Ultra-High Thermal Conductivity, Thermal Expansion Matched, Low Density Materials for Dimensionally Stable Space Structures

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James A. Cornie

CTO, Chairman, MMCC LLC

jcornie@mmccinc.com

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- This development continues under Phase II NSF IIP Grant #0750180, Dr. Cheryl Albus COTR
- "z" inserting applications were first investigated on MDA Phase I contract #W9113M-08-C-0113 for insertion into advanced radar systems, Anthony Bryan COTR
- MMCC's Advanced Pressure Infiltration Casting (APIC^{tm}) process used to manufacture $AlGr_p$ was developed primarily under SDIO/BMDO/MDA funding at MIT and later at MMCC using start-up investment by the founder

Air Force Interest: Rapid Response Satellite Systems- Thermal Management Concerns[1]

- **Heat dissipation and rejection for high power systems**
  - Increasing power density and heat flux at the component level
  - Increasing heat transport and rejection requirements at the system level
- **Thermal stability for precision metrology**
  - Tight temperature control for temperature sensitive components
  - Reducing thermal deformation to improve image quality
- **Reconfigurable thermal control for responsive space**
  - Reducing design-to-launch timeline for tactical satellites
  - Modularizing thermal control system to be compatible with system architecture

1) Slide copied from A Williams, USAF, Kirtland AFB

Project Objectives

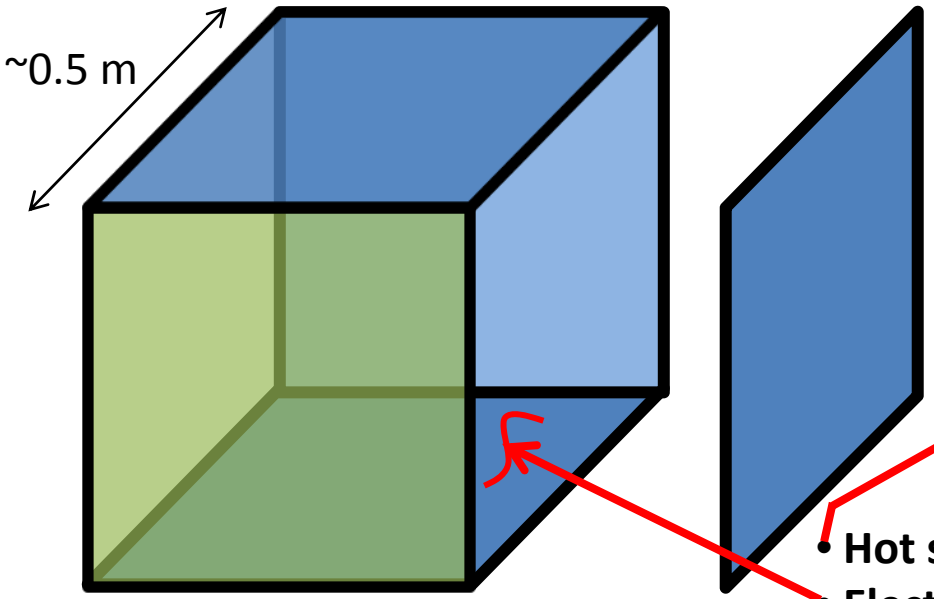
- Demonstrate materials/design concepts for integrated satellite structure/electronic thermal management substrate
- Demonstrate ability to hybridize for structure, thermal and precision thermal expansion matching
- Electronic thermal management is prime focus
  - High thermal conductivity
  - CTE matching electronic package
  - Local high thermal conductivity in “z” (through thickness)
- Structure to weigh less than conventional Al Iso-grid designs with higher structural stiffness

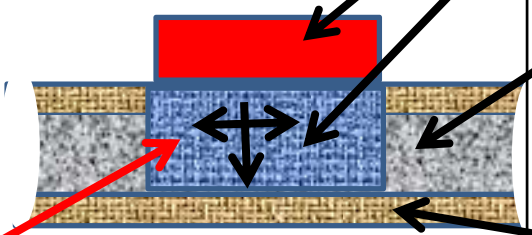
MMCC Target Concept for Satellite Structure hybridized for thermal Management

From Sat News, Jan. '09

	Skin	Core	Ave
E –msi (calc.)	34	7	18
CTE-ppm/K	~1	~3	~1.6
K- W/m-K	312	800	605

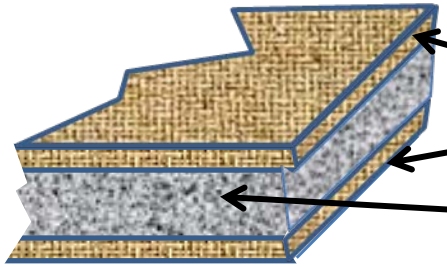
•Assuming 40%skin, 60% core





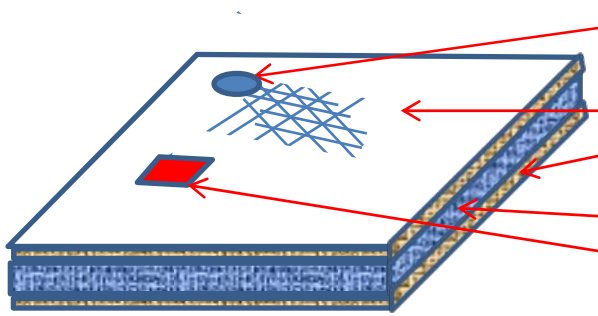
- Hot device
- "z" insert ($AlGr_p$) oriented for sinking @ 800 W/m-K
- $AlGr_p$ core for spreading at 800 W/mK
- Stiff skin for structural integrity

- Hot spot remediation
- Electronics mounted on inside of walls with "z" inserts for hot spot remediation



- High stiffness, moderately high TC quasi-isotropic filament wound skin
- 800 W/m-k $AlGr_p$ core

Structural Panels with High Thermal Conductivity Core and High Performance Skins: Basic Concept



- Hard spot Al inserts for bolting/screw attachment
- Quasi-isotropic filament wound surface skins
- $AlGr_p$ core
- ":z" insert with MetGraf surface calibrated to CTE match device.

Property:		Skin**	Core	Ave*
E –msi	(calc.)	34	7	~18
CTE-ppm/K	"	~1	~3	~1.6
K- W/m-K	"	312	800	605

Local CTE at hot spot matched to semiconductor package by use of local MetGraf skin insert over $AlGr_p$ core

- **Assuming 40%skin, 60% core**
- ****Skin preform to be Mitsubishi fiber K13D2U with 135 msi modulus and thermal conductivity = 800 W/mK axially**

"z" inserts can be either:

1) **Designed in at preform stage and co-infiltrated during pressure infiltration casting**
2) **Machined and soldered into pre-infiltrated + electroplated panel as per quick-launch requirements**

AF 83-082 Work Plan

Task 1: **Process refinement to improve thermal conductivity $AlGr_p$ to ~800-1000 W/mK** ***(One round of experiments, standardize , calibrate and benchmark (TC/CTE vs. v/f Gr flake) based upon best process refinement results) (Use NSF-21#4 data)***

Task 2: **Scale-up core and potential structural skin materials and evaluate for steady state TC, tensile strength, Young's modulus, for CTE = 4 ppm/K and CTE=7 ppm/K composites**

Task 3: **Perform experimental verification/demonstration of concept**

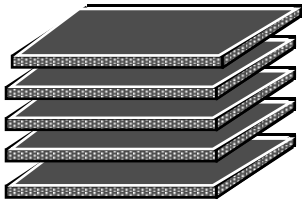
Task 4: **Demonstrate high thermal transport around structural joint on pre-prototype specimen(s)**

Task 5: **Manufacture early stage prototype for evaluation by Prime and AFRL**

Task 6: **Reporting and communicating with satellite community**

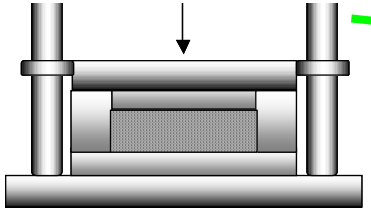
MMCC Gas Pressure Infiltration Casting Process

Graphite fiber, mat, platelet (flake) or particulate preform

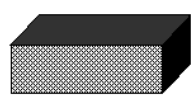


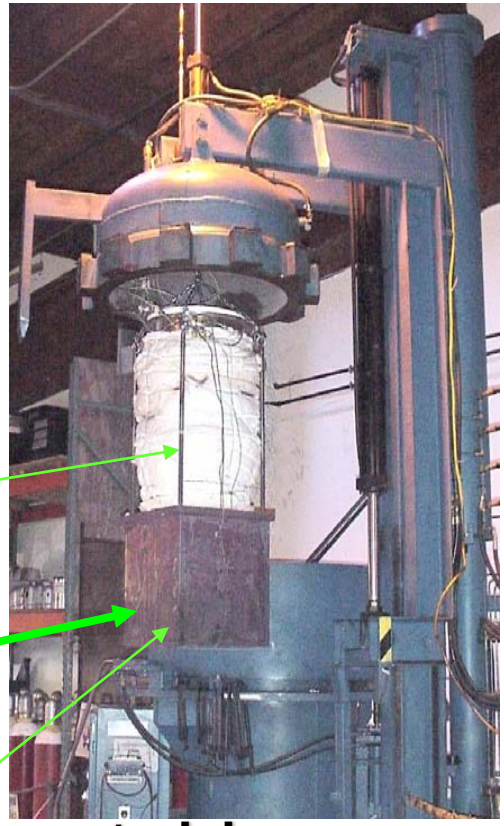
Stacked laminates

Press to desired volume % - heat under pressure to activate binder, Chill to set binder and stabilize preform



Insulated molten alloy reservoir





2 cubic ft. of preform material being transferred to autoclave for pressurization

Preliminary Concepts:

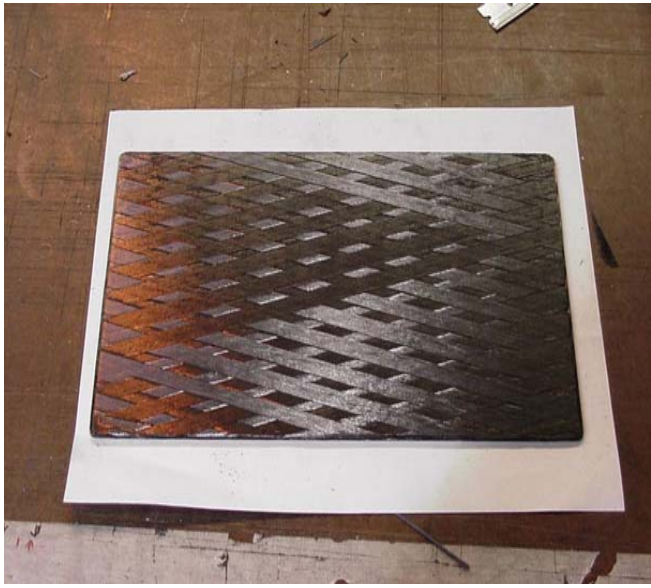
- Basic concept: All elements assembled in the preform stage and co-infiltrated during casting
- A structural skin of high modulus fiber filament wound or in fabric form will provide the structural stiffness and strength
- An $AlGr_p$ core will provide in-plane thermal transport
- $AlGr_p$ core material, rotated 90 deg and mitered provides 800 W/mK sinking as well as spreading in orthogonal directions

Component: #1) Structural Skin Candidates

Candidate Gr fibers	Cost-$/lb)	Modulus (vendor)-	Therm. Cond.-	Strength-
K13D2U	(~$925/lb)	135 msi	800 W/mK	535 ksi
K13C1U	(~$620/lb)	130	620	550
K63A12	(~$80/lb)	114	220	380
Hexcel-IM9	(~$40/lb)	44	15	890

Reinforced Al 413 matrix lamination theory & ROM calculations

K13D2U/ Al	Uniaxial(@60 v/o)	85 msi	552
(density =~ 2.35	Transverse	10	78
g/cc for all)	Quasi-Isotropic	44	312
K13C1U/Al	Uniaxial msi	82	444
	Transverse	10	78
	Quasi-Isotropic	43	158
K63A12/Al	Uniaxial	72	204
	Transverse	10	78
	Quasi-Isotropic	38	138
Hexcel IM9/Al	Uniaxial	30.4	97
	Transverse	10	78
	Quasi-Isotropic	17.2	72

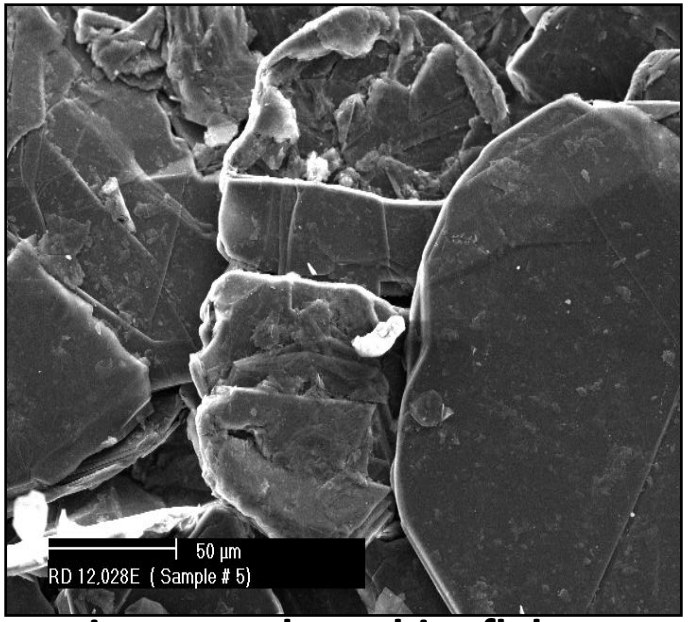


Component: #2) $AlGr_p$ Core

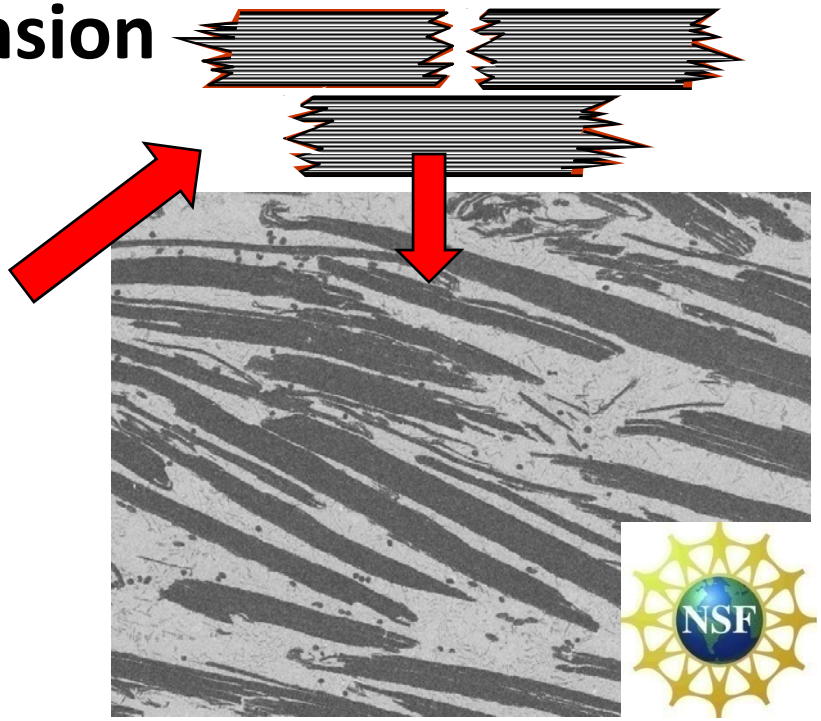
- $AlGr_p$ developed on Phase II SBIR from NSF
- Material has demonstrated >900 W/mK thermal conductivity with engineered CTE
- Material constituted from natural graphite platelets, mined from the Earth and costing ~$1.50/lb
- $AlGr_p$ Preform process nearly same as our commercial MetGraf process
- Material is pressure infiltrated with same molten Al alloy as our MetGraf products
- Recent results indicate that technology can be extended to Cu matrix alloys ($CuGr_p$)

Natural Graphite Platelets

- "Dirt cheap", mined from the earth from many locations e.g. China, Canada, NY, NJ, Ceylon, Brazil, Armenia, Ukraine, Mexico, UK, Norway, etc.
- Ultra high intrinsic thermal conductivity
- Low in-plane thermal expansion

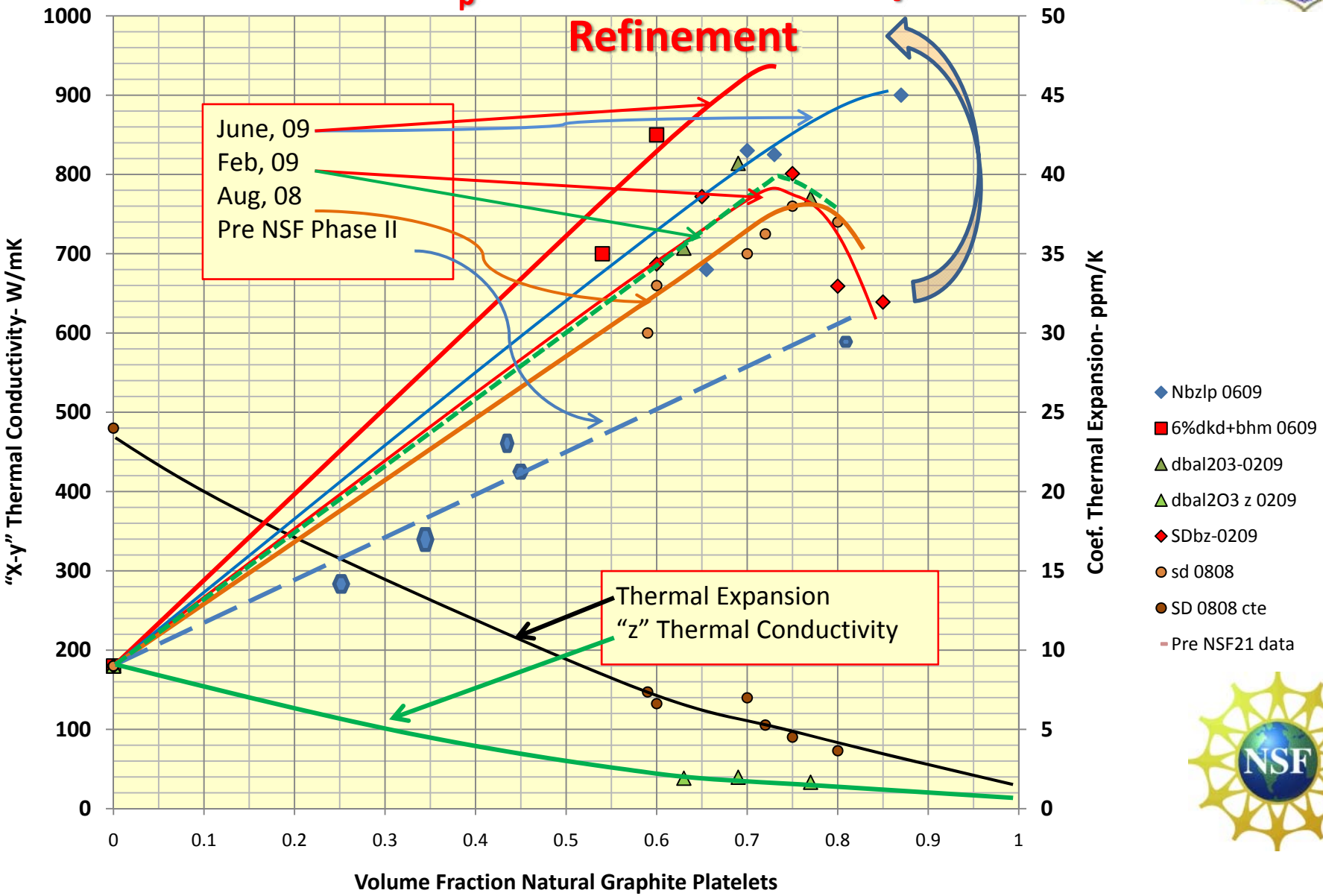


Low cost high purity natural graphite flakes



Microstructure of $AlGr_p$-7

Trend of $AlGr_p$ Thermal Conductivity with Process Refinement



Advantages of Natural Graphite Platelets over High Performance Pitch Graphite Fibers.

NGF has High TC in two directions whereas fibers have high TC in only one direction. Hence Rule of Mixtures (ROM) TC for AlGrp vs. uniaxial graphite/Al are:

$K_x = vf_{NGF} \times k_{(x-y)NGF} + (1-vf)vf_{NGF} \times k_{matrix}$ Where vf_{NGF} can be as high as 90%

Since $K_x = K_y$, composites are planar isotropic.

Measured (and ROM) conductivities approach 900 W/mK

Likewise for a uniaxial pitch based graphite fiber, practical volume fraction limit is 0.6 v/f ROM gives: $K_x = K_x = vf_F \times k_{(x-y)F} + (1-vf)vf_F \times k_{matrix}$

Assuming 1000 W/mK axial TC and 10 W/mK transverse TC, ROM give us:

762 W/mK (in the UX direction only)

72 W/mK (in the transverse direction)

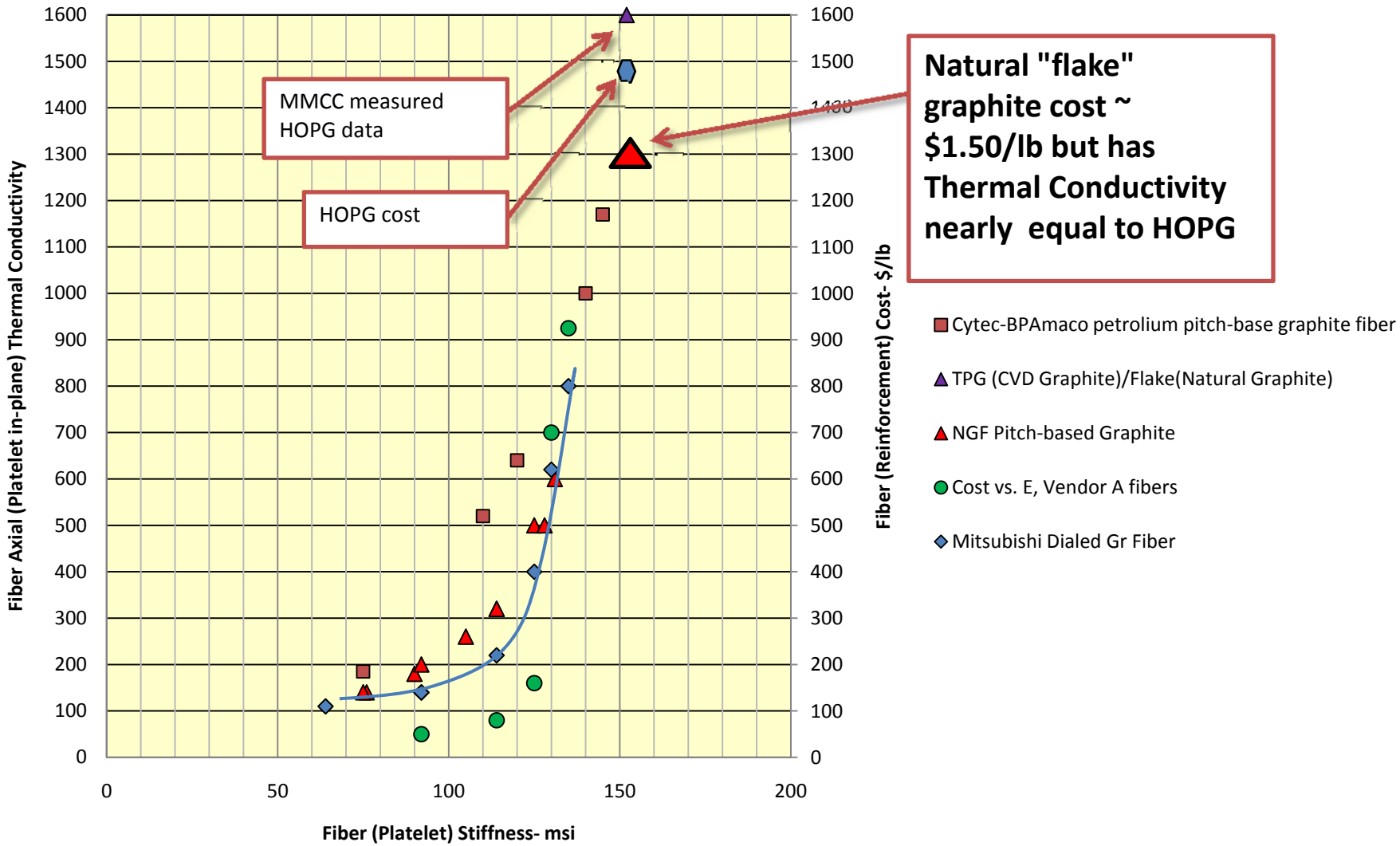
A quasi-Isotropic architecture Al matrix composite would yield:

372 W/mK in x and Y

RD 12,028E (Sample # 5)

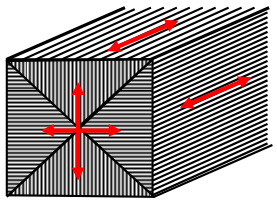
...And Then There are Materials Cost to Consider...

Vendor Published Data: Variation of Cost and Thermal Conductivity of Graphite with Modulus



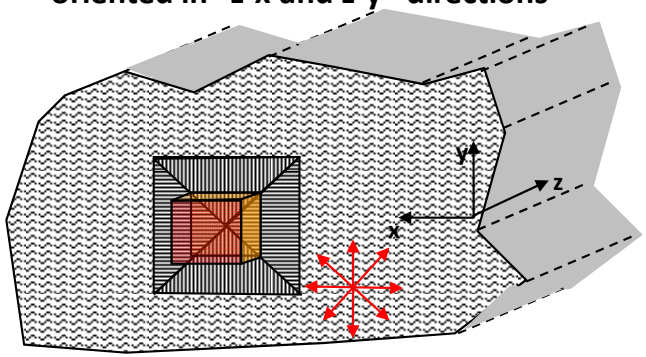
Component #3:
"z" inserts for Hot Spot Remediation

High Quasi-Isotropic Thermal Conductivity = "z" Insert Technology

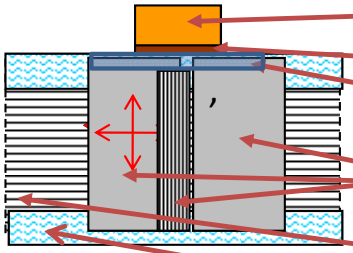


Mitered "z" insert preforms showing ~800 W/mK high TC directions after infiltration with molten Al

"z" insert arranged by mitering for high TC graphite planes oriented in "z-x and z-y" directions

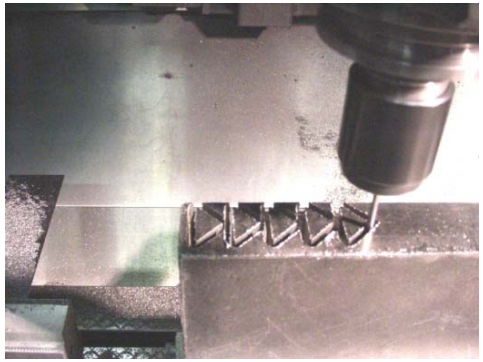


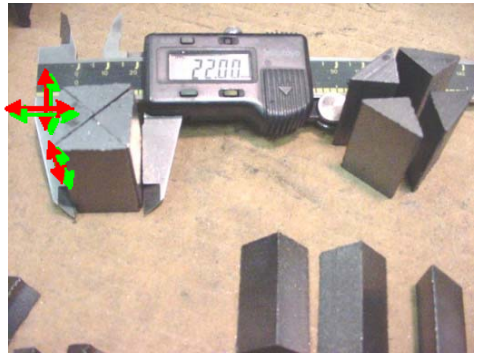
TC = ~800 W/mK sinking and 650-750 W/mK spreading after co-pressure infiltration with Al alloy (depending on engineered CTE)

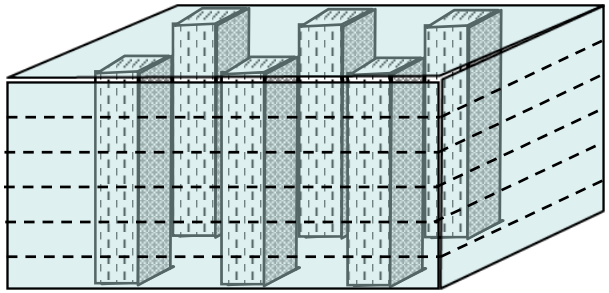


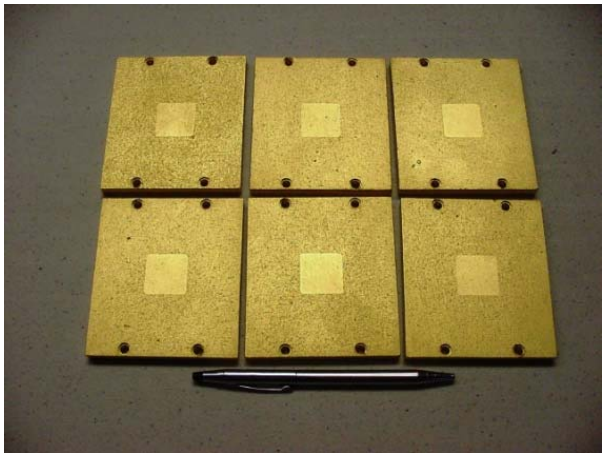
- **Semiconductor Device**
- **Solder or TIM for low impedance interface**
- **MetGraf pad for CTE matching and smoothing CTE variation over mitered sections of "z" inserts**
- **Mitered sections of "z" Al-Gr™ ~800 W/mK sinking and 800 W/mK orthogonal spreading**
- **Base-plate body can be CTE Matched Al-Gr™ or MetGraf™**
- **Structural skin**

"z" Inserts for Local Hot Spot Remediation Manufacturing Approach:





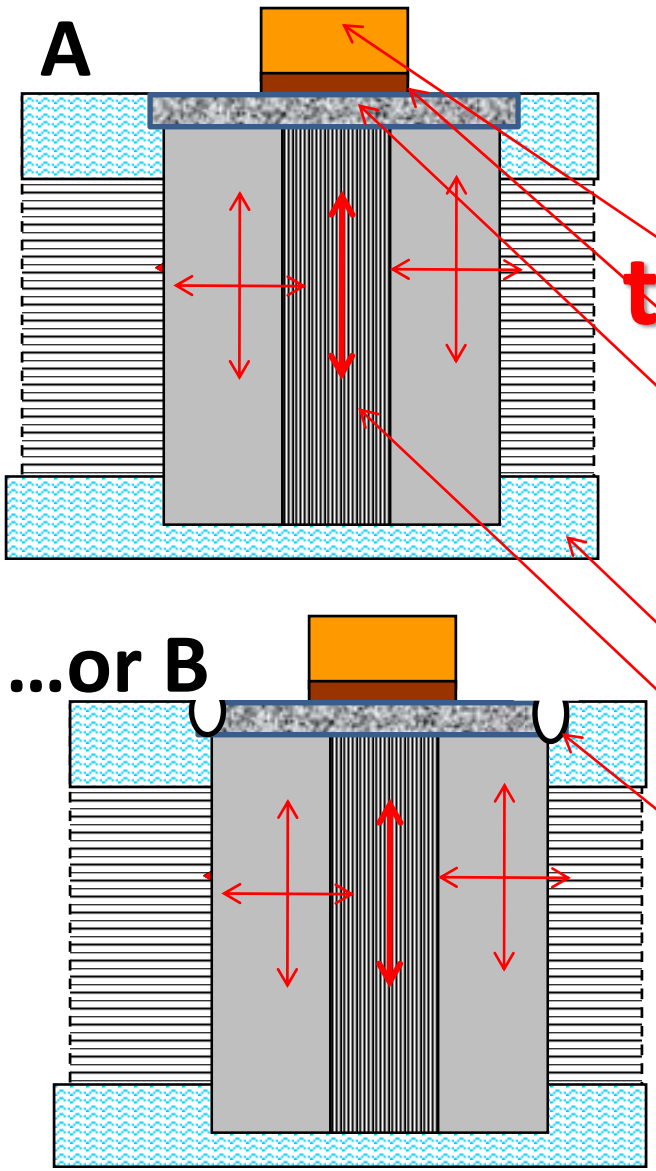




<u>In the green preform stage:</u>

1. **Fab. preform from flake natural graphite and Binder into a slab**
2. **Rotate slab 90 deg and machine or extrude into mitered preform sections for "z" inserting into base-plate preform**
3. **Pressure infiltrate to form $AlGr_p$™ ingot**
4. **Ingot can be sliced and machined into base plates and plated for die attach**
5. **Alternative, base plates can be cast to net shape with a skin (for ease of electroplating and lower surface roughness)**

Added Innovation: Locally Engineered CTE Regardless of the CTE of the Hybridized Base-plate



- Semiconductor package with CTE that must be matched
- Solder or TIM attachment
- MetGraf 9, 7, or 4 insert pad to level local CTE variations in substrate
- Structural skin
- AlGrp mitered "z" insert
- Variation B has a moat to isolate CTE of pad insert from stiffer/lower TC skin

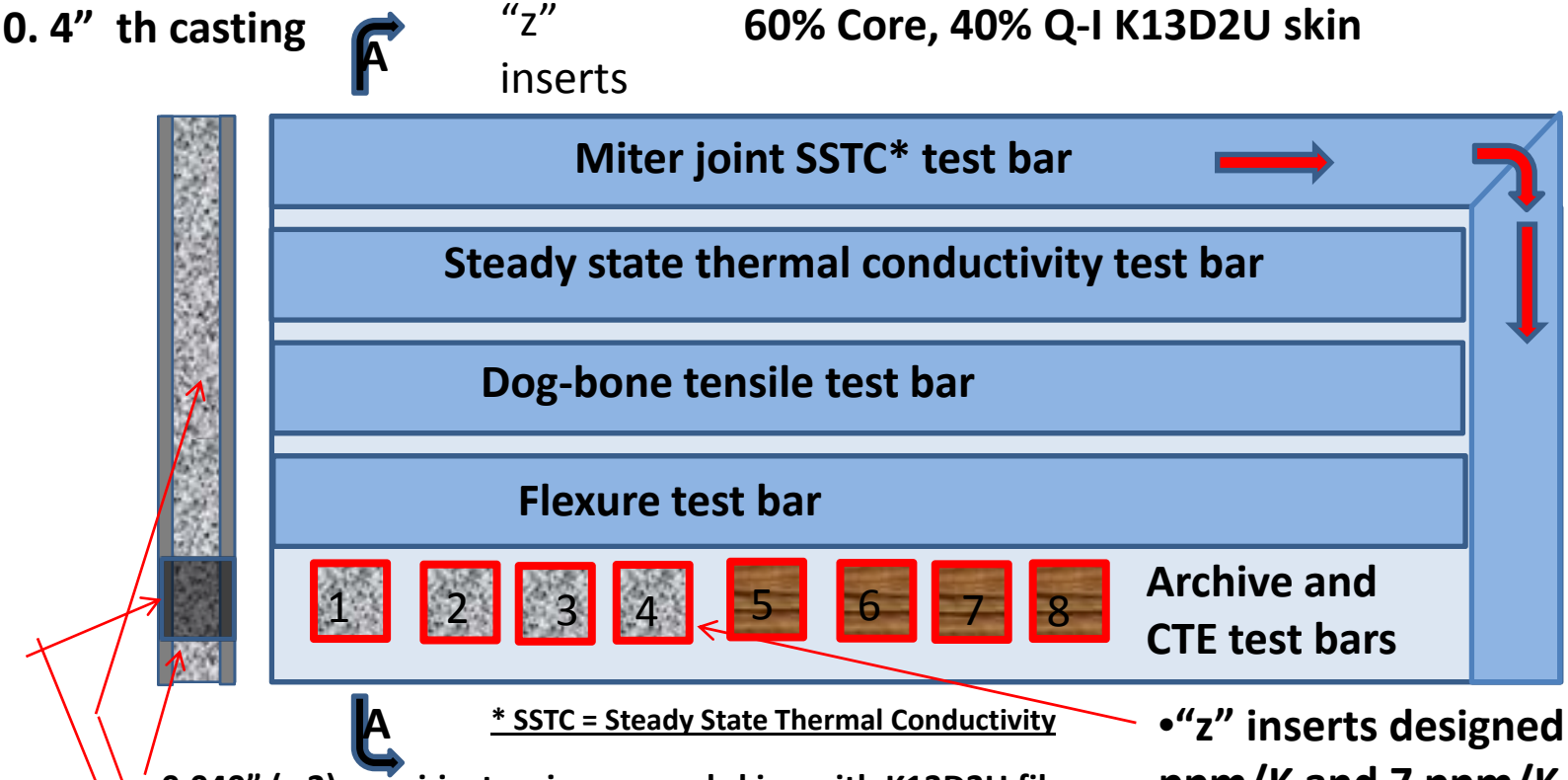
Panel/Specimen Design: Casting# 1, Panel # 1 (3” x 7¨ x ~0.4”) 800 W/mK with QI Architecture fiber skin

Section A-A

0. 4” th casting

“z” inserts

60% Core, 40% Q-I K13D2U skin

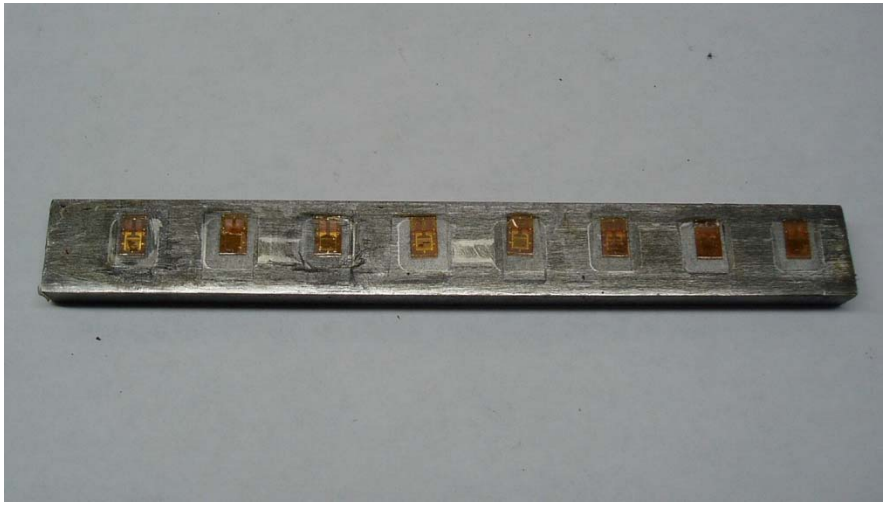


* SSTC = Steady State Thermal Conductivity

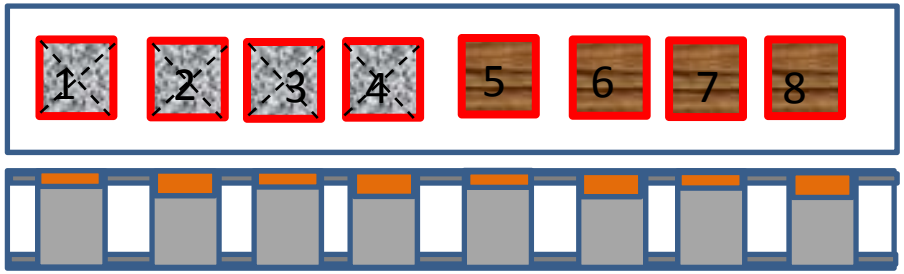
- 0.040” (x 2) quasi-isotropic wrapped skins with K13D2U fiber
- 0.240” $AlGr_p$ core calibrated to 800 W/mK (~75 v/o)
- Mitered $AlGr_p$ “z” inserts at 800 W/mK with MetGraf 4 and 7 skins

- “z” inserts designed for 4 ppm/K and 7 ppm/K (twice baked MetGraf skins) at 0.015” and 0.025” thick

Evaluation Panel before Machining Test Coupons (left). “z”Insert Test Bar (right)



"z" insert study plan for panel 1



Gr fiber quasi-isotropic
top and bottom skin
CTE measured with strain gages
And hot pad in x and y directions

CTR 20=>125C 6.05 9.09 9.56 10.47 ppm/K

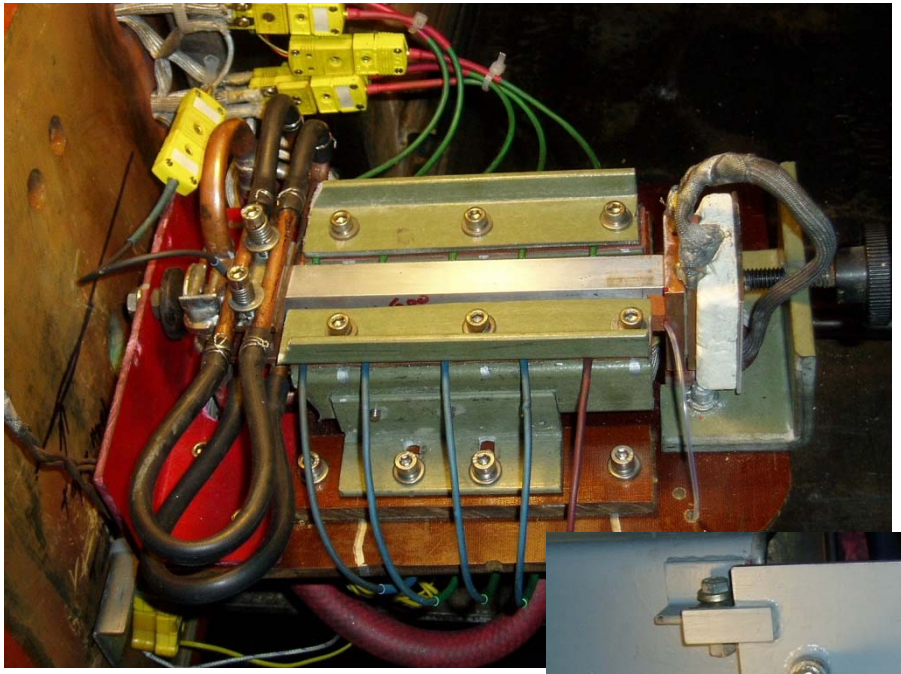
6.59 0.91 5.21 8.14 ppm/K

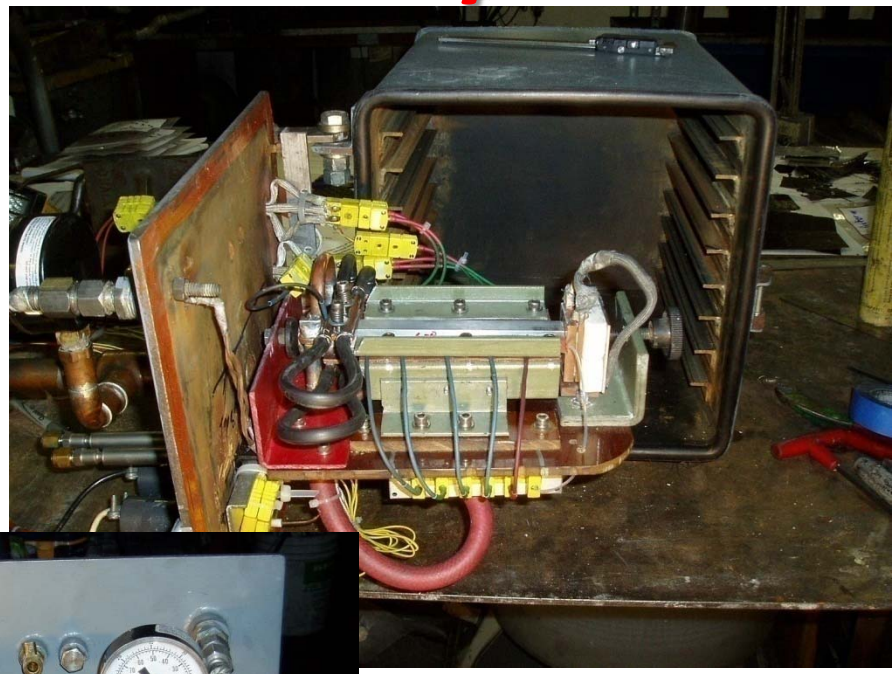
1. Mitered "z" $AlGr_p$ insert with 0.015" Metgraf 4 surface pad top face only
2. Mitered "z" $AlGr_p$ insert with 0.025" MetGraf 4 surface " " " "
3. Mitered "z" $AlGr_p$ insert with 0.015" Metgraf 7 surface " " " "
4. Mitered "z" $AlGr_p$ insert with 0.025" Metgraf 7 surface " " " "
5. x-z (non mitered) $AlGr_p$ "z" insert 0.015" Metgraf 4 surface " " " "
6. x-z (non mitered) $AlGr_p$ "z" insert 0.025" Metgraf 4 surface " " " "
7. x-z (non mitered) $AlGr_p$ "z" insert 0.015" Metgraf 7 surface " " " "
8. x-z (non mitered) $AlGr_p$ "z" insert 0.025" Metgraf 7 surface " " " "
9. Back side (no MetGraf Pads) of mitered "z" insert
10. Back side (no MetGraf Pads) of non mitered "z" insert

Preliminary Strain Gage CTE Measurement Results: Heating 25C to 125C

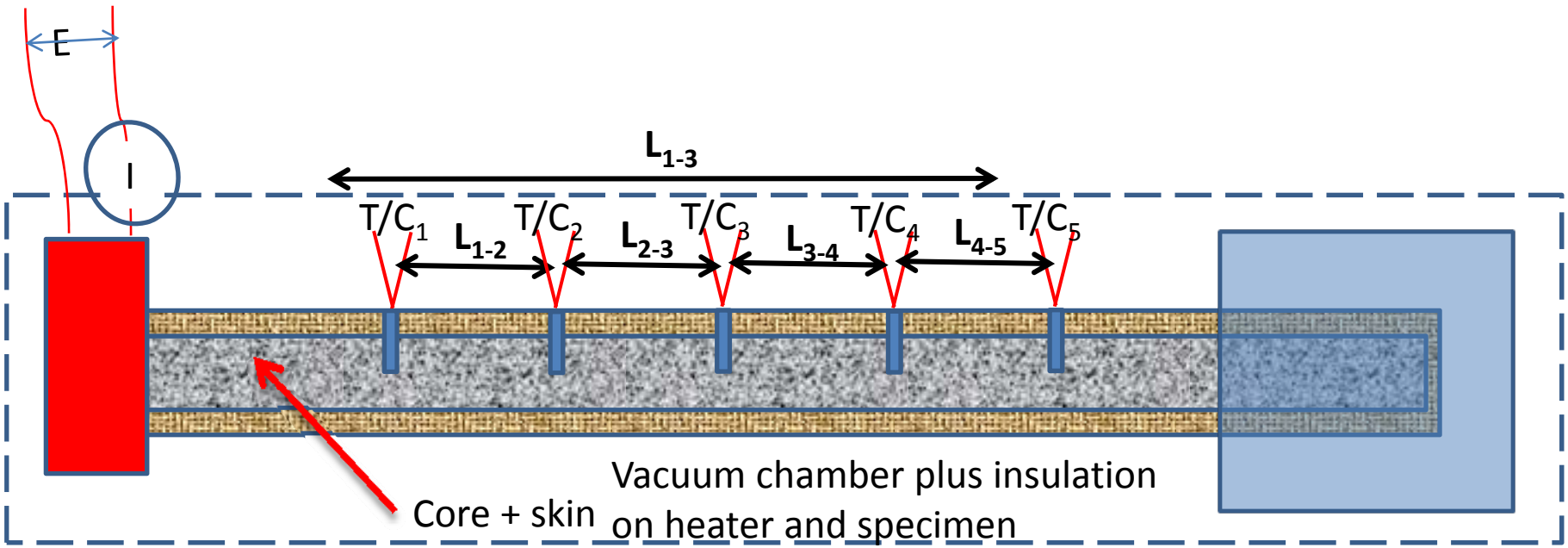
1. "z" $AlGr_p$ insert with 0.015" Metgraf 4 surface pad top face only: 6.05 ppm/K
2. "z" $AlGr_p$ insert with 0.025" MetGraf 4 surface " " " " 6.59 "
3 "z" $AlGr_p$ insert with 0.015" Metgraf 7 surface " " " " 9.99 "
4. "z" $AlGr_p$ insert with 0.025" Metgraf 7 surface " " " 10.91 "
5. x-z (non mitered) $AlGr_p$ "z" insert 0.015" Metgraf 4 surface " 9.56 "
6. x-z (non mitered) $AlGr_p$ "z" insert 0.025" Metgraf 4 surface " 5.24 "
7. x-z (non mitered) $AlGr_p$ "z" insert 0.015" Metgraf 7 surface " 10.47 "
8. x-z (non mitered) $AlGr_p$ "z" insert 0.025" Metgraf 7 surface " 8.14 "
9. Back side (no MetGraf Pads) of mitered "z" insert experiments in progress
10. Back side (no MetGraf Pads) of non mitered "z" insert " " "

Steady State Thermal Conductivity Measurement Facility





Experimental Setup for Evaluating Thermal Conductivity



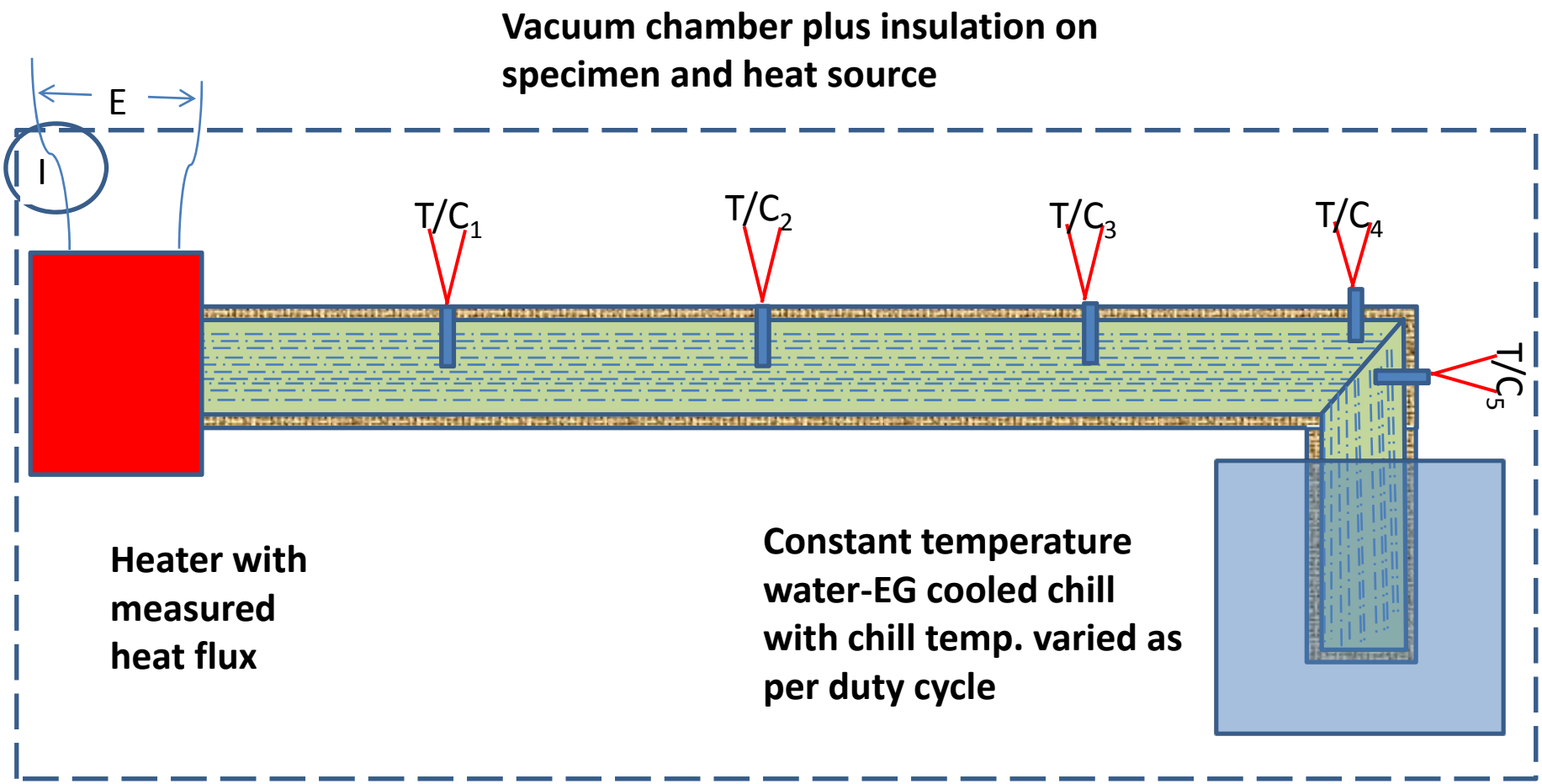
Heater with measured heat flux

$$W = q/t = EI = kA(\Delta T/\Delta L)$$

$$k = EI/(A(\Delta T/\Delta L)) = W/mK$$

Constant temperature water-EG cooled chill with chill temp. varied as per solar/shade cycle

Evaluation of Heat Transfer/Thermal Impedance at Structural joint



SSTC Measurement Results vs. ROM at 20C

Panel No.	Panel Architecture	Meas. v/f	TC-20C (meas.) W/mK	ROM TC-20C
1	60% $AlGr_p$ core- 40% QI K12D2U skin	0.72	610	605
2	UX K13D2U/Al(413hp)	0.663	660	591
3	60/40 core/skin QI-K13C1U/Al 414hp	0.625	615	583
4	UX K13C1U/Al 413hp	0.555	425	424
5	60/40 Core/skin QI K63A12	0.738	520	535
6	UX K63A12/Al 413hp	0.743	272	210

Baseline Materials Data

K13D2U	
TC vendor	800 W/mK
E vendor	135 msi
TS vendor	535 ksi
K13C1U	
TC vendor	620 W/mK
E vendor	130 msi
TS vendor	550 ksi
K63A12	
TC vendor	220 W/mK
E vendor	114 msi
TS vendor	380 ksi
$AlGr_p$ core	>800 W/mK
Al 413hp	180 W/mK

MMCC
METAL MATRIX CAST COMPOSITES

Measured Thermal/Mechanical Data:

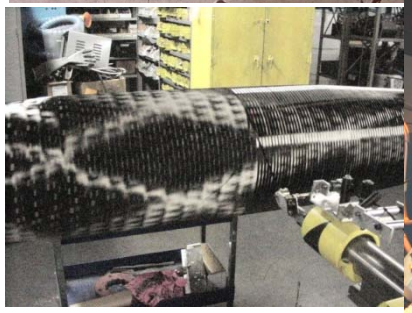
(summary of measurements to date)

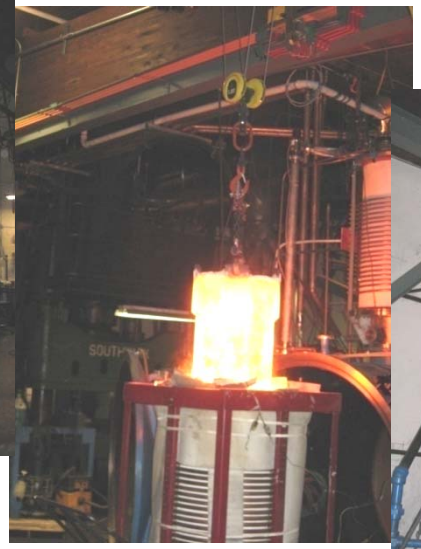
Panel #	Panel Architecture	Meas. v/f	TC 20 W/mK	ROM TC 20 W/mK	E msi	Tens. St. ksi	CTE heating 20=>200 ppm/K	CTE Cooling 300=>20
1	60%Core/40% QI K12D2U skin	0.72	610	605				
2	Uniaxial K12D2U /414 Al	0.663	660	591				
3	60%Core/40% QI K13C1Uskin	0.625	615	583			3.1	1.78
4	Uniaxial K13C1U /414 Al	0.555	425	424				
5	60%Core/40% QI K63A12 skin	0.738	520	535			3.3	2.29
6	Uniaxial K63A12/414 Al	0.743	272	210				

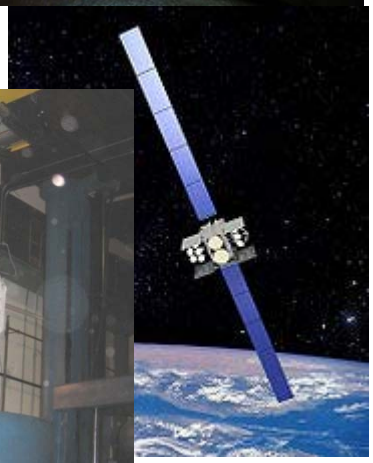
Summary of Initial Project Results

- All evaluation panels have been manufactured and machined into test specimens. Testing in progress
- Recent process refinements show that thermal conductivity of core material can be in excess of 900 W/mK
- Thermal conductivity measurements completed on hybrid panel specimens and results agree well with rule of mixtures calculations
- Local CTE control over "z" insert concept has been demonstrated at the 4 ppm/K to 7 ppm/K range but needs further refinement for precise control
- A plan of approach for the rapid response satellite project is being developed

MMCC SBIR Success Stories

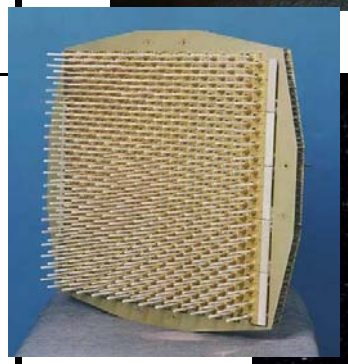


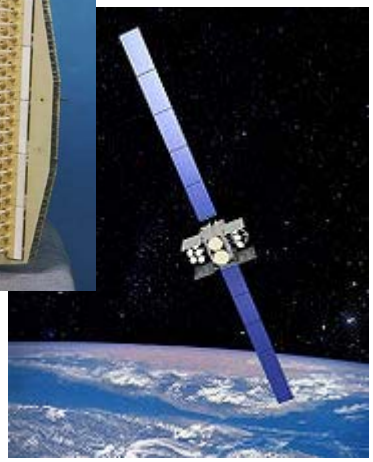




Plansee / Ma-COM / Cobham / Boeing – Ka-Band T/R Modules for Wideband Global Satcom & DirecTV HDTV Satellites

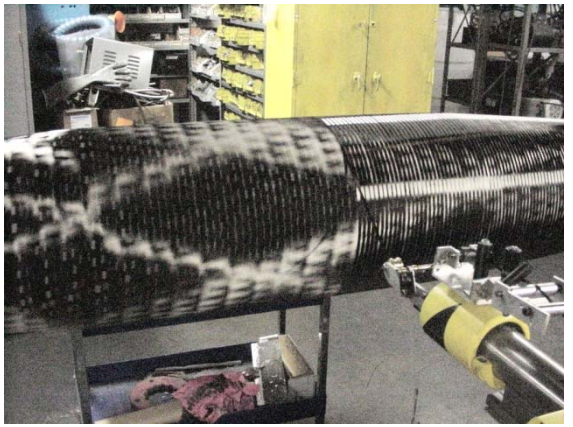
Technology	***Application/Market***
-Al infiltration -Custom Al MetGraf	-Commercial & military telecommunications satellites WideBand Global Satcom (WGS) and DirecTV HDTV. -Ka-Band TR Modules
Key Properties	***Status:***
-Lightweight -High thermal conductivity -Matched CTE	-Materials delivered for 4 WGS satellites with orders for an additional three ship-sets expected Q3, 09 -Spaceway 1 & 2 launched in 2005, two additional launches planned





Continuous Gr and Ceramic Fiber in Fabric or Filament- Wound Form

Technology	***Application/Market***
-Filament winding and fabric lay-up -Net –shape pressure infiltration casting - Hybridized with $AlGr_p$ thermal inserts	-Hybrid satellite structures -End effectors (robot arms) for semiconductor wafer handling for OEM -Mirror support structures -Electronics chassis
Key Properties	***Status:***
- High stiffness - High TC - CTE matching - Local CTE control	-Prototypes demonstrated -Database generated for Mg and Al matrices - Developing prototypes for semiconductor OEM

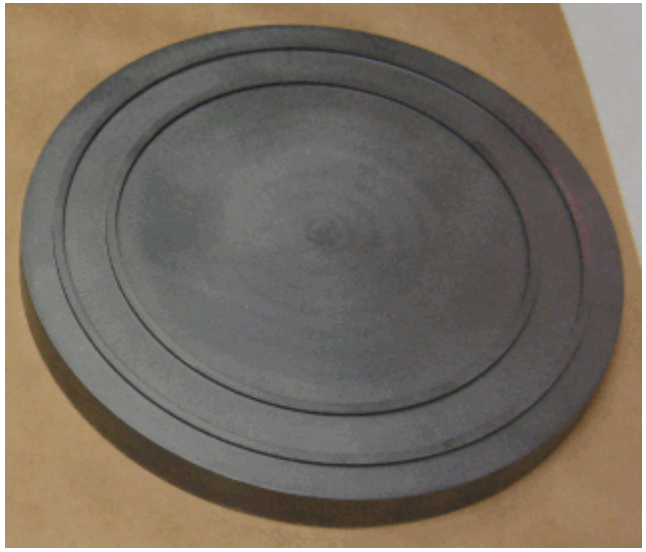


Semiconductor OEM - In-Situ Cast Liquid Cooling Tubes Into CTE Matched Al MetGraf High Thermal Conductivity Lightweight Composite Cold Plate Structures for Ion Implantation

BEFORE CASTING

Fiber pre-form halves machined to accept tubing

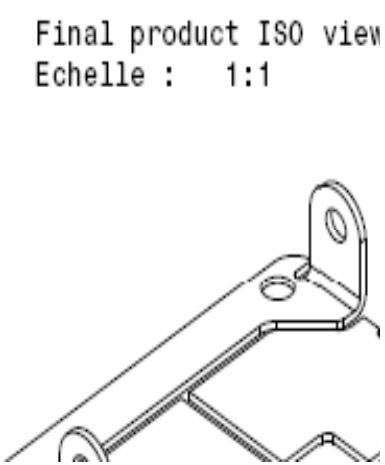
AFTER CASTING



CNC ready ROTF (Rough Oversize to Finish) composite blank

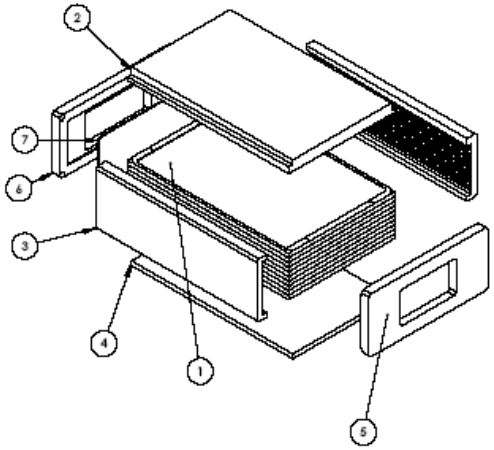
European Customer – IGBT Power Module Heat Sinks for Hybrid Electric Vehicles

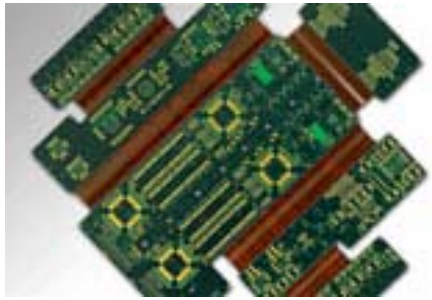
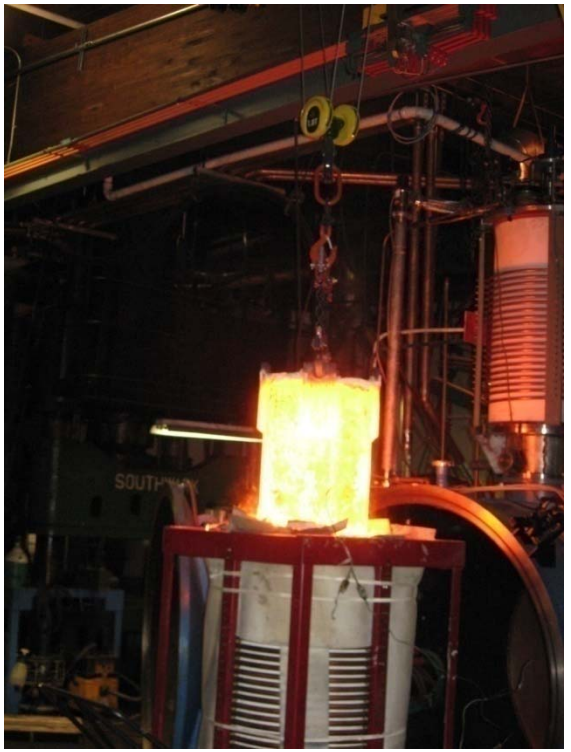
Technology	***Application/Market***
-Cu infiltration -Cu MetGraf CTE 7 -In-situ captured Cu MetGraf embedded in pure Cu	- HEV power semiconductor -IGBT cooling
Properties	***Status***
-Matched CTE -Ni/Au plating	-Prototypes in test - Quoting 1M units



Lockheed Martin Orlando – PCB Restraint Cores Made From Large Format Cu MetGraf

Technology	***Application/Market***
-Cu infiltration using 500 lb VIM -Cu MetGraf 7 -Lapping, Cu plating -12” x 18” Castings	-JCM – Joint Common Missile (JAGM) -- SDB – Small Diameter Bomb
Properties -Matched CTE -Lightweight	*Note: These are the largest copper/graphite composites ever made by pressure infiltration. Result of MDA SBIR project.*





MDA Funded Scale-up of Cu-Metgraf Castings