charge-sustaining, or CS mode) at an energy cost of 3 cents per mile.

HEV, PHEV, and EV Vehicle Market Segments

Increasing electrification with Chevrolet Volt EREV:

- 16kWh battery pack with PHEV charging system
- Self-contained pumped liquid cooling system for energy storage system
- CD (Charge-depleting) mode allows 40 miles and CS (Charge-sustaining) mode allows an additional 260 miles. Total range: approximately 300 miles
- An EREV is more similar to an EV than and HEV
- Volt is designed to operate as a fully electric vehicle, with added assurance of a gas tank to extend vehicle operating range:
  - CD mode is capable of acceleration (0-60 MPH): 9 seconds (without ICE assistance)
  - ICE is used only to sustain battery State of Charge (SOC) at a target point in battery charge depletion cycle
  - Goal: eliminate “Range Anxiety” for consumers.

Source: T. Mackintosh, General Motors Advanced Battery Lab (2009)
Examples of HEV, PHEV, and EV Vehicle Market Segments

Operational and environmental conditions and duty cycles vary across markets.
Examples of Commercial HEV, PHEV, and EV Vehicle Market Segments

Class 7 Heavy Hybrid Refuse Truck - Oshkosh

Class 6 Utility Boom Truck - Freightliner

Class 7 Utility Boom Truck - Freightliner

Class 8 OTR Tractor - Peterbilt
Bus Market Example – PHEV Heavy Vehicle Market Segment

HEV/PHEV school bus development (U.S.):
- First prototype program PHEV bus cost $220,000 each
- Premium of $139,000 each over standard bus prices
- Price goal: 20-50% purchase price premium in volume production over standard diesel buses
- First deliveries in 2007 for 2-year test program
- Why?
  - Reduction in diesel engine particulate emissions
  - Reduce children’s exposure to diesel exhaust gases, fumes
  - Improved fuel economy
- Why PHEV?
  - Increased energy efficiency
  - Recharging with reduced nighttime electricity costs
  - Reduced engine maintenance costs and downtime
  - Lifecycle costs approximately equal to a conventional diesel bus
  - Regenerative braking allows energy recovery during operation
  - Less risk because of significant reductions in fuel consumption and dual-fuel capability.

Source: Advanced Energy
Hybrid Vehicle Powertrains
HEV, PHEV, and EV Vehicle Market Segments

Major components of a current 2010MY HEV propulsion system:
HEV, PHEV, and EV Vehicle Market Segments

Major components of a current propulsion system for a rear-wheel drive light urban delivery truck:

Single-side and Double-sided Liquid Cooling – Production Examples

- Siemens ELFA2® inverter, with single-side cooling on traditional liquid cold plate, for series hybrid drive for HEV bus designs:
  - Operating $T_J = 150^\circ C$
  - Output power to 200kW
  - Liquid coolant temperature of -40°C - +70°C
  - Maximum coolant temperature of +105°C if ICE coolant is utilized
  - Operating life requirement: 15 years x 11 hrs./day or 1 million km
  - Vibration levels to 6g, wide range of frequencies

Source: M. Helsper, Siemens AG
Hybrid and Electric Powertrain Architectures

Hybrid and electric powertrains by power, energy, and electric range requirements:

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Power (kW)</th>
<th>Energy (kWh)</th>
<th>Electric Range (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild HEV Car</td>
<td>&lt; 20</td>
<td>0.5 – 1</td>
<td>No Electric-Only Range</td>
</tr>
<tr>
<td>Full HEV Car</td>
<td>25 – 50</td>
<td>1 - 3</td>
<td>No Electric-Only Range</td>
</tr>
<tr>
<td>PHEV Car</td>
<td>&gt; 40</td>
<td>10</td>
<td>Limited Range</td>
</tr>
<tr>
<td>EV Car/Light Truck</td>
<td>&gt;40</td>
<td>20</td>
<td>&gt; 150 km Range</td>
</tr>
<tr>
<td>Hybrid Bus</td>
<td>&gt; 80</td>
<td>10</td>
<td>Limited Range</td>
</tr>
<tr>
<td>Military Tactical Vehicle</td>
<td>&gt;50</td>
<td>(By vehicle type)</td>
<td>(By vehicle type)</td>
</tr>
</tbody>
</table>

Military Tactical Ground Vehicle HEV Powertrain Thermal Management Goals

US Army ground mobile vehicle overall powertrain thermal management system goals:

<table>
<thead>
<tr>
<th>Ground Mobile Vehicle Powertrain Thermal Management Key Goals</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power electronics coolant temperature (inlet)</td>
<td>65°C (baseline)</td>
</tr>
<tr>
<td>Power electronics heat flux</td>
<td>89 W/cm² (baseline)</td>
</tr>
<tr>
<td>Air filtration scavenging blower performance</td>
<td>2X improvement (motor service life)</td>
</tr>
</tbody>
</table>

| Power electronics coolant temperature (inlet)               | 80°C (threshold) |
| Power electronics heat flux                                  | 350 W/cm² (threshold) |
| Air filtration scavenging blower performance                | 400 W/cm² (objective) |

Source: RDECOM TARDEC
Military Tactical Wheeled and Tracked HEV Vehicle Requirements

Examples of on-board cooling systems developed for military tactical vehicles:

- Traditional diesel prime mover (ICE) cooling system:

![Undisclosed military tactical vehicle](image)

Source: Ametek Rotron, Woodstock NY USA; Ametek Rotron Air Technology Business Unit (UK)
### Device, Package, and System Challenges Impacted by Thermal Materials, Cooling Technologies, and Coolant Selection

<table>
<thead>
<tr>
<th>Challenge</th>
</tr>
</thead>
<tbody>
<tr>
<td>High or Increased Power Densification, Higher Total Load, and Higher Performance</td>
</tr>
<tr>
<td>Market Demands for Higher Reliability</td>
</tr>
<tr>
<td>Increased Device and Package Temperature Rating</td>
</tr>
<tr>
<td>Increased Ambient Operating Temperatures</td>
</tr>
<tr>
<td>Increased Reliability in Systems with <em>High Cylcical Loads</em></td>
</tr>
<tr>
<td>Ability to Apply Single Cooling Circuit to Multiple Subsystems</td>
</tr>
<tr>
<td>Achieve Weight and Volume Reductions</td>
</tr>
<tr>
<td>Liquid Coolant in Proximity to High Voltages and/or Coolant Circuit Internal to Electronics Module</td>
</tr>
<tr>
<td>Methods to Reduce Thermal Stacking for Multiple Loads in a Coolant Circuit</td>
</tr>
<tr>
<td>Control of Internal Self-Heating</td>
</tr>
<tr>
<td>Low Ambient Operating Temp (-55°C) without Glycol Derating</td>
</tr>
</tbody>
</table>

*Source: DS&A LLC*
### Vehicle Onboard Coolant Choices and Temperature Ranges: HEV/PHEV/EV

<table>
<thead>
<tr>
<th>Vehicle PEEM Cooling Technology</th>
<th>Coolant Maximum Temperature (Typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forced Air</td>
<td>60°C</td>
</tr>
<tr>
<td>Separate Liquid Cooling Circuit</td>
<td>65 - 80°C</td>
</tr>
<tr>
<td>Engine Liquid Cooling Circuit</td>
<td>95 - 105°C</td>
</tr>
<tr>
<td>Transmission Oil Cooling Circuit*</td>
<td>125°C</td>
</tr>
</tbody>
</table>

* Typically used only for motor stator cooling in HEV powertrain

Primary solution for future vehicles
Critical Application Issues in Power Electronics – Why Silicon Carbide?

High breakdown strength of SiC allows higher switching frequency operation and power density.

High breakdown strength of SiC allows higher switching frequency operation, comparable voltage breakdown ratings, reduced switching losses compared to silicon.

- **End goal?**
  - 2-3X current and inverter power output for the same coolant temperatures
  - Reduced volume and increased power density, SiC inverter vs. silicon inverter design

---

### Operating Condition

<table>
<thead>
<tr>
<th>Operating Condition</th>
<th>0 RPM</th>
<th>4000 RPM</th>
<th>12000 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Junction Temp. °C</td>
<td>Coolant Temp. °C</td>
<td>Max phase current A dc</td>
</tr>
<tr>
<td>All SiC Module</td>
<td>175</td>
<td>80</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>N/A</td>
</tr>
<tr>
<td>FF400R12KT3 IGBT Module</td>
<td>125</td>
<td>80</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>100</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Standard Infineon silicon 400A IGBT module**

**Compare relative current capability (higher $T_J$, same liquid coolant temp)**

**Compare relative power capability (higher $T_J$, same liquid coolant temp)**

---

Critical Application Issues in Power Electronics – Why Silicon Carbide?

Higher voltage, reduced volume, increased power density in HEV/EV powertrain inverters:

- Increased system voltage applied to enable higher-power traction motors
- Reduced volume and increased power density, SiC inverter vs. silicon inverter design

IGBT Module Typical Construction (with Baseplate)

Solder Layer 1:
- Die Attach (Yellow)
- Direct Bond Copper (Green, 2X)

Solder Layer 2:
- DBC Attach (Yellow)

IGBT and Diode Die (6-16, typ.)

Power Leads

Gel or Potting Compound

AlN Dielectric

TIM2* (Red) to Liquid Cold Plate or Air-Cooled Thermal Solution

AlSiC Baseplate (Green)

* May be specified by IGBT manufacturer in application and use instructions or may be specified by OEM

Note regarding terminology: DBC (direct bond copper) is referred to as DCB in Europe.
IGBT Module Baseplate: Primary Heat Transfer and Failure Modes

Source: DS&A LLC

Direct Bond Copper (DBC) on Aluminum Oxide

Aluminum Oxide Dielectric

IGBT Die

Diode

Aluminum Wirebonds

Source: DS&A LLC
# IGBT Module Material Roles: Improvement Needs

Module material roles and SiC IGBT development needs: ▲ Primary ▲▲ Secondary ▲▲▲ Critical

<table>
<thead>
<tr>
<th>Function</th>
<th>Baseplate</th>
<th>DBC</th>
<th>Ceramic</th>
<th>Solder/ LTJT</th>
<th>Bondwire</th>
<th>Power Leads</th>
<th>Gel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical support</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲▲</td>
<td>▲</td>
<td></td>
</tr>
<tr>
<td>Package integrity</td>
<td>▲▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲▲</td>
<td>▲</td>
</tr>
<tr>
<td>Power distribution and interconnect</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲▲</td>
<td>▲</td>
</tr>
<tr>
<td>Electrical isolation</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>Thermomechanical stress relief</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲▲</td>
<td>▲</td>
</tr>
<tr>
<td>Die protection</td>
<td></td>
<td></td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>Heat transfer</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
<td>▲</td>
</tr>
</tbody>
</table>
**Trends in IGBT Module Performance and Reliability Improvement**

- IGBT module packaging improvements:

<table>
<thead>
<tr>
<th>IGBT Module Packaging Improvements and Needed Development Materials and Components</th>
</tr>
</thead>
<tbody>
<tr>
<td>Higher-temperature packaging and thermal materials</td>
</tr>
<tr>
<td>Low-temperature joining techniques</td>
</tr>
<tr>
<td>Transition to improved wirebonding techniques (e.g., wedgebonding)</td>
</tr>
<tr>
<td>Transition to monolithic module metals (e.g., copper)</td>
</tr>
<tr>
<td>Transition from aluminum wire to aluminum ribbon bonding</td>
</tr>
<tr>
<td>Higher thermal conductivity CTE-matched baseplate materials</td>
</tr>
<tr>
<td>Double-sided liquid cooling package developments</td>
</tr>
</tbody>
</table>
HEV IGBT Module Baseplates - Integrated Liquid Cooling

Source: Rogers Corporation
HEV IGBT Module Baseplates - Integrated Liquid Cooling

Sources: CPS Technologies; Infineon Technologies
IGBT Module Current Construction: Infineon HybridPack™ 3 for HEV/EV Market

HEV IGBT Module Baseplate – Integral Copper Solder Pad

CPS Technologies’ AlSiC Net-Shape Cast Pin Fin Baseplates – Mild HEV IGBT Modules

Source: DS&A LLC; CPS Technologies 04-30-2010

Copper Flame Spray Deposition: Solder Surface Improvement
(Army Research Laboratory)
Single-side Direct Liquid Cooling – Development Examples

Cast and Machined CTE-Matched Liquid Cold Plate for GE Power Overlay Technology

Net-Shape Cast CTE-Matched Liquid-Cooled HEV Inverter IGBT Baseplate

Source: DS&A LLC
HEV IGBT Module Baseplates - Integrated Liquid Cooling

Sources (clockwise from top left):  
(a) Wolverine MicroCool, February 3, 2010;  
(b) K. Rahman, N. Patel, T. Ward, GM ATC;  
(c) DS&A LLC

Overview: Vehicle Electrification Thermal Management Challenges and Solutions
HEV IGBT Module Baseplates - Integrated Liquid Cooling

Wolverine MicroCool™ MDT Copper Pin Structure

Wolverine MicroCool™ MDT Copper Parallel Fin Structure
Ni-Plated Copper 3mm EconoDual™ IGBT Baseplate

Source: Wolverine Tube Inc.
IGBT Single-side and Double-sided Liquid Cooling – Production Examples

- Double-sided liquid cooling for integrated IGBT module in traction inverter:

![Diagram of Double-sided Liquid Cooling](image)

Examples of on-board cooling systems developed for military tactical vehicles:

- HEV Powertrain inverter cooling system for major US military vehicle OEM:
  - Pumped two-phase liquid cooling system
  - Coolant: R-134a and HFO-1234yf refrigerant

Source: Parker Hannifin Corporation
MEPTEC Thermal Workshop, San Jose CA USA
March 21, 2011
Overview: Vehicle Electrification Thermal Management Challenges and Solutions
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HEV/PHEV/EV Applications for Liquid Immersion Cooling Systems

Liquid immersion cooling has been used for decades for power semiconductor (GTO, thyristor) devices:

• AC propulsion heavy haul diesel-electric freight locomotives
  • Locomotive AC electrical system MTBF: > 900 days
• AC regional EMU trainsets (Europe)
• Heavy AC drive mining trucks:
  • AC drive cabinet power density: 1MW/m
  • Compact
  • Sealed for dirty environments

Source: 3M EMMD; Photograph: Siemens
HEV/PHEV/EV Applications for Liquid Immersion Cooling Systems

3M EMMD liquid immersion R&D with dielectric Fluoroketone liquids:

- Immersion cooling concept applied to HEV IGBT module
- Conceptual work and testing only at this time – double-side two-phase liquid cooling with surface enhancements on CTE-matched spreaders:

HEV/PHEV/EV Applications for Liquid Immersion Cooling Systems

Liquid immersion cooling in new investigations with current fluids to minimize thermal losses:

- New 3M HFE and FK dielectric liquids
- Eliminates thermal resistances of packaging materials, joining and TIM materials, and baseplate
- Latest IGBT4, IGBT5 die
- New test data published:
Energy Storage Systems
Energy Storage: Energy versus Power Requirements for HEV/PHEV/EV Vehicles

Ragone Chart, Battery Specific Power vs. Specific Energy

Battery Pack Storage Life vs. Temperature

“Coffee Bag” Li-Ion Cell Array

Proposed Application of Liquid Cold Walls for Li-Ion Battery Pack Thermal Management

Source: DS&A LLC
## Energy Storage: Energy versus Power Requirements for HEV/PHEV/EV Vehicles

Generalized statement of desirable characteristics of battery performance:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>High specific power</td>
<td>W/kg (cell level)</td>
</tr>
<tr>
<td>High specific energy</td>
<td>Wh/kg (cell level)</td>
</tr>
<tr>
<td>High power density</td>
<td>W/liter (cell level)</td>
</tr>
<tr>
<td>High energy density</td>
<td>Wh/liter (cell level)</td>
</tr>
<tr>
<td>High energy throughput</td>
<td>(Depth of discharge dependent)</td>
</tr>
<tr>
<td>High cell voltage</td>
<td>V</td>
</tr>
<tr>
<td>Zero voltage hysteresis</td>
<td>100% energy efficient</td>
</tr>
<tr>
<td>High endurance</td>
<td>Life (hours) and cycling (cycles)</td>
</tr>
<tr>
<td>Overcharge and short circuit endurance</td>
<td>--</td>
</tr>
</tbody>
</table>

### Summary: Thermal Management Challenges for Vehicle Powertrain Electrification

#### Summary of Trends and Needs:

<table>
<thead>
<tr>
<th>Trend</th>
<th>Impact</th>
<th>Needs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location of required electronic modules: placement underhood, on-engine</td>
<td>Increasing ambient operating temperatures</td>
<td>Higher-temperature materials ( &gt;150-200°C and &gt;200-300°C )</td>
</tr>
<tr>
<td>More highly integrated components</td>
<td>Higher power losses</td>
<td>Improved joining and CTE-matched materials</td>
</tr>
<tr>
<td>More electrification</td>
<td>Increasing power requirements</td>
<td>Lower cost module-level liquid cooling solutions</td>
</tr>
<tr>
<td>Increasing switching speeds</td>
<td>Higher heat fluxes</td>
<td>Improved thermal joining materials</td>
</tr>
<tr>
<td>Double-sided liquid cooling</td>
<td>Reduced cost and volume</td>
<td>Improved liquid cold plate/immersion plate design</td>
</tr>
</tbody>
</table>

*Source: DS&A LLC, after M. Rittner (Robert Bosch)*

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Market assessment, business strategy development, and new product strategy development for electronics thermal management.