# Developments for Copper-Graphite Composite Thermal Cores for PCBs for High-Reliability RF Systems

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***Summary:*** *A copper-graphite composite was selected from different candidate materials tested to determine suitability as a direct replacement of heavy copper thermal planes within high-reliability military-aerospace multilayer PCBs intended to mount and dissipate high heat loads from RF power semiconductors, with significant improvements in CTE matching for the high heat flux components. A manufacturing development process was also undertaken to develop very thin flat panels of this copper-graphite composite, required to meet IPC 6012c and other PCB industry-standard processing and manufacturing requirements. Testing with PCB manufacturing was conducted by a major mil/aero PCB manufacturer; complex multilayer PCBs were fabricated, tested, and qualified for series production. Important target requirements for CTE value, thermal conductivity, thickness, panel size, minimized warpage, and processing were met.*

## 1. Program Development Goals

***(Program goals set by Naval Surface Weapons Center, US Navy; and Lockheed Martin, USA)***

### Goals – Thermal Core PCB Development for Thermal Management and Reliability

Goals for development programs for thermal control within PCBs:

1. Evaluate alternative materials which could replace heavy copper core layers for PCBs.
2. Develop manufacturing process to yield "drop-in-place" thermal core formats for PCB fabrication, per IPC 6012(C) and related standards:
   - Dimensional requirements (X-Y)*
   - Thickness requirements – interim and final – are critical to successful development
3. Fabricate prototype thermal core PCBs for performance testing and analysis:
   - Feature capabilities (through-holes, blinds, compatibility with PCB dielectrics)
   - Flatness
   - Metallization
   - Potential for warpage control (due to moisture absorption) in handling and storage of core materials and subsequent PCB fabrication processing.
   - Potential for actual PCB weight reduction versus current copper core PCBs.
4. Develop PCB thermal performance comparative models and test data to examine:
   - Calculated Effective Thermal Conductivity values
5. Test and evaluate electrical and thermal performance:
   - Thermal and CTE matching characteristics
   - RF performance for attached RF devices
   - Solder attach and low-ignition voltage solder alternatives (such as Nanofoil®) as joining materials and processes for high heat flux device attachment.
6. Evaluate cost:
   - Matching existing standardized PCB fabrication processes is a major cost driver.*
   - Identify potential cost reduction targets and methods to achieve this.

*Notes: *Industry requirements determined by existing PCB fabrication process equipment.*
*IPC 6012(C) ) and associated standards are published by IPC, Bannockburn IL USA. Website: www.ipc.org*

## 2. Candidate Materials Evaluated

**(Materials property testing, analysis, and selection conducted by Lockheed Martin, USA)**

| Material | Thermal Conductivity (W/mK) | CTE (ppm/°C) | |
|---|---|---|---|
| MMCC Cu-MetGraf™ 7-300 | X-Y: 285-300<br>Z: 210 | X-Y: 7.0<br>Z: 16.0 | ← Selected |
| Epoxy | ~0.5 | ~55 | |
| Graphite/Epoxy (+0.5 oz. Cu each side) | XY: 175<br>Z: ~1 | XY: 4.0 – 6.5<br>Z: ~55 | |
| OFHC Copper | 390 | 17 | |

## 3. Analysis of Selected Copper-Graphite Sheet within PCB

**(Fabrication, testing, and finished PCB analysis for balanced and unbalanced PCBs conducted by TTM Technologies, USA)**

### CTE-Matched Thermal Core PCB Development Materials: Balanced PCB Stack

Development of new manufacturing processes enabling new thermal core materials:

- This example is one of several PCBs manufactured and analyzed: 4-, 10-, 20-, 21-layer PCBs
- Example of a balanced thermal core PCB materials stack:

| | | |
|---|---|---|
| 1 | Top | 1oz |
| | 0.25mm (0.010") Core (Nelco -29) | |
| 2 | | 1oz |
| | Prepreg 3-1080 (Nelco -29) | |
| | Cu-MetGraf 7-300 copper-graphite composite layer | ← Selected Thermal Core Material |
| | Prepreg 3-1080 (Nelco -29) | |
| 3 | | 1oz |
| | 0.25mm (0.010") Core (Nelco -29) | |
| 4 | Bottom | 1oz |

- Overall PCB thickness: 2.31mm (0.091")

Note: Please see manuscript for complete set of material and processing descriptions and references.

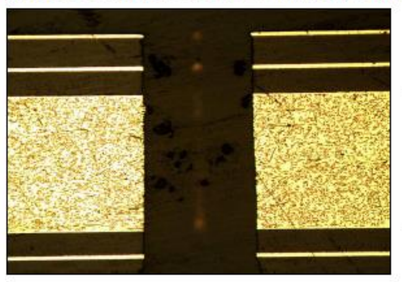
## 3. Empirical Results for PCB Fabrication with Cu-Graphite Thermal Cores

***(PCB fabrication, testing, and process analysis conducted by TTM Technologies, Inc., USA)***

### CTE-Matched Thermal Core PCB Development Materials: Balanced PCB Stack

Development of new manufacturing processes enabling new thermal core materials:

- Development PCB fabrication and analysis by TTM included drilling, plasma etch, other processes to prove out PCB industry standard production process methods.




Process step and analysis: Drill 0.90mm (0.0354") and 0.25mm (0.0098") diameter holes

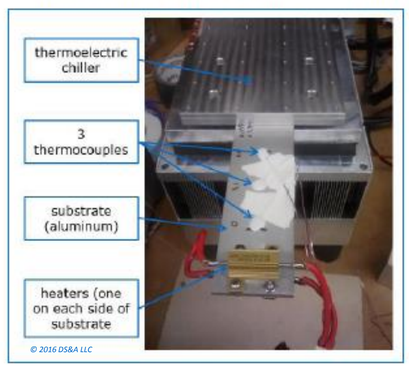
- Balanced PCB stack
- PCB development core materials must meet process requirements of MIL-P-55110 (IPC-6012).

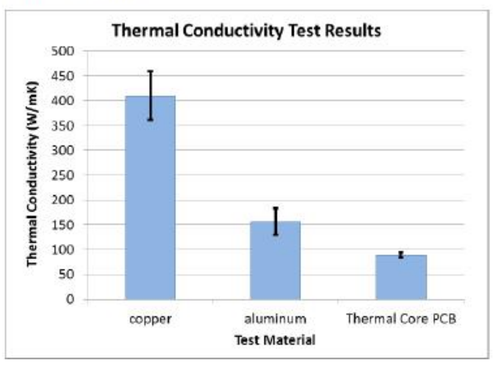
## 4. Empirical Results for PCB Effective Thermal Conductivity

***(Modeling and testing conducted by Rockwell Collins Inc., USA)***

### Empirical Data – Effective Thermal Conductivity

Thermal conductivity test fixture and sample construction:




Empirical results - effective thermal conductivity:

- Average thermal conductivity test value for fabricated thermal core PCB samples: 89 W/mK;
- Calculated effective thermal conductivity for Layer 2 (Cu-MetGraf 7-300): ~290 W/mK.

*Note: Error Bars: ± 1 standard deviation. (Inner and outer insulation for test fixture removed for photograph.)*
*Data source: R. Wilcoxon, Rockwell Collins Inc., Advanced Technology Center October 29, 2012*

## 5. Results

### Solution: Constraining Core Thermal Materials for PCBs

| Parameter or Property | Goal or Requirement © 2016 DS&A LLC | Cu-MetGraf-7 Value |
|---|---|---|
| CTE | Lower value range, appropriate for SiC, GaN<br>Packaged or bare die | 7.0 ppm/°C<br>Yes |
| Thermal Conductivity | Relatively high versus existing CTE-matched materials<br>Requirement: > 250 W/mK<br>Isotropic or near-isotropic if possible | X-Y: 287 W/mK<br>Z: 225 W/mK<br>Near-isotropic |
| Density | Reduced versus existing CTE-matched materials<br>Requirement: 30+% reduction | 6.0 g/cc |
| Young's Modulus | Relatively stiff, with reduced or no warpage in fabricated PCB | 75.8 GPa |
| Fabrication | Demonstrated compatibility, standard PCB fabrication processes<br>"Drop-in-place" replacement of heavy copper layer<br>Suitable for microdrilling, microvia processes | Yes<br>Yes<br>Yes |
| Manufactured Panel Size | Requirement: 30.5cm x 45.7cm (minimum) | Yes, demonstrated |
| Manufactured Panel Thickness | Initial requirement: 0.50mm (maximum)<br>Stretch requirement: 0.25mm | Yes, completed<br>Yes, completed |
| Manufactured Cost | Reducible with future manufacturing process cost improvement program | Yes, now underway |
| Availability | Suitable for IPC-standard PCB fabrication facilities globally<br>Not subject to legislative restrictions | Yes<br>Yes |

| Parameter or Property | Molybdenum[1] | Cu-Mo-Cu[1] | 25Cu/50Mo/25Cu[2] | 20Cu/60 Invar/20Cu[2] | Cu-Graphite (Cu-MetGraf 7-300) | Cu[1] |
|---|---|---|---|---|---|---|
| CTE (ppm/°C) | 5.0 | 6 | 7.9 | X-Y: 6.0<br>Z: 7.7 | 7.0 | 17 |
| Thermal Conductivity (W/mK) | X: 140<br>Y: 142 | 170-182 | X-Y: 268<br>Z: N/A | X-Y: 164<br>Z: 22 | X-Y: 287<br>Z: 225 | 385 |
| Density (g/cc) | 10.2 | 9.9 - 10.0 | 9.6 | 8.5 | 6.1 | 8.9 |
| Young's Modulus (GPa) | 330 | 280 | 220 | 135 | 75.84 | 120-130 |