Introduction to Aluminum and Magnesium Annealed Pyrolytic Graphite (k-Core)

MEPTEC Thermal Management Symposium

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San Jose, CA

Cooling Requirements

- High capability semiconductor devices generate large amounts of waste heat
  - Typical Aircraft Versa Module Europa (VME) board produces 250 watts over a 15.24 cm. by 22.86 cm. area
  - High power aircraft electronics can produce 500 watts in 0.16 cm^2.
- Keep operating temperatures below 125^oC

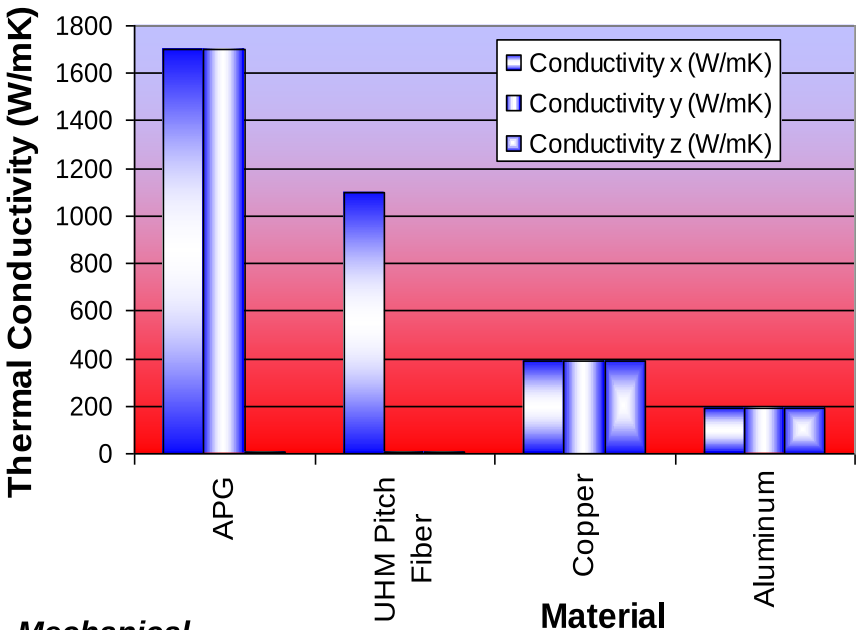
Conduction Cooling

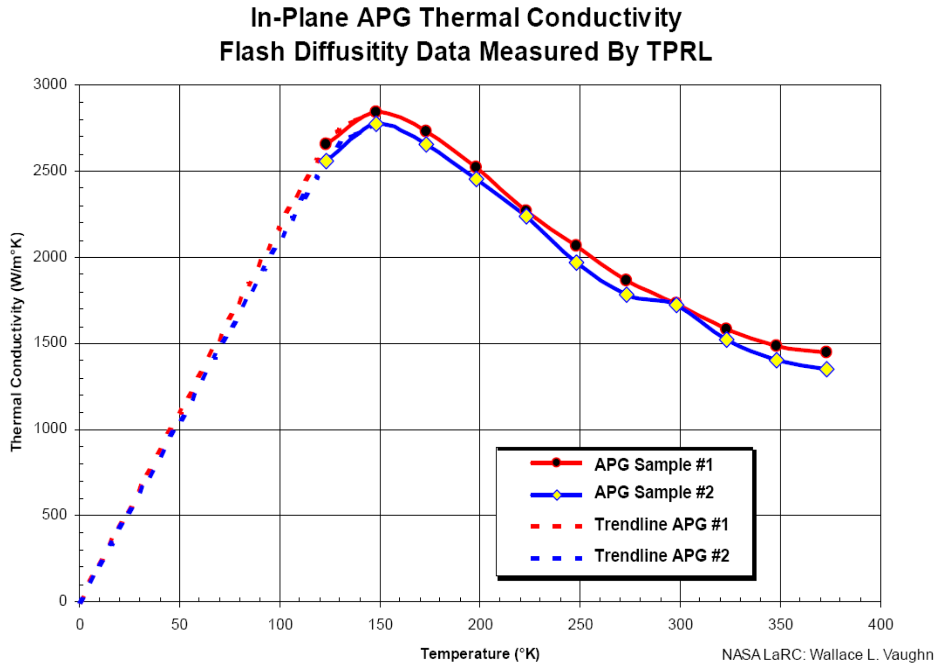
- Aluminum substrates provide the baseline
- Low Cost
- Processing well-understood

BUT

- Limited by low thermal conductivity
  - 180 to 240 W/m-K
- Copper has better conductivity, but is HEAVY

Annealed Pyrolytic Graphite (APG)





Mechanical

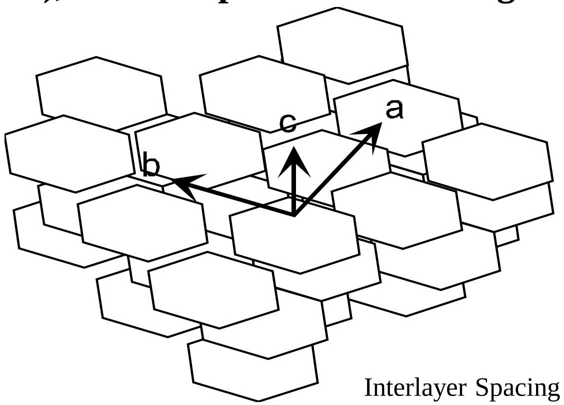
Modulus (GPa)			Poisson's Ratio			Shear Modulus (GPa)			CTE (PPM/K)		
E1	E2	E3	v12	v13	v23	G12	G13	G23	a1	a2	a3
103	103	11	0.3	0.002	0.002	11 Gpa	6.6	6.6	-6.00E-07	-6.00E-07	2.57E-05

Thermal, 25 ^{o}C

Conductivity (W/mK)			Diffusivity (cm2/K)			Specific Heat (W/gK)	Density (g/cm3)
k1	k2	k3	v1	v2	v3	Cp	d
1700.0	1700.0	10.0	1071.5	1071.5	6.3	0.702	2.26

APG Description

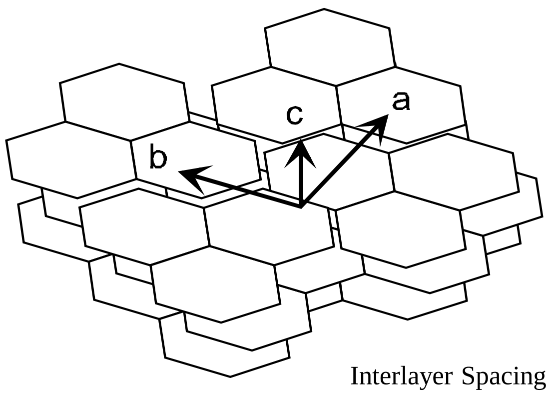
As Deposited Pyrolytic Graphite (PG), Mosaic Spread 40 to 50 Deg



Interlayer Spacing
~3.43 Angstroms

- k_{ab} = **300**. W/m-K
- k_c = 3.0 W/m-K
- E_{ab} = 34 GPa
- E_c = 11 GPa
- $CTE_{ab} = 0.5\text{x}10^{-6}\ {}^{o}C^{-1}$
- $CTE_c = 20.\ \text{x}10^{-6}\ {}^{o}C^{-1}$
- Tensile $Strength_{ab}$ = 100 MPa
- Tensile $Strength_c$ = 1.03 MPa

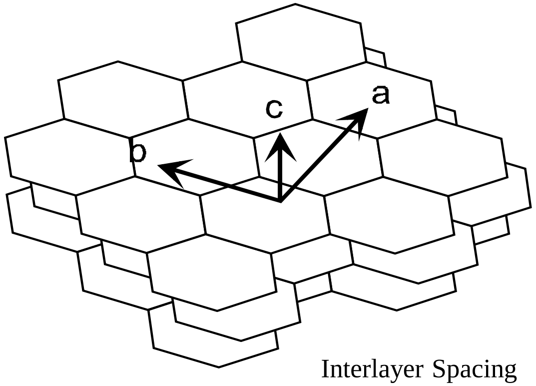
Annealed Pyrolytic Graphite (APG), Mosaic Spread 5 to 10 Deg



Interlayer Spacing
~ 3.36 Angstroms

- k_{ab} = **1700**. W/m-K
- k_c = 10. W/m-K
- E_{ab} = 103 GPa
- E_c = 34 GPa
- $CTE_{ab} = -1.0\ \text{x}10^{-6}\ {}^{o}C^{-1}$
- $CTE_c = 25.\ \text{x}10^{-6}\ {}^{o}C^{-1}$
- Tensile $Strength_{ab}$ = ---
- Tensile $Strength_c$ ---ksi

Highly Oriented Pyrolytic Graphite (HOPG), Mosaic Spread < 2 Deg



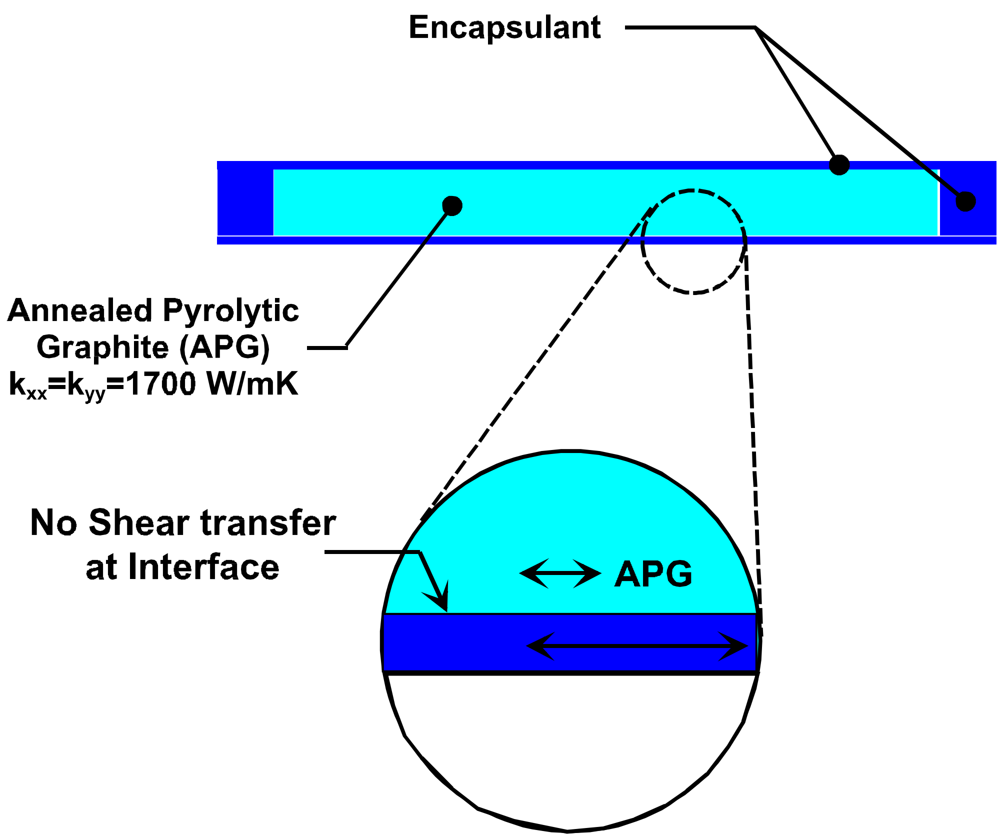
Interlayer Spacing
< 3.36 Angstroms

- k_{ab} = **2000**. W/mK
- k_c = 10. W/mK
- E_{ab} = 145. GPa
- E_c = 21 GPa
- $CTE_{ab} = -1.0\ \text{x}10^{-6}\ {}^{o}C^{-1}$
- $CTE_c = 25.\ \text{x}10^{-6}\ {}^{o}C^{-1}$
- Tensile $Strength_{ab}$ = ---
- Tensile $Strength_c$---

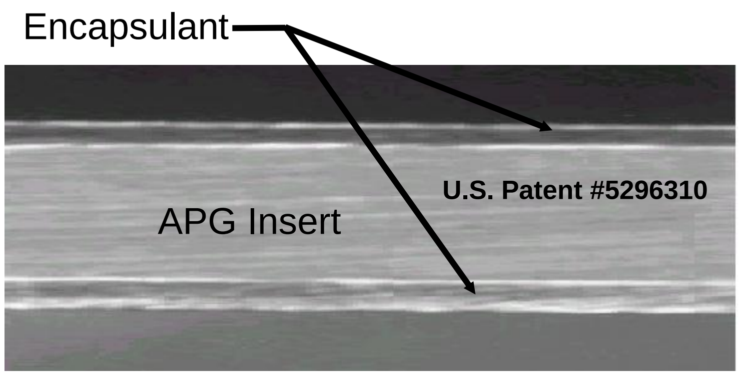
Annealed Pyrolytic Graphite (APG)

- Thermal Conductivity
  - 1700 W/m-k
  - Al is ~ 200
- Density
  - 2.1 g/cc
  - Al is 2.7 g/cc
- Fragile
- Hygroscopic

k-Core® Material Concept

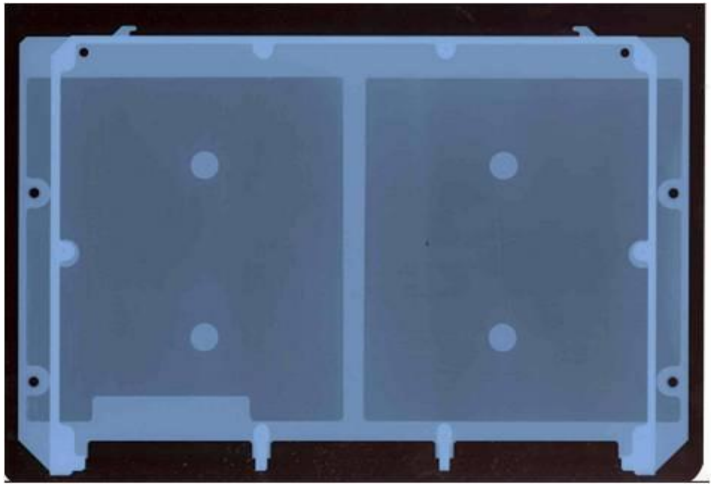


- Patented Encapsulated APG material system – 3x the conductivity (k) of copper with the mass of aluminum
- Annealed pyrolytic graphite provides a high k path
- Encapsulant sets the CTE and structural properties
- Encapsulant material selected to satisfy requirements



Production Electronics Modules

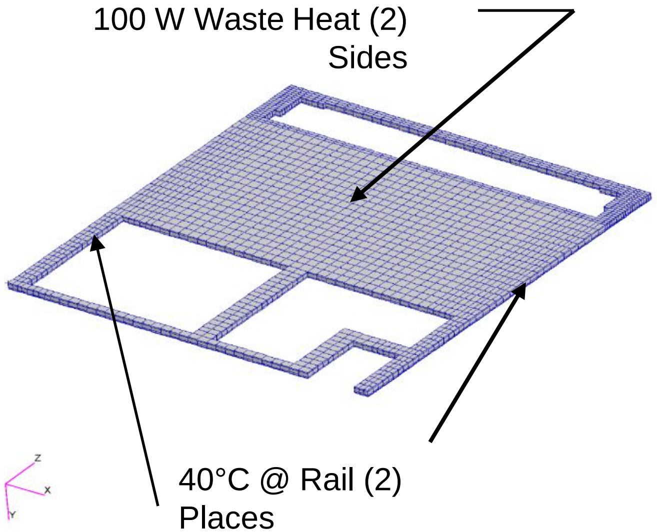
Finished part appearance



X-Ray image

Typical Performance Comparison

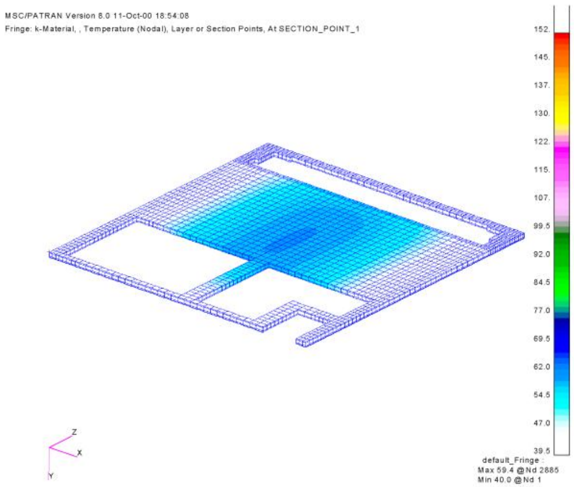
- SEM E Avionics Application
  - Dissipating 100 W Per Side
  - Design Goal - Use COTS Electronic Parts
    - Junction Temperatures Below 85°C
- Baseline Material
  - 6061-T6 Aluminum



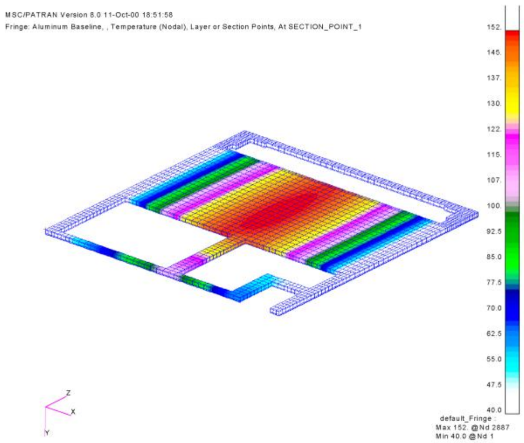
Finite Element Model of SEM E Module

SEM-E Thermal k-Core™

APG Material
Max Surface Temperature - 59.4°C



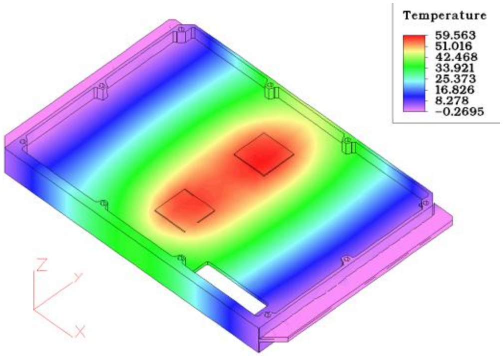
Aluminum Baseline
Max Surface Temperature - 152°C



F35 Joint Strike Fighter Standard Module

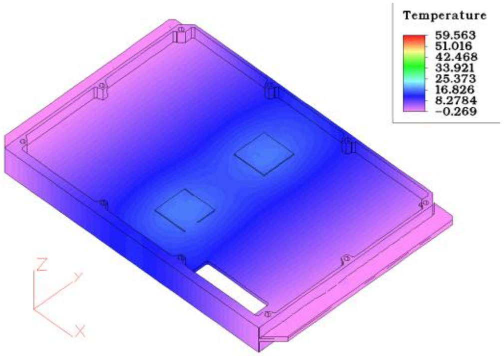
Aluminum Baseline

Max Surface Temperature – 59.8°C



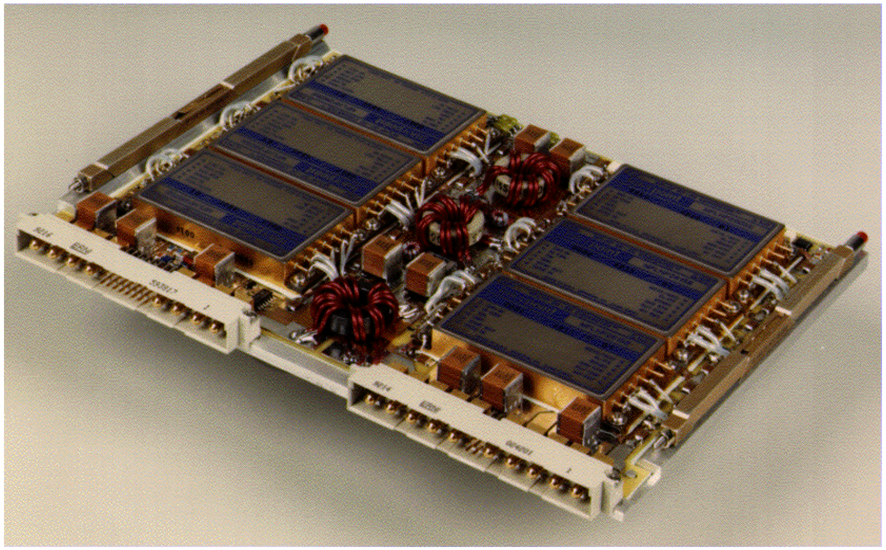
k-Core Material

Max Surface Temperature – 17.5°C

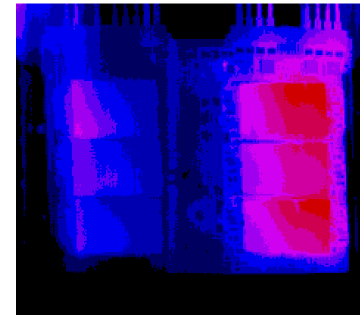


- Conduction cooled module, F35 standard
- Standard APG configuration with core personalization
- Up to 250 W heat dissipation through core
- Aluminum encapsulation

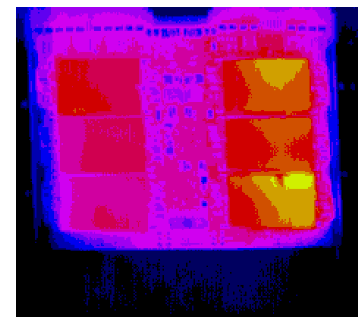
VME k-Core™ Power Supply



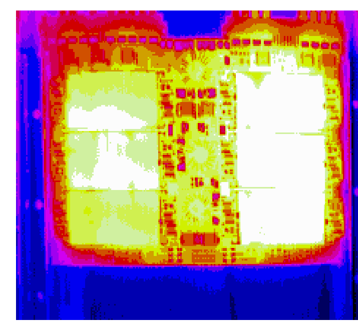
Encapsulated APG
Delta Temp = 18°C
Weight = 204 gm



OFHC Copper
Delta Temp = 24°C
Weight = 731 gm

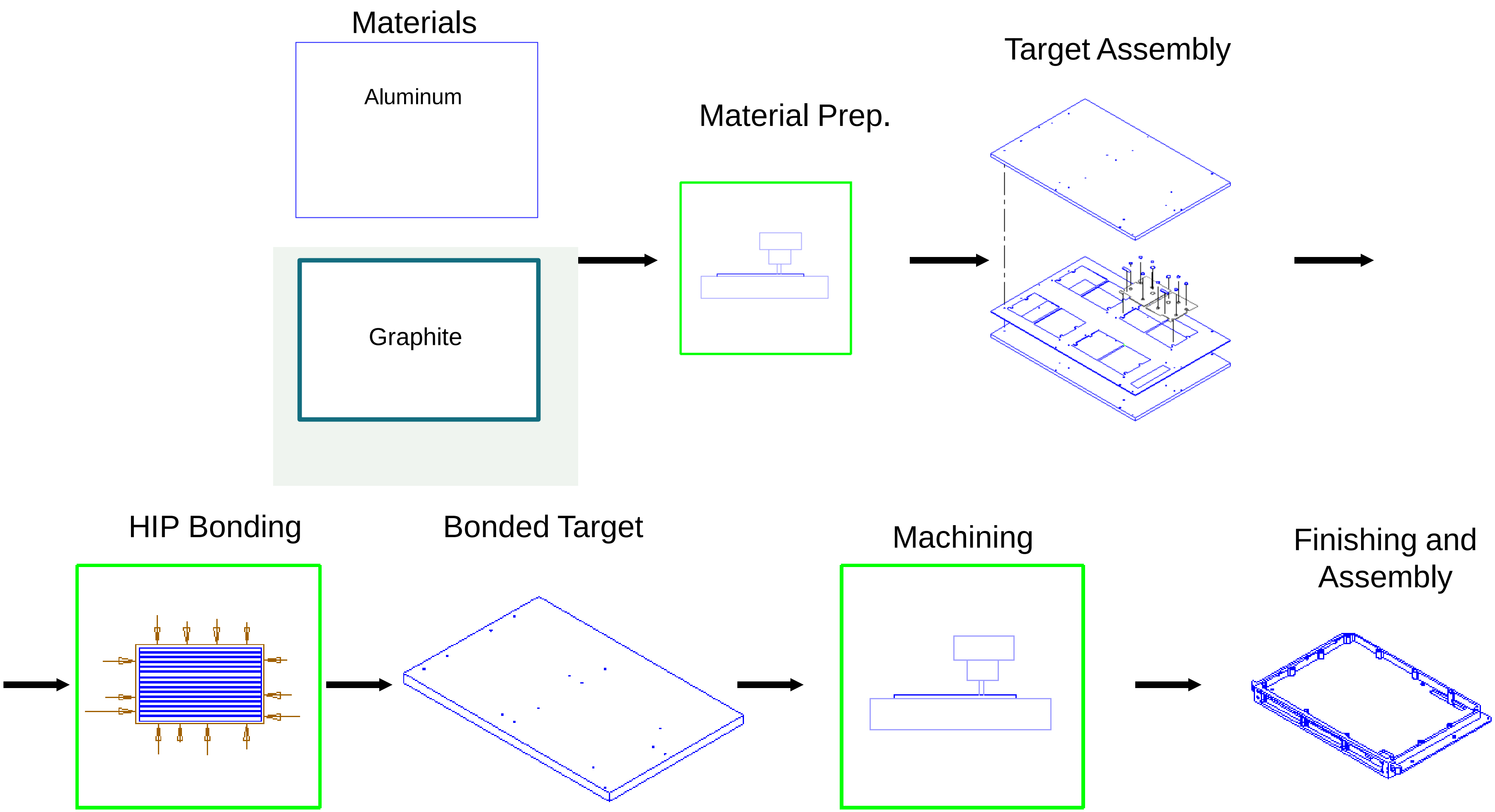


Carbon Fiber Composite
Delta Temp = 28°C
Weight = 172 gm



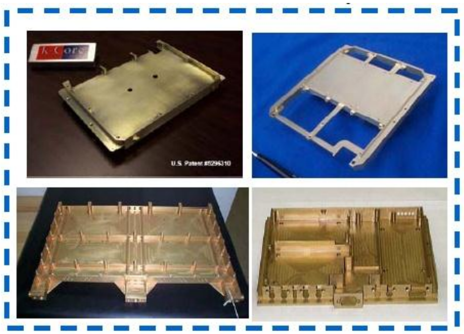
- Conduction cooled VME 1101.2 Format
- 80 W Heat Dissipation through Core
- Aluminum Encapsulation
- Airborne Qualified -- MIL-STD-810C, Cat 6.
- In Service

k-Core™ Process

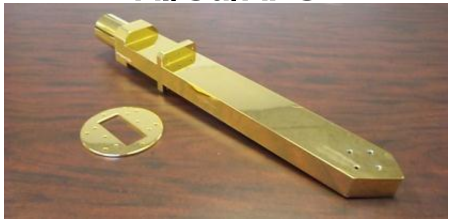


k-Core Applications Over Temperature

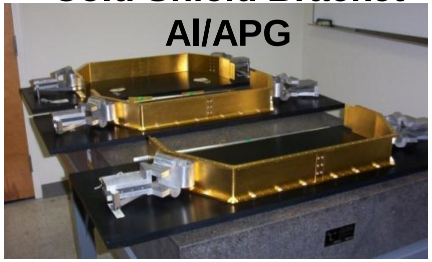
Electronic Packaging

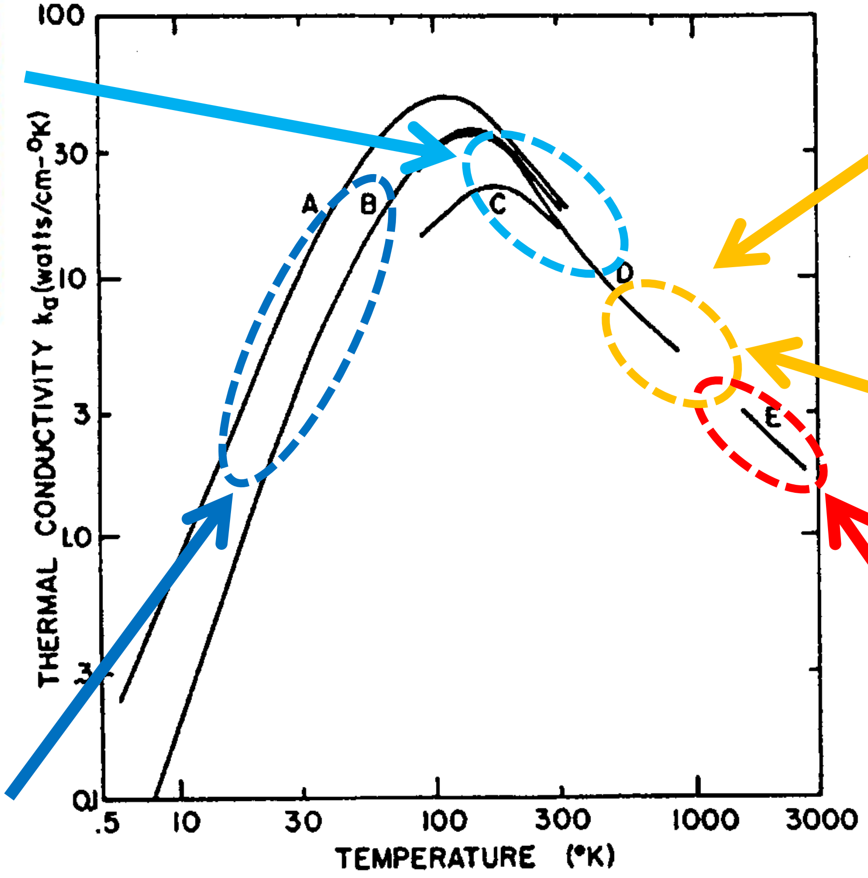


Cryo Conduction Bar
Al/Cu/APG



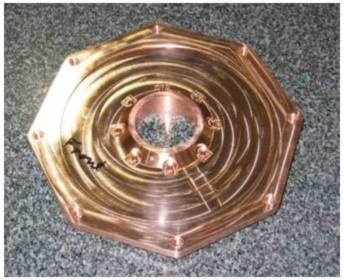
Cold Shield Bracket
Al/APG





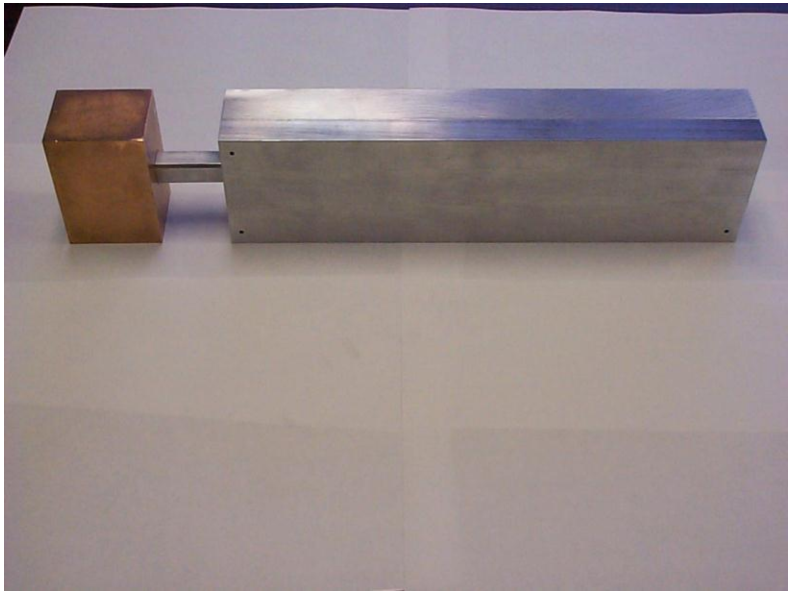
Power Conversion
Ni/APG Conductors

Power Generation
BeCu/APG Conductors



Re-entry Carbon-Carbon/APG nose cone

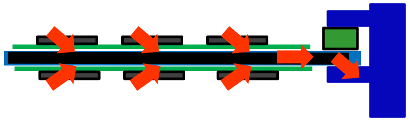
Bi-Metallic k-Core
Conduction Bar



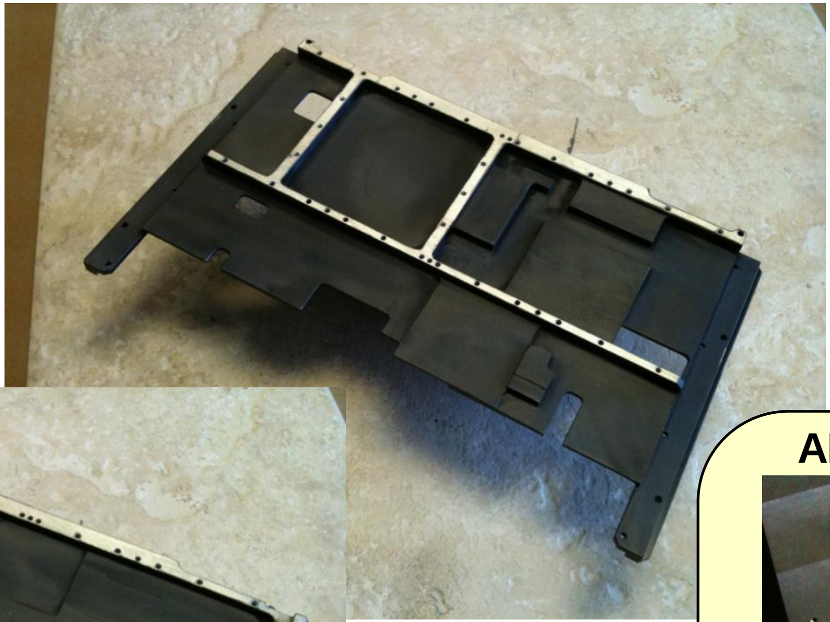
K-Core Aluminum with Copper Flange

Bonded and Machined Bi-Metal Bar

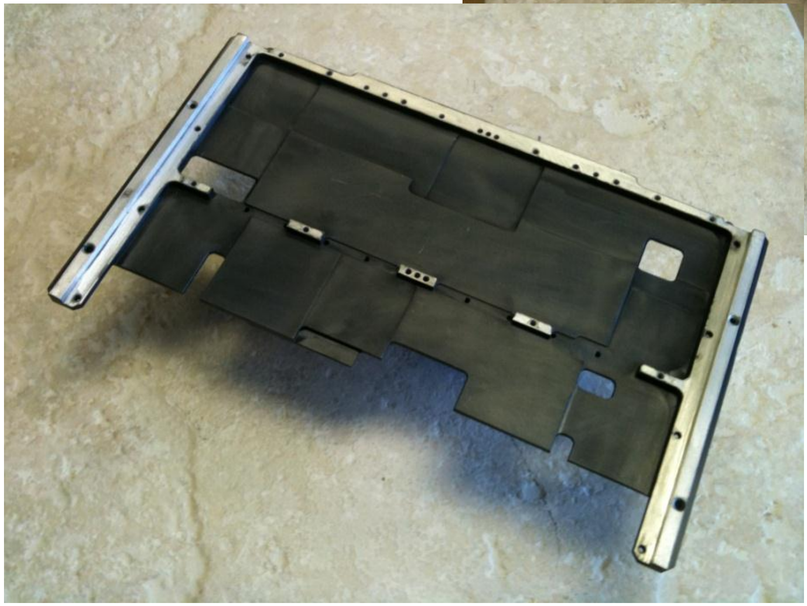
k-Core® VME 1101.2 Module



Aluminum Encapsulated APG
Ruggedized Conduction Cooled VME Format (IEEE 1101.2)

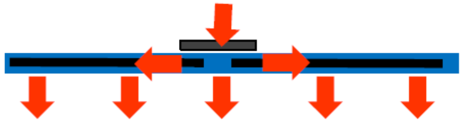


Qualified and Fielded

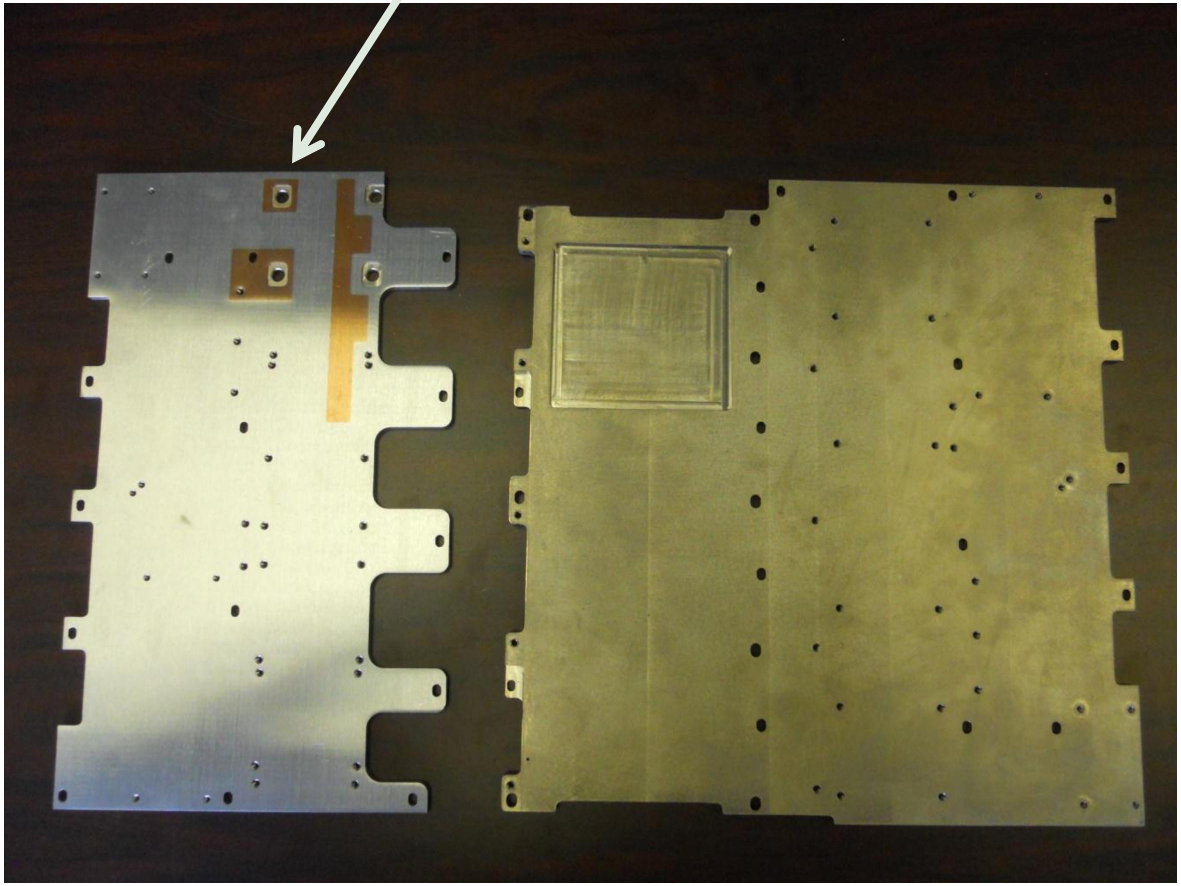


AL/APG Assembly View

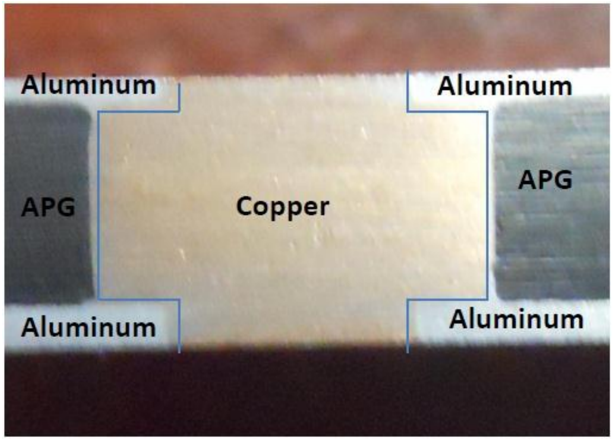
k-Core® Travelling Wave Tube Radar Cold Plate



Aluminum Encapsulated APG with Copper Vias
DoD Radar Systems



Copper Via Section View



Qualified and Fielded

Magnesium k-Core

Density Comparison

Al, Al k-Core, Mg, Mg K-Core

Component Material	Weight % APG	Weight % Encapsulant	Overall Density (gm/cc)	Density Improvement (%)
6061 Al	0	100	2.7	Baseline
Al k-Core	50	50	2.48	8.1
Mg AZ80A	0	100	1.8	33
Mg k-Core	50	50	2.03	25

Thermal Conductivity Comparison

Component Material	Volume % APG	Volume % Encapsulant	Thermal Conductivity (W/m-k)
6061 Al	0	100	170
Al k-Core	65	35	1071
Mg k-Core	65	35	1054

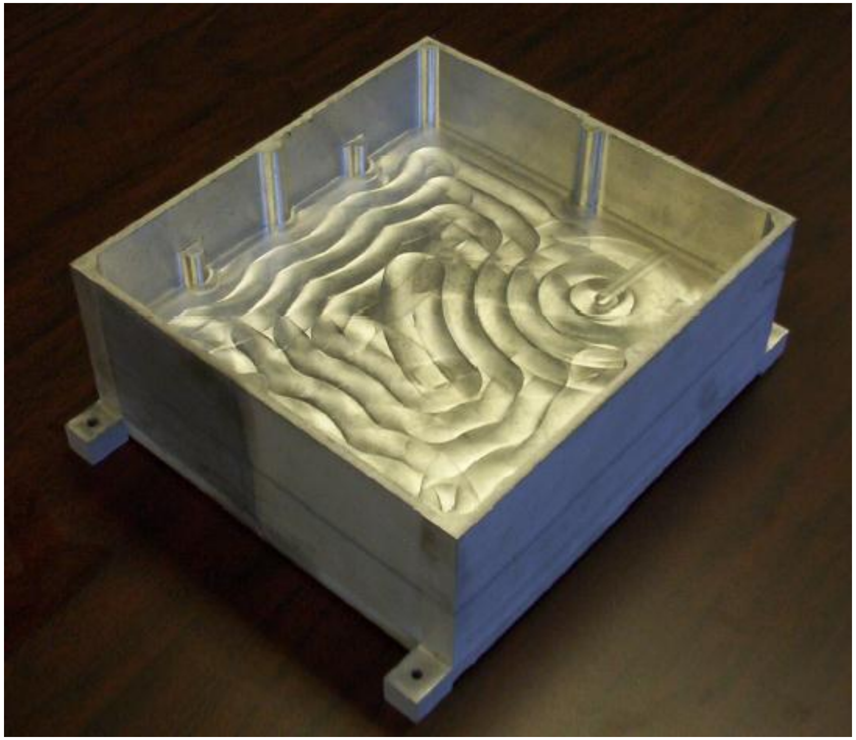
Property Overview

- Magnesium k-Core significantly reduces weight
  - 25% weight reduction below Al
  - 10 to 20% weight reduction below Al k-Core
- Thermal conductivity values equivalent to Al k-Core

Conclusion-Mg k-Core saves weight with no thermal management penalty

Prototype Chassis

Completed k-Core, Prototype Magnesium Chassis (Adhesive Bonded-not hardware suitable)



Prototype Chassis

Data Comparison

Chassis Composition	Mass (g)	Mass Reduction (%)	Delta Temp (K)	Temp Reduction %
Aluminum 6061	1235	Baseline	28.0	Baseline
Magnesium AZ31B	808	35%	67.0	-139%
k-Core, Aluminum	1199	3%	17.4	38%
k-Core, Magnesium	**881**	**29%**	**16.7**	**40%**

Other Considerations

- Cost Reduction Possibilities
  - Magnesium Forming Technologies such as die casting may prove useful
  - The low density of magnesium compared to aluminum compensates for the higher per pound cost