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k-Technology Corporation

AECV 2007

Integrated Thermal Modules for Cooling Silicon and Silicon Carbide Power Modules

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Report Documentation Page

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Program Team

Acknowledgements

k Technology Corporation – Thermal Component Design

- **Design – Parameter Evaluation**
- **Fabrication – Heat Spreaders/Fins**
- **Thermal/Fluid Bench Tests**

Comprehensive Power – Converter/Motor System

- **System analyses – Thermal Loads**
- **Converter Controls (Design Fab and Test)**
- **Motor Test and Evaluation**

Semikron, New Hampshire – Major Supplier of Power Modules

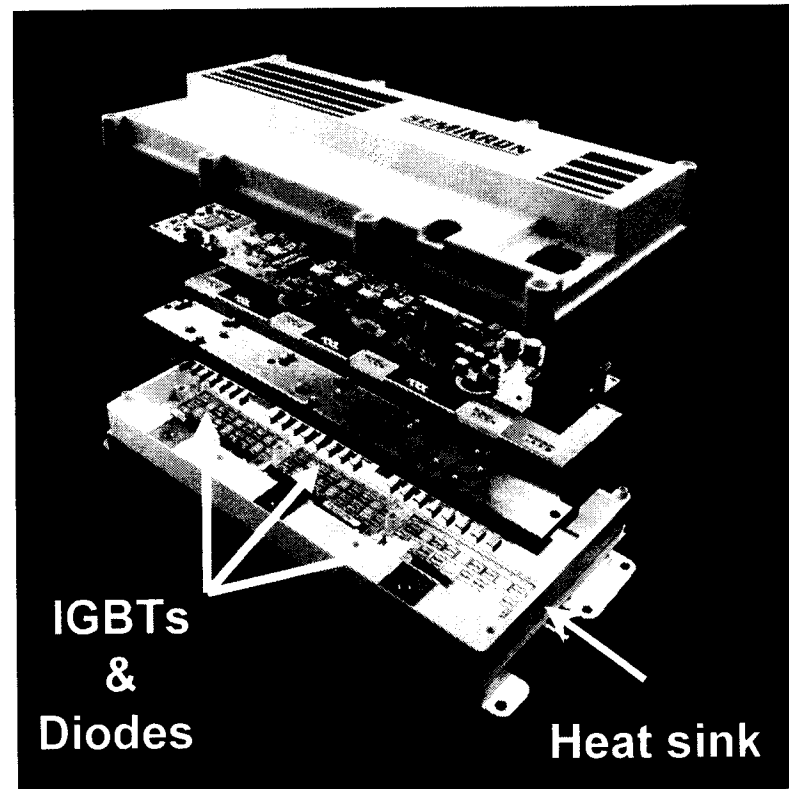
- **Engineering Support**
- **Power Module Supplier**
- **Power Module Modification for SiC Diodes**

U.S Army – TARDEC

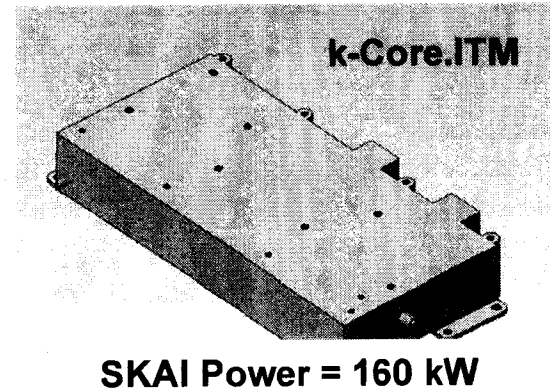
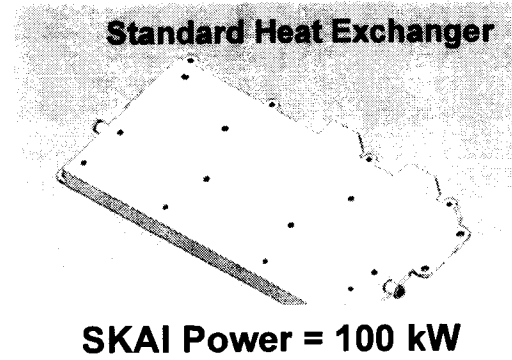
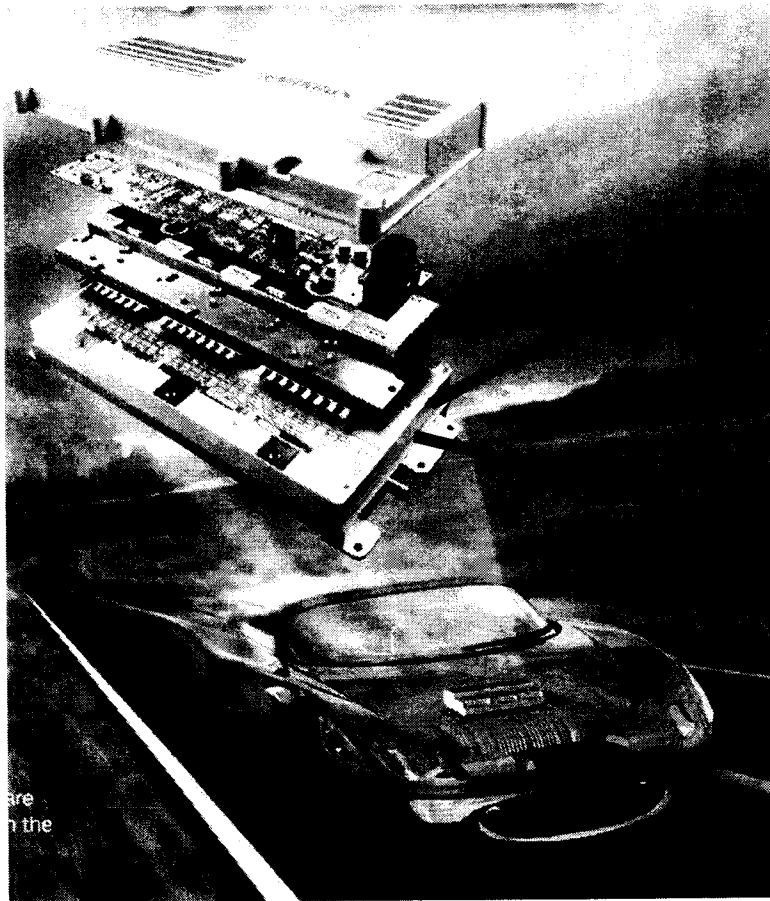
- **Technical Support**
- **Program Management**
- **System Requirements**

SKAI Inverter Module for Heatsink Evaluation

- **SKAI Module contains complete drive inverter**
 - DC to 3 phase AC
 - IGBTs & gate drive
 - Bus capacitors
 - Current sensors
 - Digital Signal Processor
- **Heat sinks and semiconductors can be substituted for comparison**



Integrated Thermal Module (ITM)
Performance Gains for Semikron SKAI™



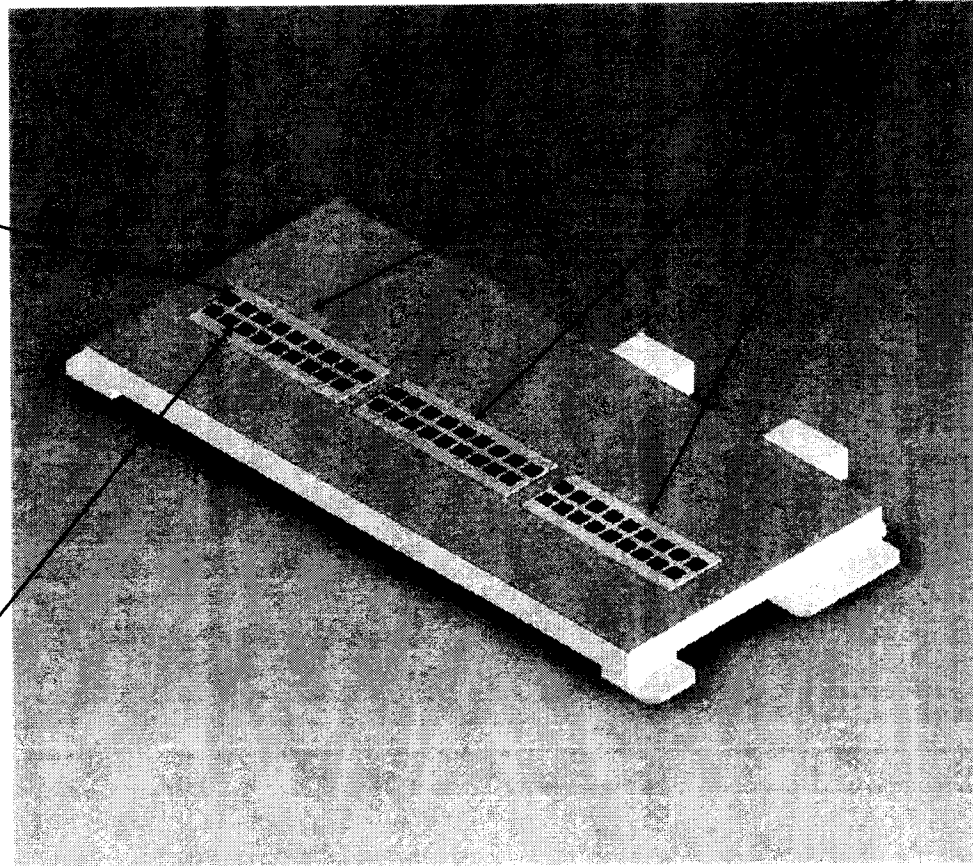
Loads

Heat Loads for SKAI 100kW 6 Operational Conditions

3 phase inverter

12 IGBTs per
phase

6 Diodes
per phase



Vehicle Operational Conditions

Case

1. Normal Operation at High Speed
2. Normal Operation at Low Speed
3. Acceleration at High Speed
4. Acceleration at Low Speed
5. Stall at 0 degrees Offset
6. Stall at 30 degree Offset

} IGBT, Diode
Heat loads

Design Load Cases SKAI

Case 3 Acceleration at High Speed

Case 6 Stall 30 Degrees Offset

SKAI 3001GD12
Acceleration at High Speed

SKAI 3001GD12
Stall, 30 degree offset

Assumed Parameters:

Motor Voltage	400 VAC RMS line to line
DC Bus Voltage	620 VDC
Phase Current	225 Amperes, RMS line to line
Motor Frequency	240 Hz
PWM Frequency	10 kHz
Power Factor	0.96
Power	150 kW

Assumed Parameters:

Motor Voltage	7 VAC RMS line to line
DC Bus Voltage	620 VDC
Phase Current	150 Amperes, RMS line to line
Motor Frequency	0 Hz
PWM Frequency	2.5 kHz
Power Factor	0.96
Power	0 kW

Calculated Losses

	IGBT, per	IGBT total	Diode, per	Diode total	Total
A Upper	49.4	296.6	15.2	45.6	342.2
A Lower	49.4	296.6	15.2	45.6	342.2
B Upper	49.4	296.6	15.2	45.6	342.2
B Lower	49.4	296.6	15.2	45.6	342.2
C Upper	49.4	296.6	15.2	45.6	342.2
C Lower	49.4	296.6	15.2	45.6	342.2
Total					2053.2

Calculated Losses

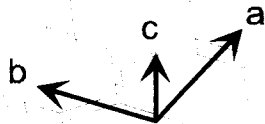
	IGBT, per die	IGBT total	Diode, per die	Diode total	Total
A Upper	13.2	79.3	0	0	79.3
A Lower	0	0	41.3	123.9	123.9
B Upper	0	0	0	0	0
B Lower	53.3	319.8	0	0	319.8
C Upper	13.2	79.3	0	0	79.3
C Lower	0	0	41.3	123.9	123.9
Total					726.2

Heat Load: 2053W/3 (684 Watts) is over all three phases. Circuit board for each phase is 113mm x 40 mm

Material Systems

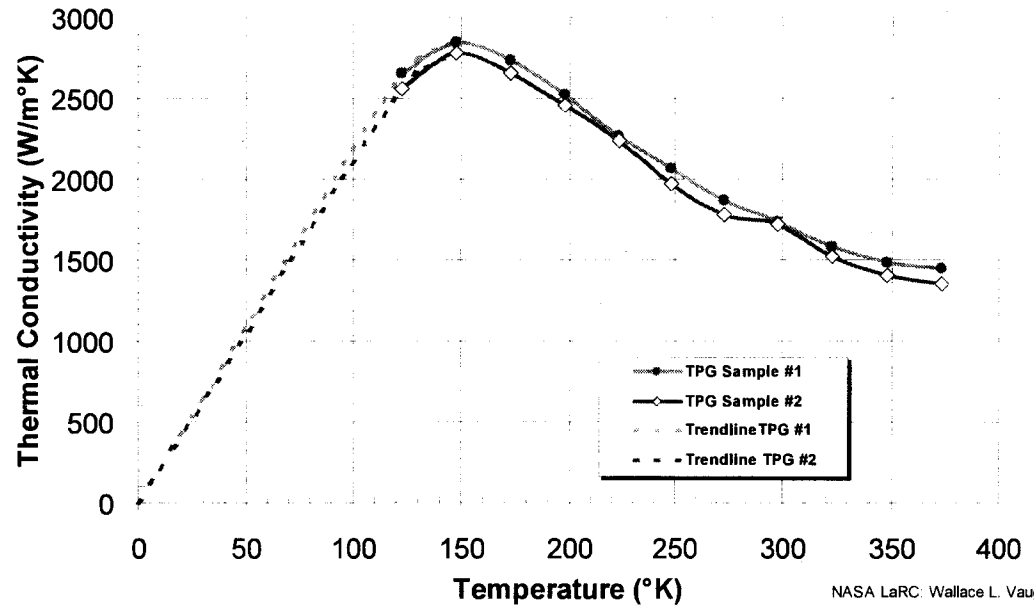
Advanced Pyrolytic Graphite (APG)

Advanced Pyrolytic Graphite
(APG), Mosaic Spread 5 to 10 Deg



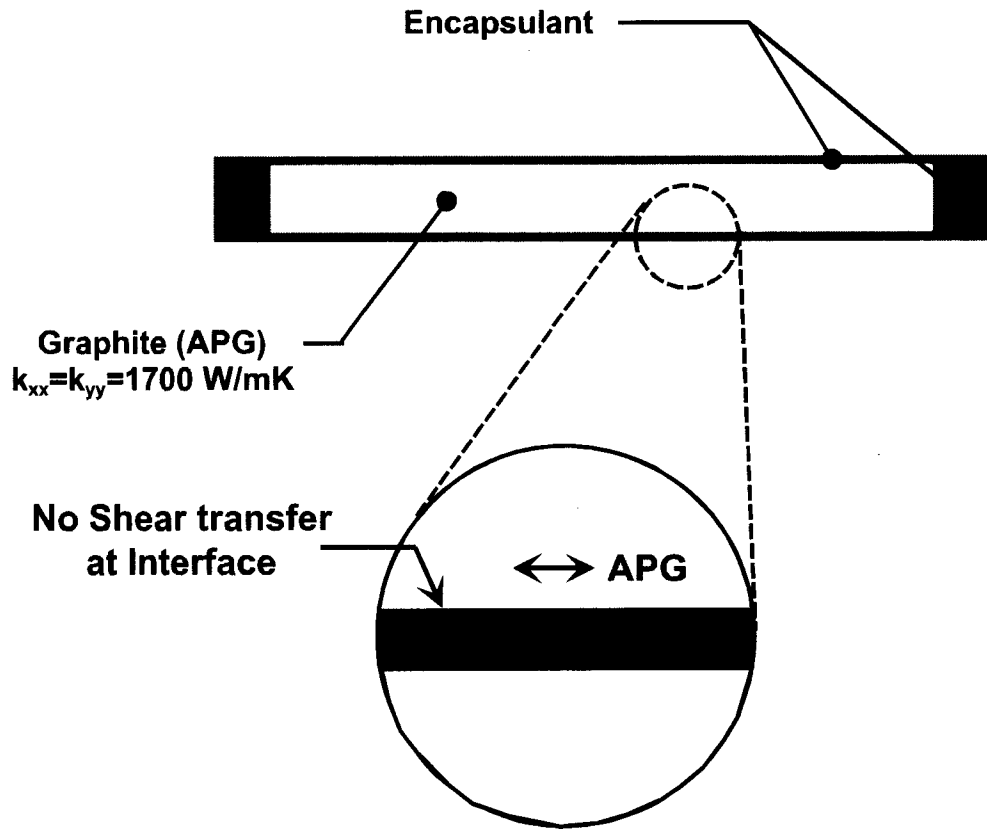
- $k_{ab} = 1700. \text{ W/mK}$
- $k_c = 10. \text{ W/mK}$
- $E_{ab} = 120 \text{ Msi}$
- $E_c = 5.0 \text{ Msi}$
- $CTE_{ab} = -1.0 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$
- $CTE_c = 25. \times 10^{-6} \text{ }^\circ\text{C}^{-1}$
- Tensile Strength_{ab} = - ksi
- Tensile Strength_c < 0.2 ksi

In-Plane APG Thermal Conductivity
Flash Diffusivity Data Measured By TPRL

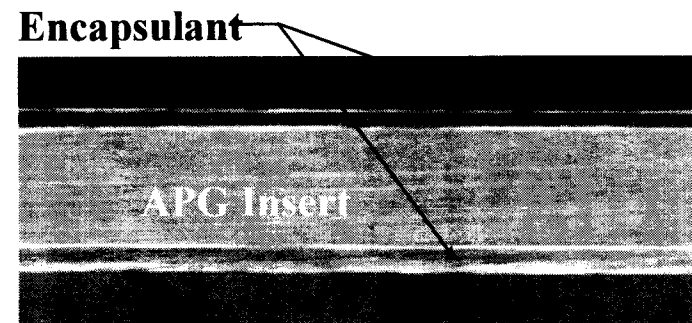


NASA LaRC: Wallace L. Vaughn

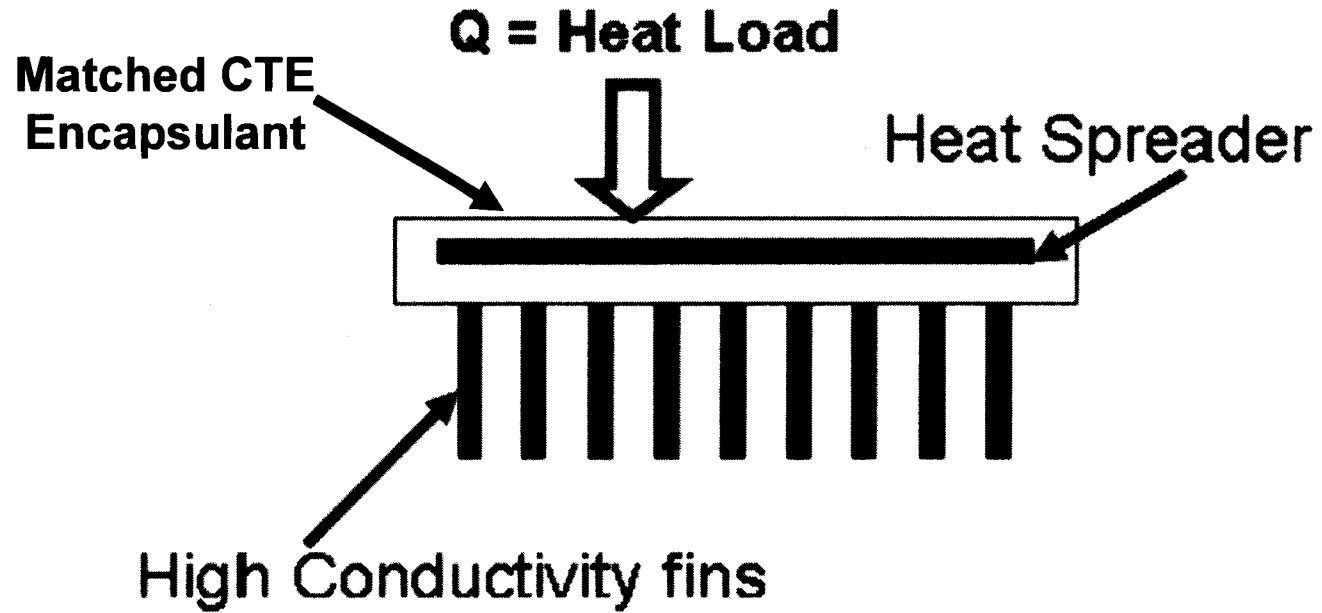
k-Core™ Material Concept



- ◆ Encapsulated APG material system
- ◆ Advanced pyrolytic graphite provides a high k path
- ◆ Encapsulant sets the CTE and structural properties
- ◆ Encapsulant material selected to satisfy requirements



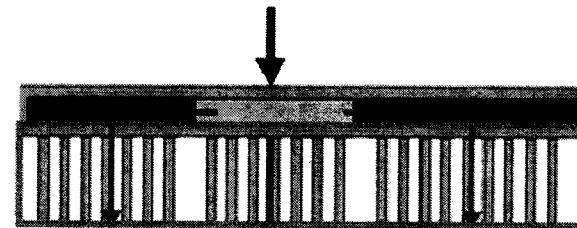
Use of APG in Integrated Thermal Module



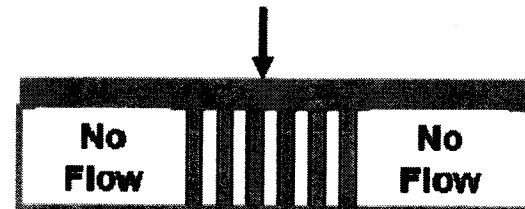
Integrated Thermal Module (ITM) Configurations

Configuration	Spreader	Pins/Fin/Foam
Wide Plenum	Alum	Alum Pins
Wide Plenum	k-Core.Al	Alum Fins
Wide Plenum	k-Core.Al	APG Fins
Wide Plenum	k-Core.mm	APG Fins
Channel	Alum	APG Fins
Channel	k-Core.Al	APG Fins
Channel	Alum	POCO Foam
Channel (Baseline)	Alum	Alum Pins

**Wide Plenum
Heat Transfer to Side
Channels**

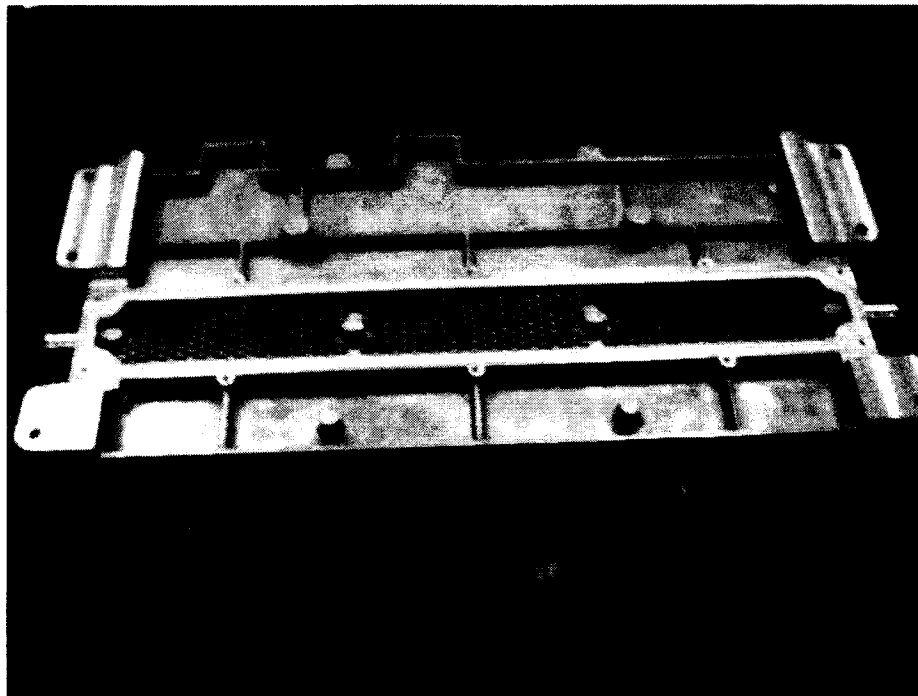


**Basic
Heat Sink with
Single flow Channel**



Bench Tests

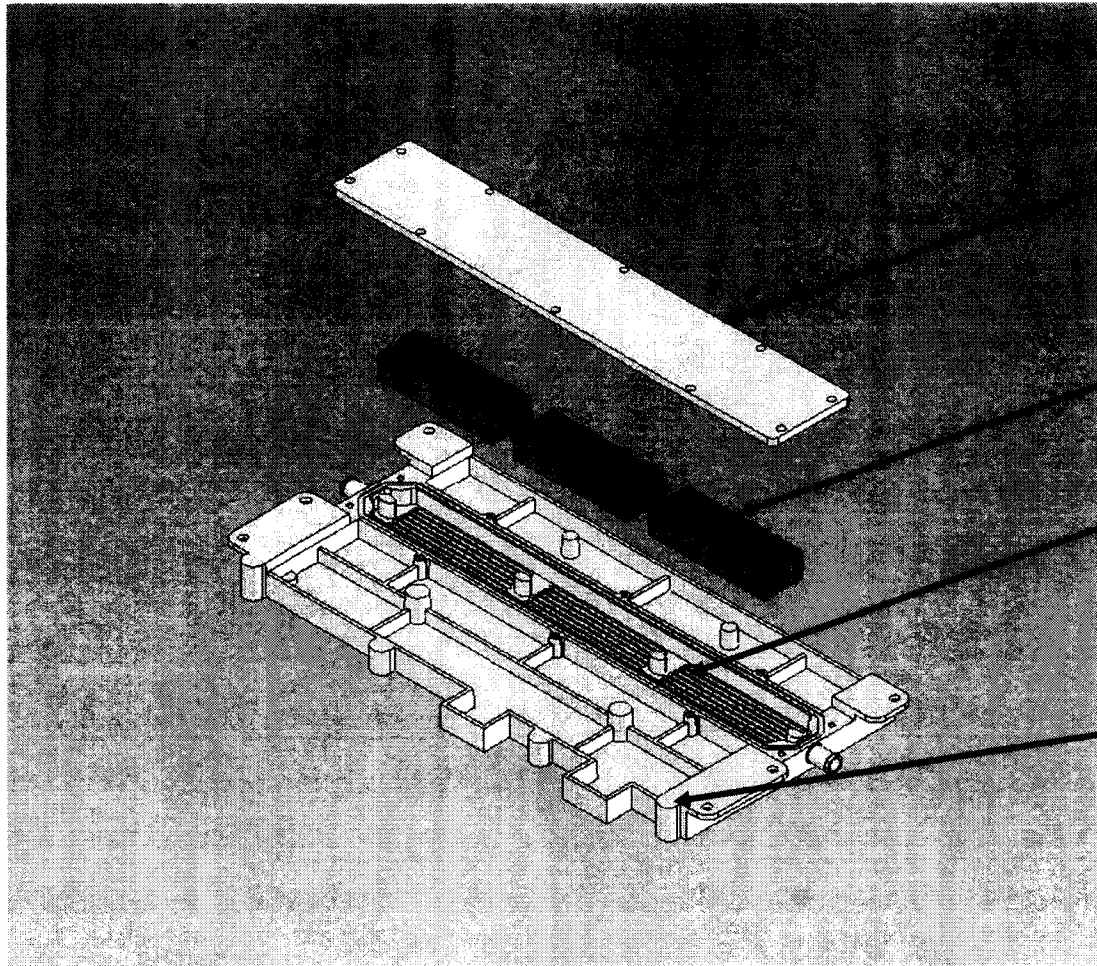
Off-the-Shelf Semikron Heat Sink Base Line



- All Aluminum
- Pin Fins
- Fluid Flow 5 to 15 Liters/min
- Single Flow Channel

(inverted – Cover Removed)

Fabrication with k-Core Fins



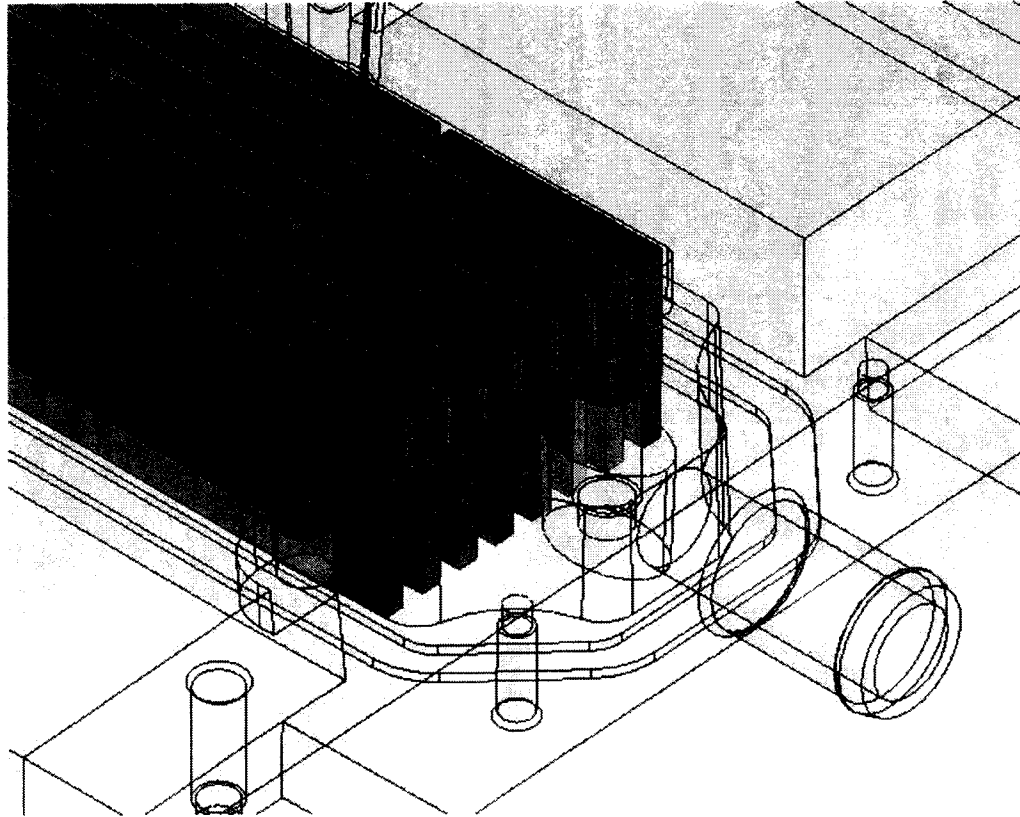
Cover Plate

k-Core Fins

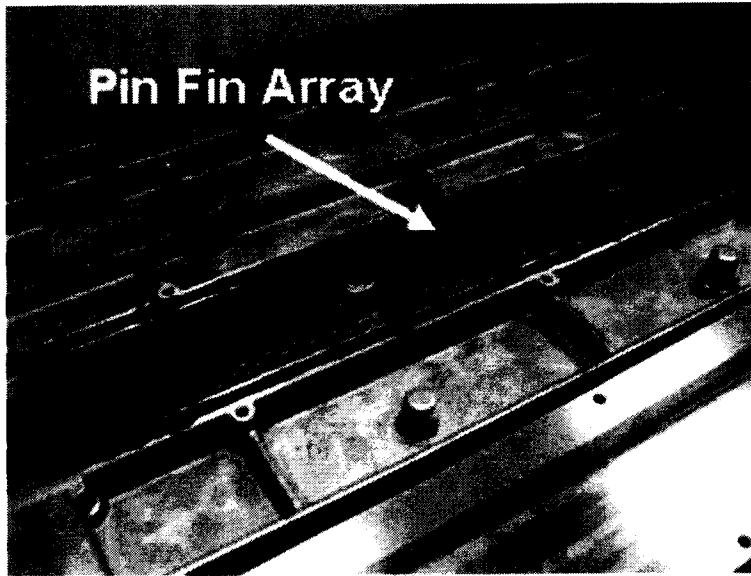
**Machined Grooves
in Place of Pin Fins**

**Modified Semikron
SKAI Heat Sink**

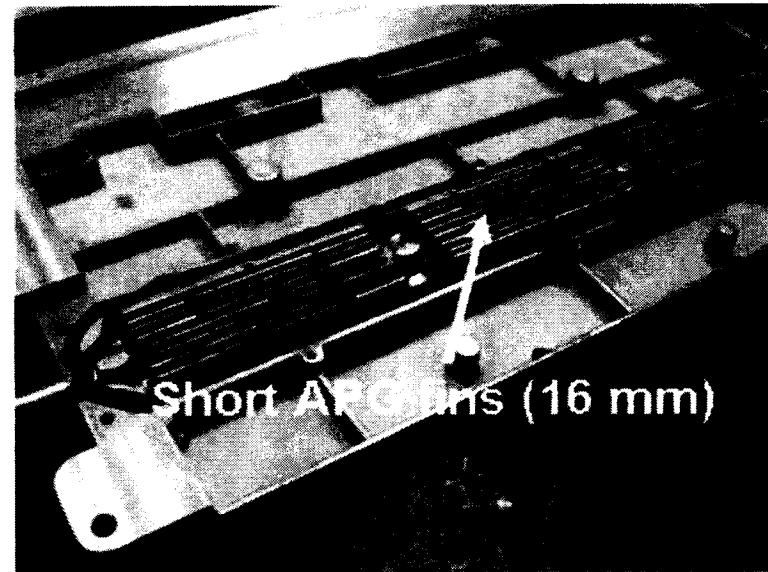
Assembly with k-Core Fins



Base Line and ITM with APG Fins



(a) Standard Heat Sink
with pin fin array



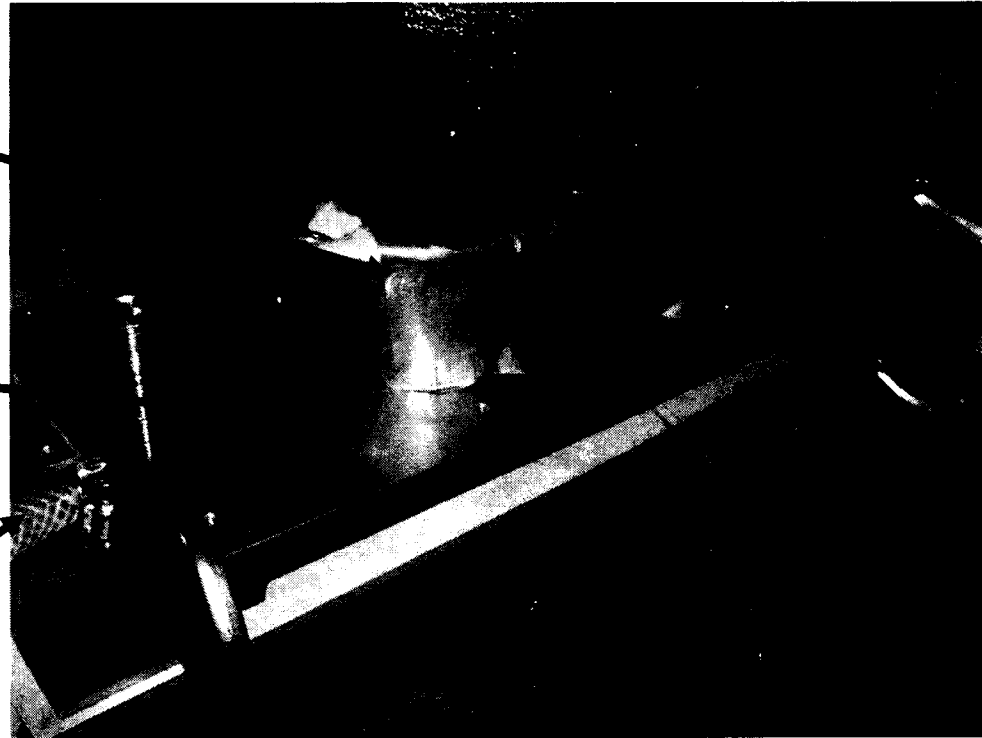
(b) ITM with APG Fins

ITM In Bench Test

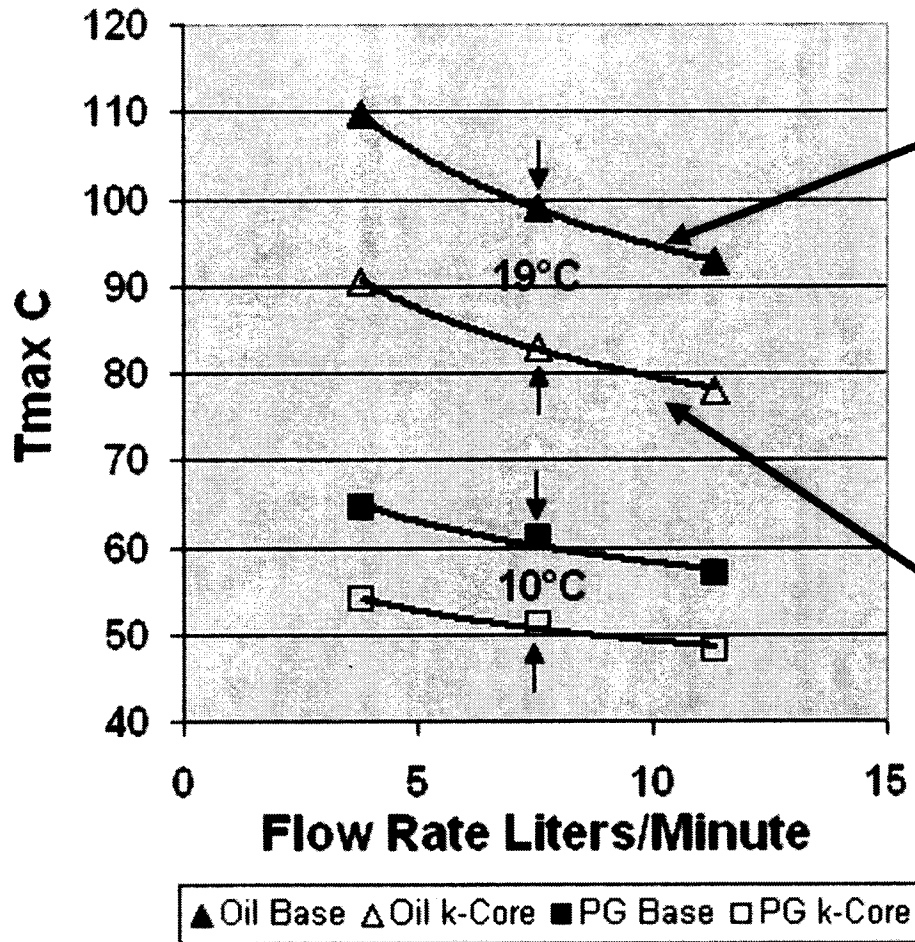
Simulated Chip Loads

ITM

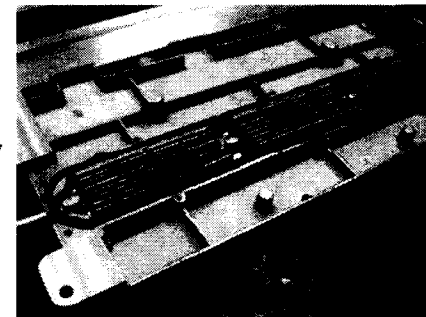
Coolant Loop



Reduction in T_{surface} with ITM



Baseline Pin Array



APG Fin ITM

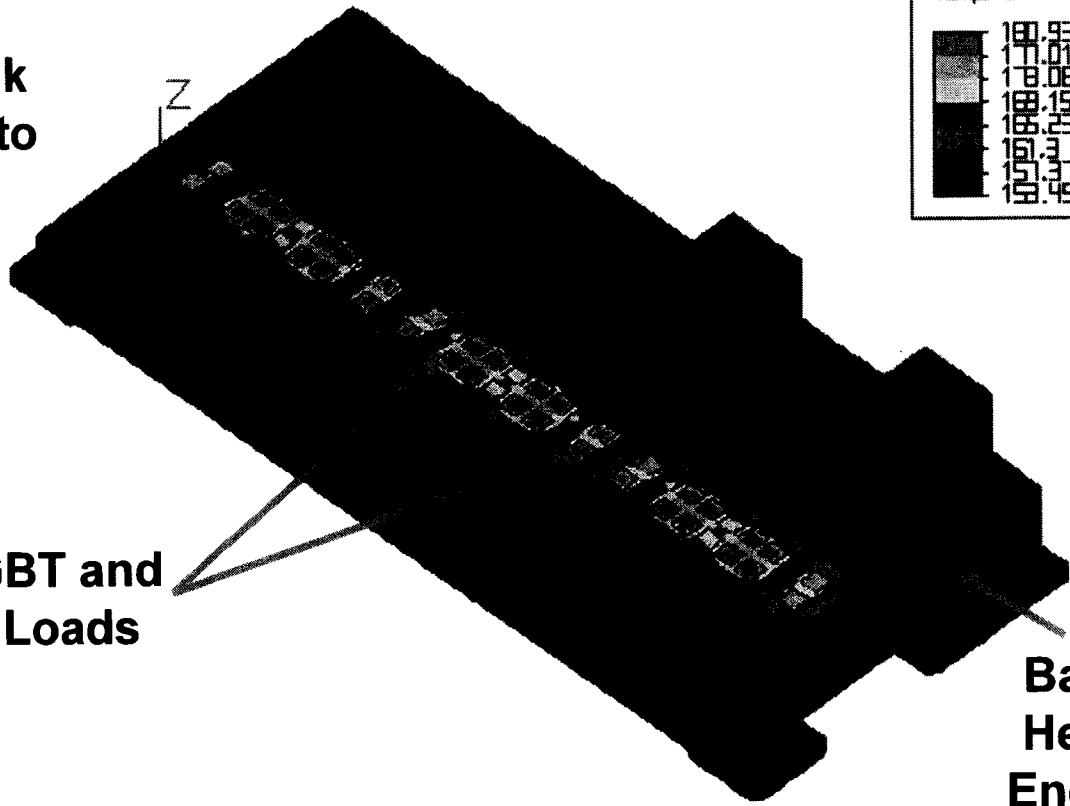
Analyses

Typical 3d, Orthotropic Material Analysis

Convection Coefficients Based on Empirical Correlations with Fin Configuration, Fluid Properties, and Flow Rates

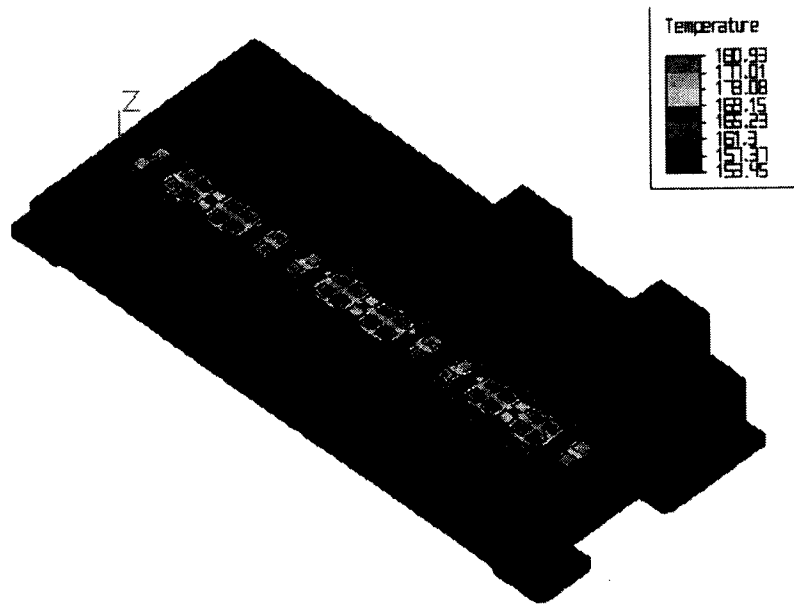
Includes Stack up from Chip to ITM Surface

Individual IGBT and Diode Heat Loads

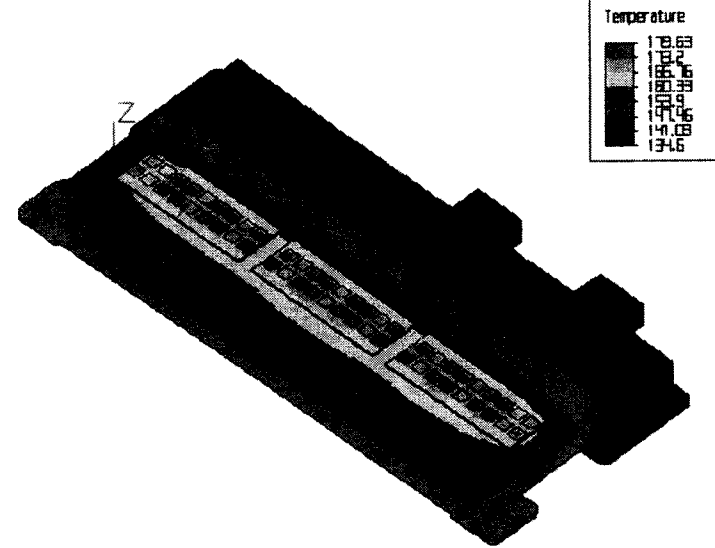


Baseline Heatsink Enclosure

Standard and Wide Plenum Analyses



Baseline Channel Cooling



Wide Plenum Cooling

Silicon Carbide

Silicon Carbide Electrical Characteristics

Electrical Characteristics

Symbol	Parameter	Typ.	Max.	Unit	Test Conditions	Note
V_f	Forward Voltage	1.65 2.6	2.0 3.0	V	$I_f = 50 \text{ A } T_j = 25^\circ\text{C}$ $I_f = 50 \text{ A } T_j = 175^\circ\text{C}$	
I_r	Reverse Current	10 50	200 1000	μA	$V_r = 1200 \text{ V } T_j = 25^\circ\text{C}$ $V_r = 1200 \text{ V } T_j = 175^\circ\text{C}$	
Q_c	Total Capacitive Charge	305		nC	$V_r = 500 \text{ V, } I_f = 50 \text{ A}$ $di/dt = 500 \text{ A}/\mu\text{s}$ $T_j = 25^\circ\text{C}$	
C	Total Capacitance	4500 396 325		pF	$V_r = 0 \text{ V, } T_j = 25^\circ\text{C, } f = 1 \text{ MHz}$ $V_r = 200 \text{ V, } T_j = 25^\circ\text{C, } f = 1 \text{ MHz}$ $V_r = 400 \text{ V, } T_j = 25^\circ\text{C, } f = 1 \text{ MHz}$	

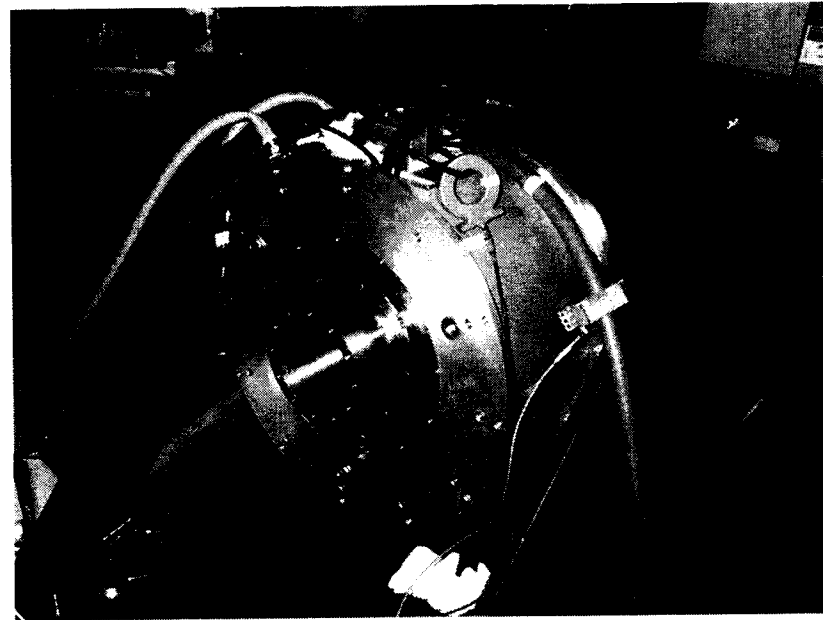
Note:

1. Assumes θ_{j-c} Thermal Resistance of 0.5°C/W or less.

Motor Tests

Motor Test Set Up

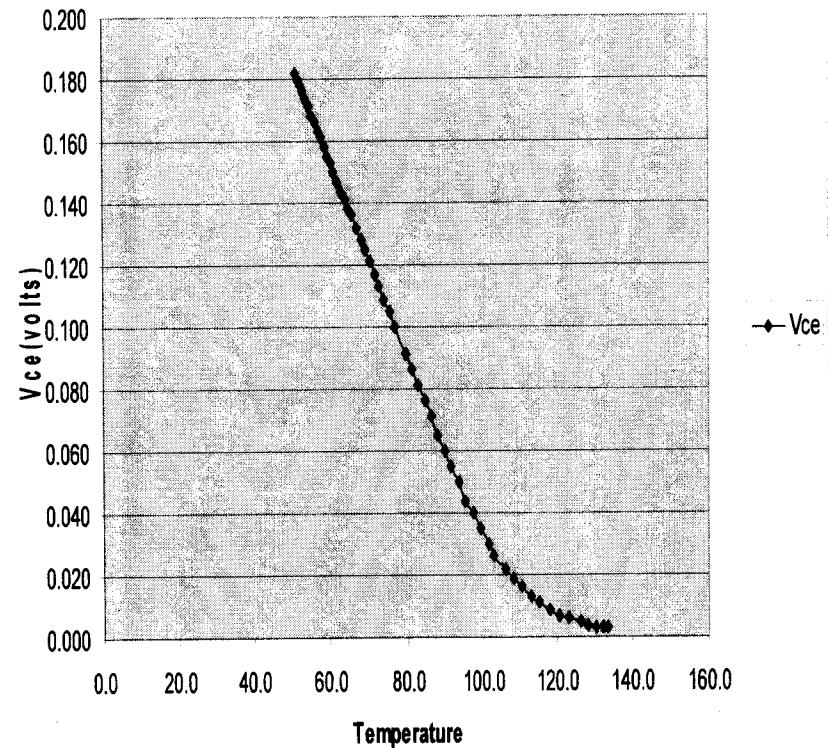
- Inverter load tests are performed with high horsepower PM motors on a back to back test stand
 - 650 VDC input to inverter
 - 0-480 Hz output to motor
 - 0-300 kW steady state
- Programmable load cycles with full four quadrant operation



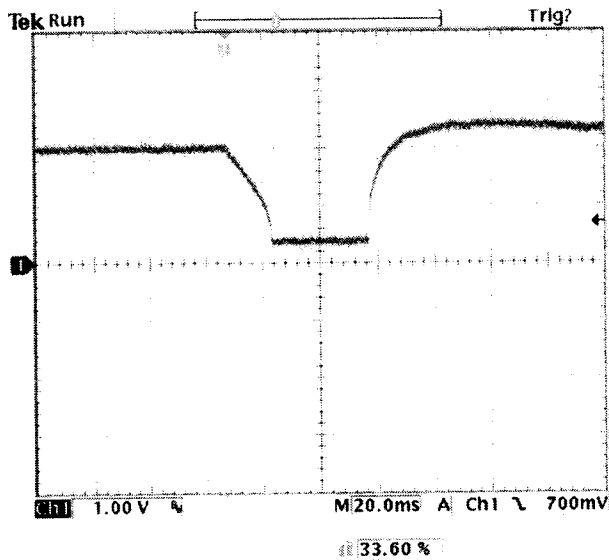
IGBT Die Temperature Measurement

- IGBT forward voltage is measured at a small reference current
 - Voltage decreases with increasing temperature
 - Offset will vary among wafers
- Scale can be calibrated by measurement at zero power
 - Data shown is for 500 amp IGBT
- Higher reference current is needed for resolution at higher temperature

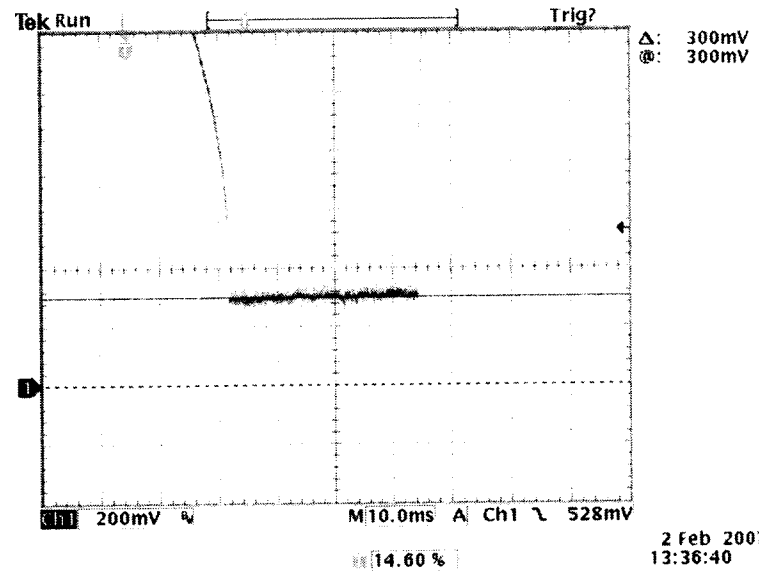
IGBT Vce vs Temp



Measurement of Thermal Resistance



5 Feb 2007
09:24:29



- Heat the dice by feeding a known heat load into IGBTs
 - High current at low voltage
- Disable current and measure forward voltage at reference current
 - Voltage has known temperature dependency
 - Speed of measurement is vital

**COMPREHENSIVE
POWER Inc.**

Motor Test Matrix

Motor tests X - Completed	Heat sinks					
	Baseline		ITM-1		ITM-2	
	Engine Oil	Propylene Glycol	Engine Oil	Propylene Glycol	Engine Oil	Propylene Glycol
		X				
SKAI-Standard		X				
SKAI-SiC Diodes		X				

SKAI-SiC Shows an 8% Reduction in IGBT Temp
versus SKAI Standard
Both Using Standard Heat Sink

Summary

Integrated Thermal Modules (ITMs) are being developed to cool power modules with high-temperature fluids.

3D FEM analyses, bench tests, and motor tests comprise the program.

The ITMs, in place of standard heatsinks, use a highly conductive pyrolytic graphite to passively cool power modules.

Initial results show that even simple ITMs can lower chip temperatures by 20°C and 10°C with engine oil and propylene glycol coolants, respectively.

Motor tests record real-time IGBT temperatures. Two converters, one using Silicon (Si) diodes and the other using Silicon Carbide (SiC) diodes, are being used for testing the ITMS.

Initial Motor tests with the baseline heatsink have shown that the SiC diodes lower IGBT temperatures by 8% as compared to Si diodes.