High Heat Flux Applications in Power Electronics

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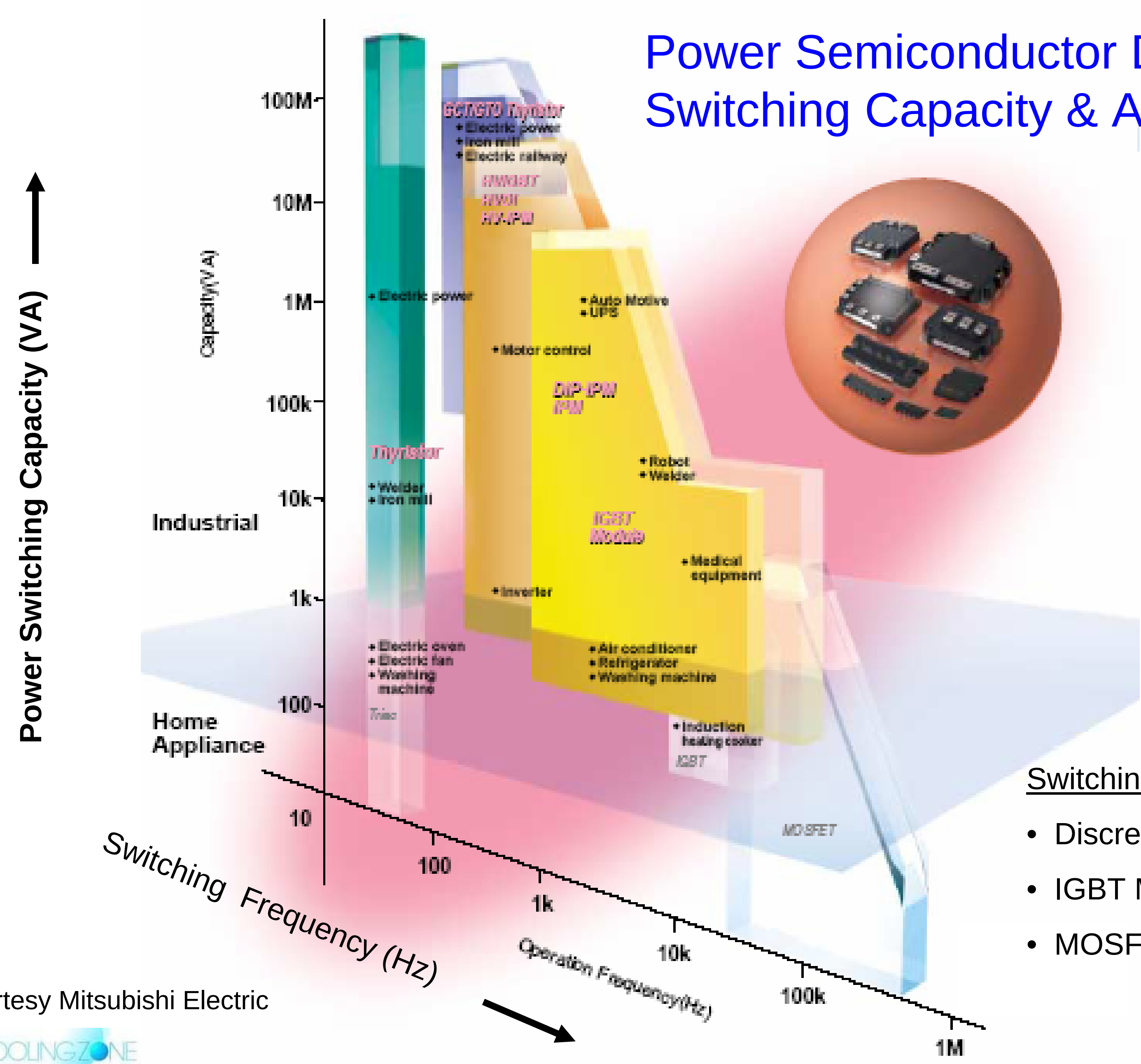
Power Semiconductor Device Power Switching Capacity & Application Map



Switching Frequency Capability

- Discrete SCR → 10 kHz
- IGBT Module → 60 kHz
- MOSFET → 500 kHz

Courtesy Mitsubishi Electric

High Heat Flux Applications in Power Electronics

- From the perspective of a high power semiconductor device manufacturer
- Primary focus is on applications utilizing power semiconductors > 500V & 50A
- Review power semiconductor device types & present cooling techniques - how they vary by application
- Discuss advances in silicon-based power semiconductor chip technology & impact on cooling requirements
- Discuss advances in semiconductor packaging technology & impact on cooling
- Cooling challenges associated with new power electronics applications
- Cooling challenges associated with new power semiconductor materials, i.e. SiC

High Power Electronics Systems Trends

- More power delivered / switched in smaller volumes & less weight
- Higher voltage & higher current power semiconductor devices required
- Industry moving to power devices that are electrically isolated from heatsinks
- Higher efficiency demanded of systems & power devices
- Shift from analog to digital control of systems
- New circuit topologies have increased system efficiency & reduced stresses on power devices (soft switching, zero voltage & current switching (ZVS & ZCS))
- Move to eliminate fuses has increased overload requirements of power devices
- Switching frequency increases to the limit of the power devices
- Demand is for costs ($$/watt) to keep decreasing
- High reliability demanded
- Need for alternate energy generation & energy conservation is generating new applications

High Power Semiconductor Device Trends

- Discrete & module devices have increased voltage & current capability
- Development of IGBT spurred revolution in high power electronics
- Power transistor modules have decreased in size – by 50% in some cases, thus increasing power density
- Incorporation of basic power electronic “building block” circuits in a module or assembly has reduced system size
- Integration of control, gate drive & sensing functions in power modules has
  - Improved performance & reliability
  - Reduced system size & parts count & required design effort
- New power semiconductor chip designs have reduced conduction & switching losses (trench gate, CSTBT, super-junction MOSFET)
- New semiconductor materials such as Silicon Carbide will extend voltage, frequency & operating temperatures beyond the capabilities of silicon

How Do These Trends Impact Cooling?

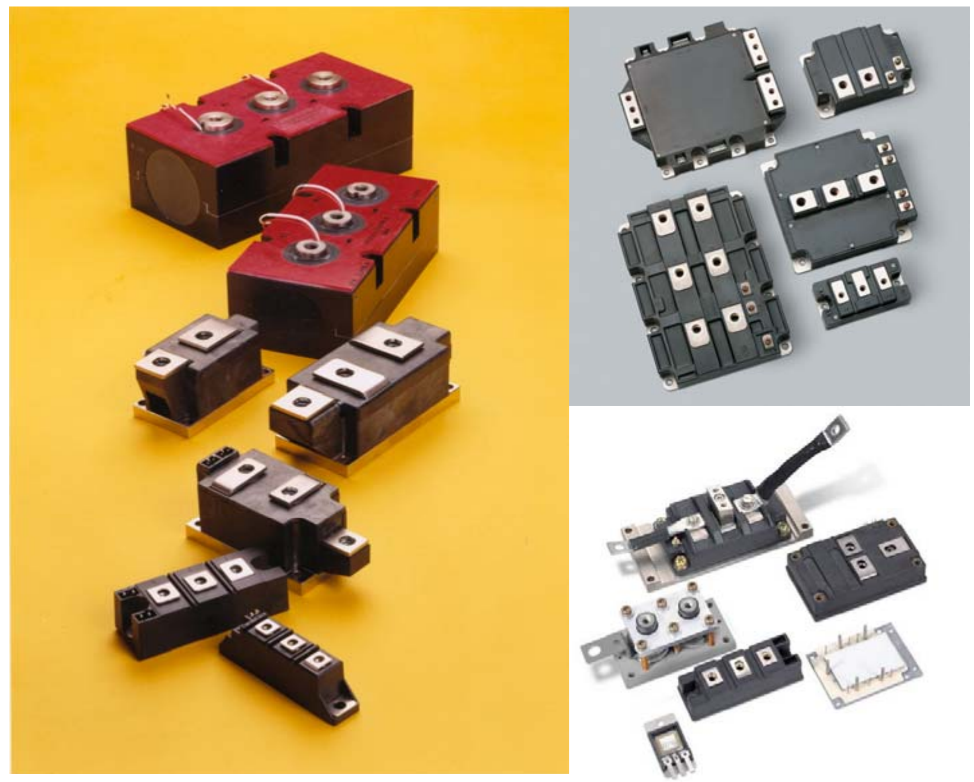
- Higher voltage rated devices typically have higher power dissipation
- Higher frequency operation typically means higher power dissipation
- Smaller module sizes mean higher power dissipation densities
- Electrically isolated baseplate / heatsink makes it more difficult to cool power devices
- Air cooling not adequate – shift to liquid cooling
- Improve cooling efficiency – eliminate layers in thermal path
- Current overload “ride through” requirements require low transient thermal impedance designs
- Need more efficient air & liquid cooling methods

Power Device Types

A discrete device consists of a "single" silicon element individually packaged in a two or three lead package.

Diode / SCR / IGCT

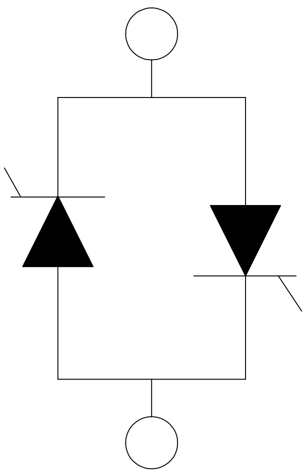
A module consists of one or more chips connected in a specific circuit configuration enclosed in a plastic, ceramic or metal housing.



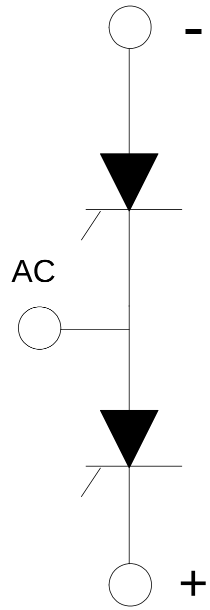
Diode / SCR / GTO / IGBT / MOSFET / BJT

Power Electronics Building Block Configurations

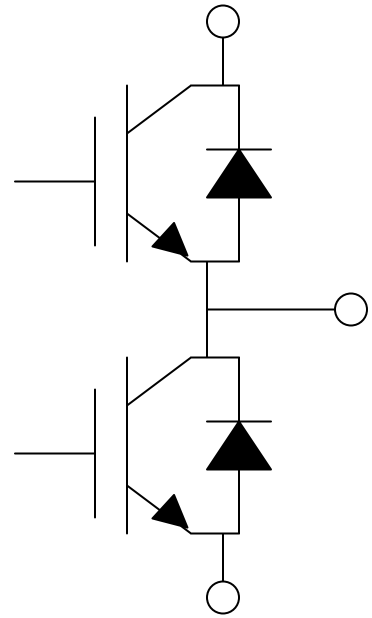
AC Switch

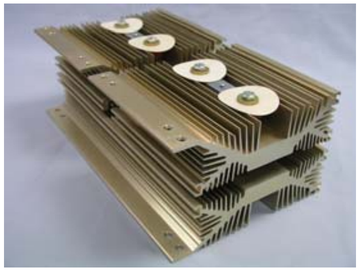


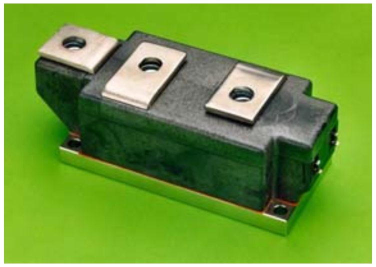
Dual / Doubler



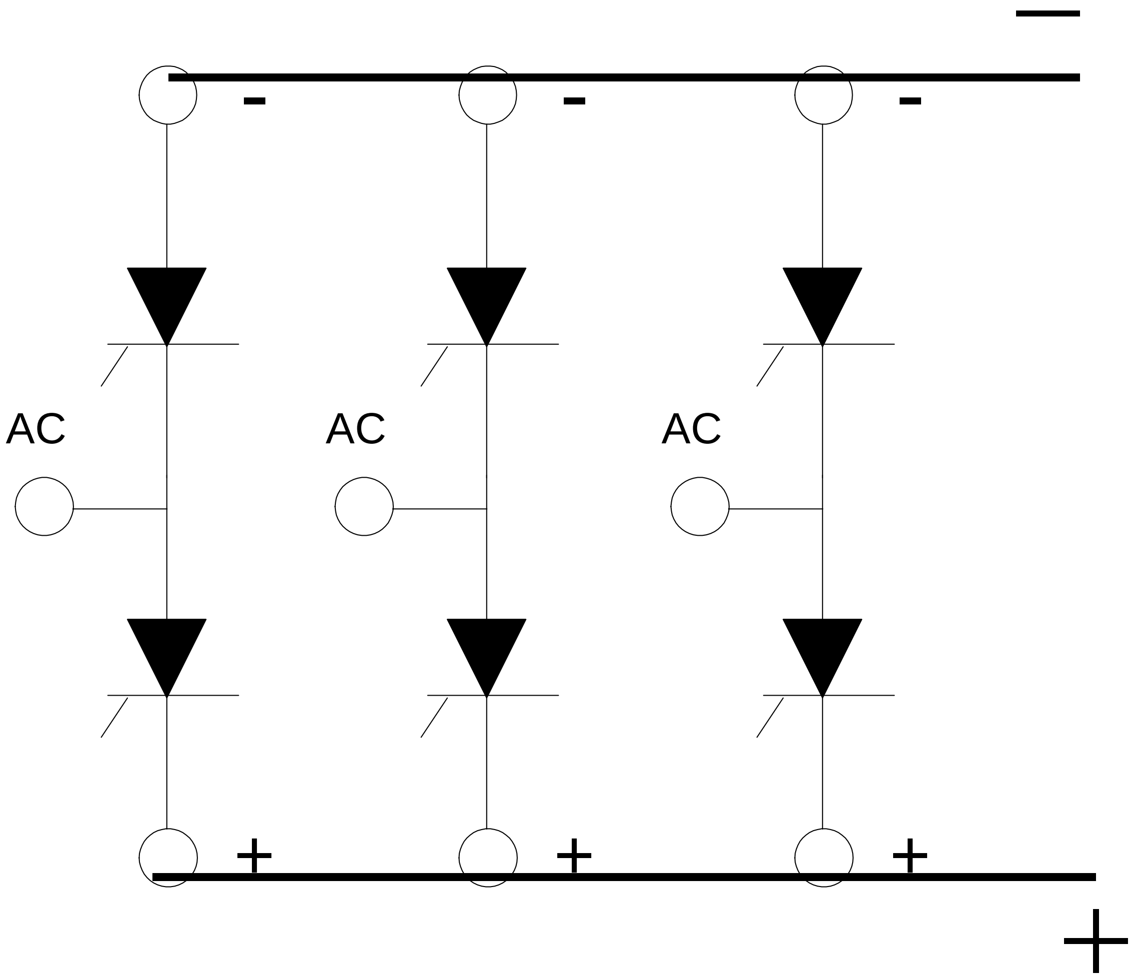
Dual / Half H-Bridge

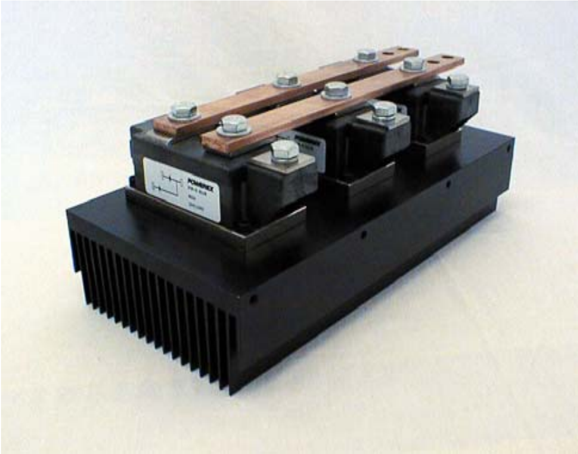


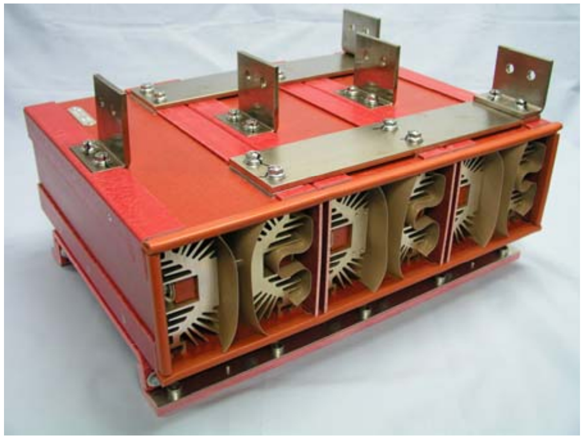




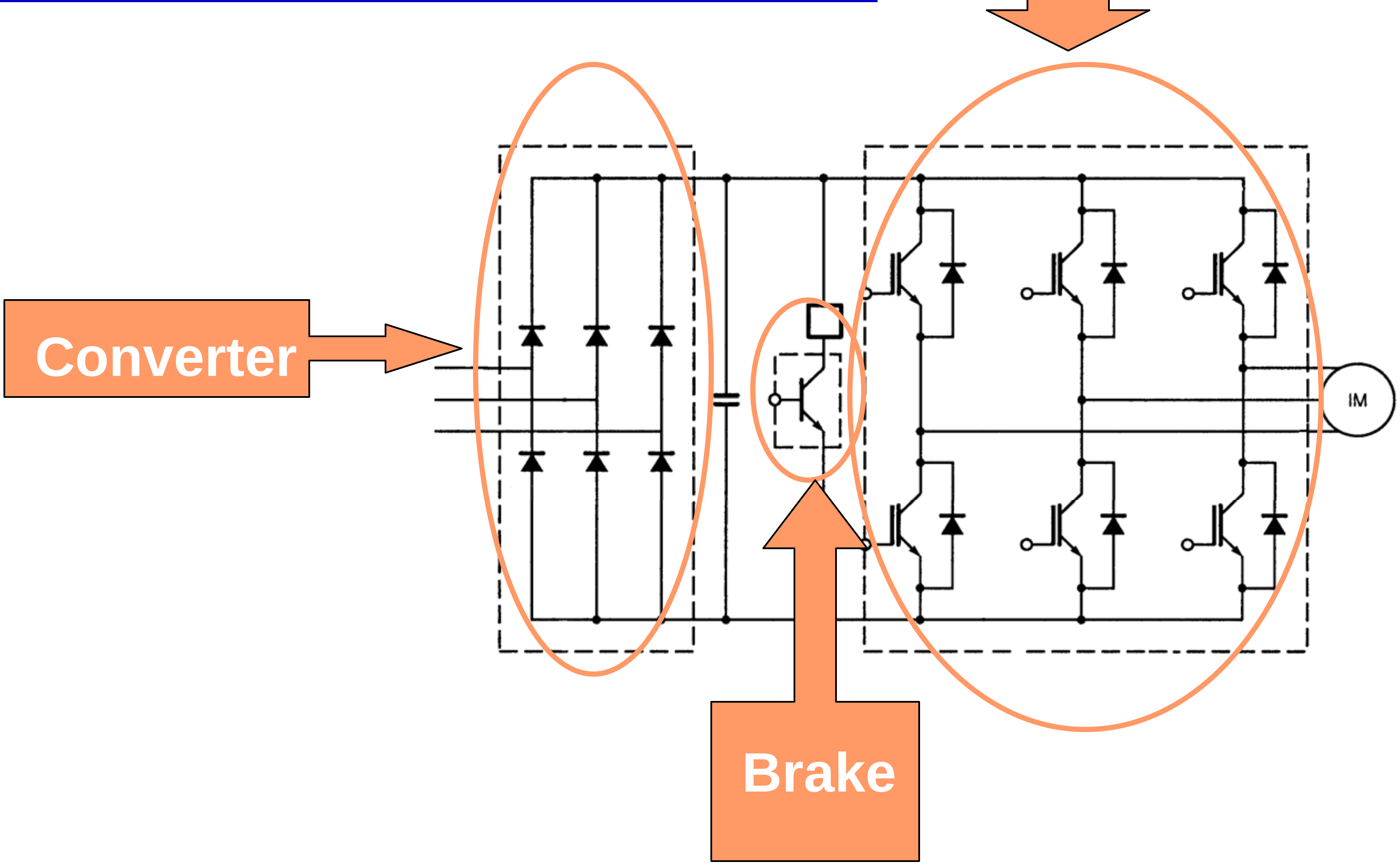
Power Electronics Systems Are Built From The Basic Building Blocks - 3 Phase Bridge Rectifier





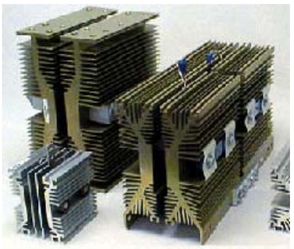


3 Phase Motor Drive
From Basic Building Blocks

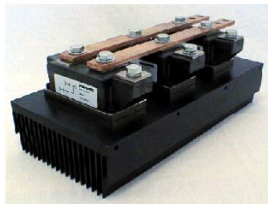


Power Semiconductor Device Evolution

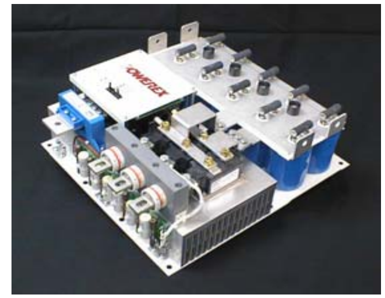
Discrete Assemblies



Module Assemblies



Complete Power System
Standard & Application Specific



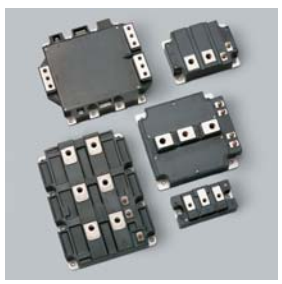
Powerex
Pow-R-Pak

Semikron
Skiip Pak

SCR / Diode /
GTO Discretes

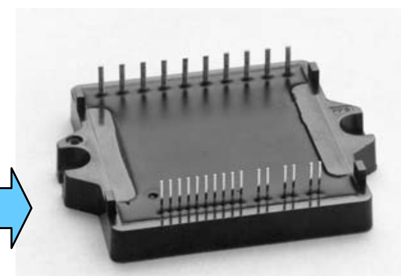
SCR / Diode Modules

BJT / MOSFET
Discretes



Darlington Transistor /
MOSFET / IGBT Modules

Intelligent IGBT Modules
(IPM)



Application Specific IPM

Electrical Isolation Integrated

Gate Drive & Protection Integrated

System in a Package

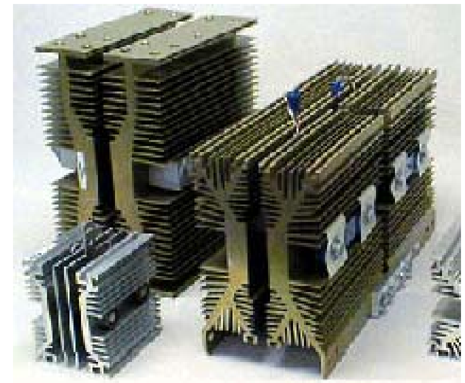
System with Passives

Power Switch Cooling - Discretes

Advantages

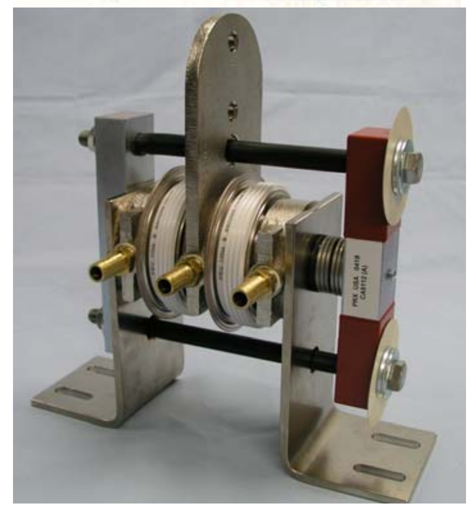
- Double or single side cooled
- Lowest thermal impedance
- Good transient thermal impedance

Air Cooled



Disadvantages

- Compression bonded - devices require clamping forces up to 20,000 lbs. -- Increases with chip diameter
- Electrically "hot" heatsink - part of circuit
- Heatsink isolation required
- High resistivity water needed for liquid-cooled applications
- Clean, dry air needed for air-cooled applications

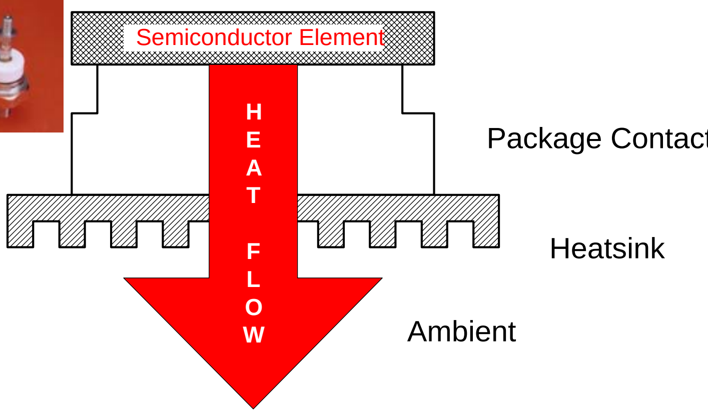


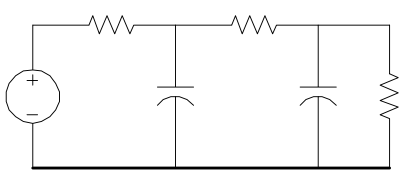
Liquid Cooled

Compression Bonded Discrete Device Thermal Paths

Single Sided Cooling

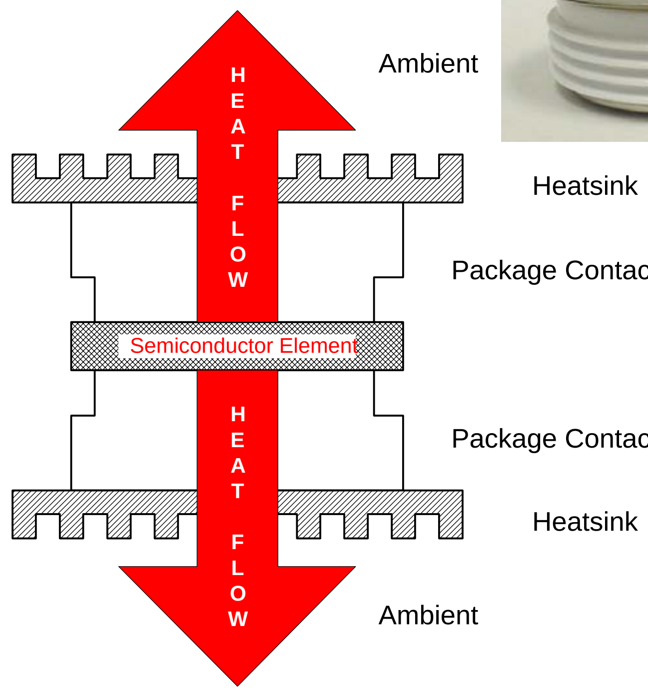
(Stud Devices)

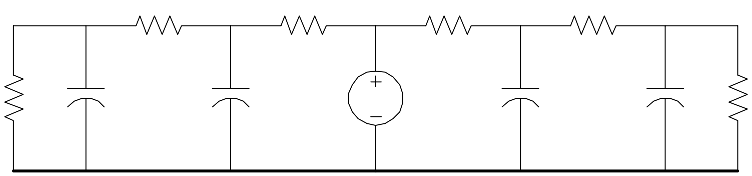




Double Sided Cooling

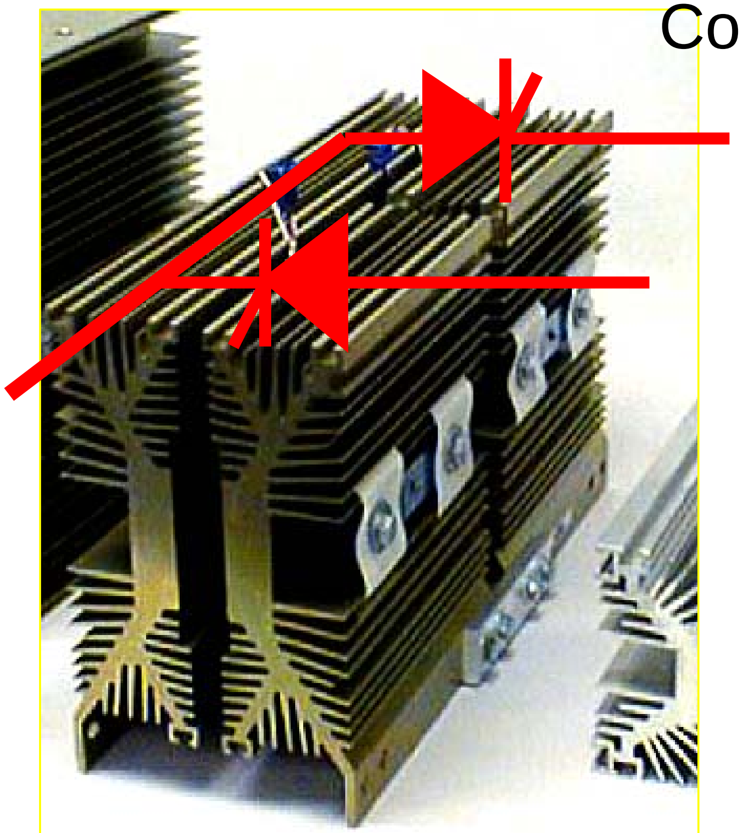
(Disc Devices)

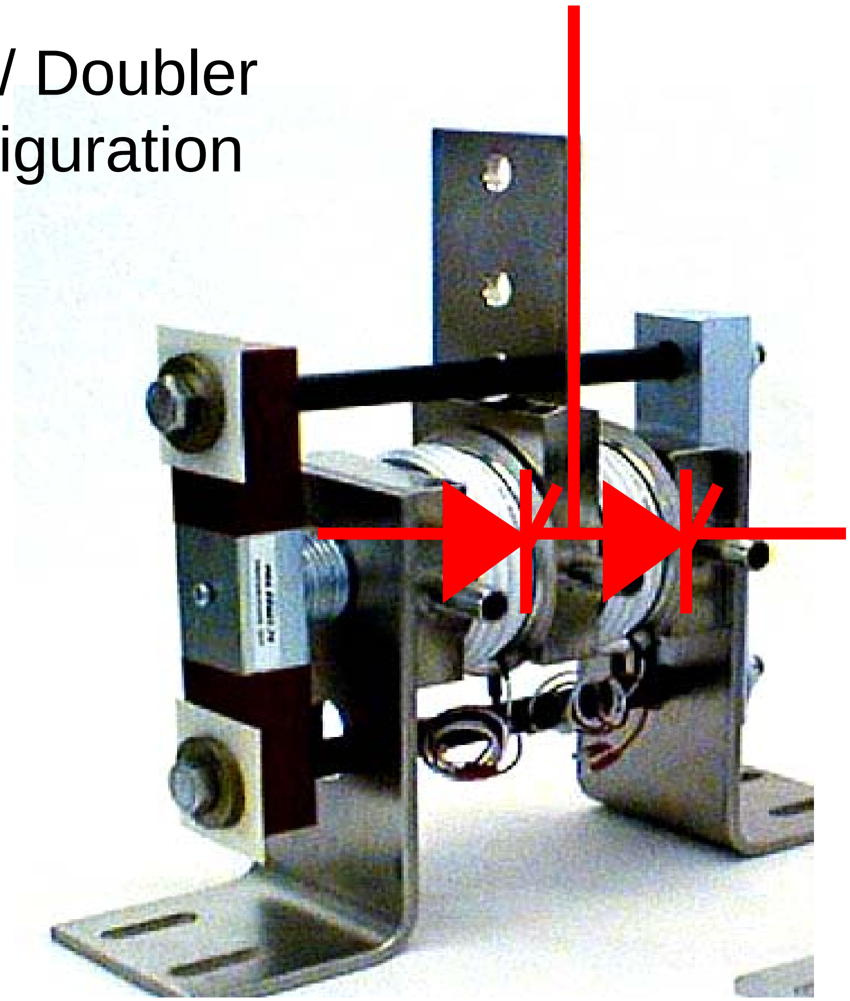




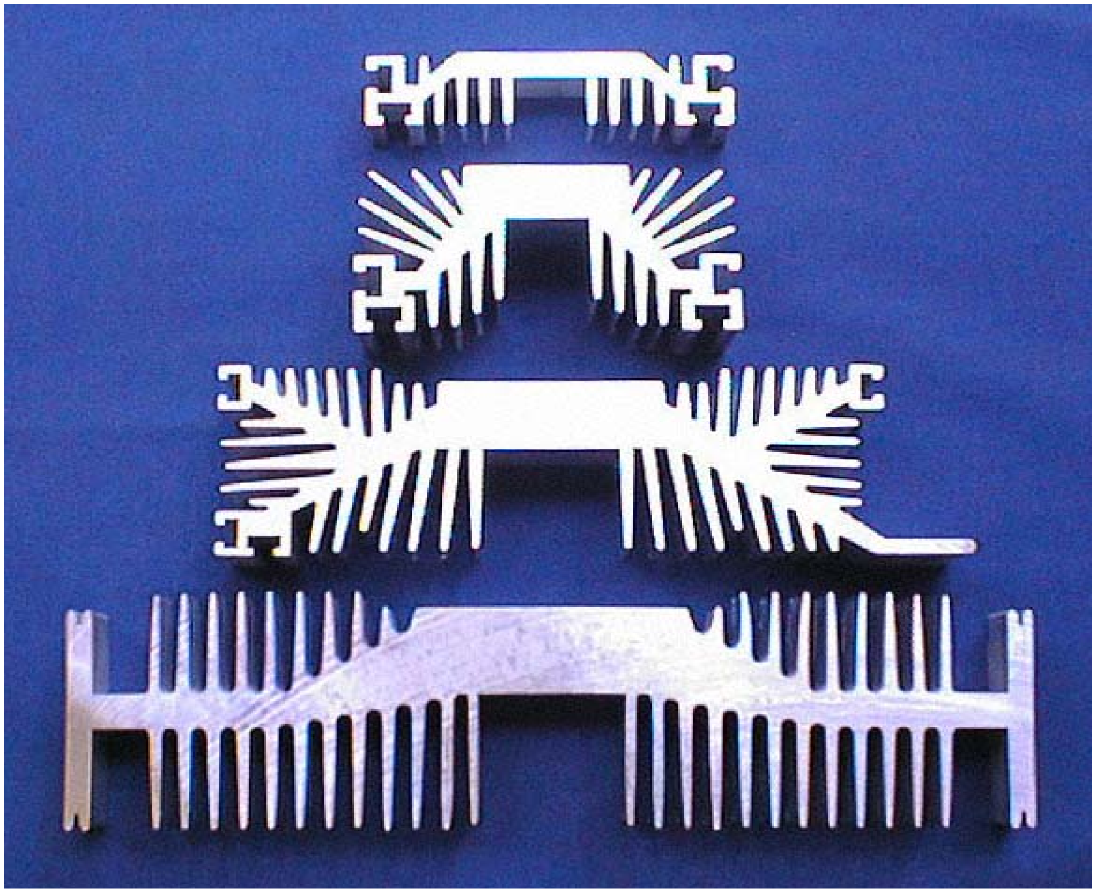
Discrete Device Heatsinks - A Part of the Circuit

Dual / Doubler Configuration





Common Stud & Disc Device Air Cooled Aluminum Extrusions



23mm Stud/Disc

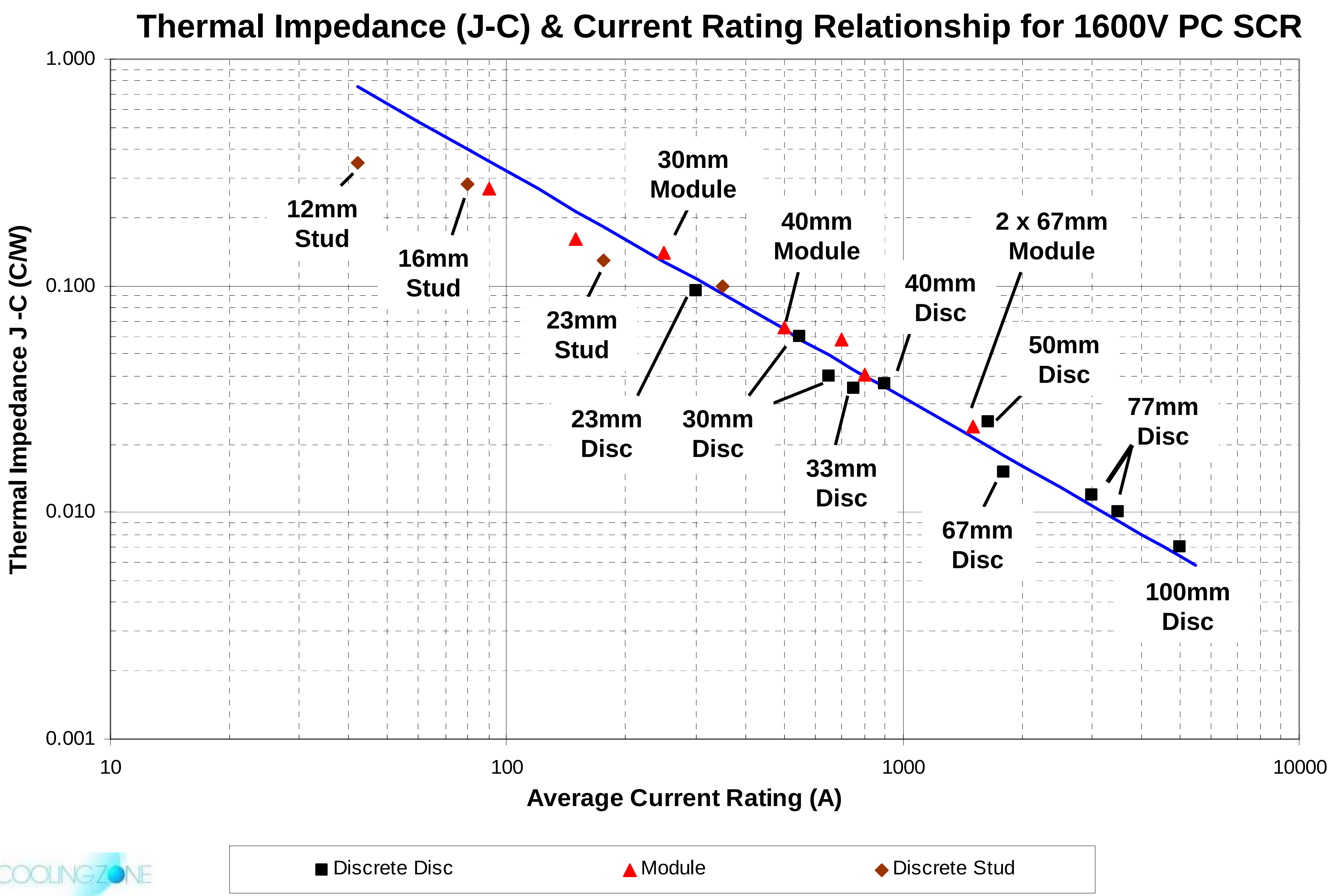
Up to 50mm Disc

Up to 67mm Disc

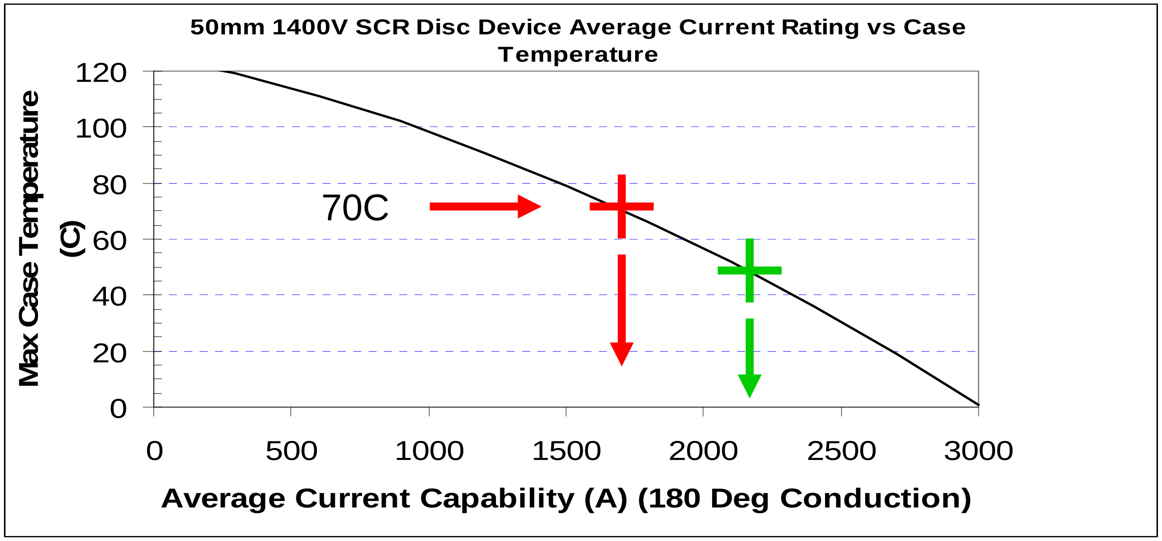
Up to 77mm Disc

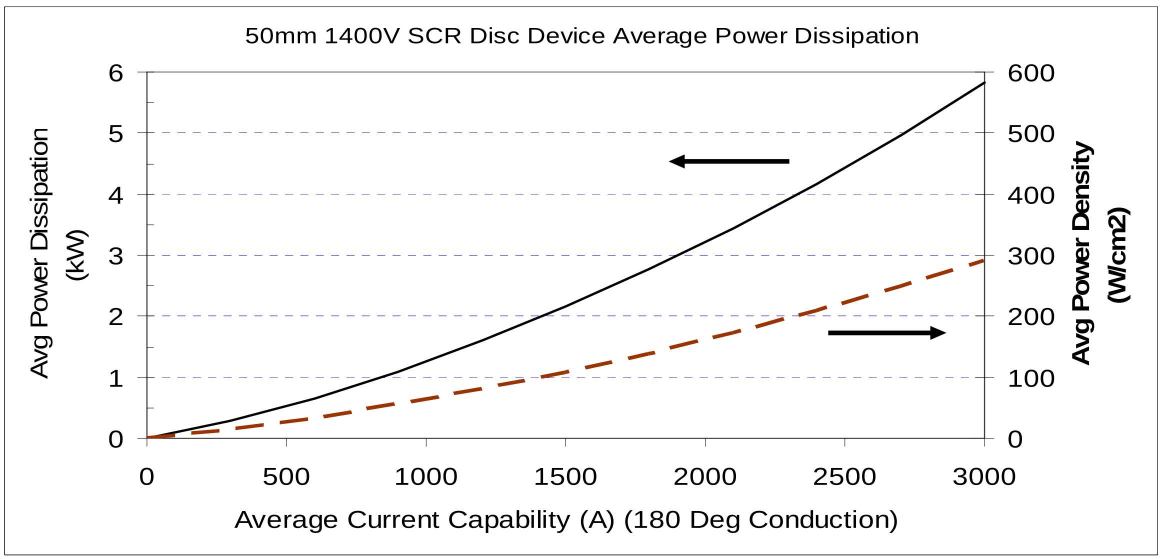
2”

Power Device Thermal Impedance & Current Rating



Increase in Device Current Rating if Heatsink is Capable



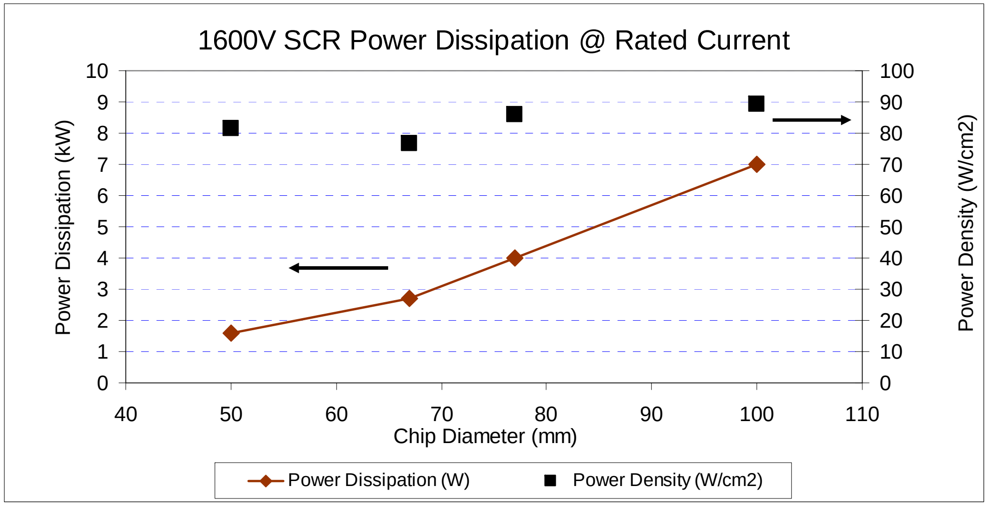


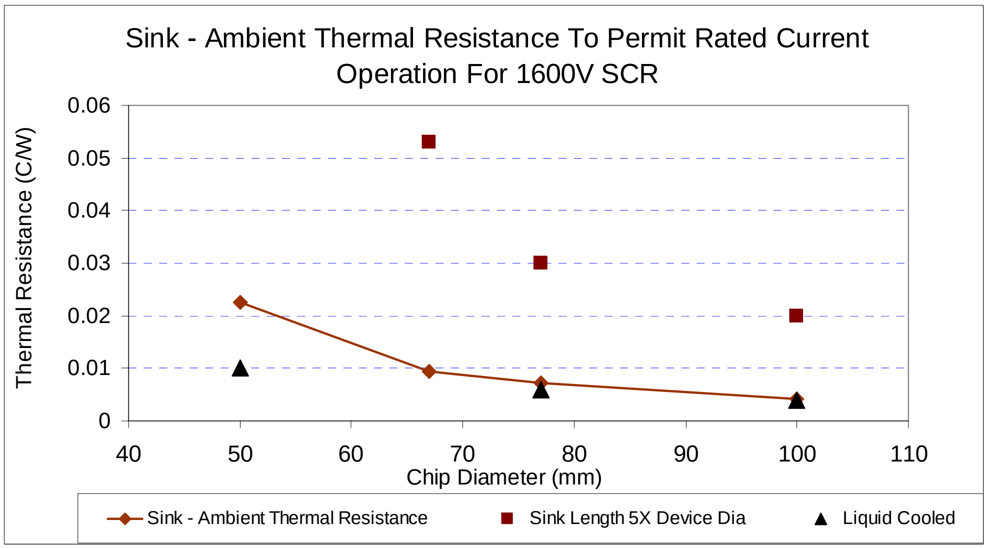
SCR Rated @ 70C Case

Increase Current Capability by Reducing Case Temp With More Efficient Heatsinks

20C Case Temp Reduction Leads to 25% Increase in Average Current Capability & 50% Increase in Power Dissipation

Air Cooled Heatsink Limitations for Large Diameter Disc Packages





Air Cooled Heatsinks Limit Device Performance

- **Tcase = 70C**
- **Inlet Air = 40C & 1000 LFM**
- **Sink Length = 5 X Device Dia.**
- **Liquid Cooled Flow = 3 GPM.**

Heatsinks for Discrete Stud & Disc Devices - Summary

Air Cooled

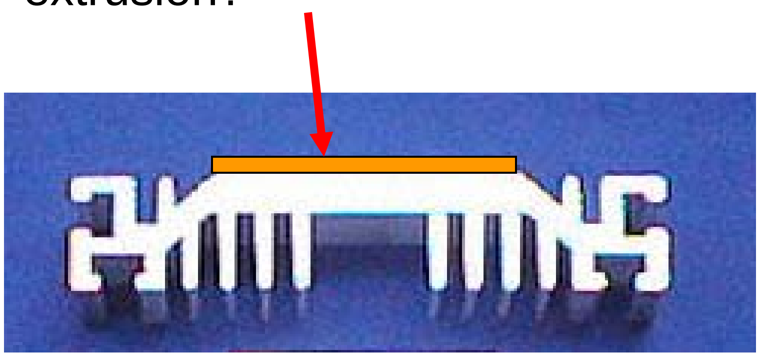
- Low cost approach adequate, but limits capability of power devices
- Large heat capacity & long thermal time constant good for short term overloads
- Bonded fin family of heatsinks presently not capable of high clamping pressures (5,000 - 20,000 lbs) required by large disc devices

Liquid Cooled

- Not an option in many applications
- Works well for large diameter devices > 77mm
- Field replacement of power device difficult
- Insulating liquids required for electrical isolation

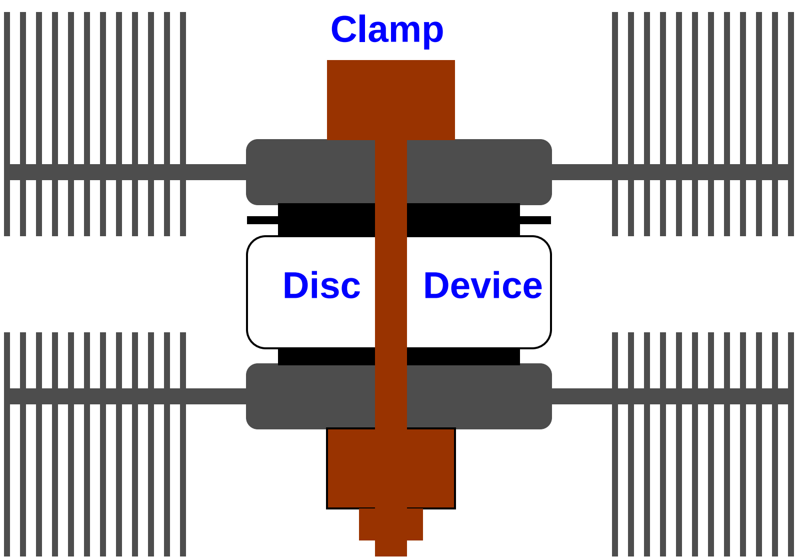
Is it Possible?

Can a thin layer with a very high thermal conductivity, high delectric strength & high compression strength like diamond be applied to the device contact area of an extrusion?



Result -- Isolated discrete device heatsink with minimal added thermal resistance.

Can a heat pipe / bonded fin heatsink hybrid be developed for large diameter disc devices? Can the heat pipe materials & liquid have electrical insulating properties?



Result – Low thermal resistance, isolated air cooled heatsink for large diameter discs.

Power Switch Cooling - Modules

Advantages

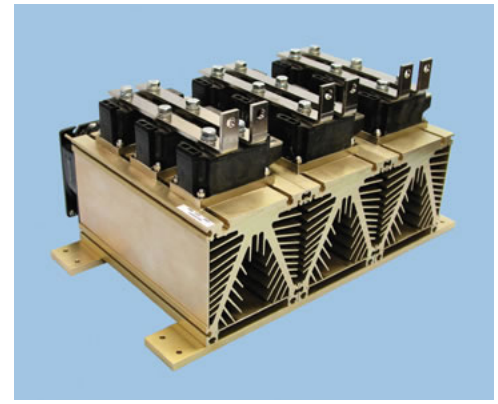
- Do not require external clamping
- Isolated base plate permits grounded heatsink
- Mount multiple modules on a common sink
- Air & liquid quality requirements are much lower
- Basic circuit building blocks in one package

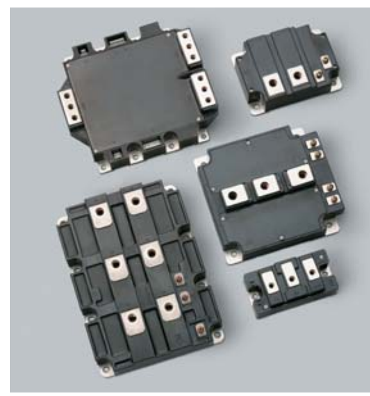
Disadvantages

- Higher thermal impedance than discretes
- Lower average current rating - 40% of disc device with same chip
- Lower overload capacity in some cases

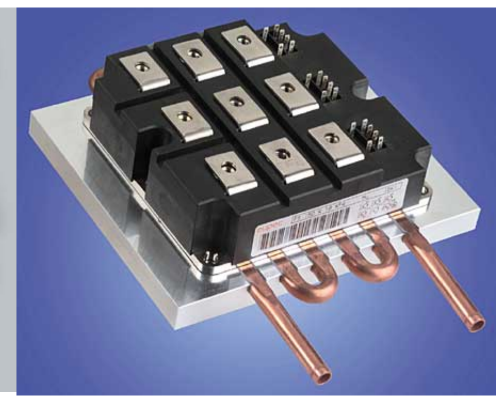
Compression Bonded

Air Cooled





Soldered & Wirebonded



Liquid Cooled

Planar Chip Mounting Methods – Thermal Paths

Conventional Solder Down

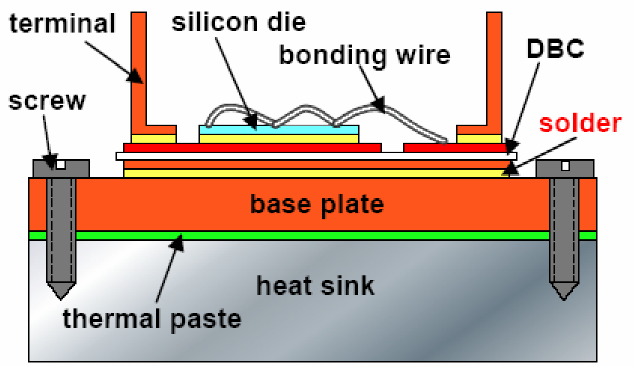


Fig.2: Cut through a conventional power module with base plate (housing not shown)

Semikron Compression Bonding in Skiip Packs:

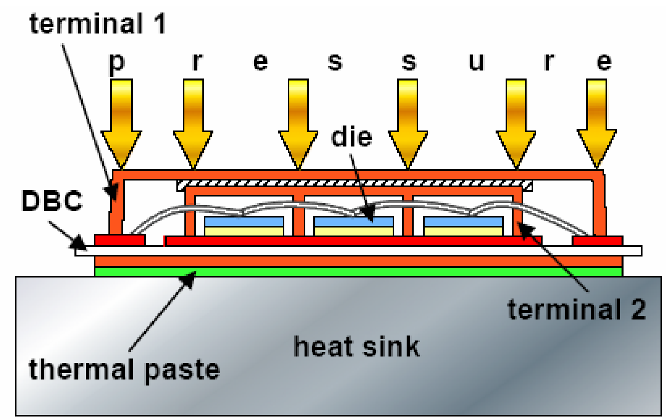
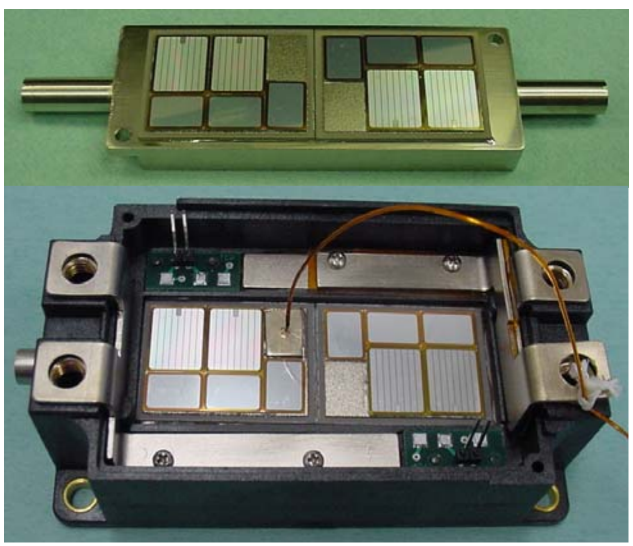


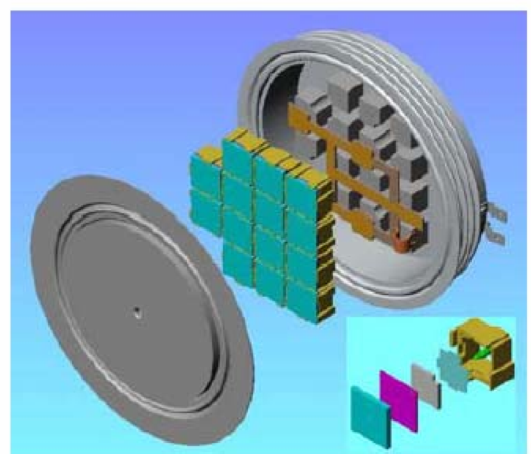
Fig.4: Power module without base plate in SKiiP technology (housing not shown)

Semikron - PCIM Euro 2005 Proceedings

Powerex – Substrate Soldered Directly to Microchannel Chill Plate

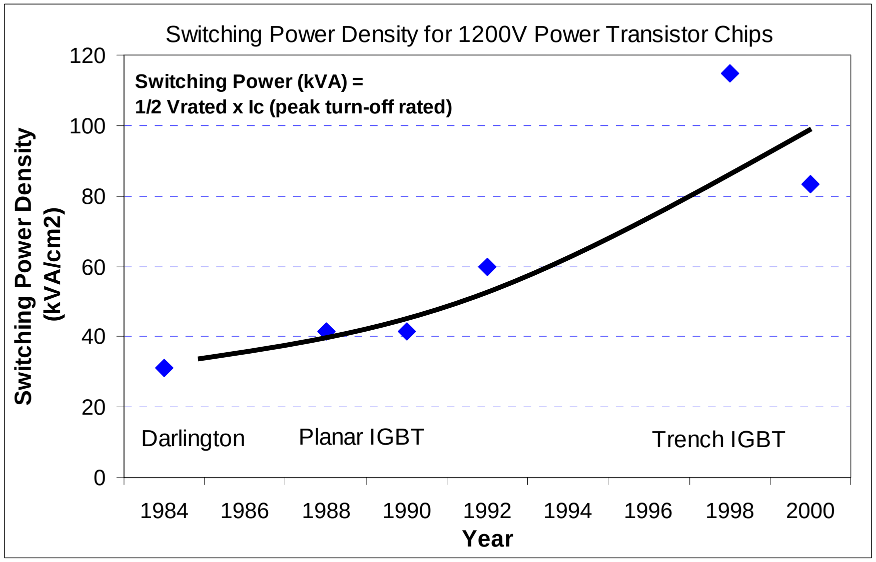


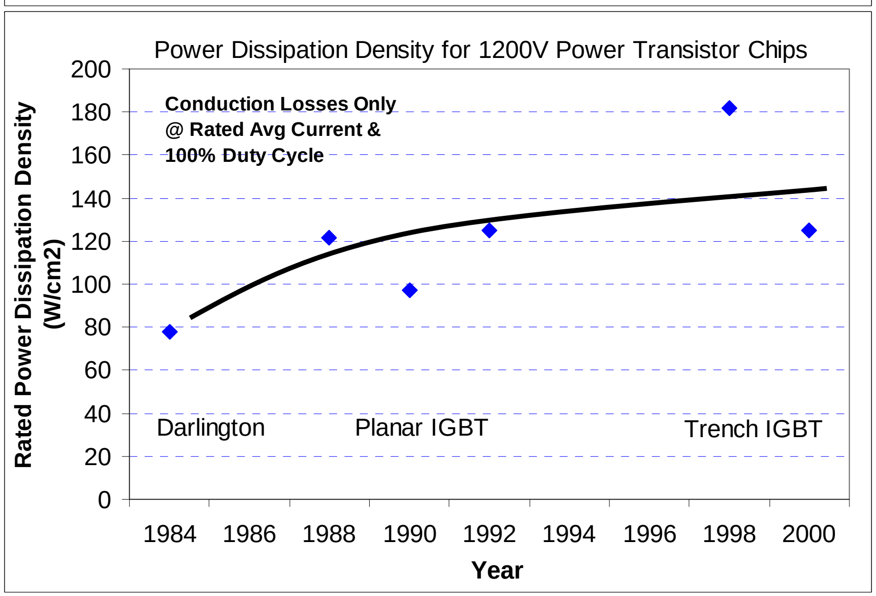
Westcode/IXYS Compression Bonded IGBTs in Disc Packs:



Westcode - PCIM Euro 2005 Proceedings

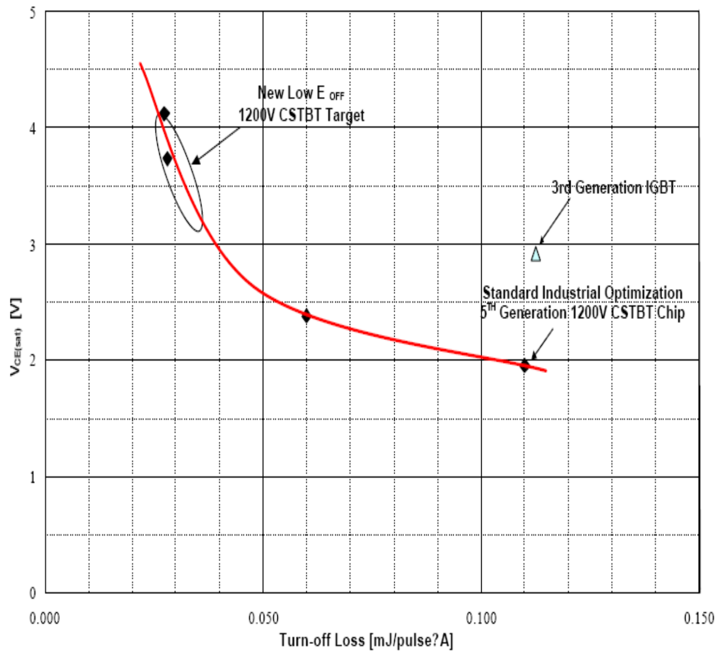
1200V Transistor Chip Power Density Trends



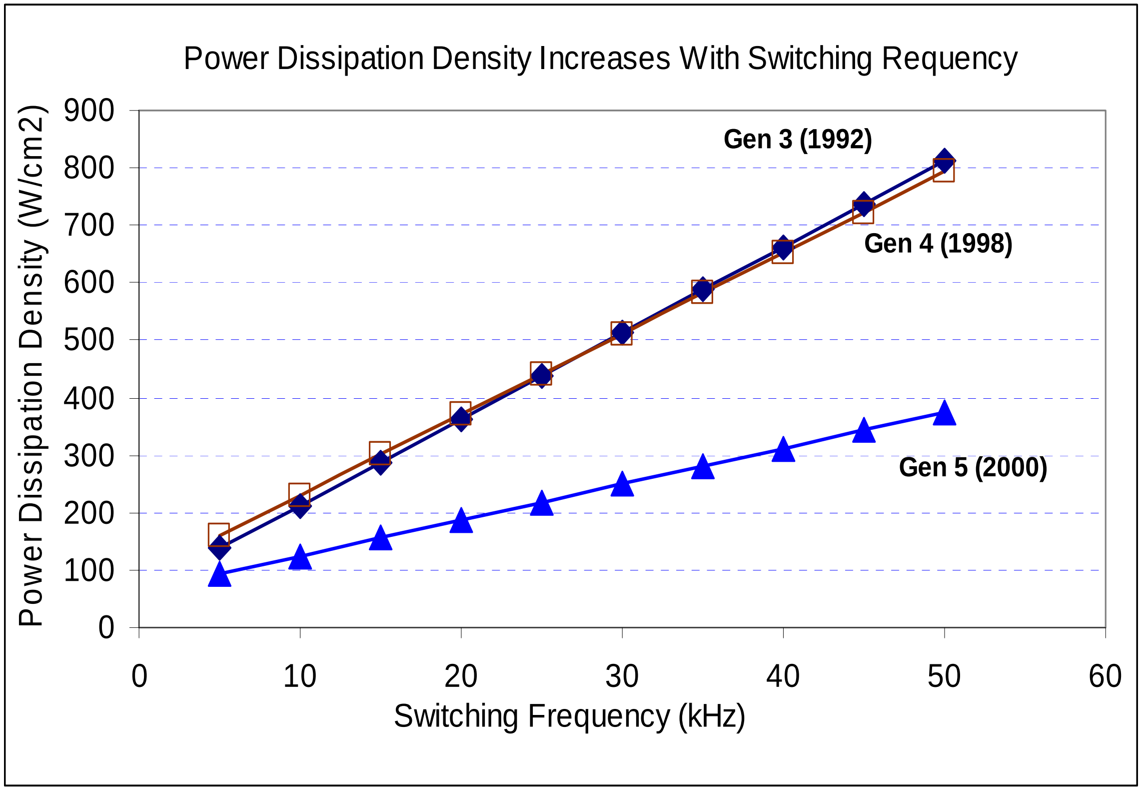


Improvements in IGBT cell density, conduction & switching losses have resulted in higher switching power densities while power dissipation densities remain relatively constant

High Frequency Operation Increases Chip Power Dissipation

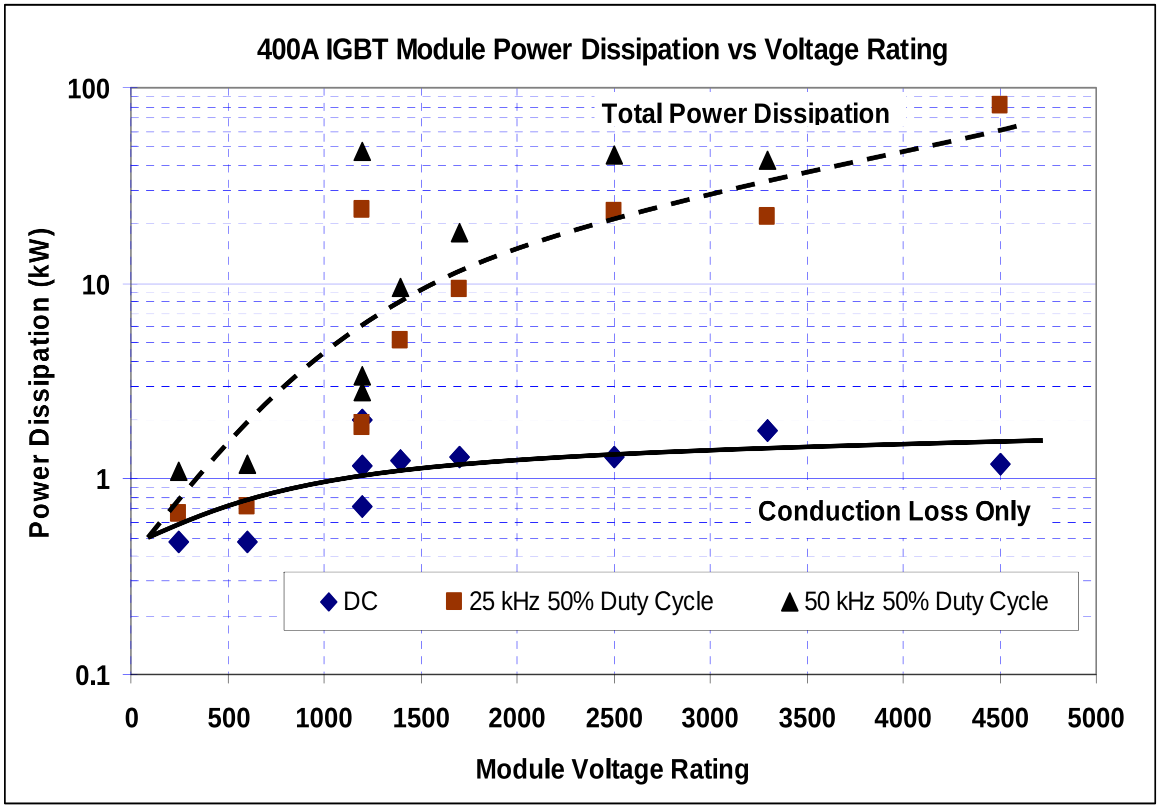


Conduction vs Switching Loss Trade-Off



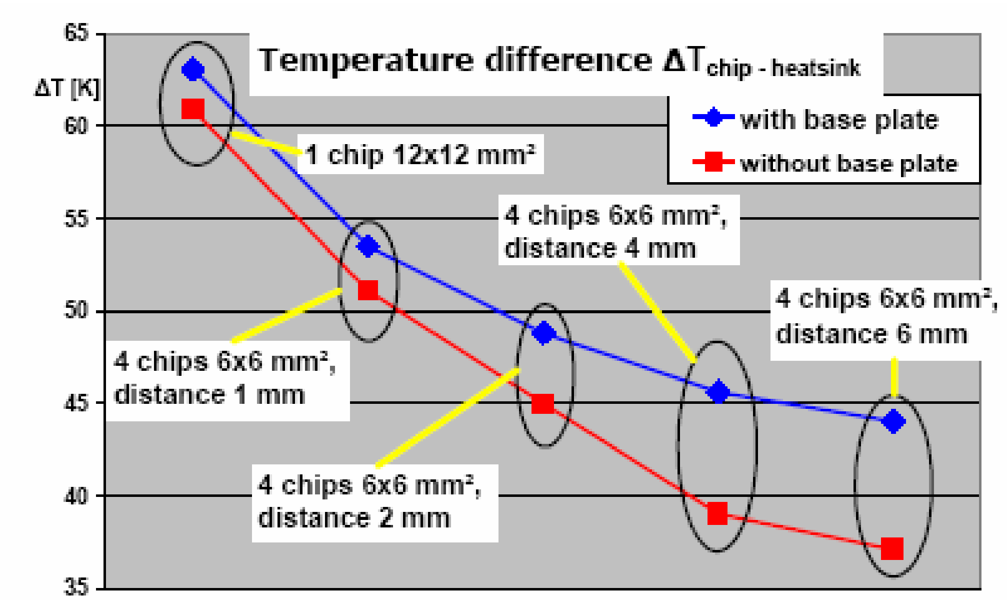
Vcc = 600V, Ic = 100A, 50% Duty Cycle -- Calculated

Higher Module Voltage Ratings Increase Chip Power Dissipation



Vcc = 50% Rated Vce, Ic = 400A, 50% Duty Cycle -- Calculated

Power Dissipation Density vs Cooling



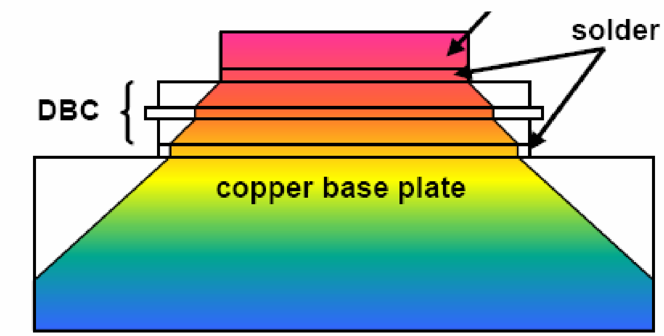
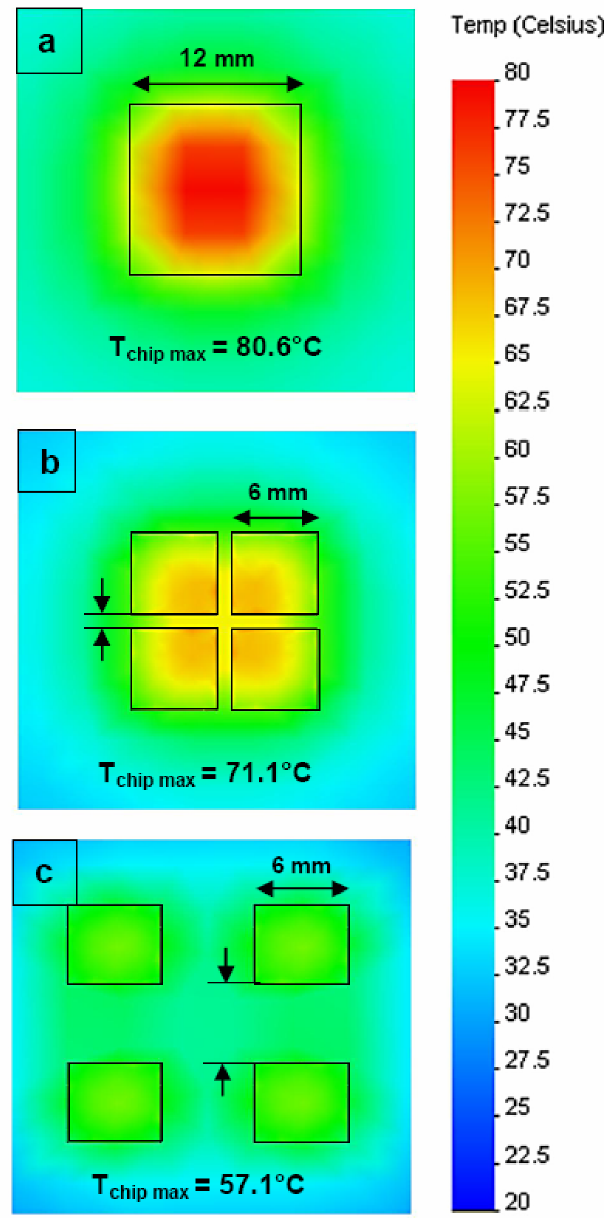
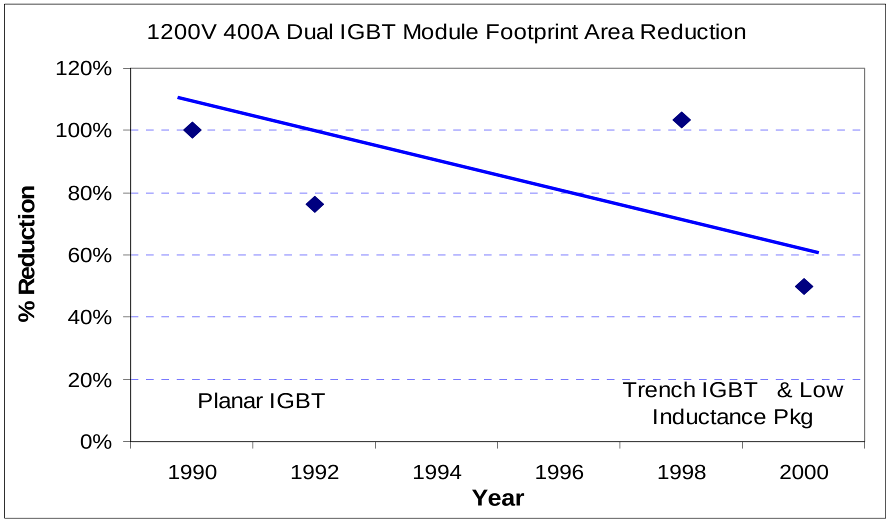


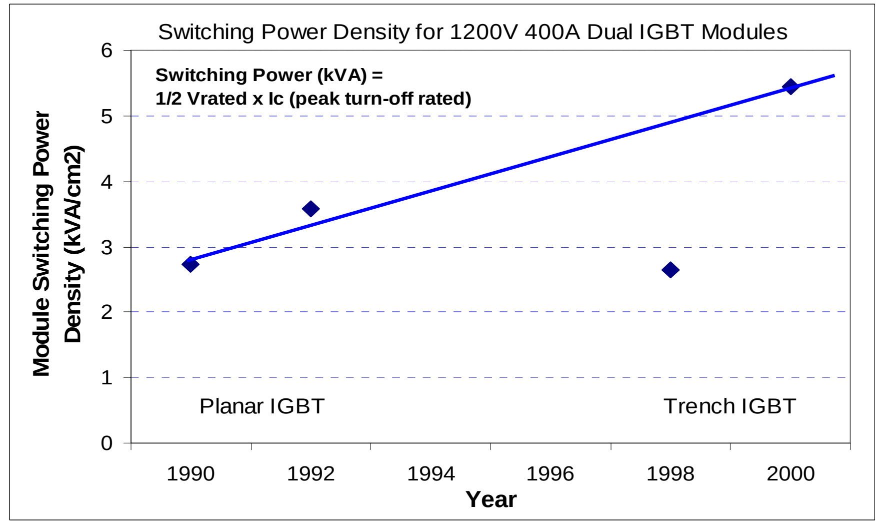
Fig. 5: Principle of heat spreading in a module

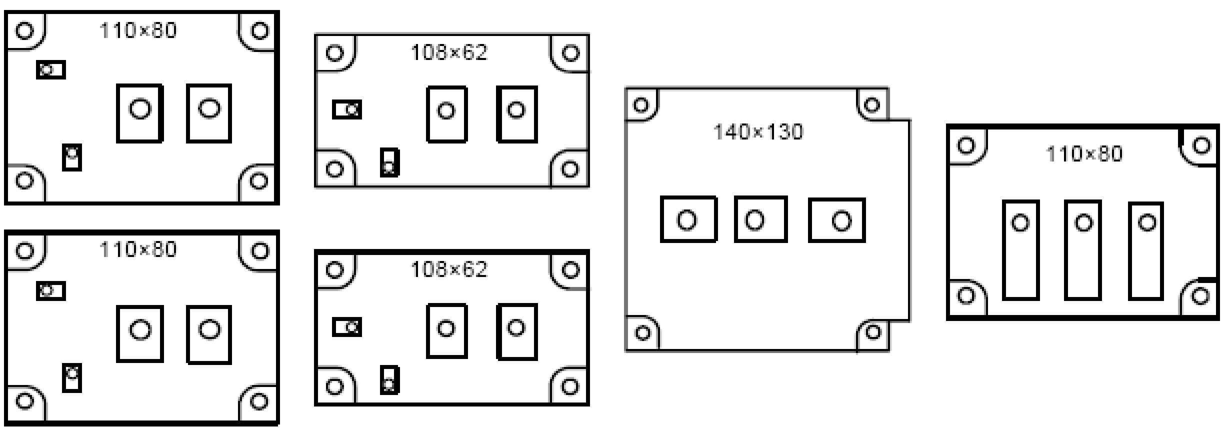


Ref: Beckedahl et.al. (Semikron) PCIM Euro 2005

IGBT Module Footprint Area Reduction (1200V, 400A Dual)





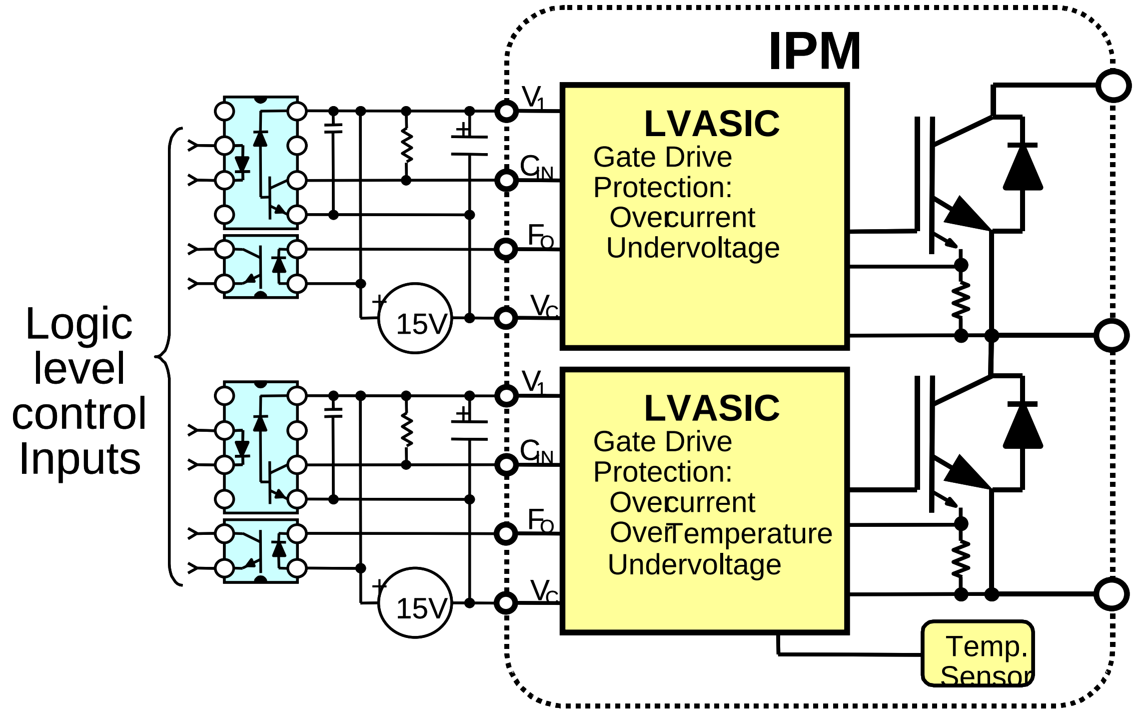


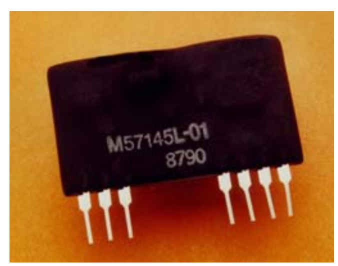
2nd Generation 3rd Generation 4th Generation 5th Generation

Reduction in IGBT package footprints have resulted in higher module switching power densities, higher power dissipation densities & lower inductance

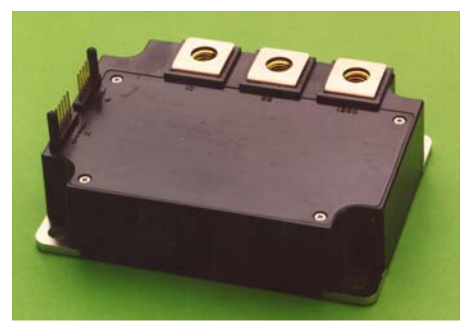
Power Switch Evolution - Integrated "Intelligent" Power Module = IGBT + Smarts

- Gate drive, temperature sensing & protection elements are integrated in the power switch package
- Protection for:
  - **Overtemperature**
  - **Overvoltage & current**
  - **Low supply voltage**
  - **Fault signal feedback**
- Improves switch performance since protection functions are integrated in package
- Ease in application





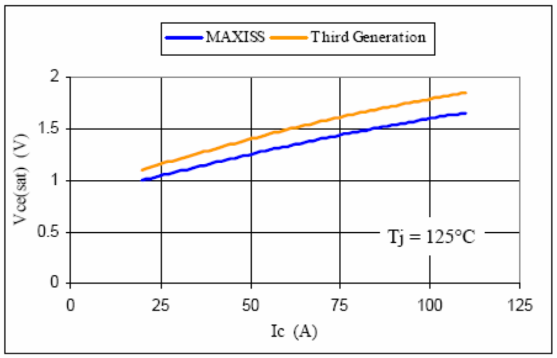
DC-DC Converter

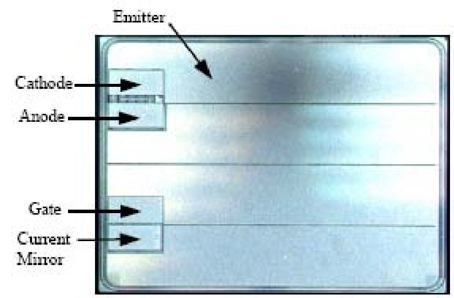


Intelligent Power Module

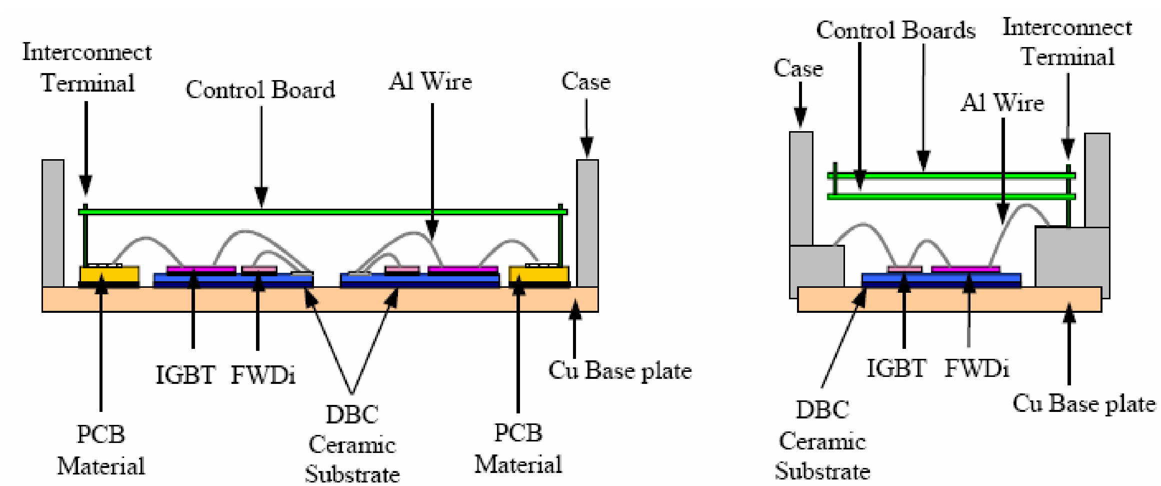
Increased Module Integration -- Size Reduction
600V 150A Servo Motor Controller IPM

Reduced cell pitch & increased density results in lower losses

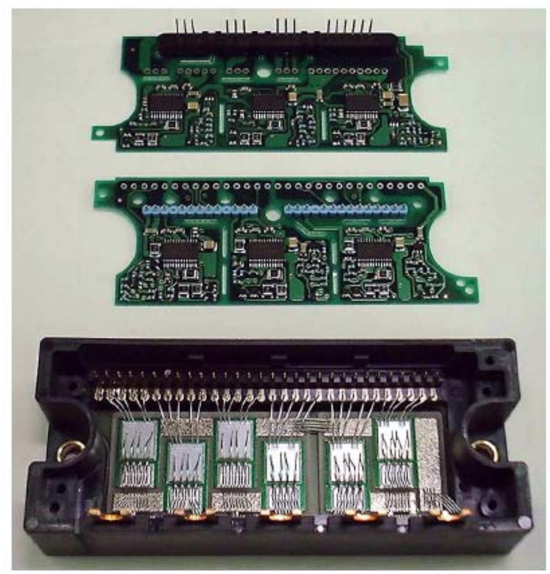




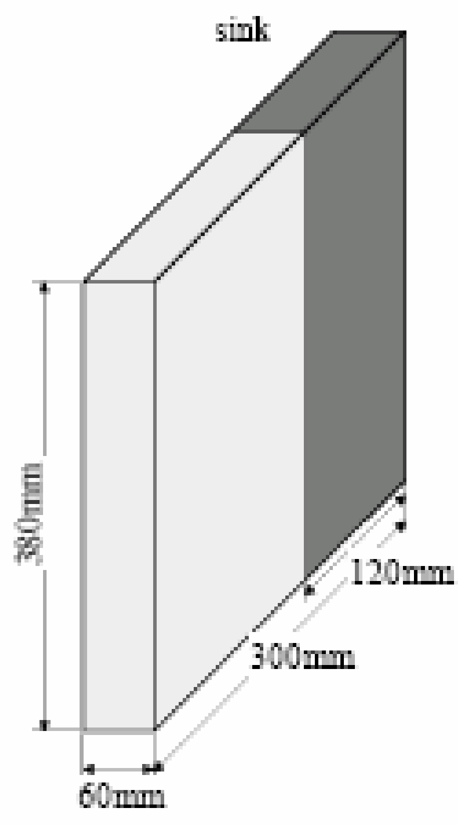
On chip current & temperature sensing along with advanced package design resulted in 30% - 40% reduction in module footprint for same current rating

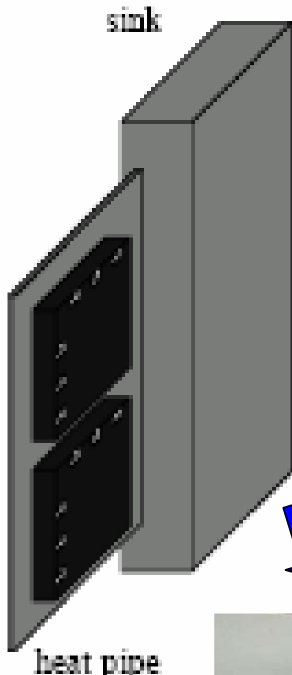


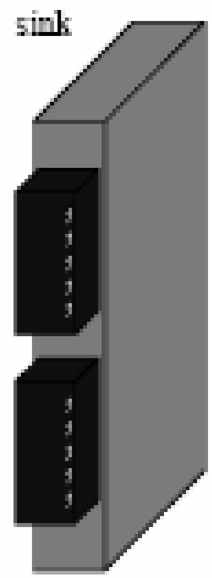
a. Third Generation b. MAXISS



System Impact of Increased Integration & Reduced Module Size







Gen 4 Module

Heat Pipe

Gen 3 Module

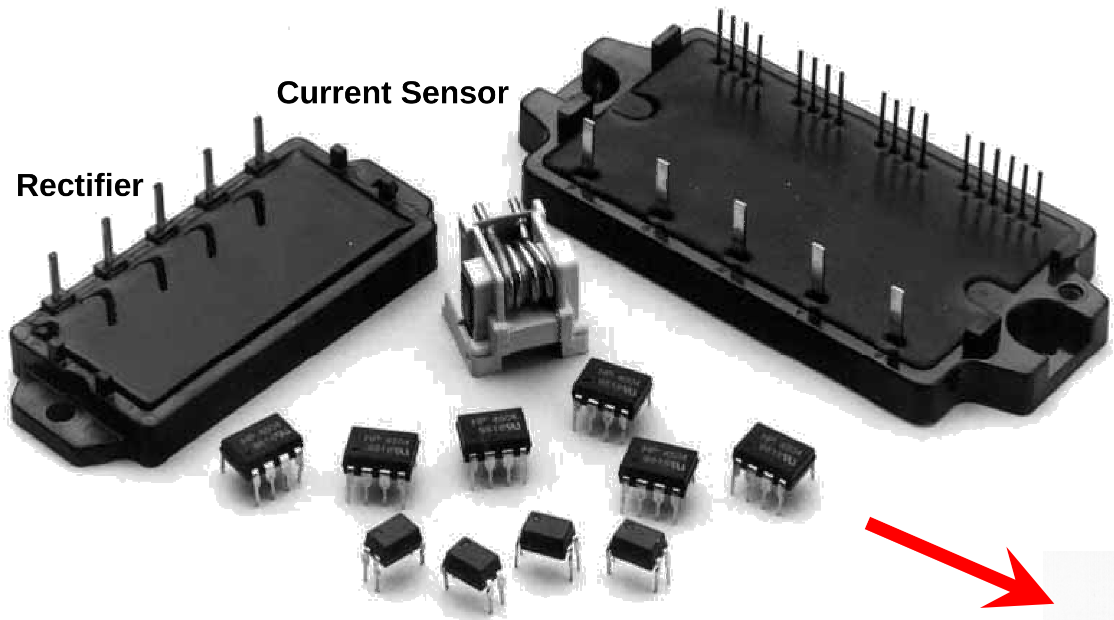
Smaller module resulted in smaller system & heatpipe elimination.

Small Motor Drive Integration

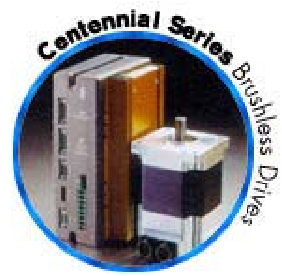
Conventional IPM

Current Sensor

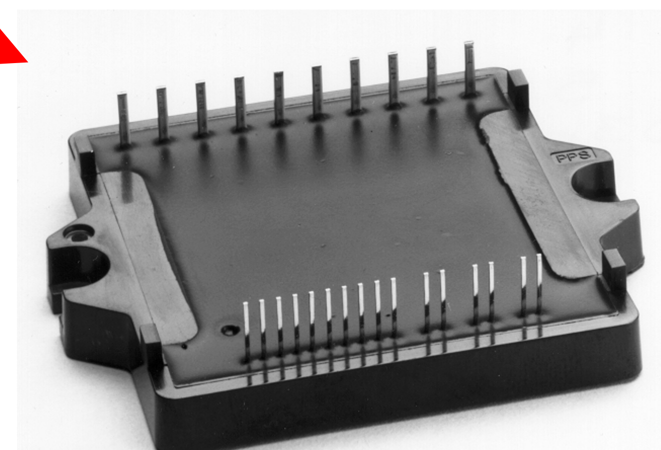
Rectifier



Optocouplers

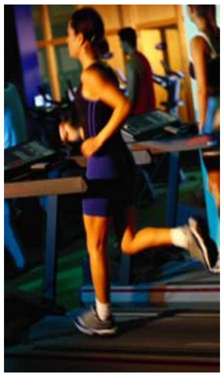


- **Small Servo Drives**
- **Pumps**
- **Low End Industrial Drives**
- **HVAC, Compressors and Blowers**
- **Robotics**

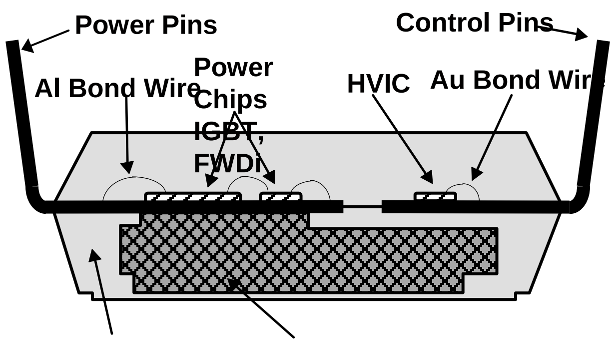


Version 3 ASIPM

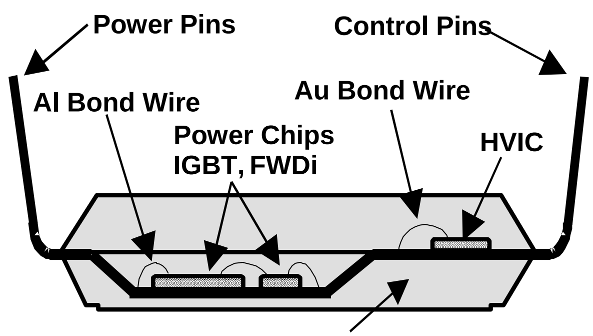
Appliance Motor Drives

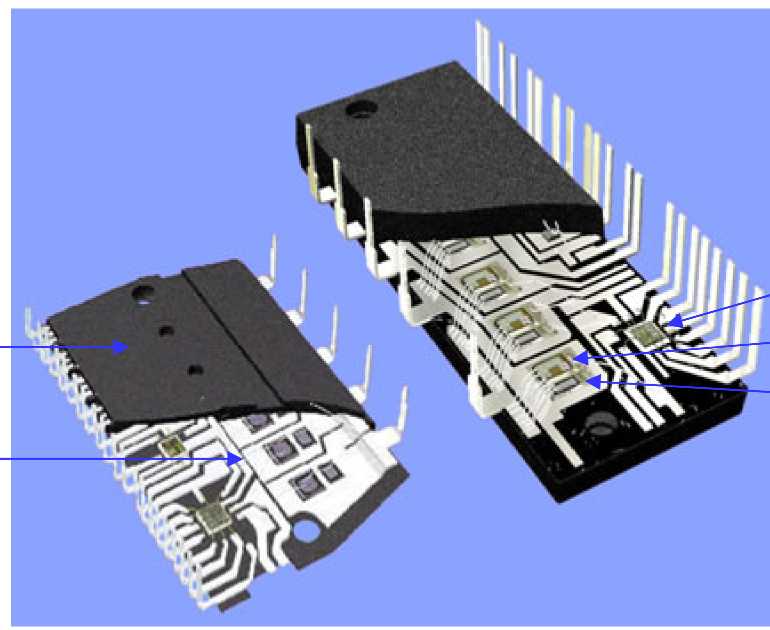


Original DIP-IPM



New Mini DIP-IPM

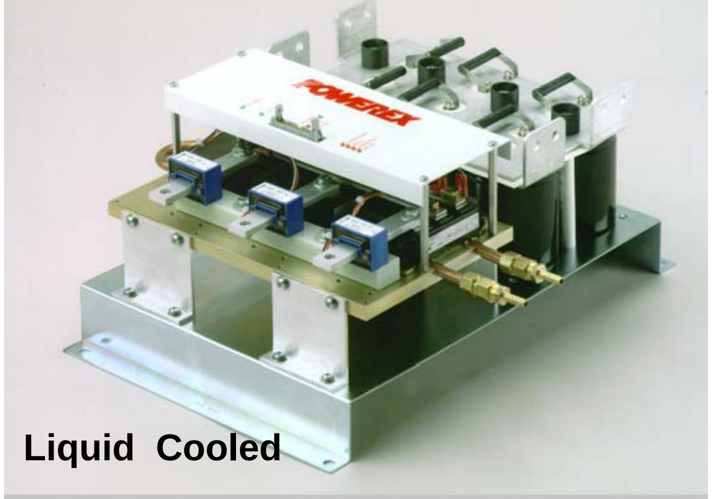


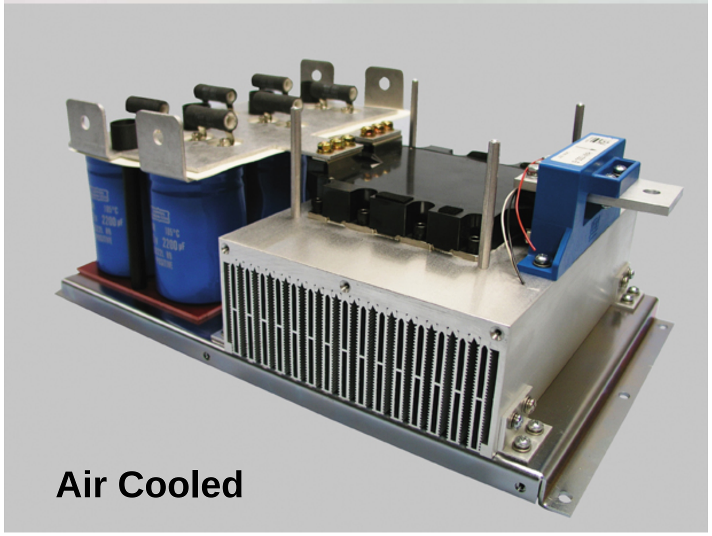


Assembly Subsystems – Beyond Systems in a Module

- Power switches
- Energy storage devices
- Current sensing
- Gate drives
- Protection
- Heatsinking

Powerex Pow-R-Pak

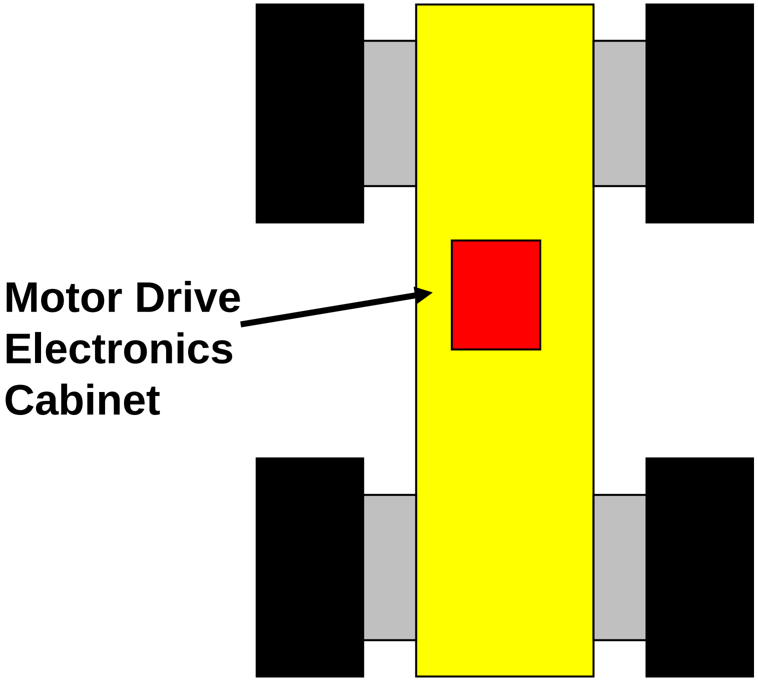




Semikron Skiip Pack

Large Off Road Vehicle Motor Drive Application

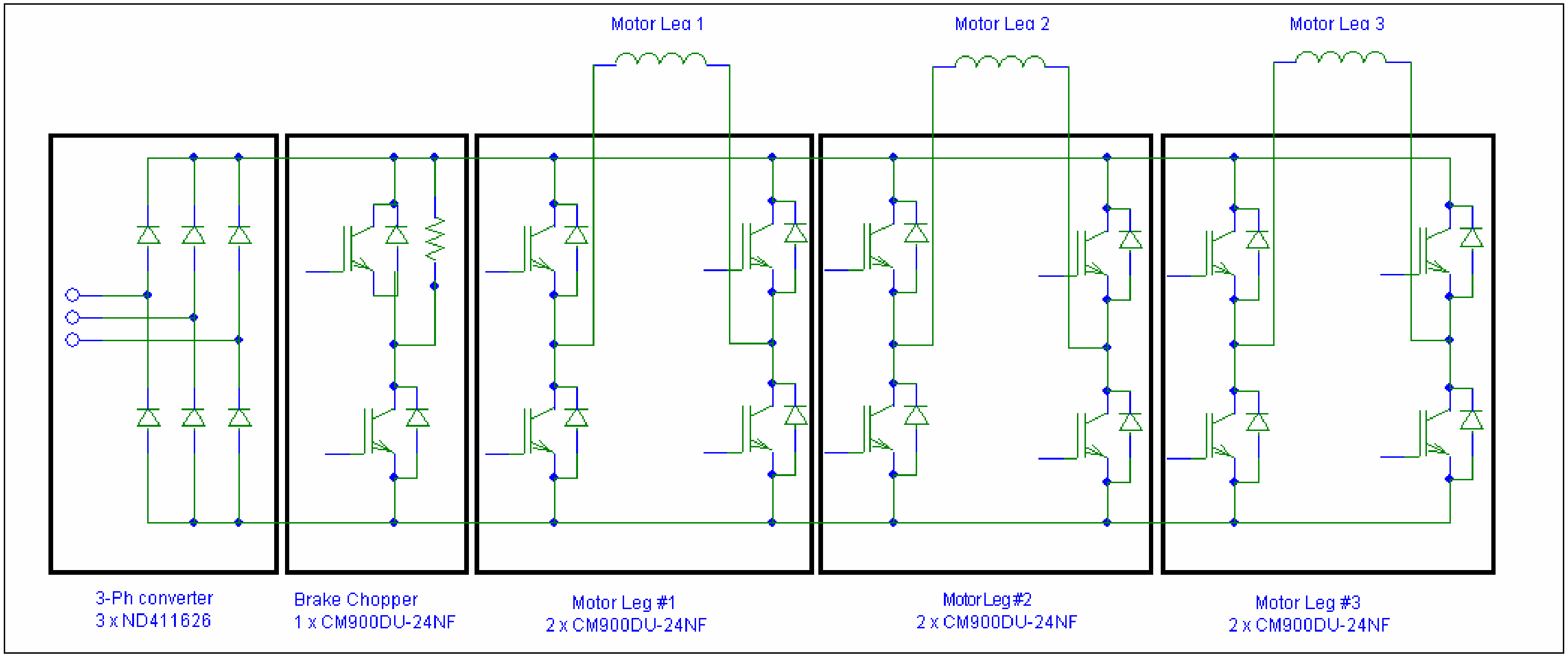
- Front end loader with a 400 HP motor driving each wheel
- Four independent motor drives fed by 2000HP on-board generator



Motor Drive Topology

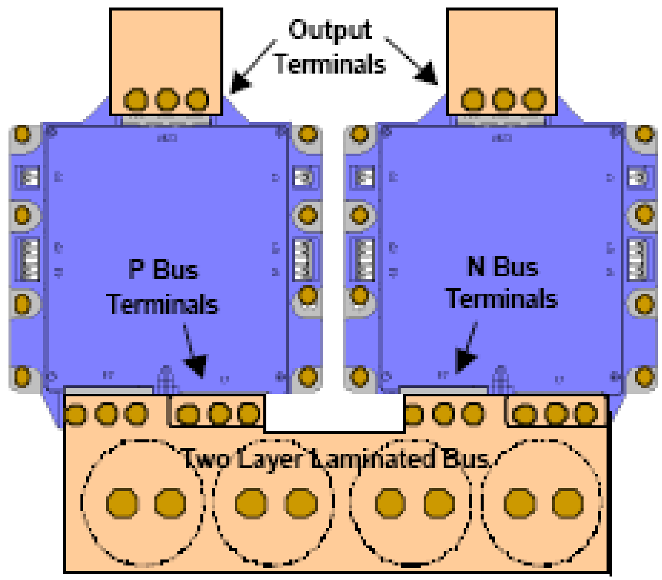
- Front end converter, Brake chopper, Inverter for each phase
- Four subsystem assemblies per motor – 16 per vehicle
- Three Rectifier & six IGBT modules per motor

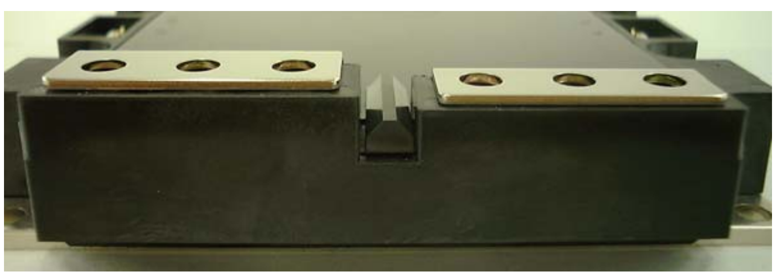
Single Motor Topology

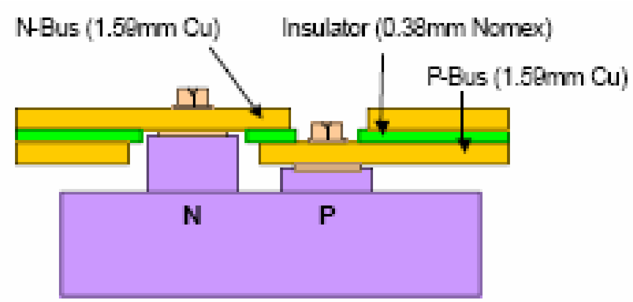


Module Design Reduces System Inductance & Complexity

1200V, 900A Mega Power Dual IGBT Module

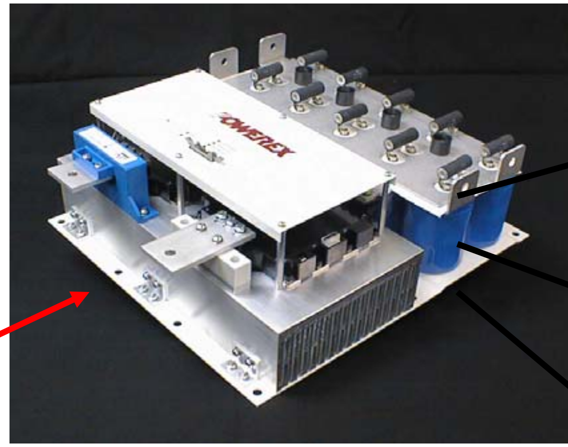






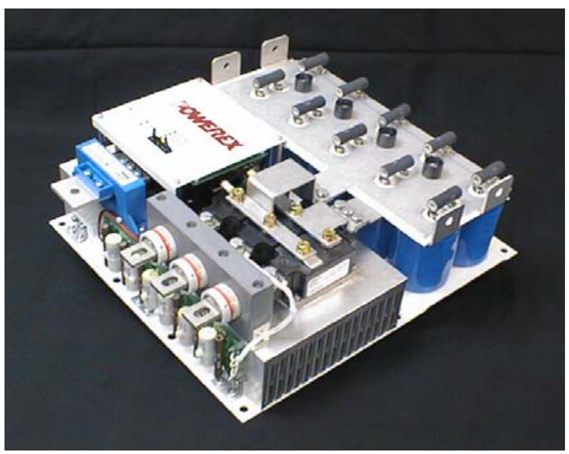
Drive System Integration

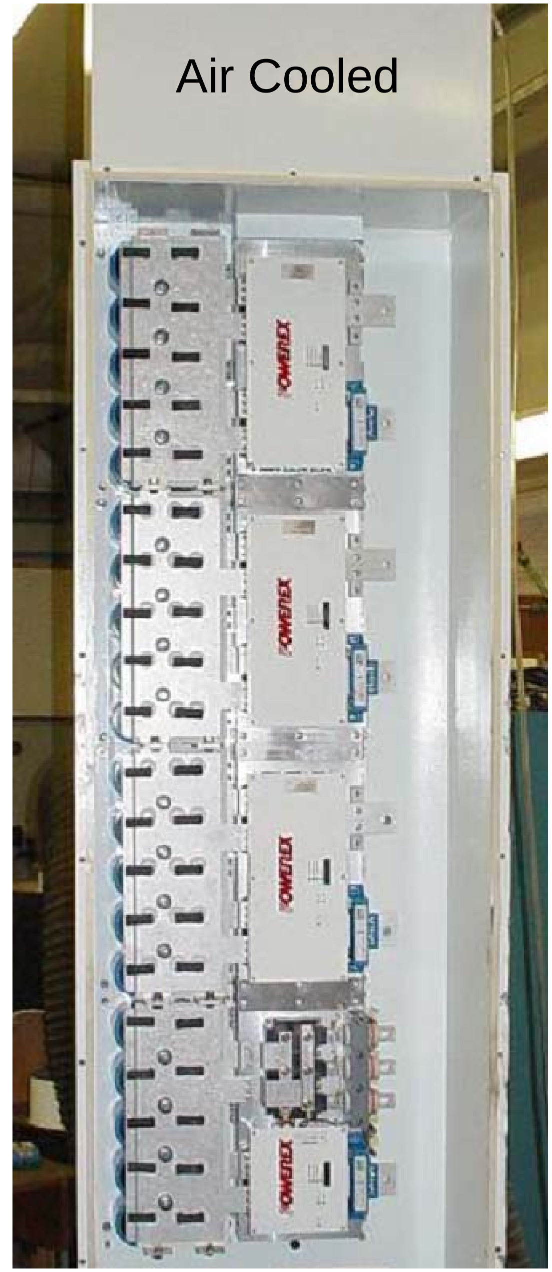
Motor Leg Inverter



Folded Fin Heatsink

Converter & Brake Chopper

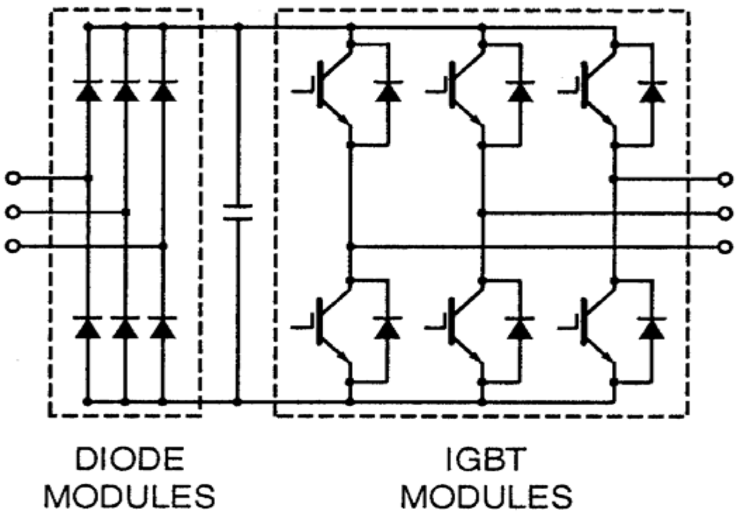


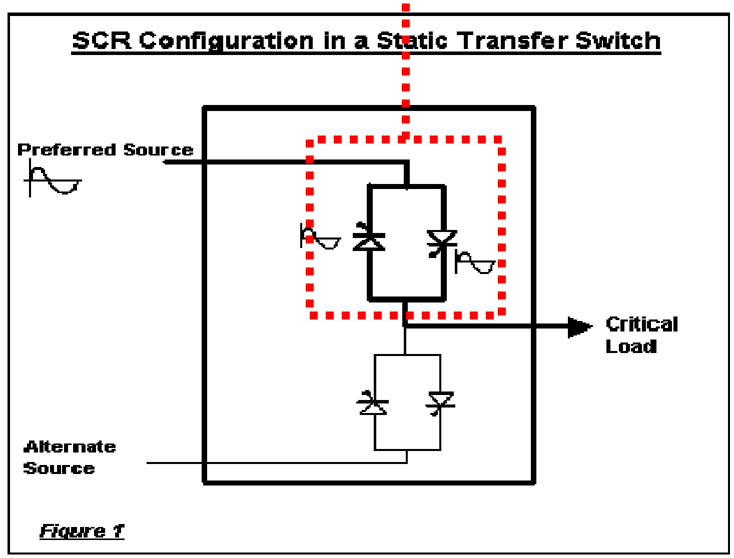


UPS & Transfer Switches

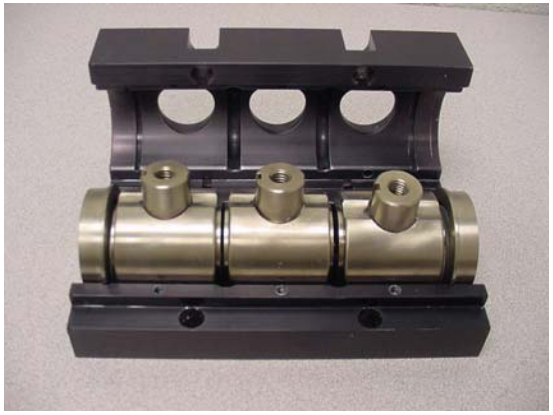
- Air cooled
- Primarily use isolated base plate modules
- Large systems still use discrete devices
- Overload requirements

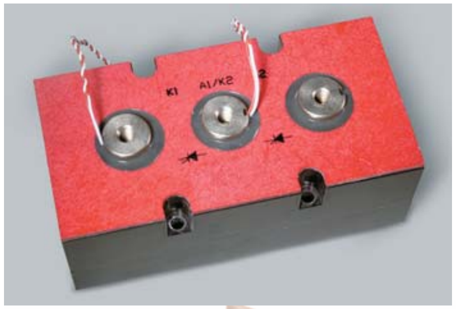
CVCF INVERTER (UPS)

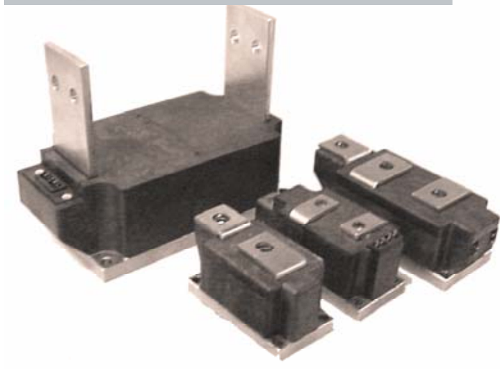


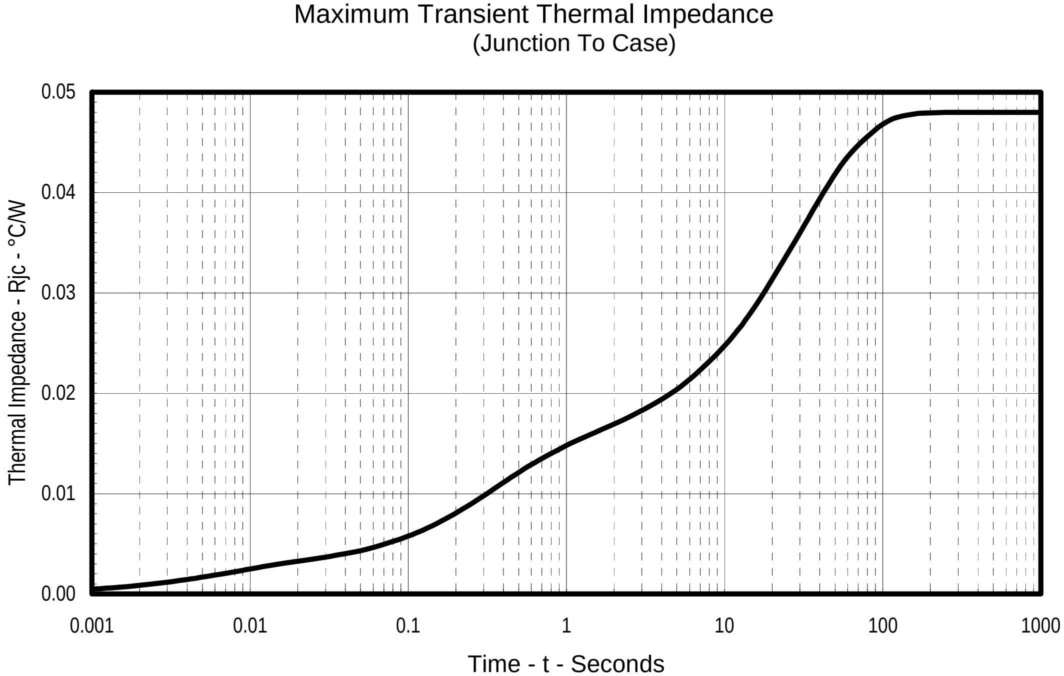


Low Transient Thermal Impedance for Overload Capacity



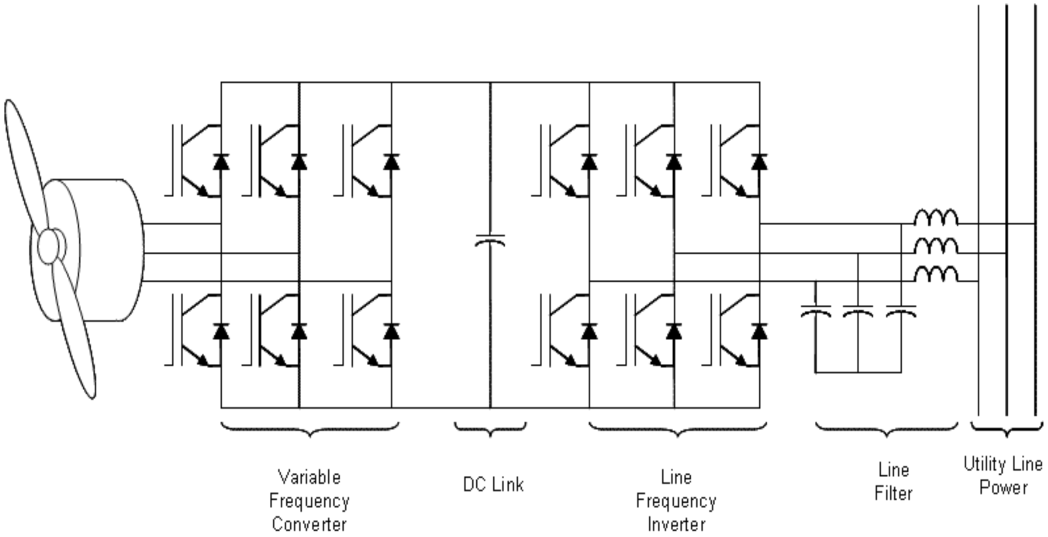




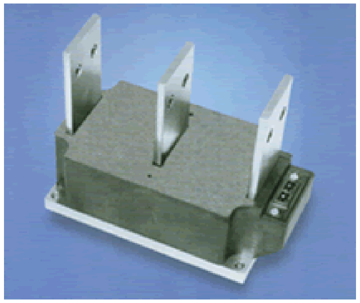


- UPS, Transfer Switches, Motor Drives
- Duration - millisecond to minutes
- Need high capacity material close to chip
- Short circuit overload (< 50 us) – heating is in chip only

Power Generation & Conditioning

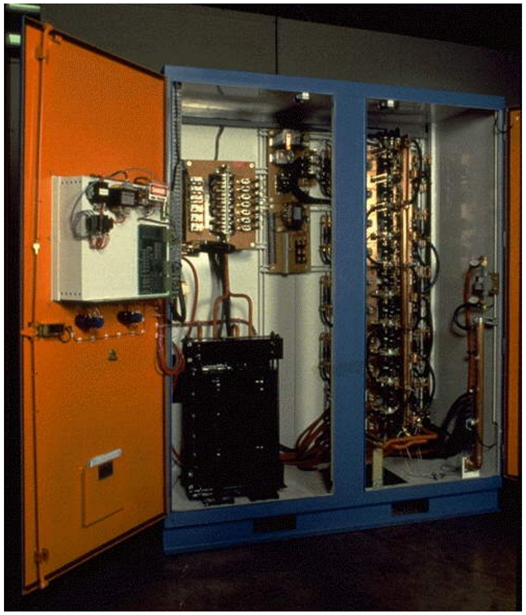


Typical Wind Power Inverter Circuit

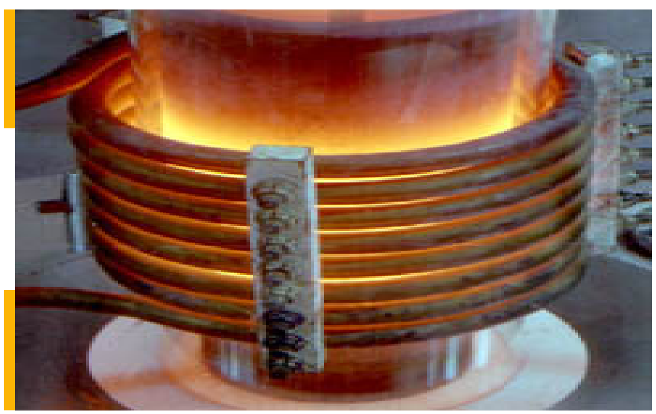


- **Air cooled**
- **Isolated base plate modules**

Induction Heating & Melting



Large metal melting systems use SCRs & are water cooled



Smaller high frequency heating / sealing systems use IGBTs or MOSFETS & are air cooled

Large DC Power Supplies

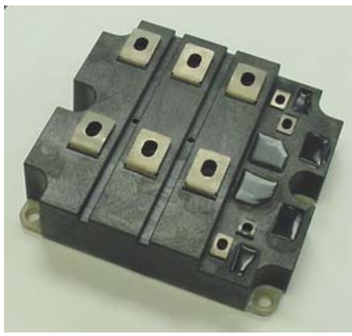
Ref: Applied Power Systems Inc.

- Discrete or module SCRs, Diodes
- IGBT modules
- Air or liquid cooled

Military & Aerospace - Future Trends

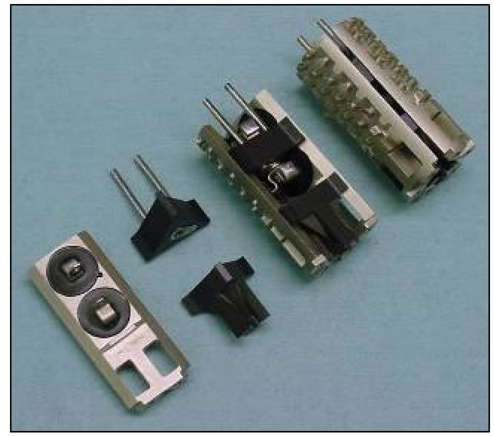
- More naval, aerospace & military applications are going electric
- Electric propulsion for military vehicles & ships
- Electromagnetic weaponry & aircraft catapults
- Active power conversion systems replacing conventional transformers on ships
- Aircraft "fly by wire" actuators for flight surface control
- Impact on power electronic systems & devices:
    - High power densities & high temperature device operation
    - Power electronics on aircraft & military vehicles cooled with engine oil
    - Higher operating temperatures & increased cooling efficiency required
    - Higher temperature power semiconductor devices needed – SiC
    - Integration of chill plate into ceramic insulator of module

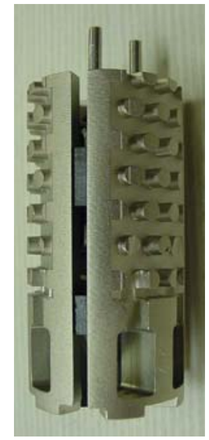
Aircraft Applications



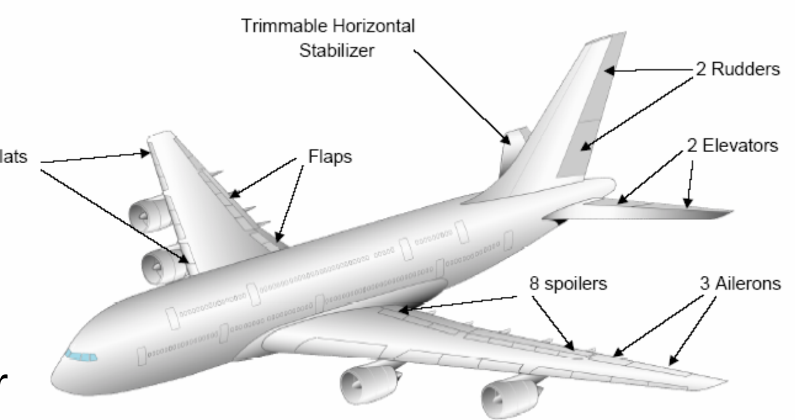
Aircraft Generator / Starter

- AlSiC baseplates
- Cooled with jet engine oil





Pin fin heat sink diode assembly is cooled by flowing jet engine oil



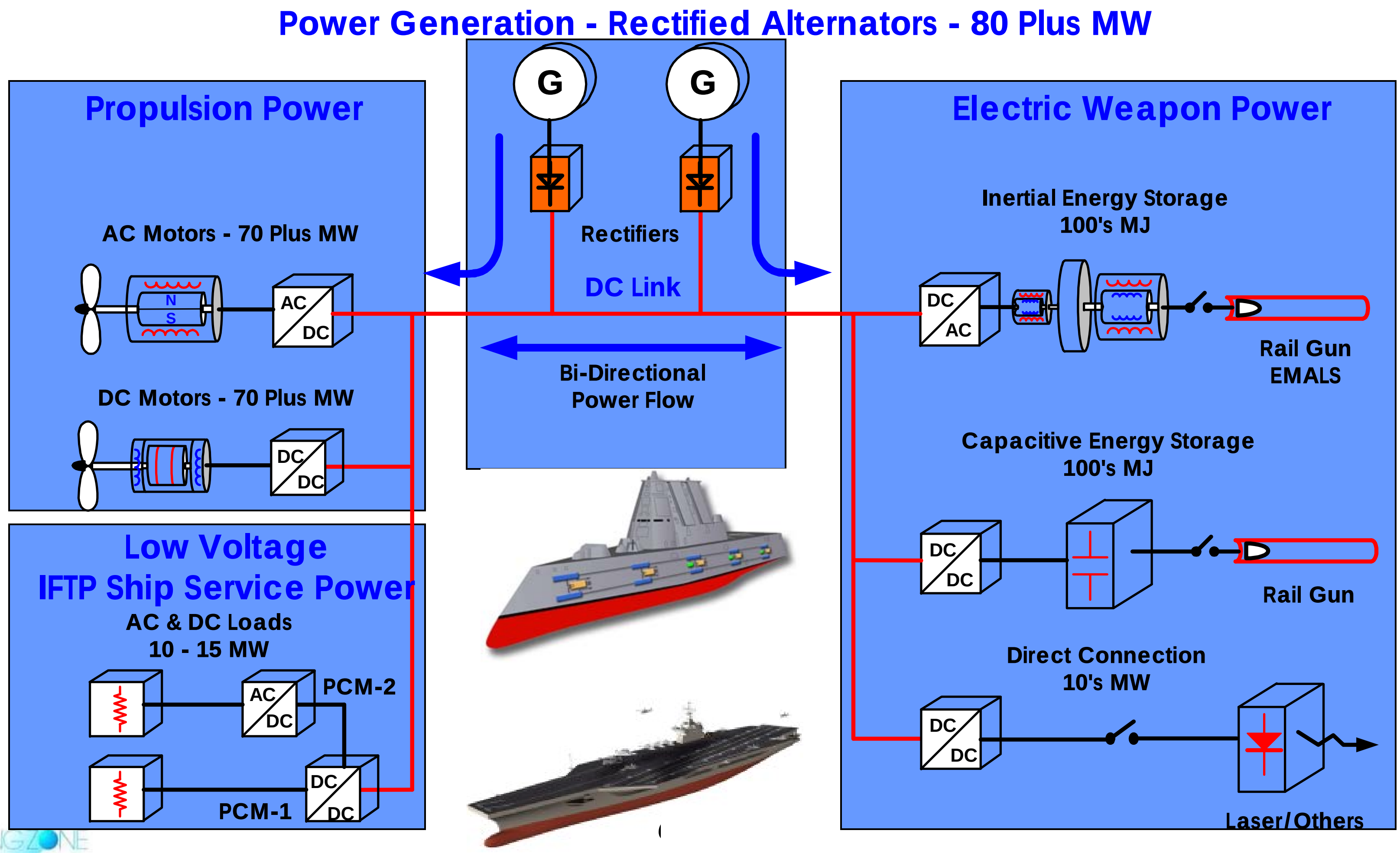
Ref: PCIM Euro 2005 Van Den Bossche -- AIRBUS.

"Fly by Wire" - Servomotor actuators for flight surface control

Ship Propulsion & Power Conditioning

Future Electric Ships Will Make Extensive Use of Power Conversion Systems That Require a "DC Link"

GENERAL ATOMICS



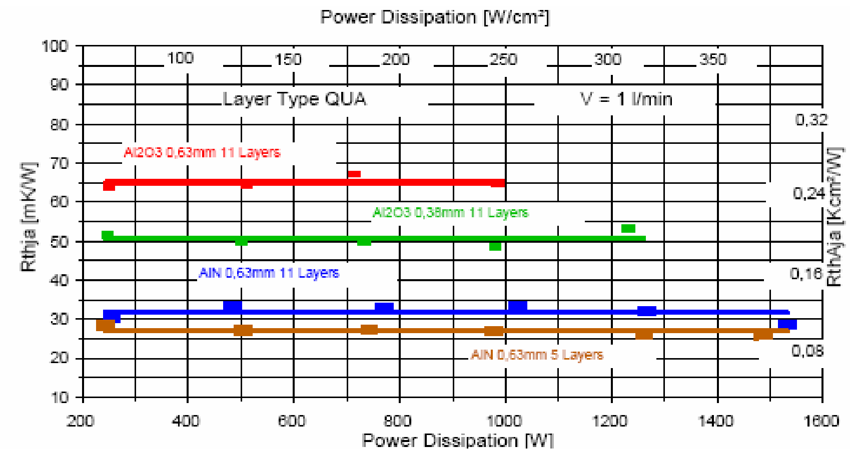
Shipboard Power Conditioning - PCM-2 -- 800 Vdc to 450 Vac

- PCM-2 contains modular 90 kW DC-AC inverters (800 VDC/450 Vac 3 ph)
- Current design has 6 SSIMs rated at 540 kW
- Design expandable to 3.24 MW
- NEMA 4 Sealed Cabinet uses internal air-cooled design to air to water heat exchanger. Power electronics in each SSIM are cooled by a sealed water-cooled cold plate.

SHIPS SERVICE INVERTER MODULE (SSIM)

- IGBT modules & liquid heatsinks comprise < 20% of SSIM module

Ceramic Micro-Channel Liquid Cooled Heatsink



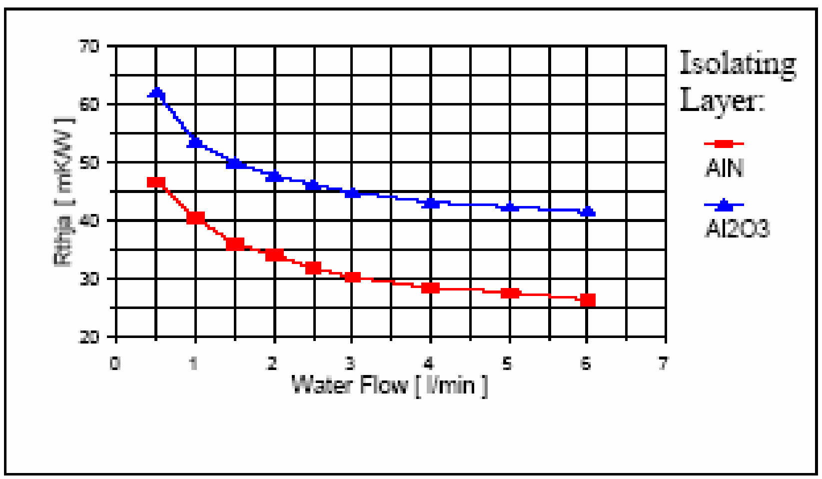


Fig. 13: Rthja as a Function of Water Flow

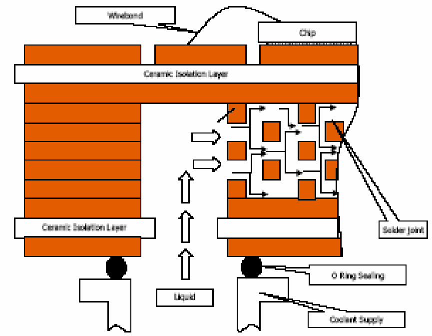
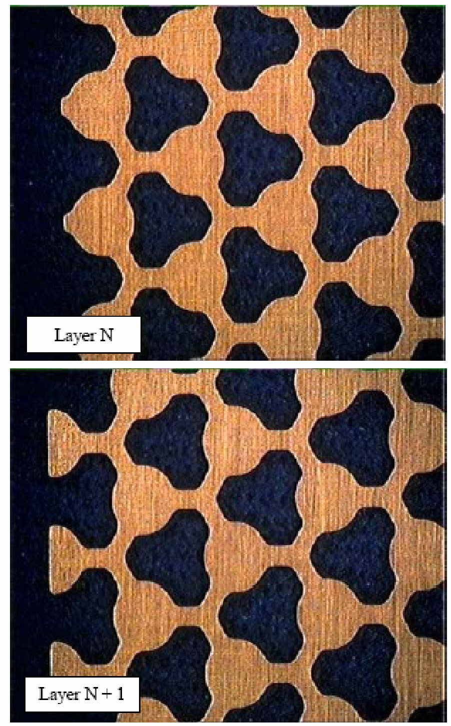


Fig. 10: Cooler Section of a DBC Sandwich with 3 Dimensional Micro Channels for Liquid Cooling

Typically the inner cooling structure is built up by 8 - 10 copper layers (0.3mm thickness each) with a hexagonal basic structure shown in fig. 11.



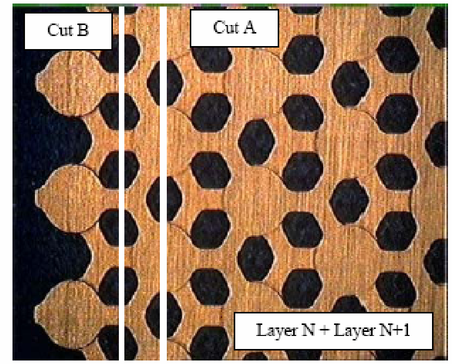


Fig. 11: Inside Cooler Design

The pillars have a diameter of 1.5mm. Fig. 12 depicts cross section cuts at the cut lines A and B. Heat arising at the chip mounting layer is diffusing through the copper pillars shown in cut A (fig. 12) and the wings (cut B) connected with pillars into the liquid. This assembly has an extremely low thermal resistance.

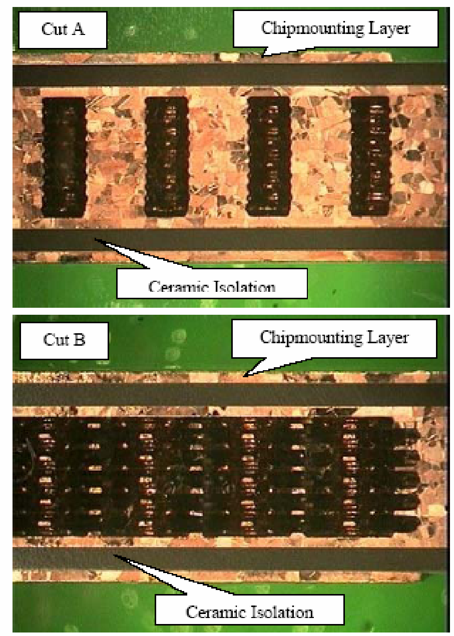
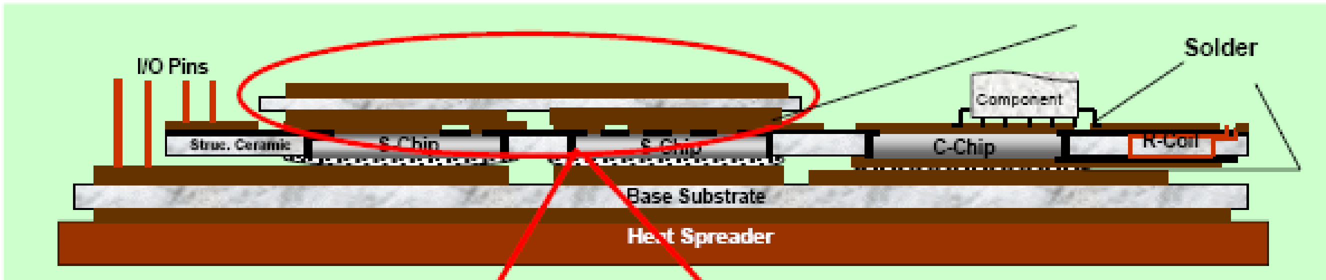
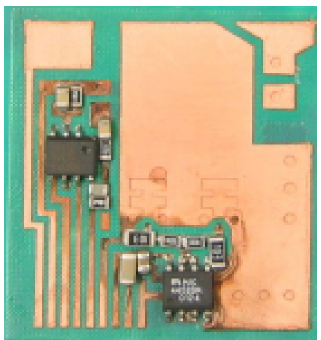


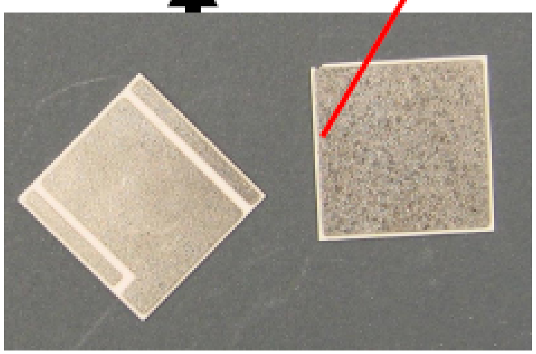
Fig. 12: Cross Section Cut of a DBC Cooler

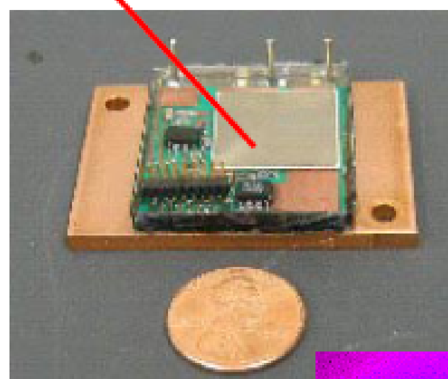
Ref: Schulz-Harder et.al. - Curamik

Power Semiconductor Module --- Double - Sided Cooling

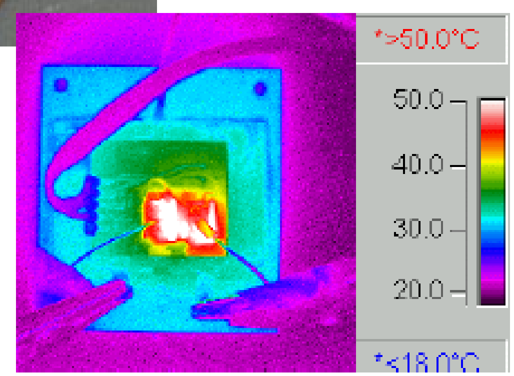








CPES
Center for Power Electronics Systems
A National Science Foundation Engineering Research Center



Silicon Carbide Power Devices - Benefits

MATERIAL

- High Breakdown Field
- High Thermal Conductivity
- Robust
- Wide Bandgap

⇩

DEVICE

- Low Conduction losses
- Low Switching losses
- Higher Voltage
- High Temperature Operation
- High Surge Current

⇩

SYSTEM

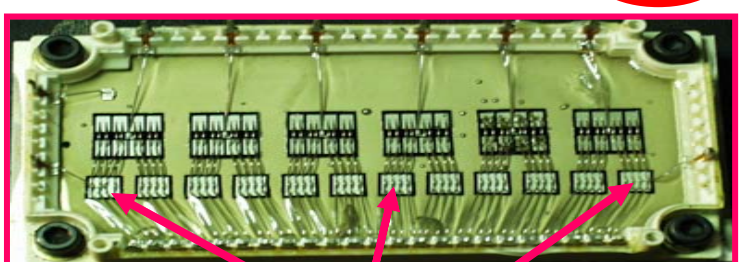
- High Efficiency
- Smaller
- Lighter
- Less Cooling
- Lower EMI/RFI
- More Reliable

Courtesy of Cree Inc.

Silicon Carbide Power Devices Switching Power Dissipation Comparison

Switching Comparison of Si and SiC 1200 Volt, 5 Amp Devices*

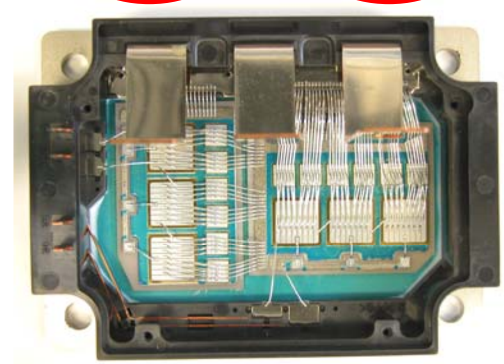
		125 degree C	125 degree C	125 degree C	125 degree C	**250 degree C**
		Si IGBT w/	**Si IGBT w/**	**SiC MOSFET w/**	**SiC BJT w/**	**SiC BJT w/**
Parameter	Units	**Si PiN**	**SiC Schottky**	**SiC Schottky**	**SiC Schottky**	**SiC Schottky**
Peak reverse current	Ipr (A)	6	1	2	1.9	1.3
Reverse recovery time	Trr (nS)	148	30	14	15	20
Recovery charge	Qrr (nC)	540	20	14	14	13
Diode loss turn-off	Eoff Diode (mJ)	0.16	0.02	0.015	0.016	0.014
Diode loss turn-on	Eon Diode (mJ)	0.03	0.02	0.014	0.02	0.013
Diode loss total	Ets Diode (mJ)	0.19	0.04	0.029	0.036	0.027
Switch loss turn-on	Eon SW (mJ)	0.98	0.44	0.2	0.29	0.28
Switch loss turn-off	Eoff SW (mJ)	0.57	0.41	0.13	0.34	0.3
Switch loss total	Ets SW (mJ)	1.55	0.85	0.33	0.63	0.58
Total (Switch + Diode)	Ets (mJ)	1.74	0.89	0.36	0.67	0.61
% Reduction			**49%**	**79%**	**61%**	**65%**



Courtesy of Cree Inc

Si PiN Diodes

Replaced with SiC Schottky Diodes

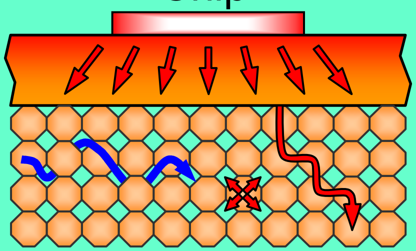


Agarwal et al: 1st Annual Ground -Automotive Power & Energy Symposium 2005

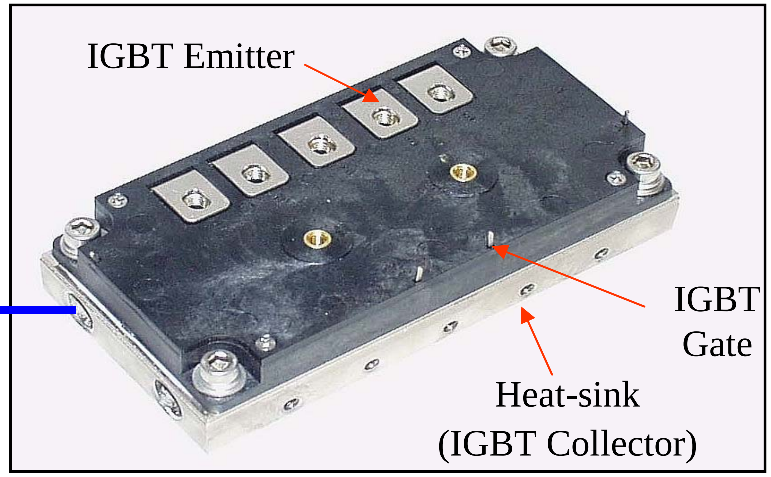
750A -1200V Oil Cooled Si/SiC IGBT Module

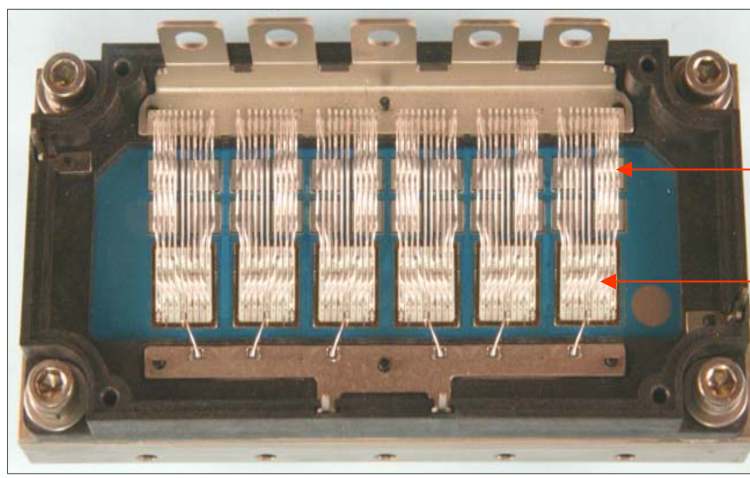
- Replace Si ultra fast diodes with SBD SiC to reduce switching losses for Diode and IGBT
- Porous metal heat sink with high heat transfer capability

Integral Heat Sink



- The tortuous fluid path enhances fluid mixing
- Soldered bed design yields contiguous solid phase for enhanced thermal spreading via conduction.
- The porous media provides a large surface area for convective transport to the coolant.





UDLP

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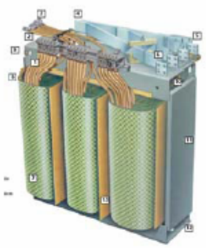
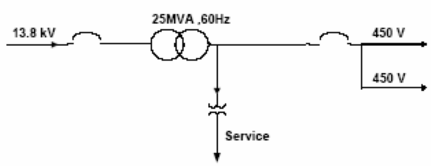
Shipboard Power Conditioning Systems With SiC Devices

13.8 kV – 450 V Solid State Power Substation (SSPS)

Conventional Approach:
Low Frequency Transformer (analog)

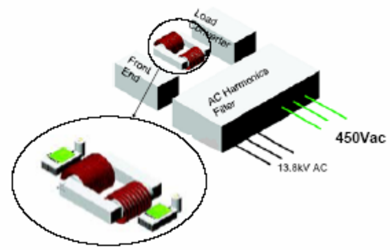


Transformer:
- 2.7MVA
- 13.8kV/450V 60Hz
- **6 tons/each**
- **10 m³/each**
- **Fixed, single output**



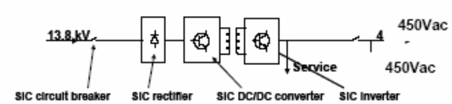
CVN-78

Future: SiC-based Solid State
Power Substation (digital)



Solid State Power Substation (estimated):
- 2.7 MVA
- 13.8kV/1450V 20 kHz
- **2.7 tons/each***
- **~4 m³/each***
- **Multiple taps/outputs**

* Initial estimates



- 10 kV, 110A SiC MOSFET Dual Module
- 200C junction operating temperature
- 20 kHz
- Liquid cooled, isolated base module
- Power dissipation 250 – 500 W/cm2

Power Module Cooling - Where Do We Go From Here?

- More direct mounting (solder & compression) of chips / ceramic substrate on liquid cooled substrate
  - High quality Ni or Au plating on soldering surface of chill plate
  - Flatness of mounting surface important
  - Concern about CTE match of materials for long term reliability
- New heatsink materials & composites
- Micro-channel sinks – High potential – what about reliable long term operation?
- Replace DBC aluminum nitride insulator with DBC diamond layer bonded directly to chill plate?
- Ceramic micro-channel liquid cooled chill plate potential?
- Double sided cooling of IGBT & MOSFET chips in modules?