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

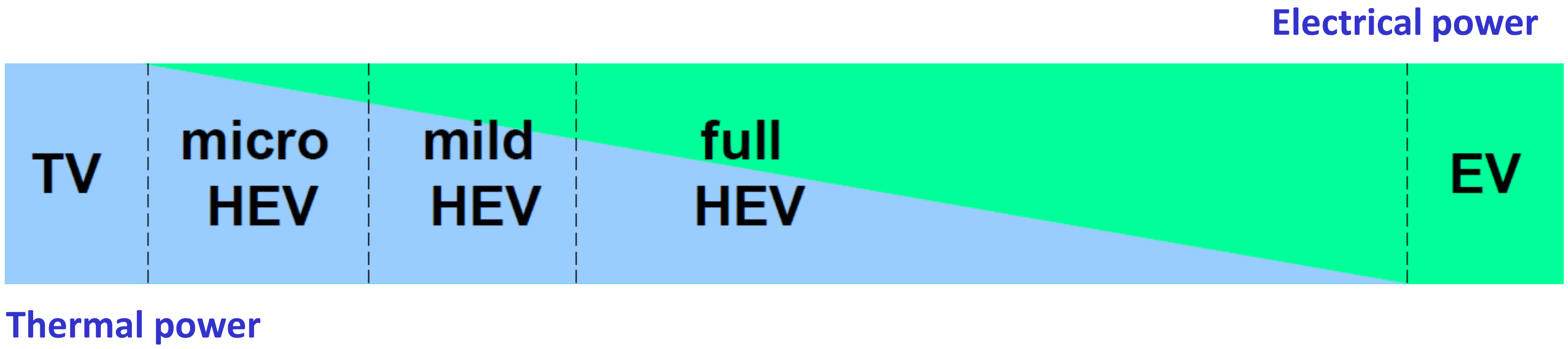
Common terms:

HEV	Hybrid electric vehicle
EREV	Extended-range electric vehicle
PHEV	Plug-in hybrid electric vehicle
BEV	Battery electric vehicle (or, simply, electric vehicle)
FCEV	Fuel cell electric vehicle
ICE	Internal combustion engine
PEEM	Power electronics and electrical machine
IGBT	Isolated gate bipolar transistor
SiC	Silicon carbide
GaN	Gallium nitride

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:



Source: A. Bouscayrol, R. Trigui, University of Lille, "Modelling of Hybrid Electric Vehicles for Energy Management", IEEE Vehicle Propulsion and Power Conference 2009, Dearborn MI USA, Sept. 6-9, 2009.

Issues in Vehicle Power Electronics – Market Drivers

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

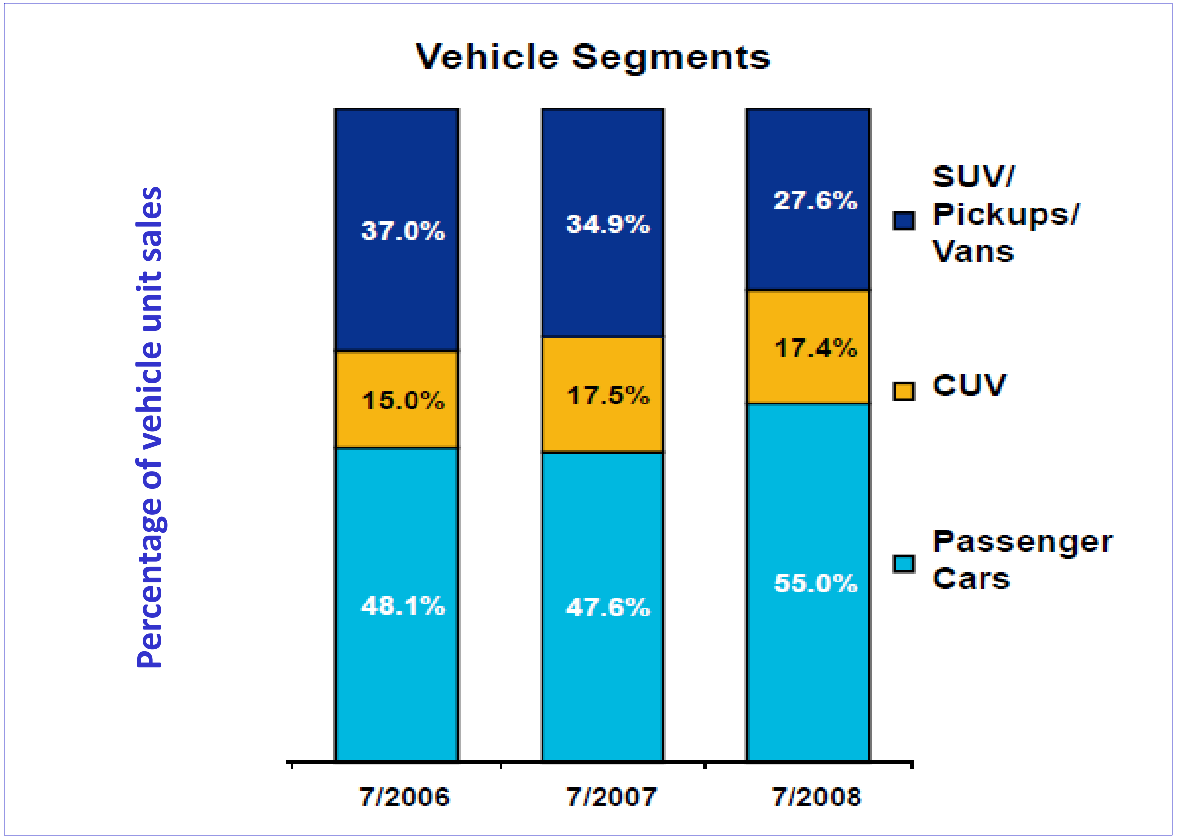
- All forms of energy generation, transmission, storage, application.
- Power semiconductor fabrication: transition from silicon to silicon carbide:
  - Higher temperature capability with smaller semiconductor footprint
  - Reduced device size, reduced losses
  - Higher reliability, improved life
- Power 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:



Source: Johnson Controls Inc.

HEV, PHEV, and EV Vehicle Market Segments

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

Think OX 5-passenger sedan

Tesla Roadster, 300HP

STILL FCEV Forklift Drive

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.

Source: L. Burns, General Motors VP R&D and Strategic Planning, "Driving to a Sustainable Future", Keynote Presentation (Unpublished, with permission), IEEE VPPC 2009 Conference, Dearborn MI USA September 6-10, 2009.

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.

Construction and agricultural vehicles

Military tactical and transport vehicles

Light Rail Vehicles (LRV)

Urban Buses

Military tactical and transport vehicles

Examples of Commercial HEV, PHEV, and EV Vehicle Market Segments

Class 7 Heavy Hybrid Refuse Truck - Oshkosh

Class 7 Utility Boom Truck - Freightliner

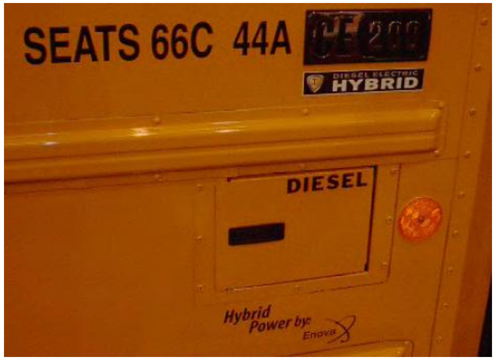
Class 6 Utility Boom Truck - Freightliner

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.



International PHEV School Bus

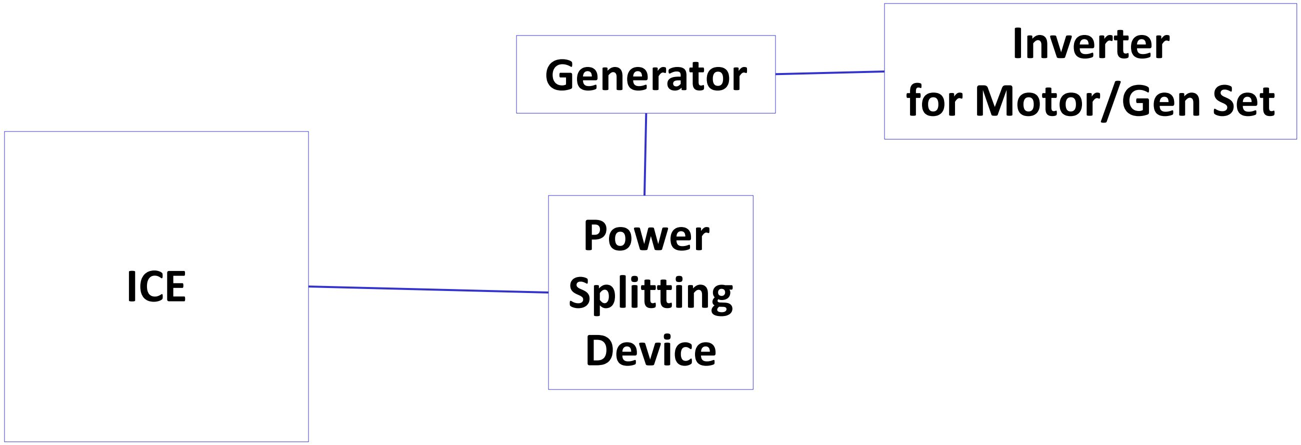
Bus Traction Motor

Source: Advanced Energy

Hybrid Vehicle Powertrains

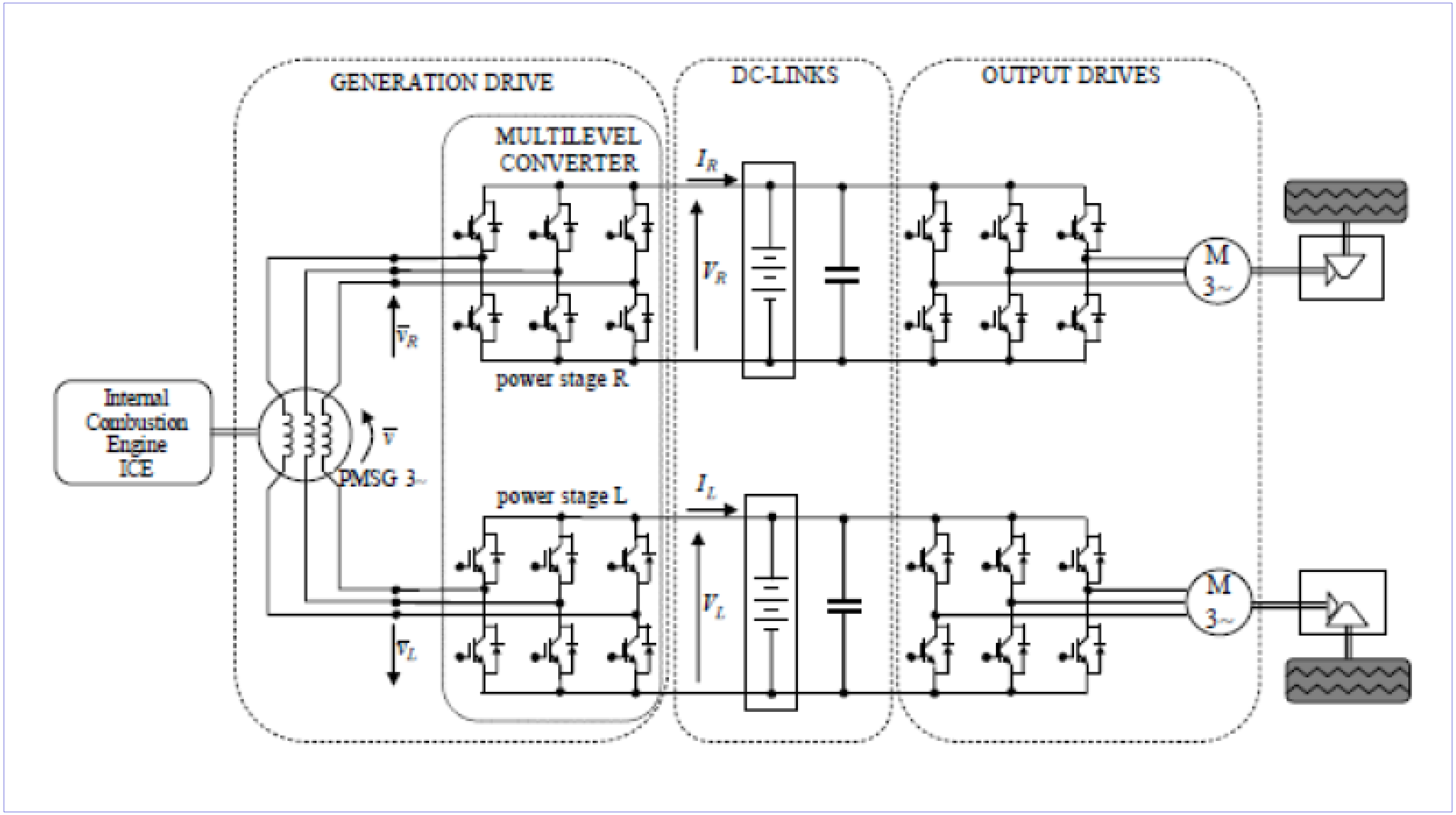
HEV, PHEV, and EV Vehicle Market Segments

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:



Source: C. Rossi, G. Grandi, P. Corbelli, D. Casadei, University of Bologna, Italy: "Generation System for Series Hybrid Powertrain Based on the Dual Two-Level Inverter", EPE 2009 Conference, Barcelona, Spain. September 3, 2009.

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 $T_J = 150°C$
  - 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:

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

Sources: C.A. Rosenkranz, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Modern Battery Systems for Plug-in Hybrid Electric Vehicles"; also, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Li-Ion Battery Systems for the Next Generation of Hybrid Electric Vehicles", Nineteenth International AVL Conference "Engine & Environment", September 6-7, 2007, Graz, Austria.

Military Tactical Ground Vehicle HEV Powertrain Thermal Management Goals

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

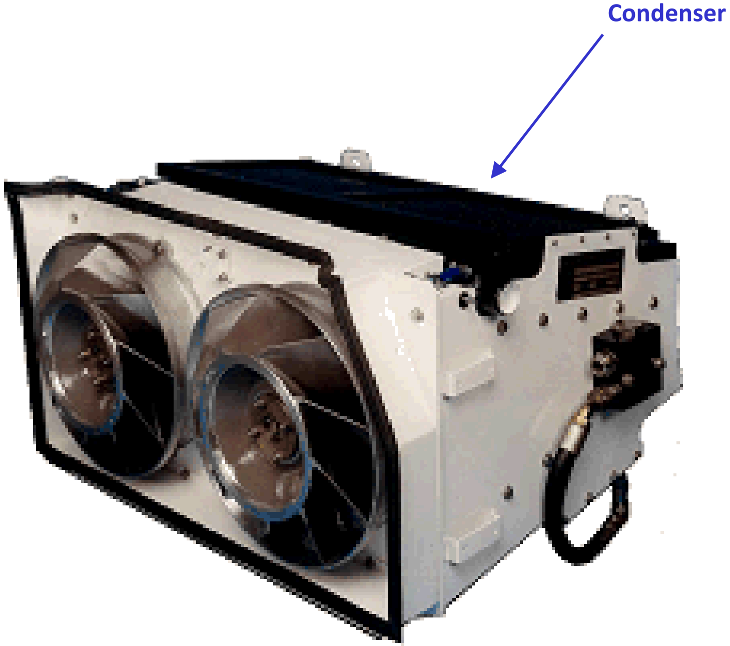
Ground Mobile Vehicle Powertrain Thermal Management Key Goals	Target
Power electronics coolant temperature (inlet)	65°(baseline) 80°C (threshold) 100°C (objective)
Power electronics heat flux	89 W/cm^2 (baseline) 350W/cm^2 (threshold) 400W/cm^2 (objective)
Air filtration scavenging blower performance	2X improvement (motor service life)

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

Source: Ametek Rotron , Woodstock NY USA ; Ametek Rotron Air Technology Business Unit (UK)

Critical Application Issues in Power Electronics – What's Important, Where?

Device, Package, and System Challenges Impacted by Thermal Materials, Cooling Technologies, and Coolant Selection
High or Increased Power Densification, Higher Total Load, and Higher Performance
Market Demands for Higher Reliability
Increased Device *and Package* Temperature Rating
Increased Ambient Operating Temperatures
Increased Reliability in Systems with *High Cyclical Loads*
Ability to Apply Single Cooling Circuit to Multiple Subsystems
Achieve Weight and Volume Reductions
Liquid Coolant in Proximity to High Voltages and/or Coolant Circuit Internal to Electronics Module
Methods to Reduce Thermal Stacking for Multiple Loads in a Coolant Circuit
Control of Internal Self-Heating
Low Ambient Operating Temp (-55°C) <u>without</u> Glycol Derating

Source: DS&A LLC

Vehicle Onboard Coolant Choices and Temperature Ranges: HEV/PHEV/EV

Vehicle PEEM Cooling Technology	Coolant Maximum Temperature (Typical)
Forced Air	60°C
Separate Liquid Cooling Circuit	65 - 80°C
Engine Liquid Cooling Circuit	95 - 105°C
Transmission Oil Cooling Circuit*	125°C

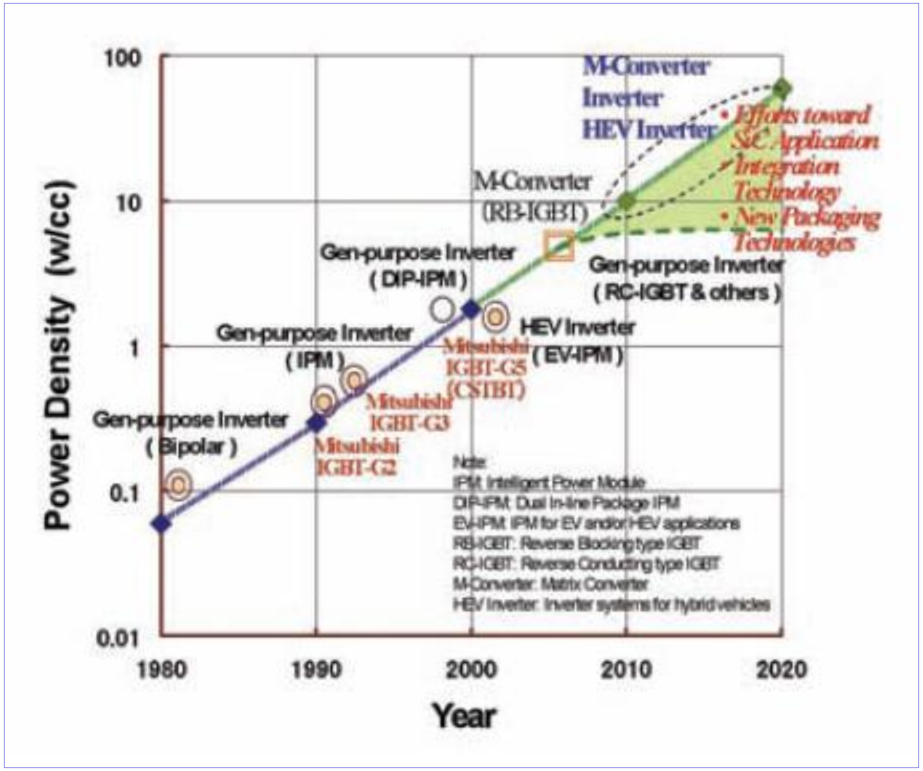
* Typically used only for motor stator cooling in HEV powertrain

Primary solution for future vehicles

Source: After I. Graf, Infineon Technologies

Critical Application Issues in Power Electronics – Why Silicon Carbide?

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

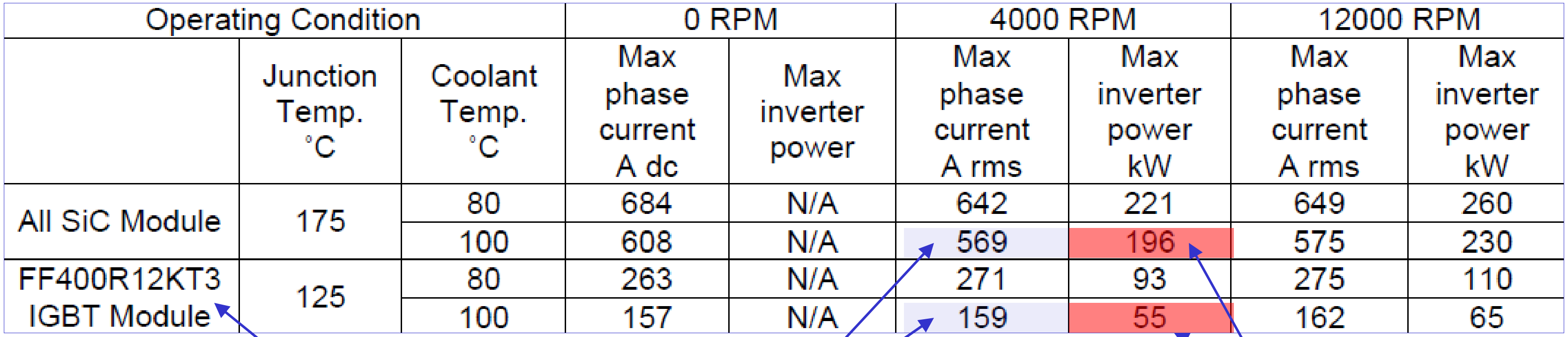


Source: G. Majumdar, Mitsubishi Electric, "Power Device Technologies for Sustainable Growth of Power Conversion Applications", 11-2008

Critical Application Issues in Power Electronics – Why Silicon Carbide?

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			0 RPM		4000 RPM		12000 RPM	
	Junction Temp. °C	Coolant Temp. °C	Max phase current A dc	Max inverter power	Max phase current A rms	Max inverter power kW	Max phase current A rms	Max inverter power kW
All SiC Module	175	80	684	N/A	642	221	649	260
		100	608	N/A	569	196	575	230
FF400R12KT3 IGBT Module	125	80	263	N/A	271	93	275	110
		100	157	N/A	159	55	162	65

Standard Infineon silicon 400A IGBT module

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

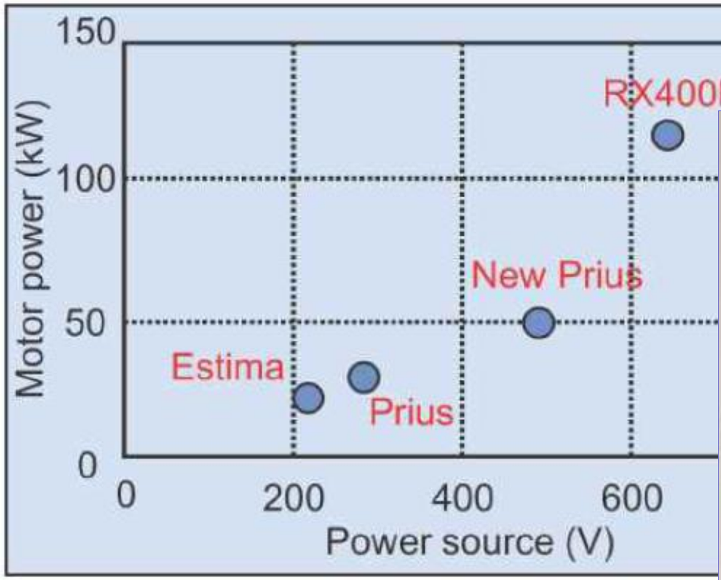
Compare relative power capability (higher T_J, same liquid coolant temp)

Source: D. Urciuoli, R. Wood, T. Salem, G. Ovrebo, US Army Research Laboratory; T. Salem, US Naval Academy; "Design and Development of a 400A, All-Silicon Carbide Power Module," NDIA Michigan USA, 2008.

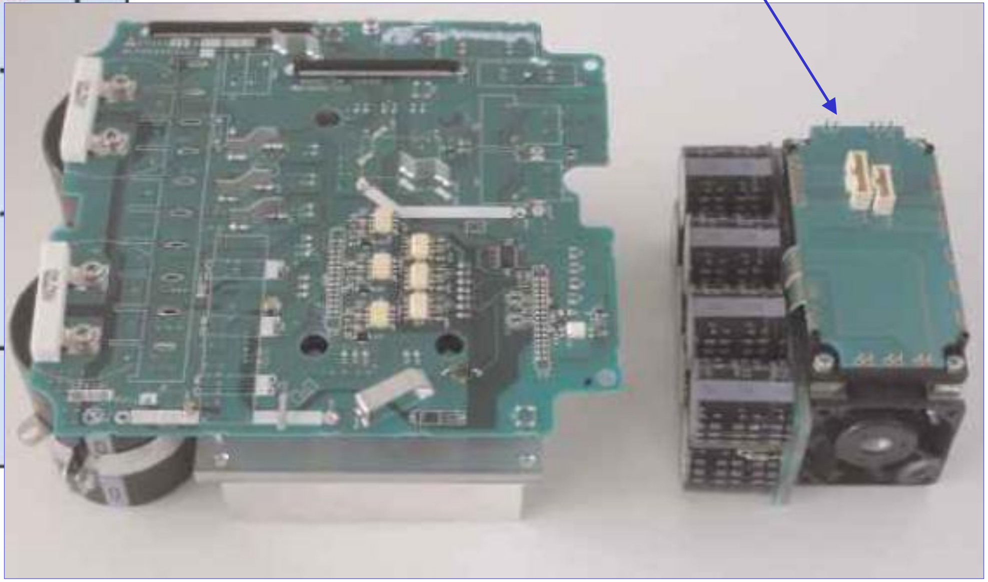
Critical Application Issues in Power Electronics – Why Silicon Carbide?

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



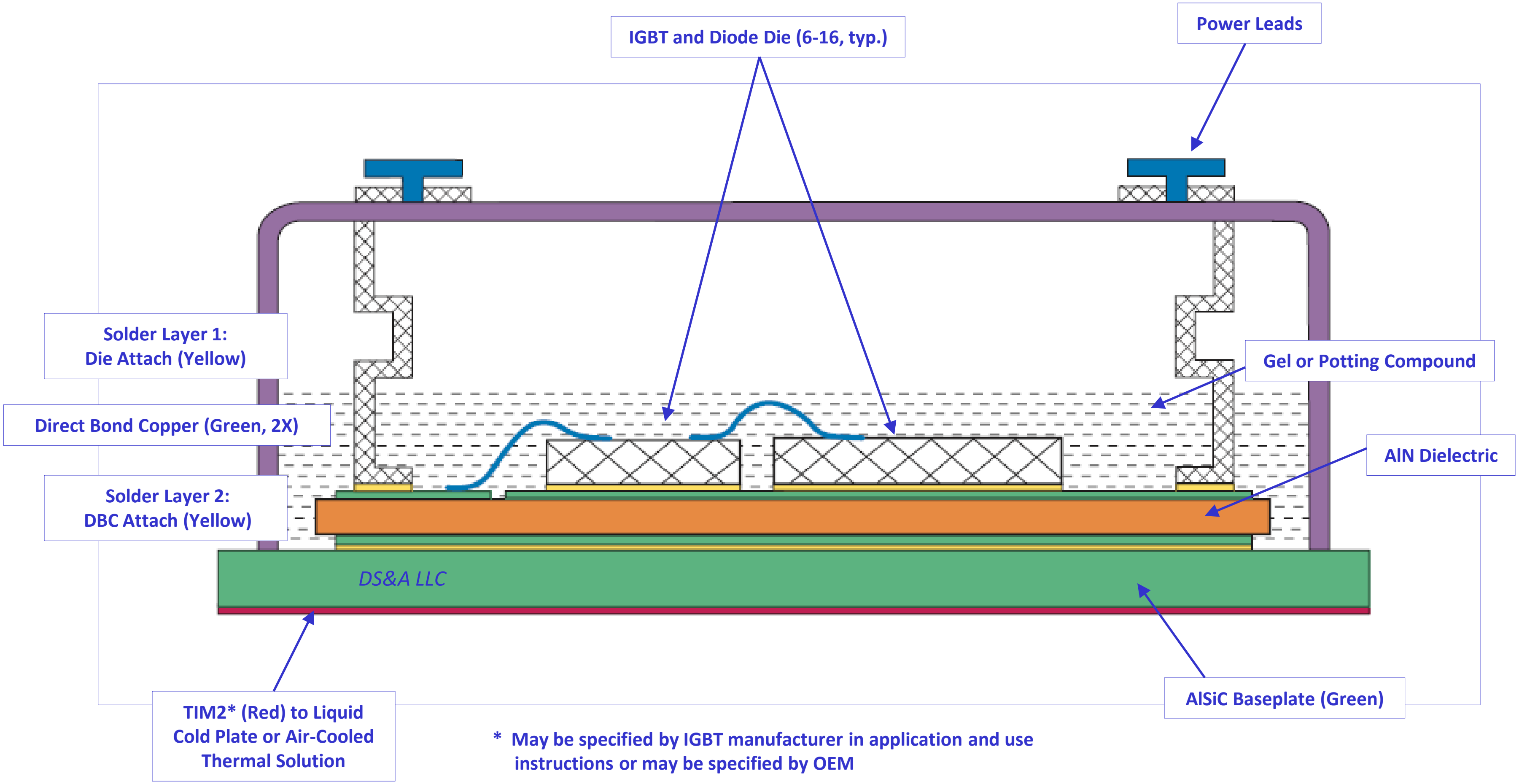
Power density: 10W/cm^3; Increased T_J ; ¼ volume



Mitsubishi 11kW Silicon inverter (left); SiC inverter (right) T_J

Source: M. Cooke, "Wide Load Potential for Electric Vehicles," Semiconductor Today, Vol. 4, Issue 5, June-July 2009, pp. 70-75.

IGBT Module Typical Construction (with Baseplate)



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

Power Leads

Solder Layer 1:
Die Attach (Yellow)

Gel or Potting Compound

Direct Bond Copper (Green, 2X)

AlN Dielectric

Solder Layer 2:
DBC Attach (Yellow)

DS&A LLC

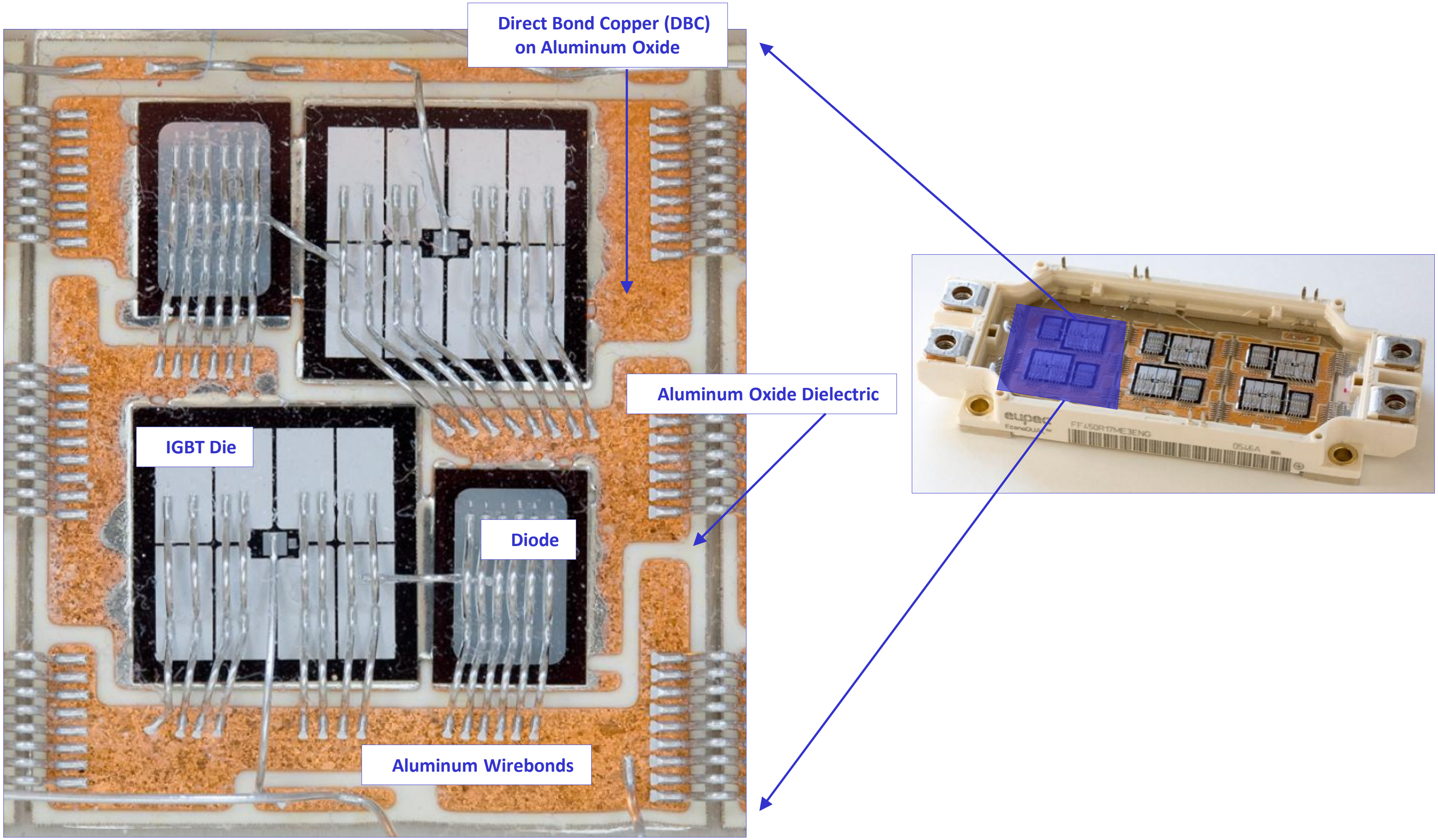
TIM2* (Red) to Liquid
Cold Plate or Air-Cooled
Thermal Solution

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

IGBT Module Material Roles: Improvement Needs

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

IGBT Module Package Materials and Functions

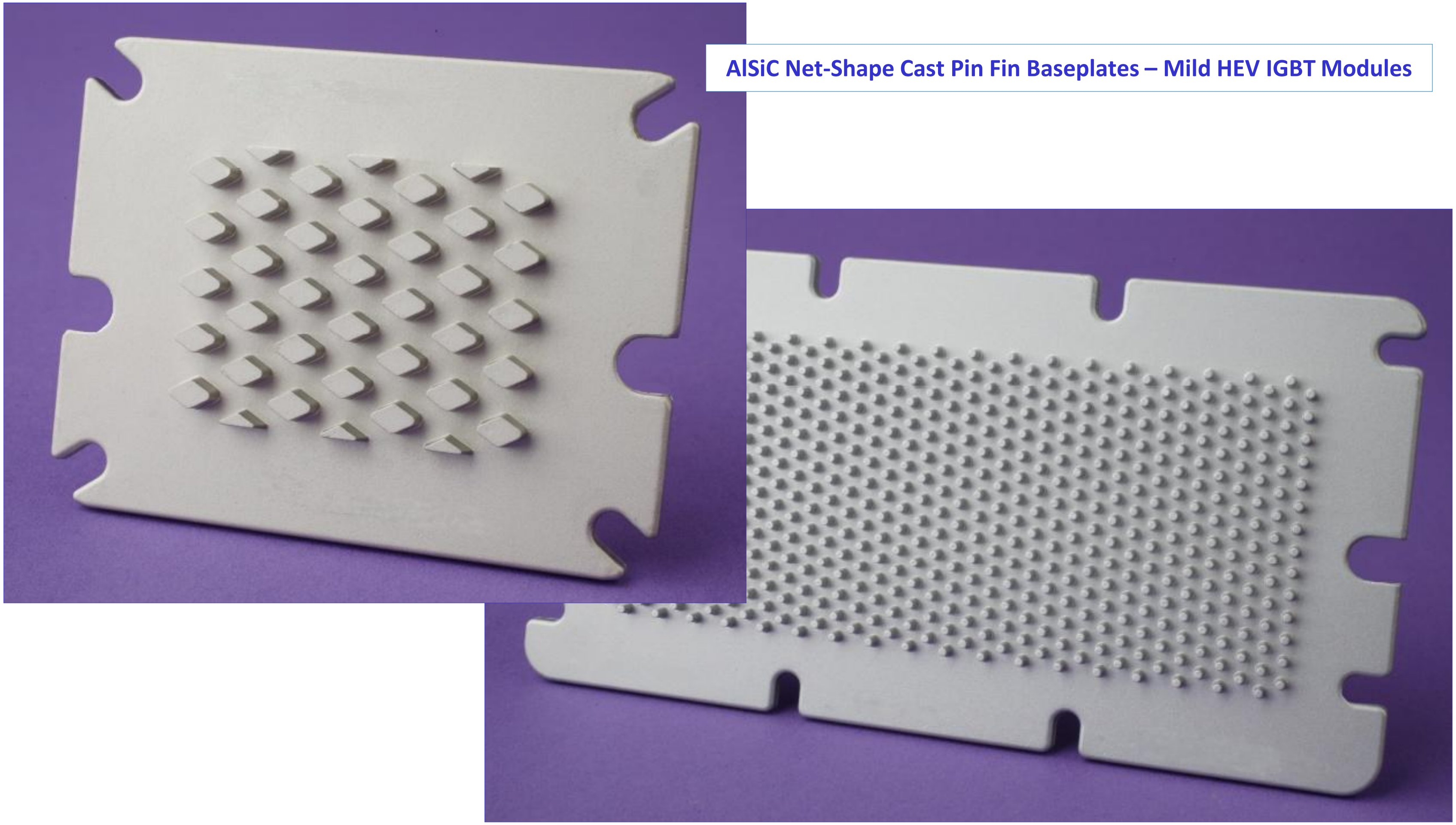
Function	Baseplate	DBC	Ceramic	Solders/ LTJT	Bondwire	Power Leads	Gel
Mechanical support	▲	▲		△			
Package integrity	🔺		▲	🔺	🔺		🔺
Power distribution and interconnect		▲		🔺	▲	▲	
Electrical isolation			▲	▲			🔺
Thermomechanical stress relief	🔺	🔺	▲		▲	🔺	
Die protection							🔺
Heat transfer	▲	▲	🔺	▲	▲	△	

Trends in IGBT Module Performance and Reliability Improvement

- IGBT module packaging improvements:

IGBT Module Packaging Improvements and Needed Development Materials and Components
Higher-temperature packaging and thermal materials
Low-temperature joining techniques
Transition to improved wirebonding techniques (e.g., wedgebonding)
Transition to monolithic module metals (e.g., copper)
Transition from aluminum wire to aluminum ribbon bonding
Higher thermal conductivity CTE-matched baseplate materials
Double-sided liquid cooling package developments

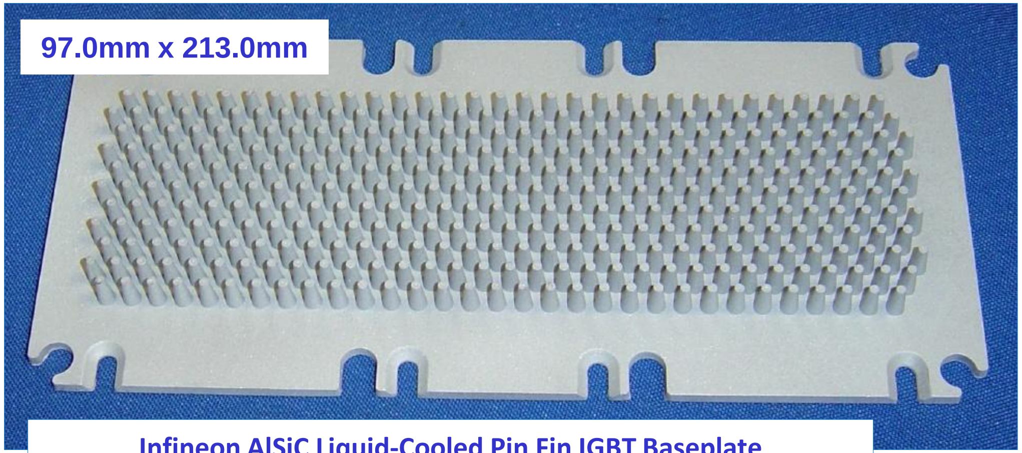
HEV IGBT Module Baseplates - Integrated Liquid Cooling



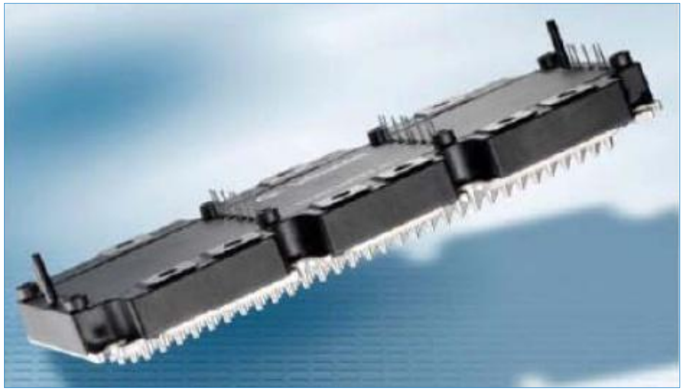
AlSiC Net-Shape Cast Pin Fin Baseplates – Mild HEV IGBT Modules

Source: Rogers Corporation

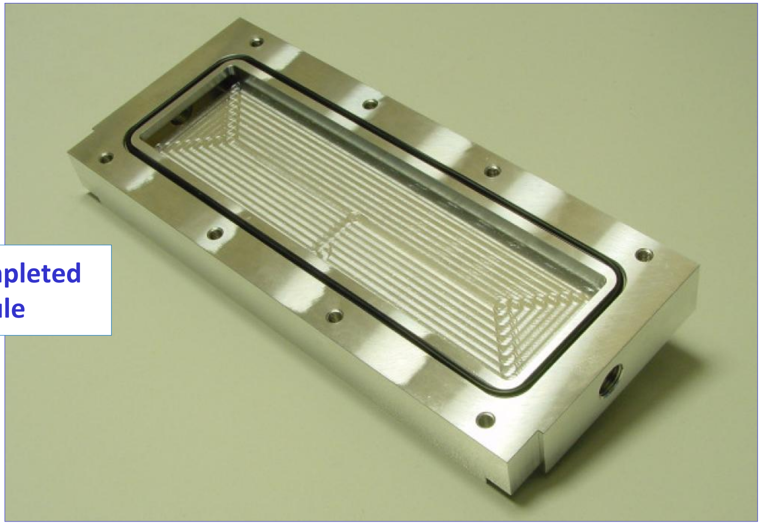
HEV IGBT Module Baseplates - Integrated Liquid Cooling



Infineon AlSiC Liquid-Cooled Pin Fin IGBT Baseplate
for HybirdPack2™ for Mercedes S-Class Sedan (CPS Technologies)



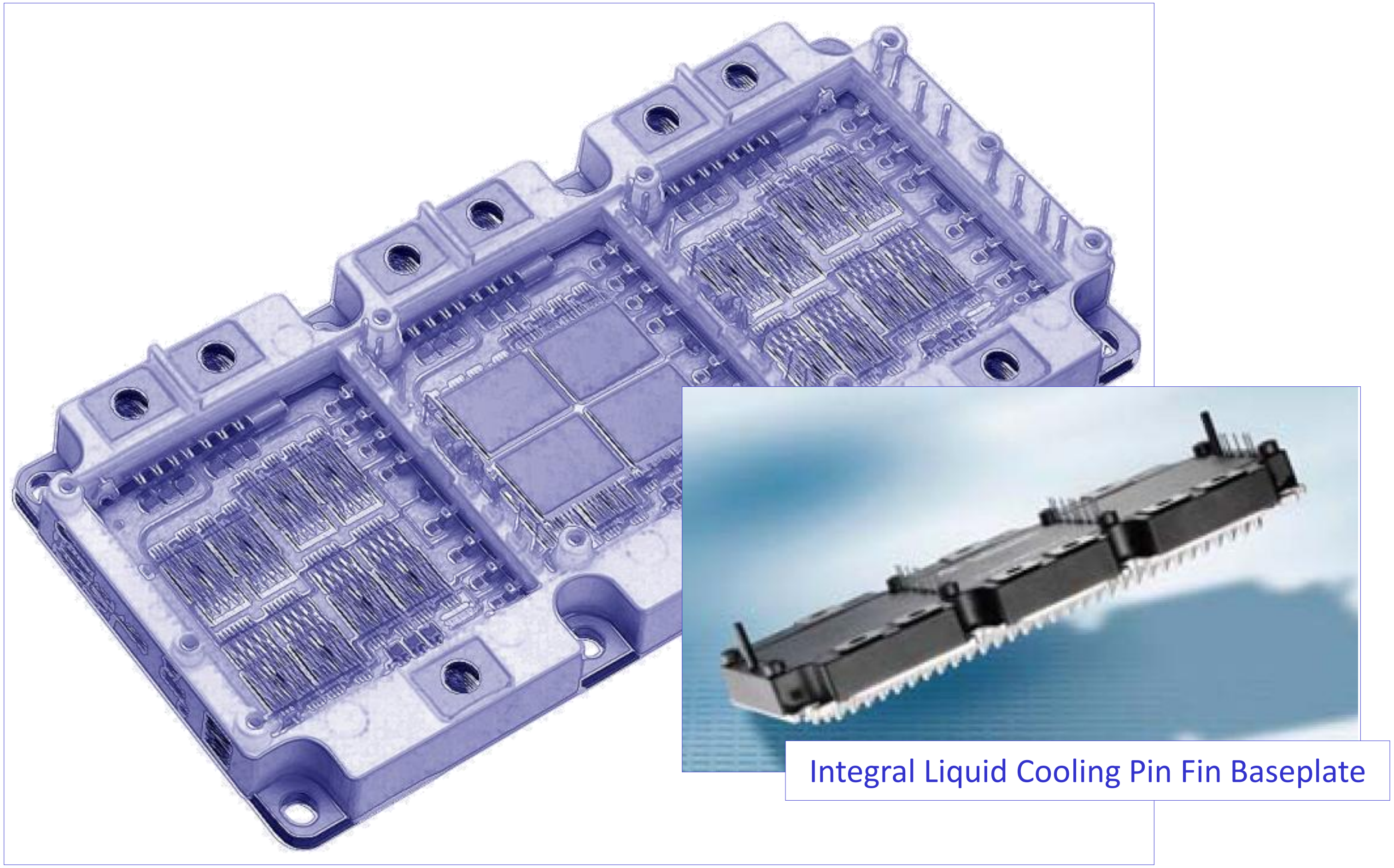
Infineon HybridPack2™ Complete Liquid-Cooled IGBT Module with AlSiC Pin Fin Baseplate



Example of “bathtub” component and O-ring for completed liquid cold plate for Infineon HybridPack2 Module

Sources: CPS Technologies; Infineon Technologies

IGBT Module Current Construction: Infineon HybridPack™ 3 for HEV/EV Market

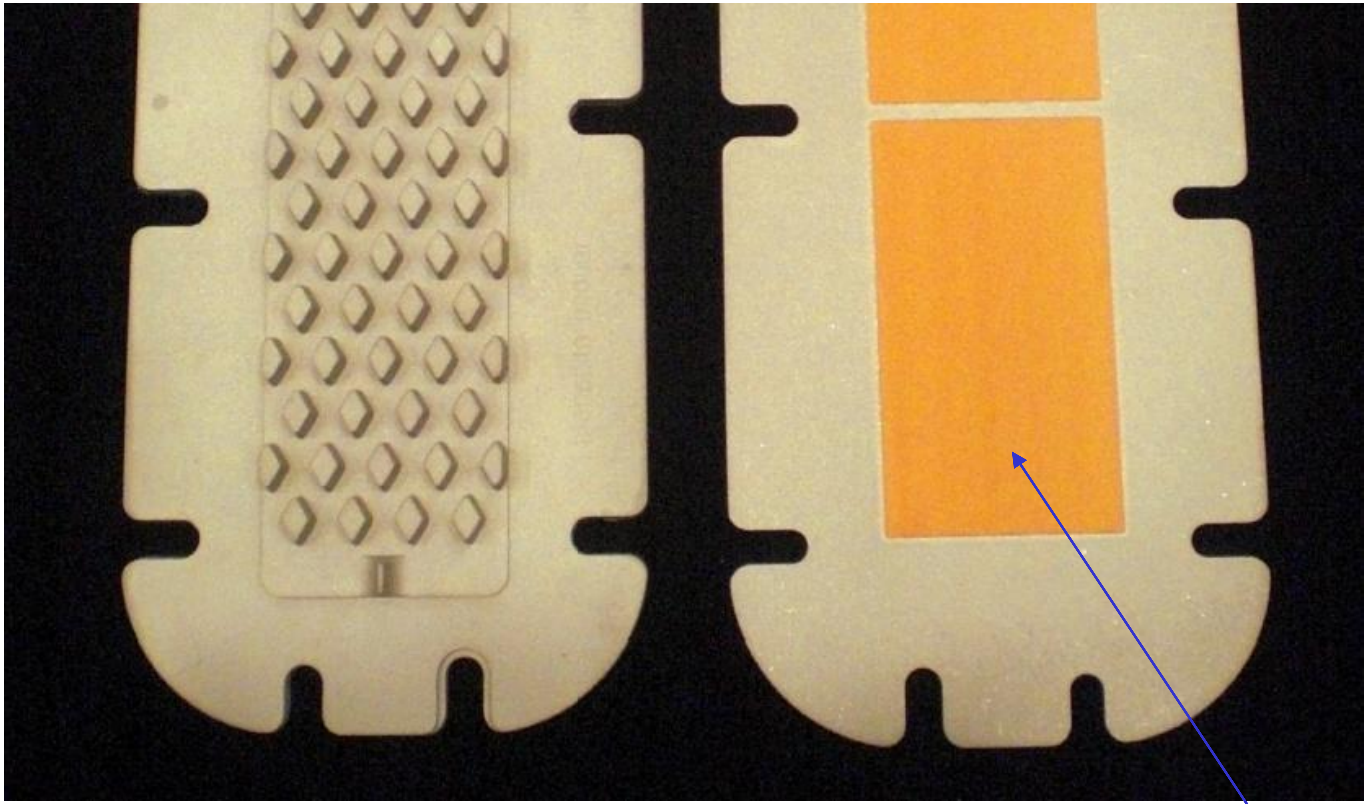


Integral Liquid Cooling Pin Fin Baseplate

Source: J. Hanebeck, Infineon Automotive Power, February 2011.

HEV IGBT Module Baseplate – Integral Copper Solder Pad

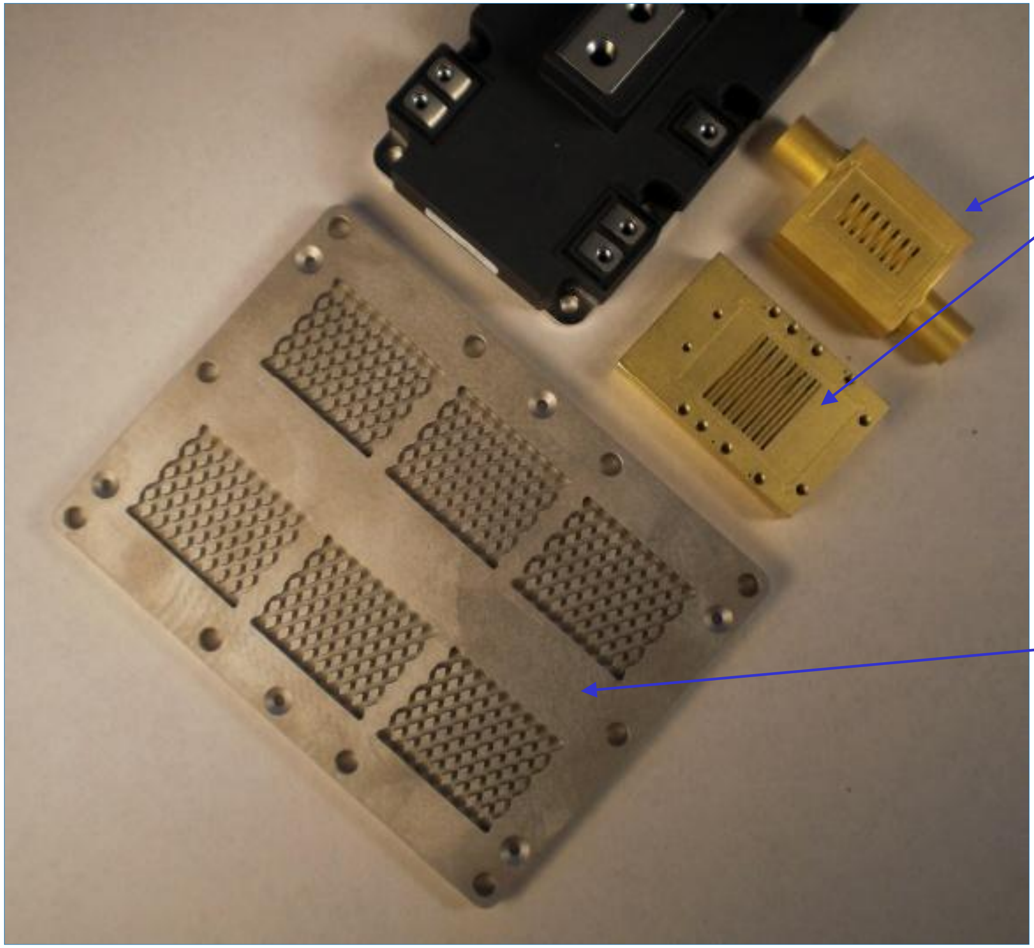
CPS Technologies' AlSiC Net-Shape Cast Pin Fin Baseplates – Mild HEV IGBT Modules



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



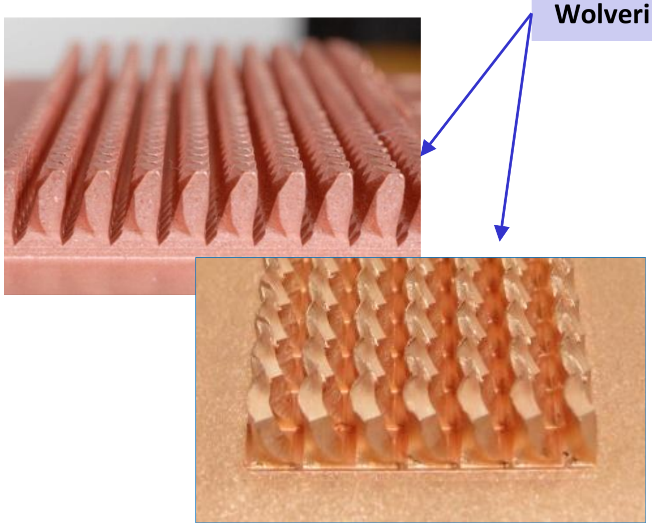
Cast and Machined CTE-Matched Liquid Cold Plate for GE Power Overlay Technology

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

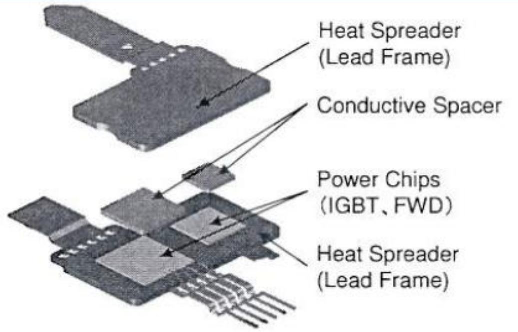
Source: DS&A LLC

HEV IGBT Module Baseplates - Integrated Liquid Cooling

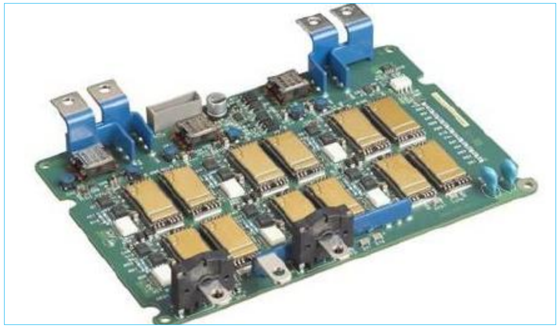
Wolverine MicroCool™ MDT Copper Pin Structure



IGBT Baseplates with Integral Pin Array



**IGBT Die w/integral heat spreaders –
Toyota (Denso) THS-II HEV Double-Sided IGBT Module**

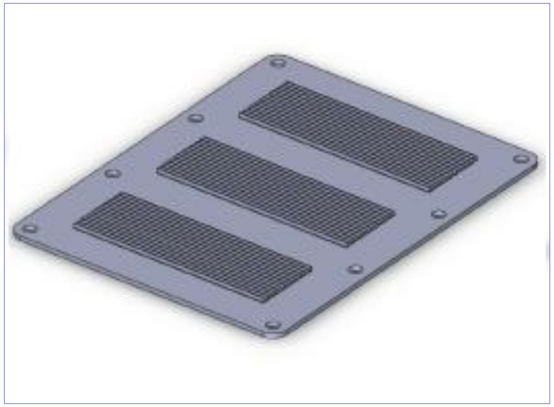


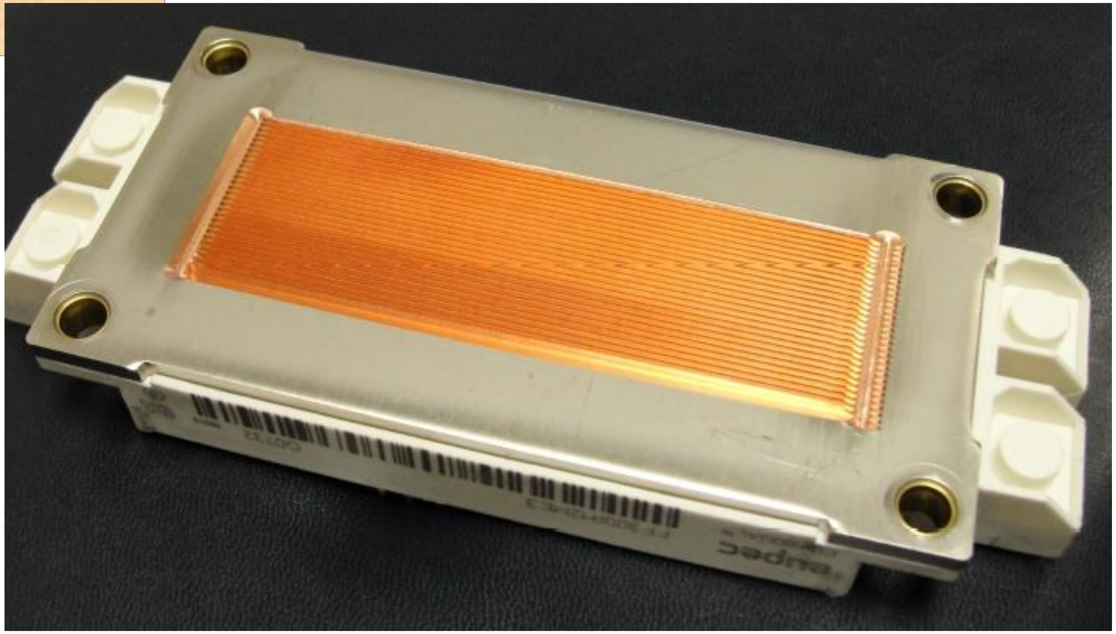
Delphi "Viper" Single-sided Liquid Cooled Inverter

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

HEV IGBT Module Baseplates - Integrated Liquid Cooling

Wolverine MicroCool™ MDT Copper Pin Structure



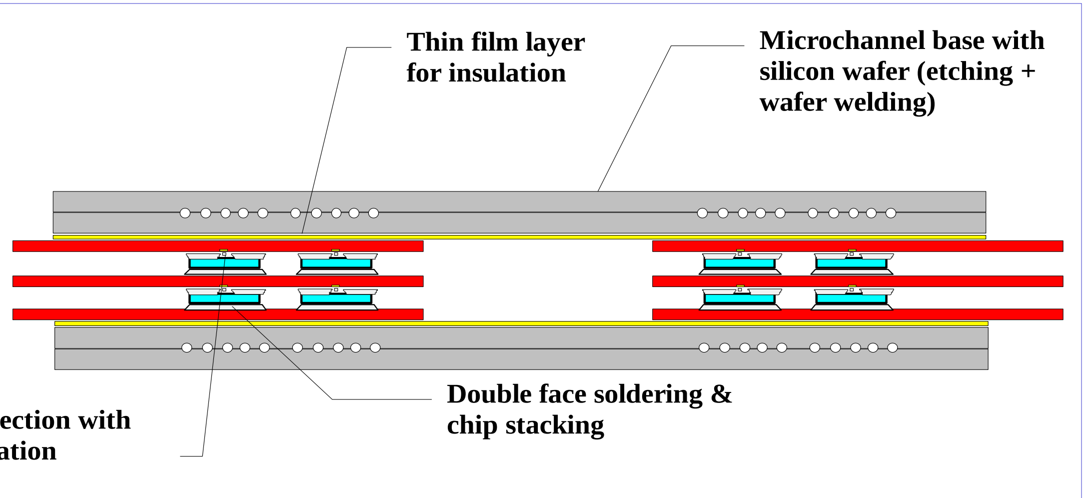


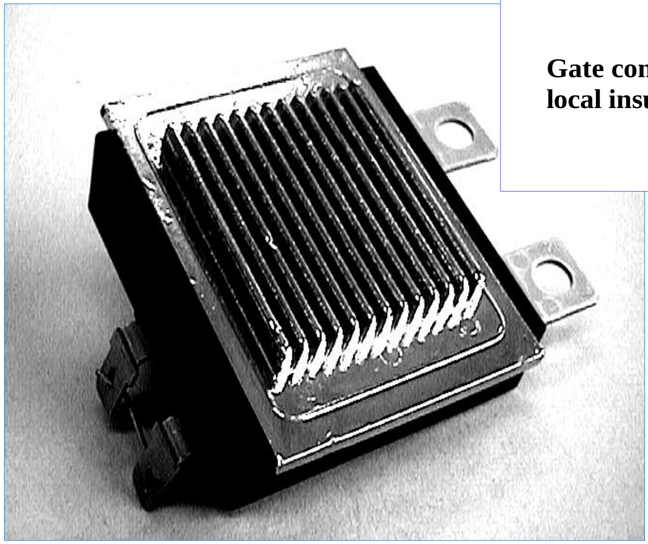
Wolverine MicroCool™ MDT Copper Parallel Fin Structure
Ni-Plated Copper 3mm EconoDual™ IGBT Baseplate

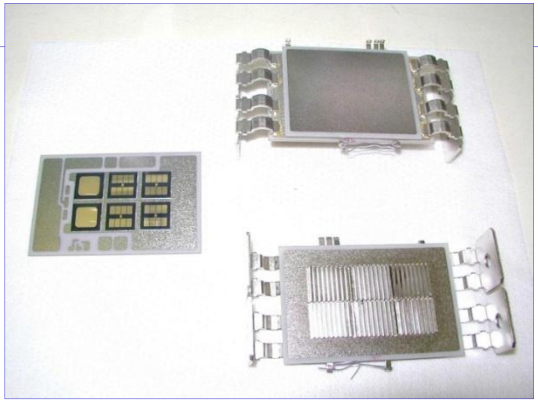
Source: Wolverine Tube Inc.

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

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





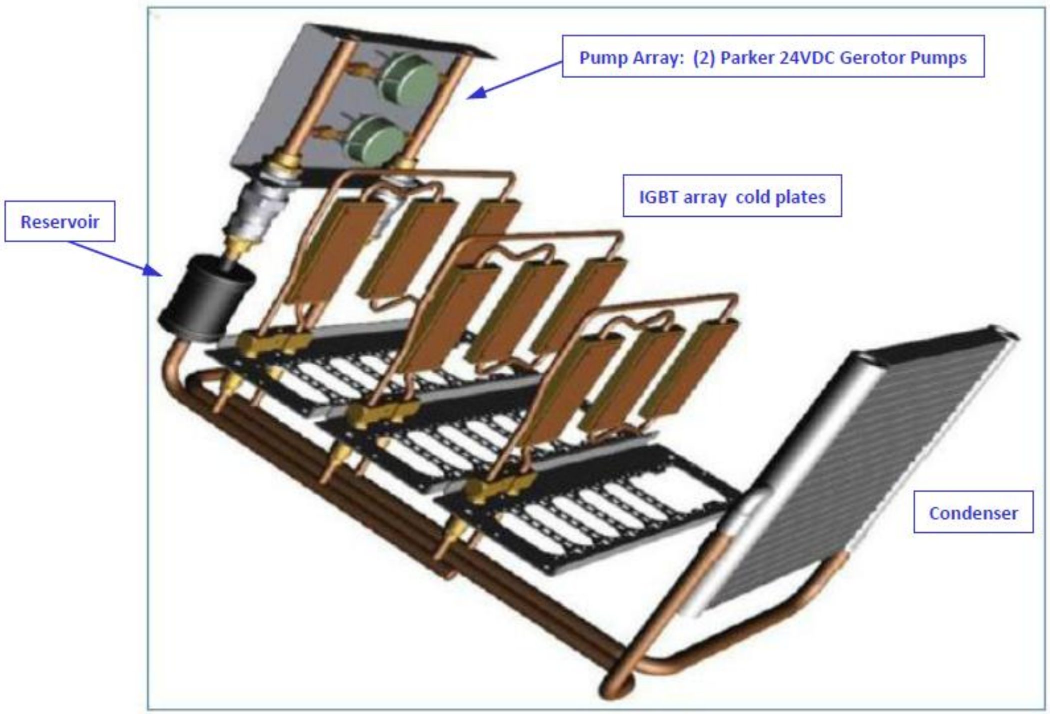


Source: M. Mermet-Guyennet, Alstom Transport, "An Overview on Thermal Management for Power Chips", IMAPS France ATW Thermal 2006, La Rochelle, France, February 1-2, 2006

HEV Inverter Thermal Management Developments – Military Vehicles

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



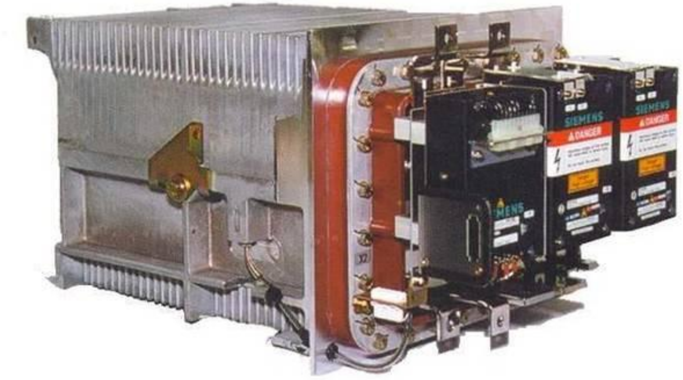
Undisclosed military tactical vehicle platform

Source: Parker Hannifin Corporation

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

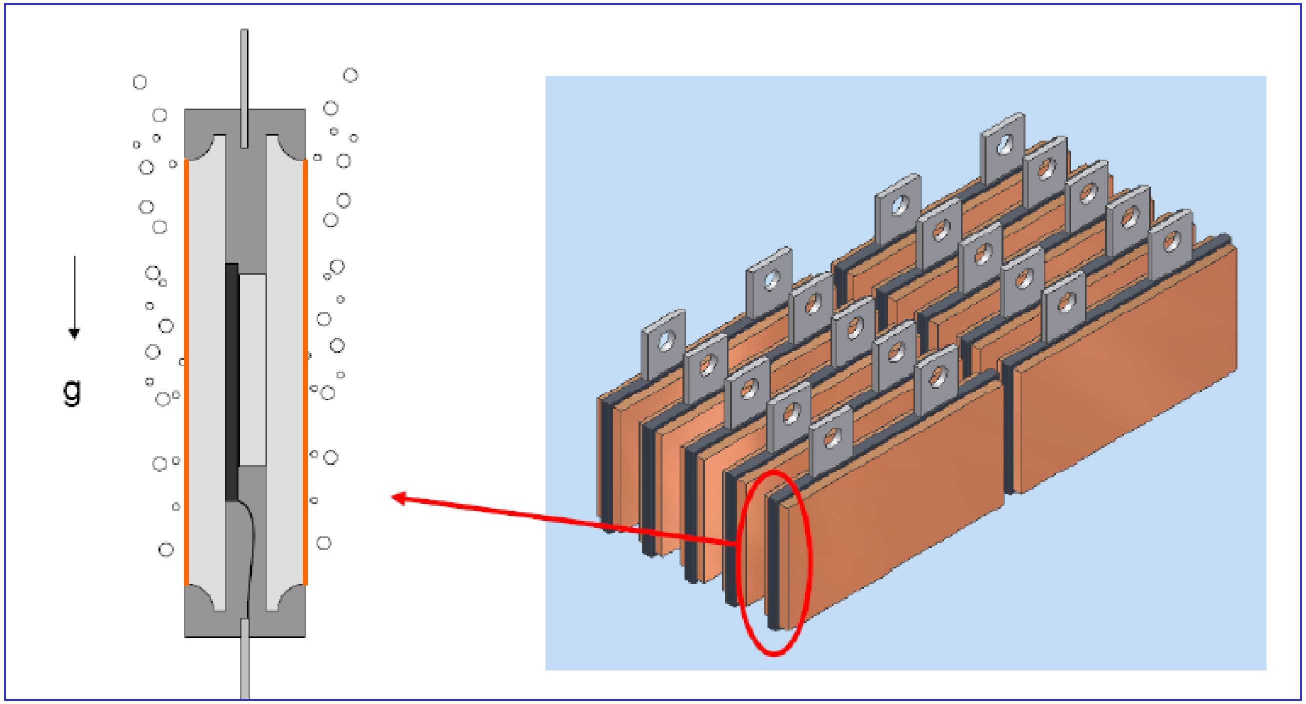


Source: 3M EMMD; Photograph: Siemens

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:

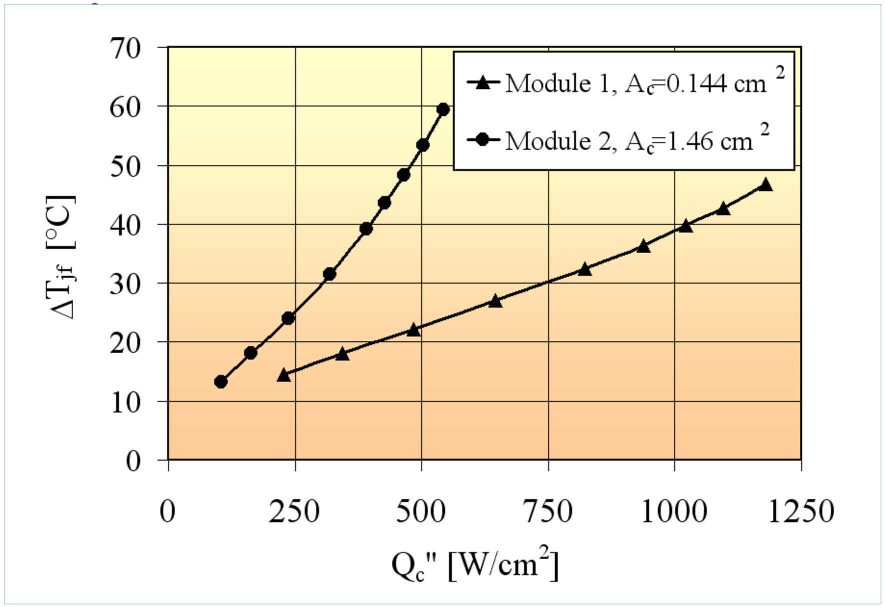


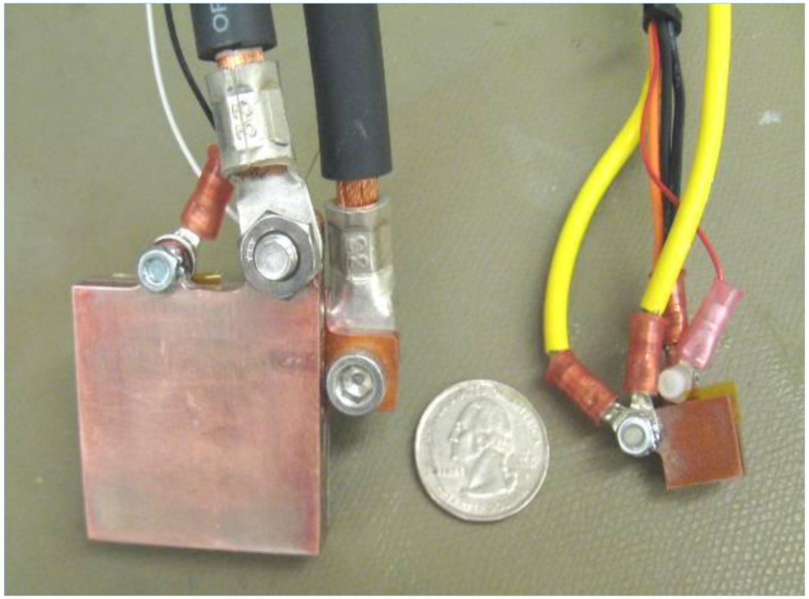
Source: C. Barnes, 3M EMMD, "Immersion Cooling of Power Electronics in Segregated Hydrofluoroether Liquids," ASME Heat Transfer Conference 2008, Jacksonville FL USA, August 10-14, 2008; IMAPS ATW Thermal 2008, Palo Alto CA USA, Oct. 14-16, 2008.

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:
    - Barnes, C. M., and Tuma P. E., “Practical Considerations Relating to Immersion Cooling of Power Electronics in Traction Systems,” IEEE Trans. Power Electronics, 25(9), pp. 2478-2485, September 2010.
    - Tuma, P. E., “Immersion Cooling of IGBTs: Thermal Performance, Packaging Density and In Situ Degassing Techniques,” Presentation, IMAPs 5th European ATW on Thermal Management, La Rochelle, France, 3-4 February 2010.

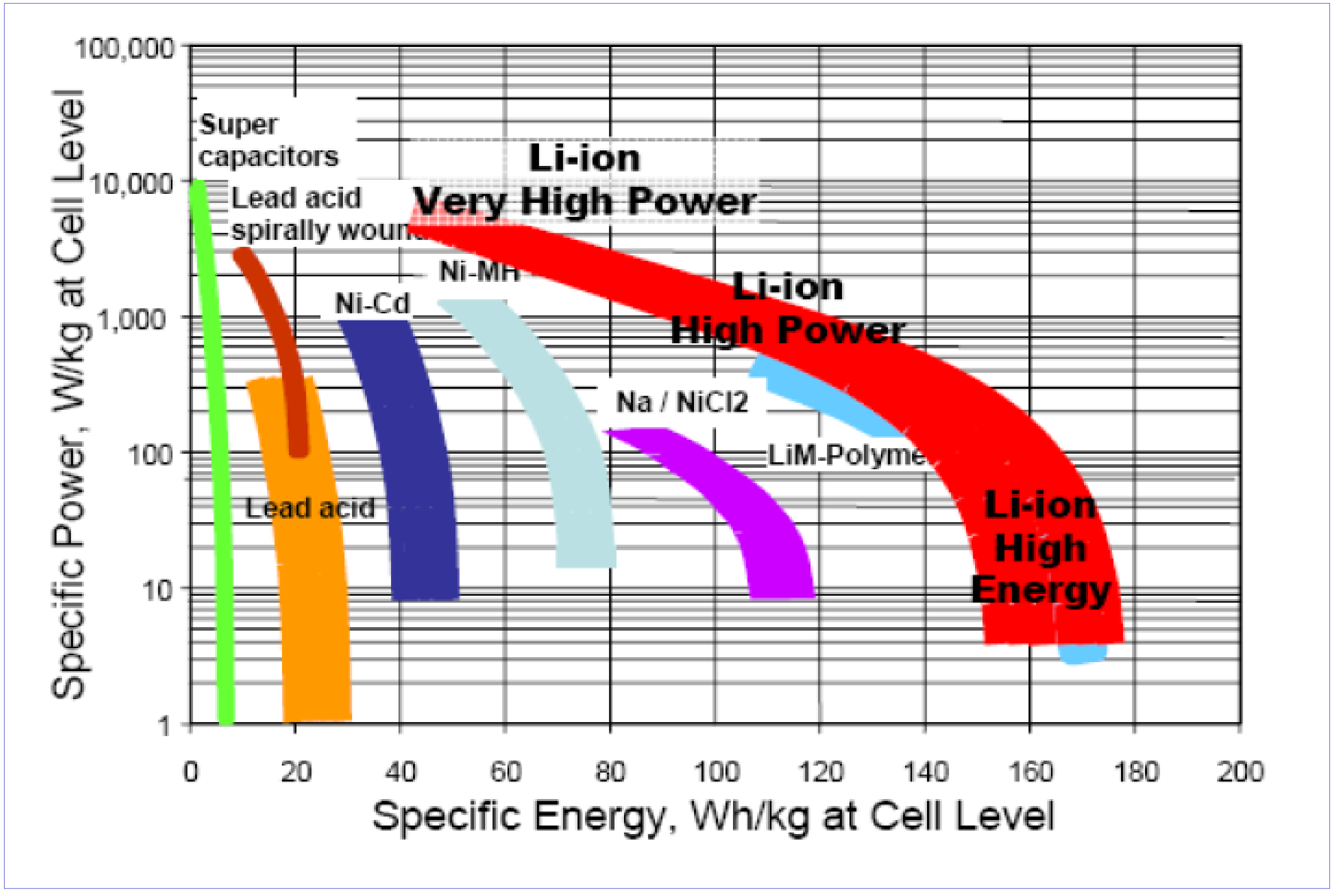




Energy Storage Systems

Energy Storage: Energy versus Power Requirements for HEV/PHEV/EV Vehicles

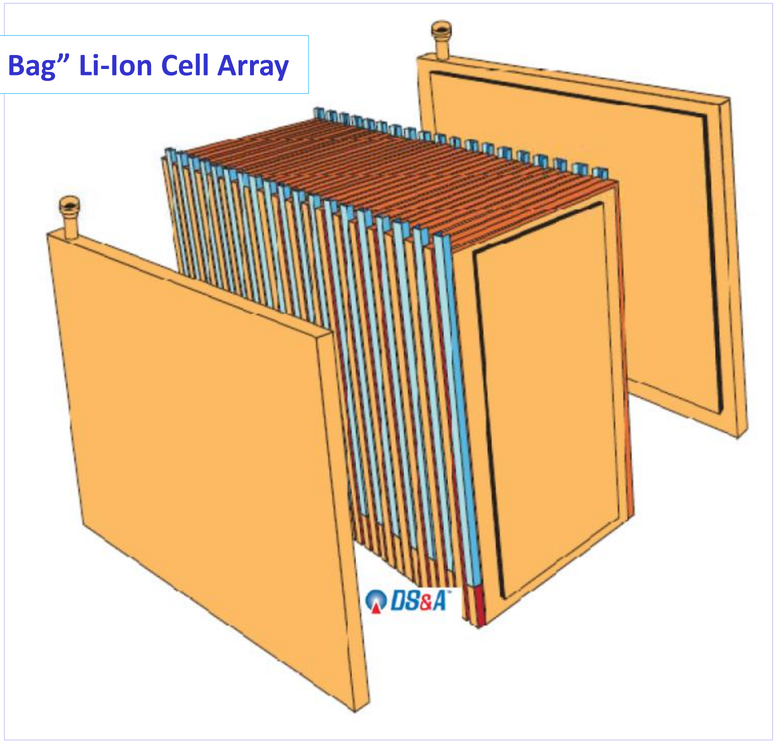
Ragone Chart, Battery Specific Power vs. Specific Energy



Sources: C.A. Rosenkranz, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Modern Battery Systems for Plug-in Hybrid Electric Vehicles"; also, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Li-Ion Battery Systems for the Next Generation of Hybrid Electric Vehicles", Nineteenth International AVL Conference "Engine & Environment", September 6-7, 2007, Graz.

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:

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

Sources: C.A. Rosenkranz, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Modern Battery Systems for Plug-in Hybrid Electric Vehicles"; also, U. Köhler, J.L. Liska, Johnson Controls-SAFT, "Li-Ion Battery Systems for the Next Generation of Hybrid Electric Vehicles", Nineteenth International AVL Conference "Engine & Environment", September 6-7, 2007, Graz.

Summary: Thermal Management Challenges for Vehicle Powertrain Electrification

Summary of Trends and Needs:

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

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.