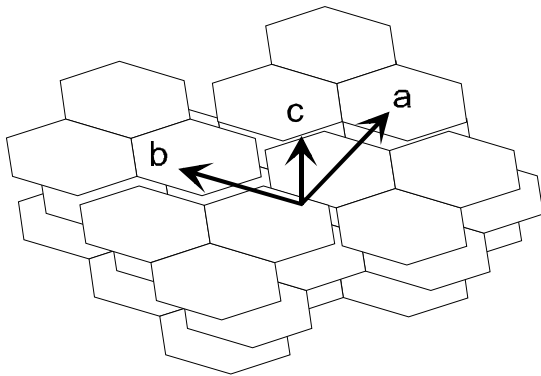


**ENCAPSULATED ANNEALED
PYROLYTIC GRAPHITE
CRYOGENIC APPLICATIONS**

Annealed Pyrolytic Graphite (APG)

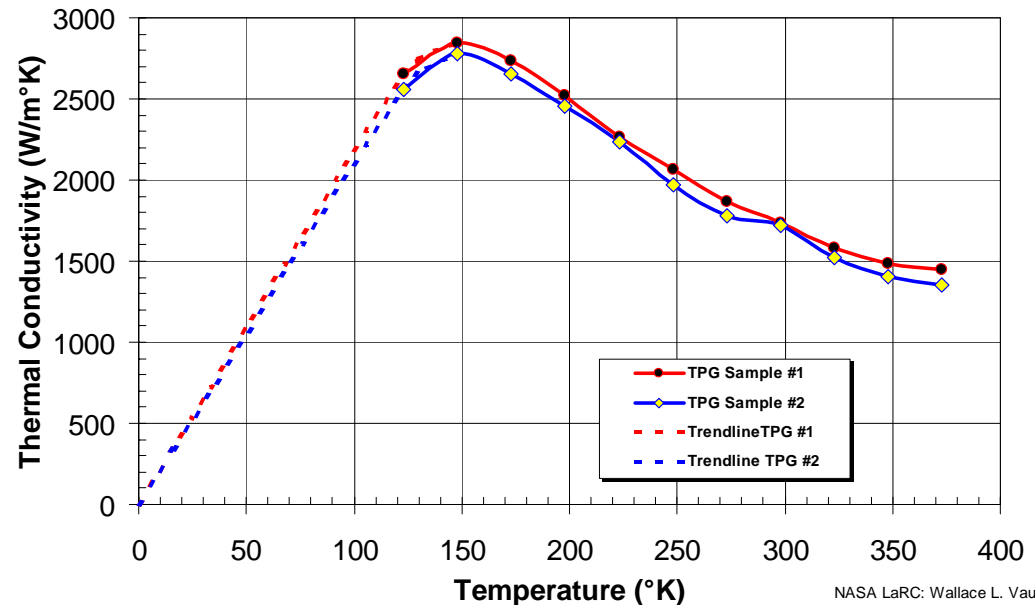
Description

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



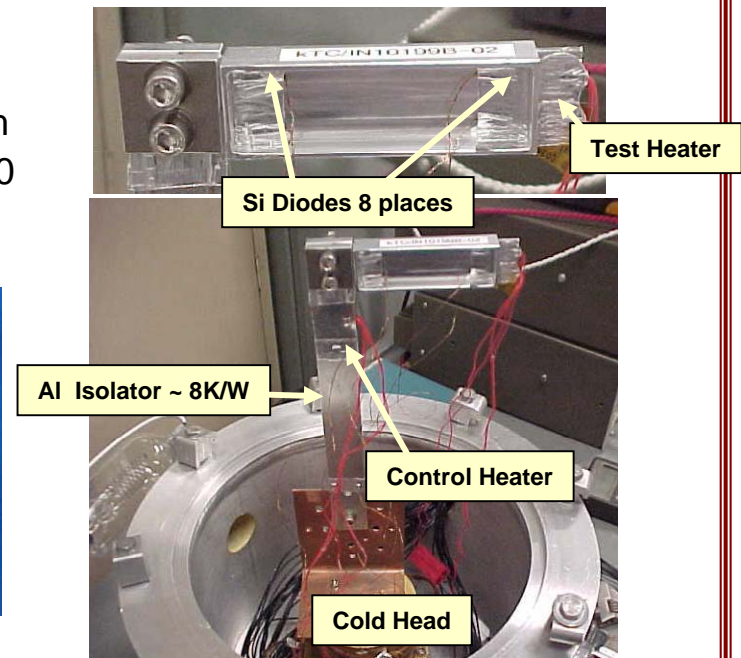
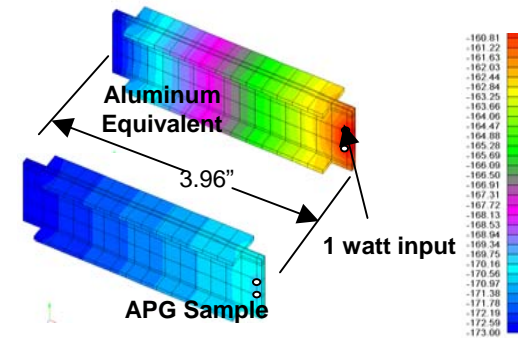
- $k_{ab} = 1700. \text{ W/mK}$
- $k_c = 10. \text{ W/mK}$
- $E_{ab} = 120 \text{ Msi}$
- $E_c = 5.0 \text{ Msi}$
- $\text{CTE}_{ab} = -1.0 \times 10^{-6} \text{ }^\circ\text{C}^{-1}$
- $\text{CTE}_c = 25. \times 10^{-6} \text{ }^\circ\text{C}^{-1}$
- Tensile Strength_{ab} = - ksi
- Tensile Strength_c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

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



Aluminum Encapsulated APG

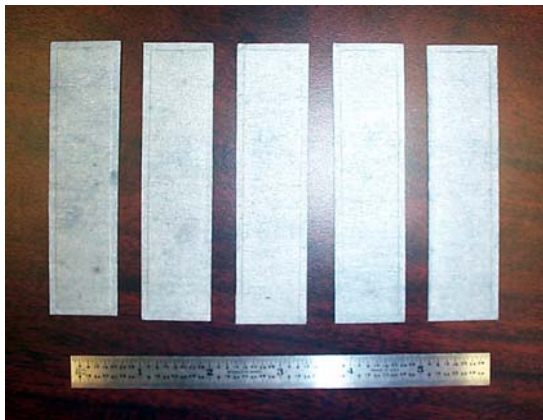
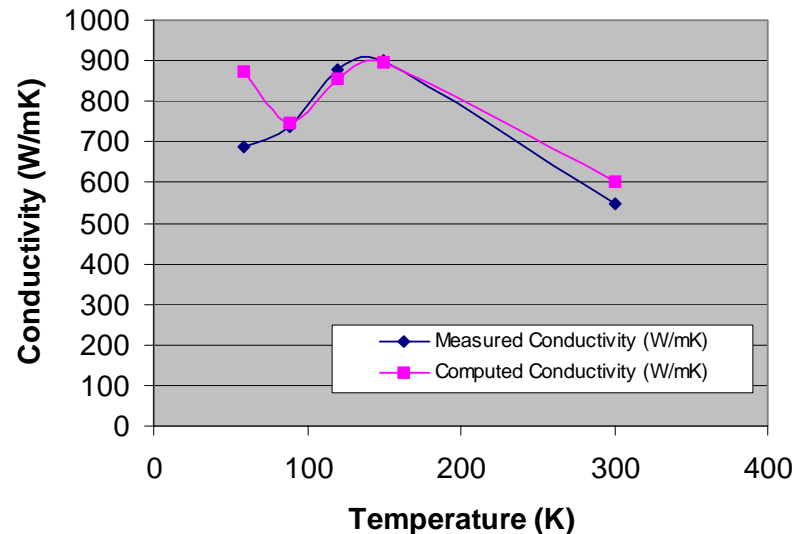
- Potential benefit of the technology ($\sim 6X K_{be@90k}$) has been proven
- An aluminum encapsulated APG sample from k Technology received, modeled and tested and material agrees with manufacturer's predictions
 - APG conductivity along long axis of sample, 1800 W/m-k at 290 K, 3000 W/m-k at 90 K
 - Integrity of APG/Al bond verified by cycling APG from 90K to 290K 15 times (cooled below 90K to 40K on 10 cycles)



Aluminum Encapsulated APG – Foils, Conductivity Measurements

- 1 x 4 inch aluminum foil (99.9999% pure) encapsulated APG coupons
- 25% APG volume fraction
- .016 inch thick
- Measured data matched predictions except for the 60K measurement – PMIC suspected parasitic losses

Thermal Strap Conductivity Results
(APG volume fraction = 25%)



Nominal Temperature (K)	300	150	120	90	60
Tested Temperature (K)	301	150	120	89	59
Conductivity (W/mK)^[1]	548	899	877	736	687
Conductivity (W/mK)^[2]	603	895	854	747	873
Variance (%)	-9%	0%	3%	-1%	-21%
Strap Conductivity (W/mK)^[3]	916	1438	1340	1076	986

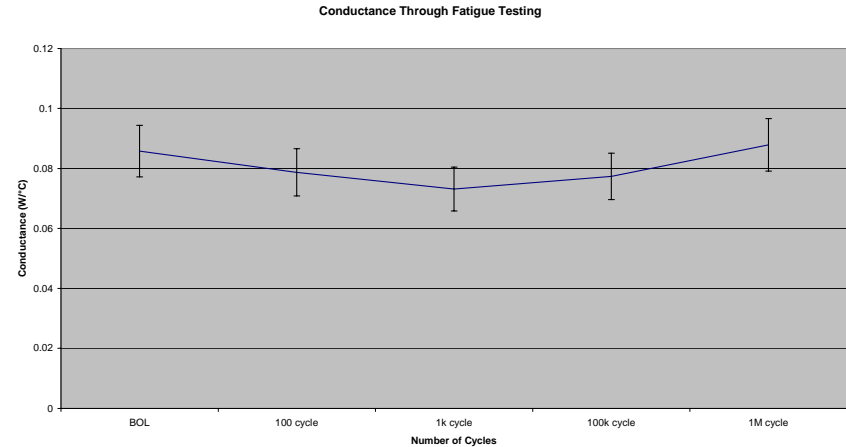
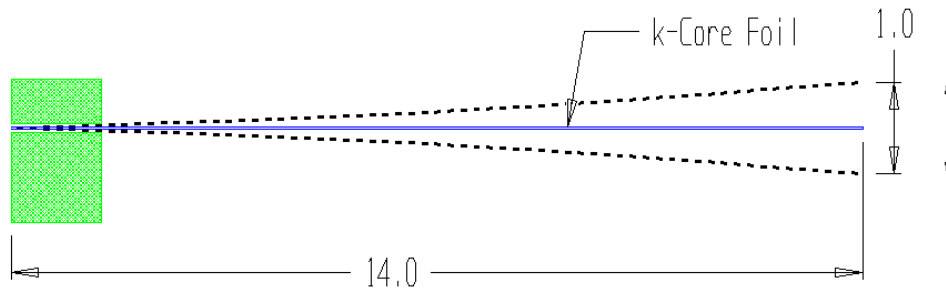
[1] Measured conductivity of sample IN10423, APG volume fraction = 25%

[2] Computed conductivity from TRPL APG and aluminum properties

[3] Computed conductivity of thermal straps (part number IN10422)

Aluminum Encapsulated APG – Foils, Strain Endurance Measurements

- k Technology Corporation (kTC) completed the 1M cycle fatigue test and thermal evaluation
- The 1M cycle conductance was found to be $.088\text{W}/^\circ\text{C}$. This nominal value is nearly the same as the beginning-of-life measurements ($.085\text{W}/^\circ\text{C}$)
- 2 x 14 inch aluminum foil (99.9999% pure) encapsulated APG foils
- .016 inch thick
- Deflection approximately 1"

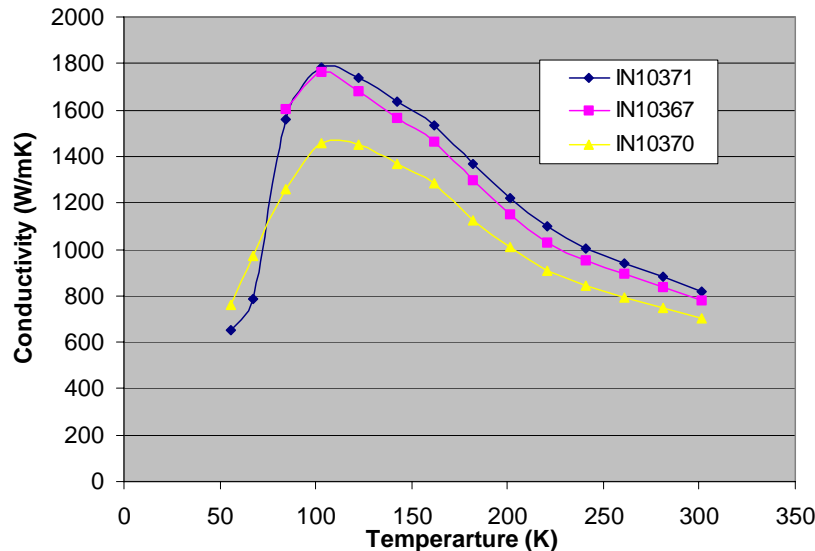


kTC Part Number IN10422

CFC Encapsulated APG

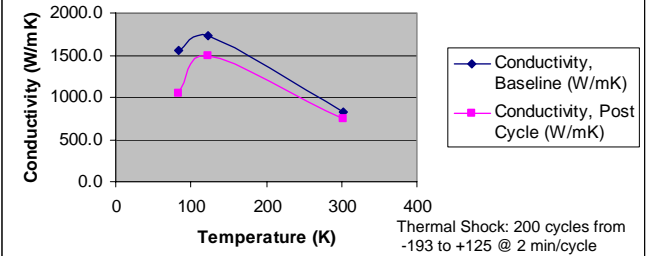
- Carbon fiber encapsulated APG evaluation coupons (K13C2U/RS-3 composite)
- APG volume fractions are 49%, 46% and 42% for the coupons IN10371, IN10367, and IN10370 respectively

Coupon Conductivity, Measured

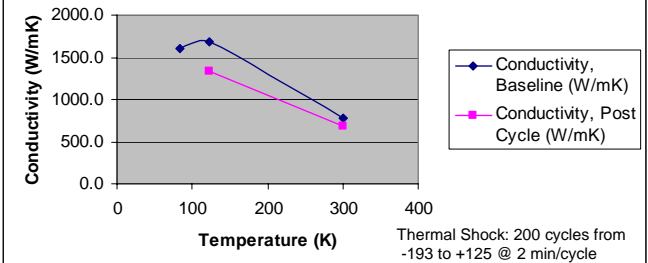


Tested Temperature (K)	301	281	261	241	221	202	182	162	142	122	103	85	67	56
IN10371-02 Conductivity (W/mK)	820	883	939	1005	1096	1222	1365	1536	1634	1735	1785	1560	788	652
IN10367-02 Conductivity (W/mK)	781	837	892	949	1028	1150	1296	1466	1567	1681	1766	1604	na	na
IN10370-02 Conductivity (W/mK)	702	749	796	847	909	1007	1127	1283	1366	1451	1455	1261	974	761

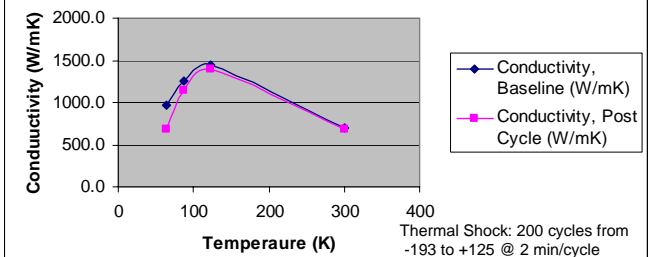
IN10371 Thermal Characterization



IN10367 Thermal Characterization

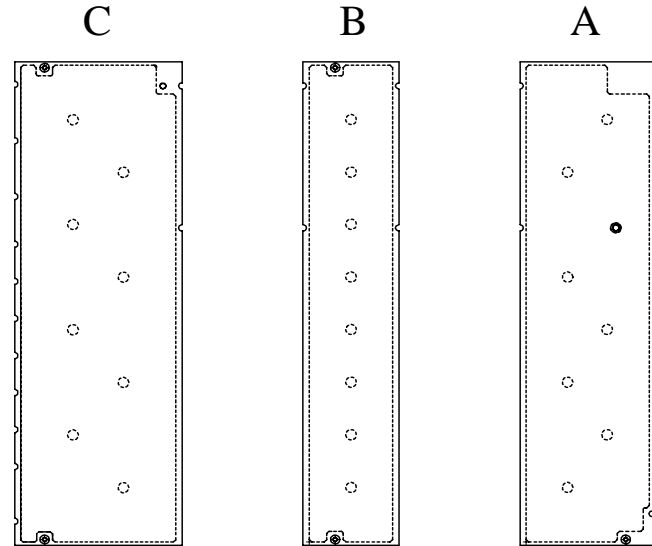
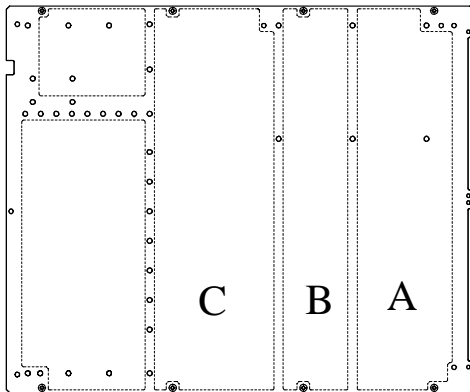


IN10370 Thermal Characterization



Aluminum Encapsulated APG – Temperature Cycling Integrity

- Flight thermal core sectioned along internal ribs producing four evaluation coupons (no exposed APG)
- Three coupons with APG insert “rail to rail”



Coupon Data

	Thickness (in)	Width (in)	T apg (in)	W apg (in)	A (in ²)	A apg (in ²)
Coupon A	0.12	3.38	0.08	3.05	0.41	0.24
Coupon B	0.12	2.28	0.08	2.07	0.27	0.17
Coupon C	0.12	4.06	0.08	3.84	0.49	0.31

k apg (W/mK) =

1637.0 TPRL Data

k aluminum (W/mK)

175.0 Supplier data

Aluminum Encapsulated APG – Temperature Cycling Integrity

Item	BOL Conductivity, Computed (W/mK)	BOL Conductivity, Measured (W/mK), MII Data	BOL Conductivity, Measured (W/mK), kTC Data	10 Cycles, Conductivity, Measured (W/mK), kTC Data*	50 Cycles, Conductivity, Measured (W/mK), kTC Data*	100 Cycles, Conductivity, Measured (W/mK), kTC Data*	250 Cycles, Conductivity, Measured (W/mK), kTC Data*	500 Cycles, Conductivity, Measured (W/mK), kTC Data*	2 Cycles, Conductivity, Measured (W/mK), kTC Data **
Copper Standard	390.0	372.0	375.0	-	-	-	-	-	-
Coupon A	1054.4	921.0	978.0	993.0	897.0	974.0	929.0	923.0	925.0
Coupon B	1057.4	790.0	981.0	982.0	1027.0	946.0	1052.0	966.0	1050.0
Coupon C	1096.2	874.0	1068.0	1087.0	1022.0	944.0	1094.0	887.0	930.0

* -55°C to 125°C thermal cycle

** -25°C to 200°C thermal cycle

Conductivity Life Characterization

