



Advanced Thermal Packaging Technologies for RF Hybrids

BGP2

June 23, 2010

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In Participation with: Louise Veilleux DESDynI Instrument Eng.



Advanced Thermal Packaging Technologies for RF Hybrids

PI: James Hoffman, JPL

Objective

- Develop improved RF hybrid fabrication techniques using new materials—and proven materials in new ways—to increase hybrid's RF power-density capacity while improving reliability over thermal cycling by improving thermal conductivity at all levels of hybrid fabrication.
- Combine the thermally advanced RF hybrid with a chassis designed with Phase Change Material (PCM) used as a thermal capacitor, reducing internal temperature swings to improve reliability over thermal cycling.
- Demonstrate that these improved RF hybrids enable more compact and cost-effective electronically steered feeds for spaceborne radars such as those in DESDynI Mission.

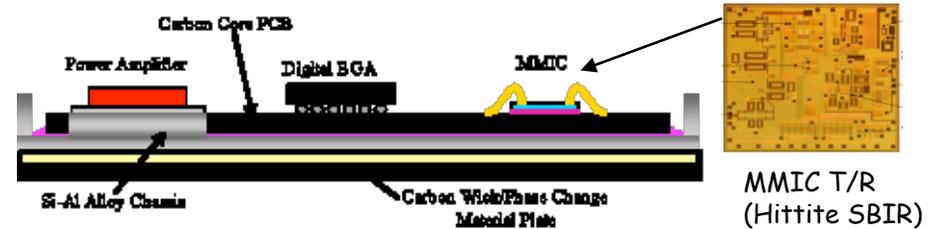
Approach

Build prototype RF hybrid Transmit/Receive (T/R) module and the demonstration model of the antenna feed tile to show improved power handling and reliability by:

- using new materials and techniques to improve thermal transfer at all levels of module fabrication,
- building prototype (~150W) hybrid T/R modules with new technique and materials, using an existing low-power Monolithic Microwave Integrated Circuit (MMIC) based T/R — using a PCM as thermal capacitor,
- incorporating T/Rs into antenna array feed demonstration model to show reliability and power handling of the new RF hybrid module.

Co-Is/Partners:

Linda DelCastillo, Gaj Birur, Jennifer Miller, JPL



RF hybrid with the new thermal materials, to be built using the existing MMIC T/R (photograph shown) from a recently completed SBIR, and commercially available Power Amplifier and digital control in a ball grid array (BGA) package.

Key Milestones

- | | |
|---|-------|
| • Complete thermal model of hybrid T/R | 12/09 |
| • Complete RF testing of materials | 02/10 |
| • Complete thermal model of array tile | 08/10 |
| • Complete RF hybrid T/R fabrication | 12/10 |
| • Complete T/R stand-alone thermal verification | 05/11 |
| • Complete Multiple T/R array feed demonstration model's thermal verification | 09/11 |

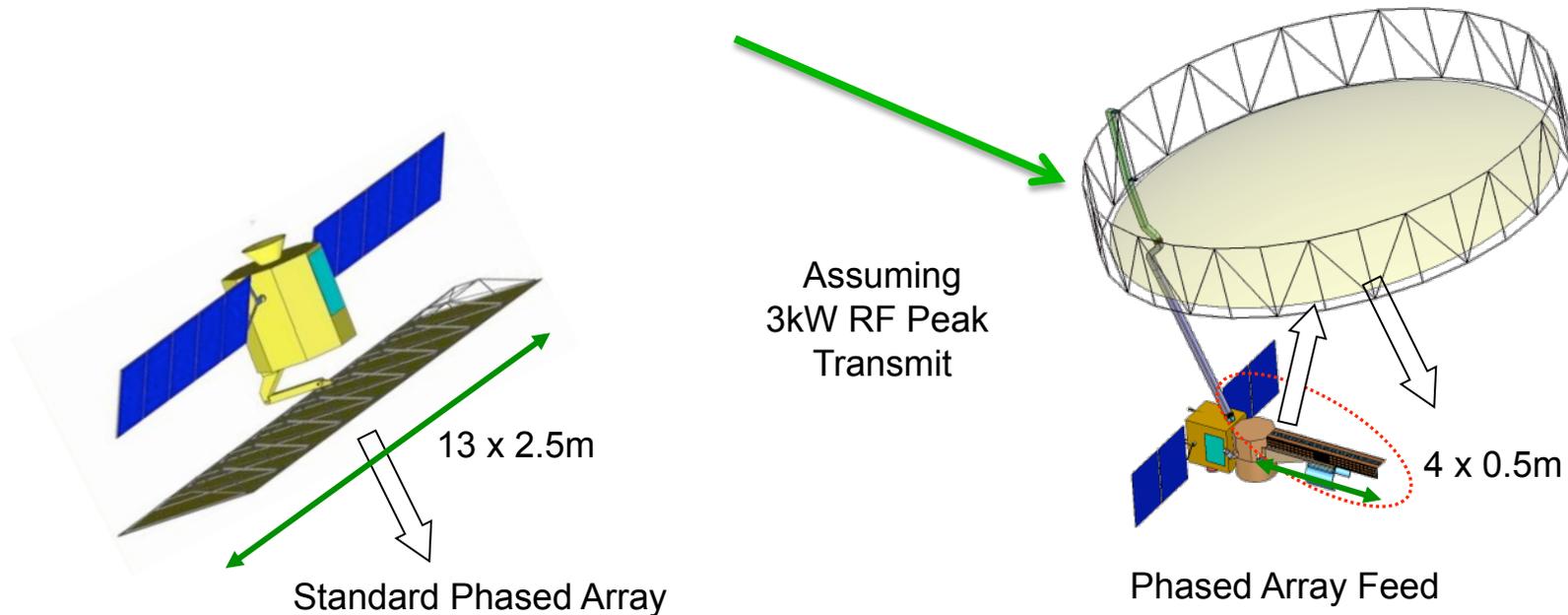
TRL_{in} = 3 TRL_{current} = 3



High Power Density Phased Arrays

Integrate thermal management into RF Hybrid Packaging Designs to:

- Improve reliability
- Increase RF power density
- Improve component stability
- Enable new instrument architecture



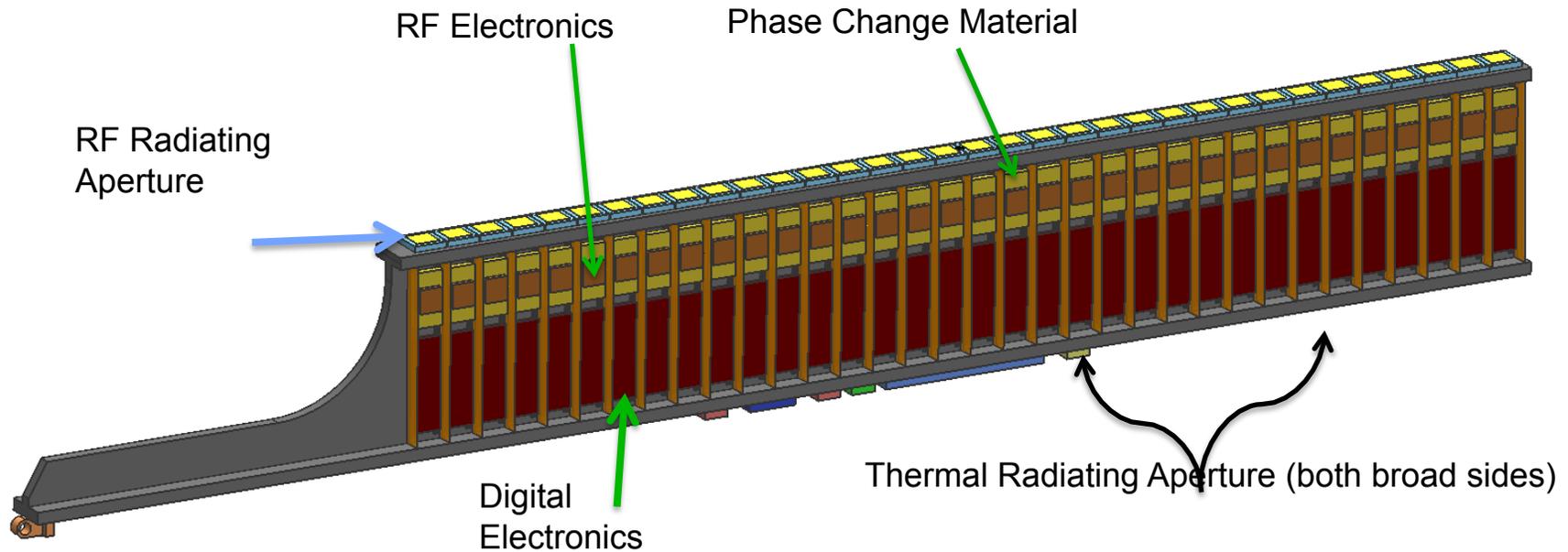
- Lower RF Power Density (92 W/m^2)
- Larger Radiator Area (32.5 m^2)
- Higher Thermal Inertia

- Higher RF Power Density (1500 W/m^2)
- Smaller Radiator Area (2 m^2)
- Lower Thermal Inertia



Flight Concept Array Feed

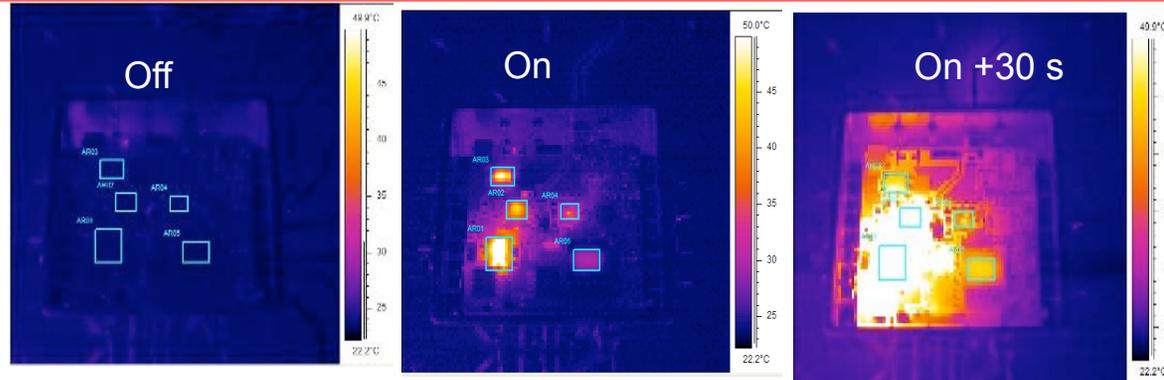
DESDynI (*Deformation of Earth's Surface Dynamics of Ice*) Array Feed



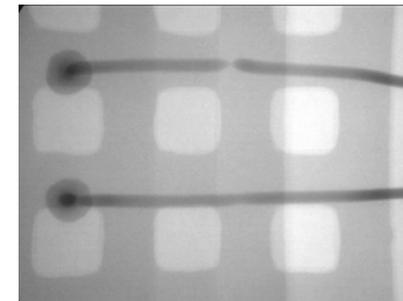
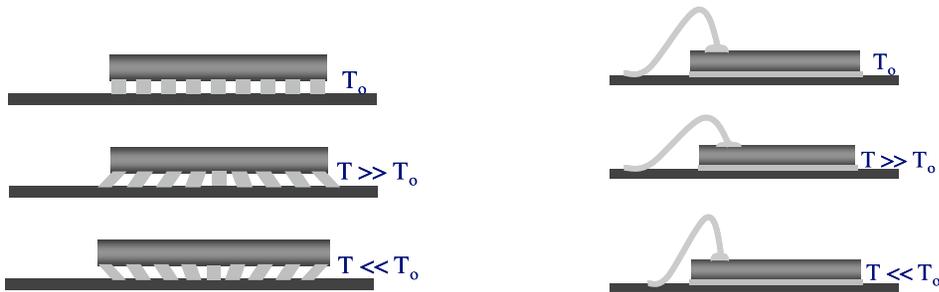
- Power cycling of Radar Array, due to limited areas of interest, will have reduce power from an operating level of ~900W (average) to ~150W (average) idle
- Estimates show 5-10 minutes operating, with 2-6 minutes idle—several times per orbit, equaling hundreds of thousands of thermal cycles—with $\Delta T > 40$ degrees C
- This technology can reduce the ΔT to less than 4 degrees C, reducing the number of effective cycles, improving reliability
- Also allows for increased density of electronics, regardless of cycling



Thermal Reliability



- Series of three thermal images of a 2W 1.5x2 inch L-band T/R module
- Hot RF part impacts all parts nearby—ceasing operation & reducing reliability
- RF parts often can handle these temps, support electronics and bonds cannot



X-ray image of hybrid assembly that failed due to thermal cycle related fatigue.

Schematic illustrating the influence of temperature on assemblies composed of materials with differing CTEs.

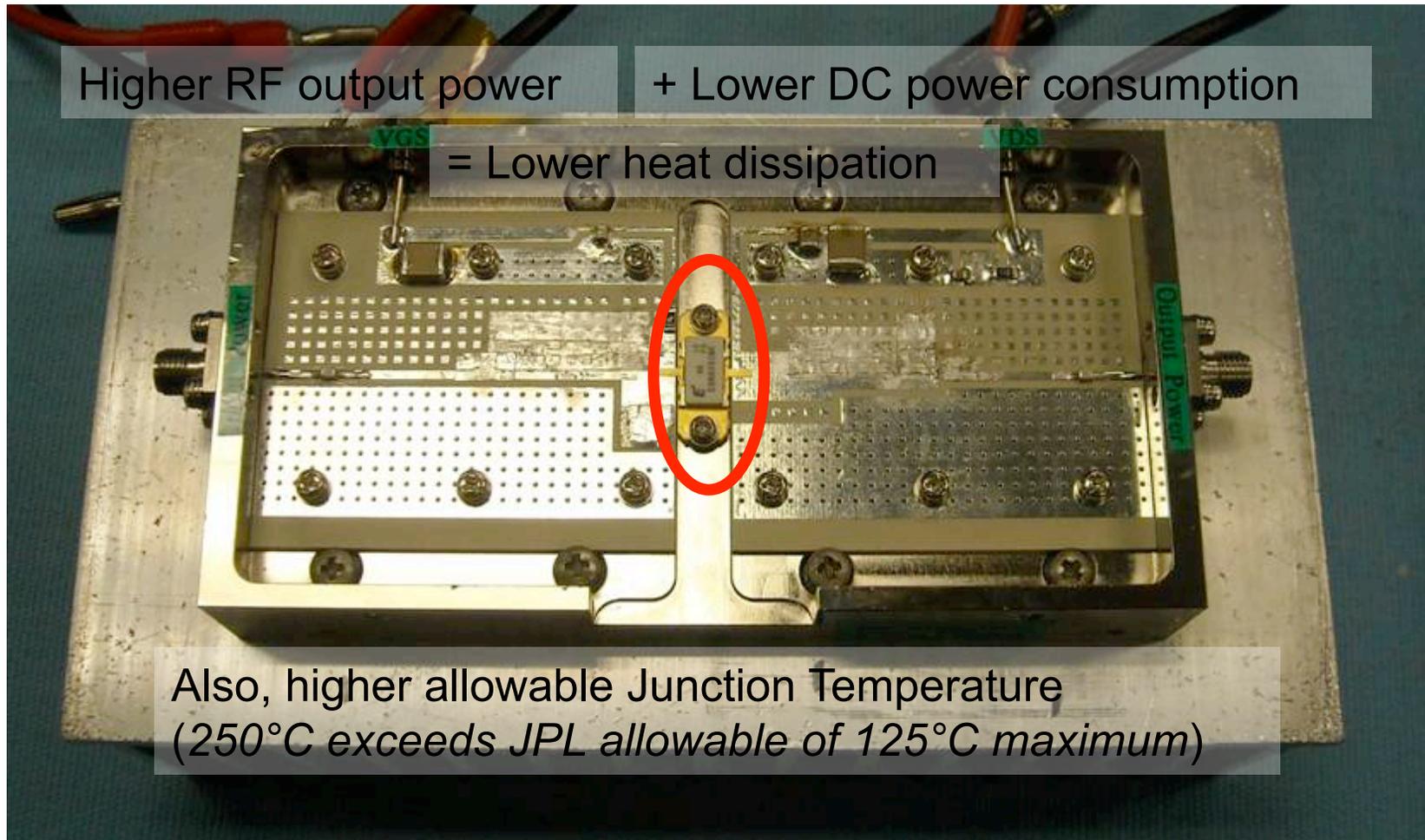


Approach

- Investigation and integration of several technologies to:
 - Reduce heat generated
 - New, more efficient device technologies
 - Gallium Nitride power amplifier/driver
 - Point of load regulators for RF
 - Reduce impact of heating
 - Reduce CTE (coefficient of thermal expansion) mismatch between materials
 - Silicon Aluminum, Aluminum Silicon Carbide for die attach
 - Reduce thermal resistance of interfaces (get the heat out faster)
 - Increase heat capacity
 - Build PCM (phase change material) into the module's chassis



GaN Power Amplifier: Reduced Heating

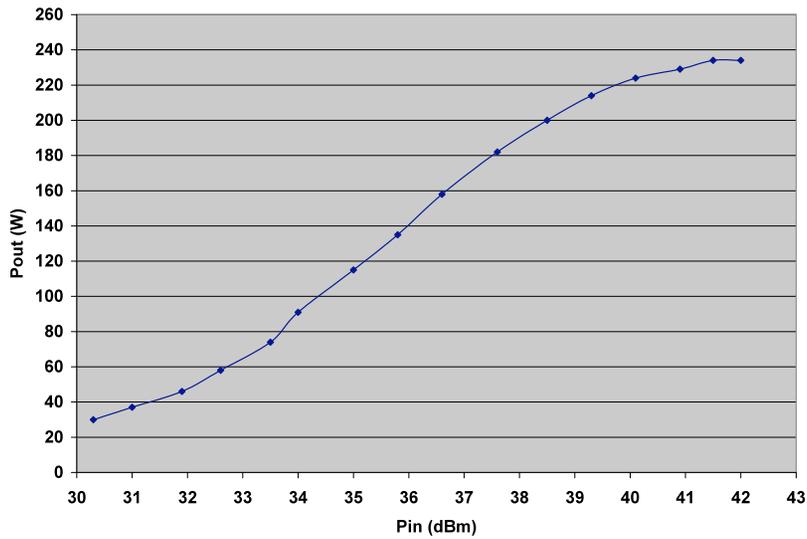


Eudyna GaN HEMPT Device for L-band Power Amplifier

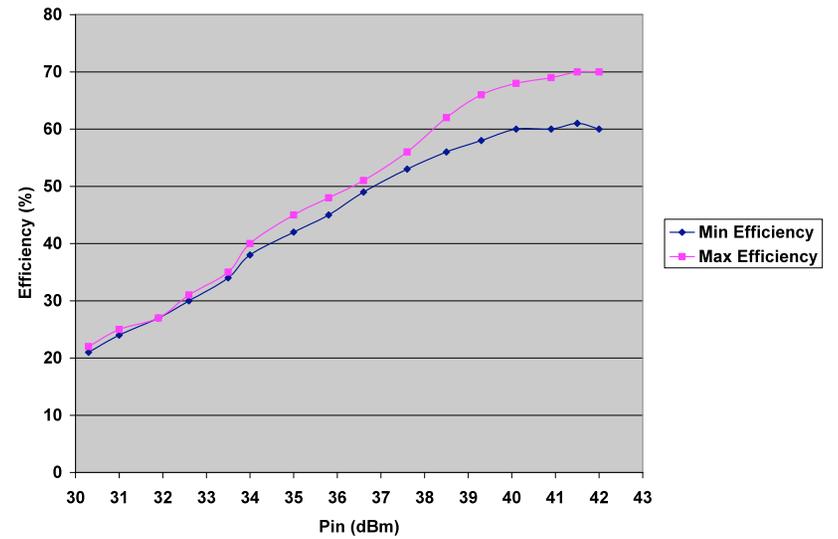


GaN Amplifier Tests

Pout & Efficiency vs. Pin at 1.2 GHz PW=78usec PRF=1260 Hz



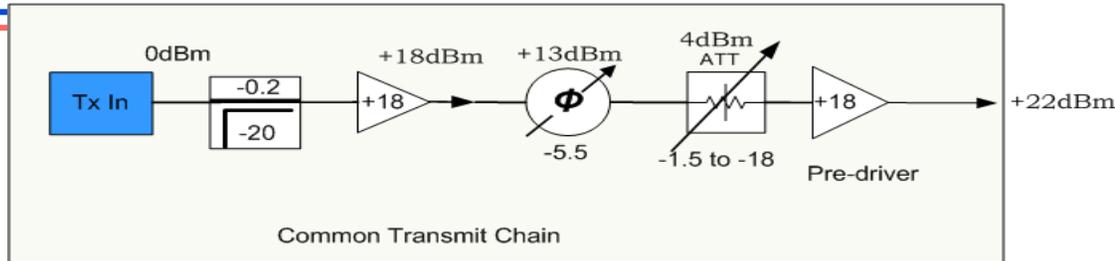
Output Power



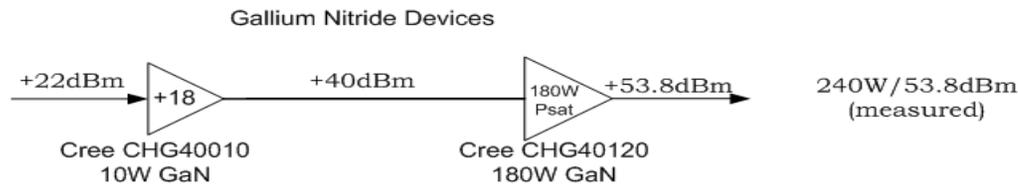
Max & Min Efficiency



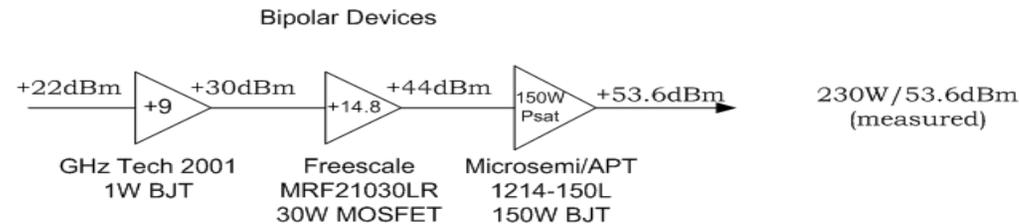
GaN Amplifier Chain versus Standard Bipolar



Common linear Transmit chain and common Receive (not shown)



Higher gain of GaN requires less amplifier stages, and can be operated in CW. This greatly simplifies stability tests and tuning.



Bipolar has much lower gain, and requires additional stage(s). The saturated output power is slightly lower, but not much.

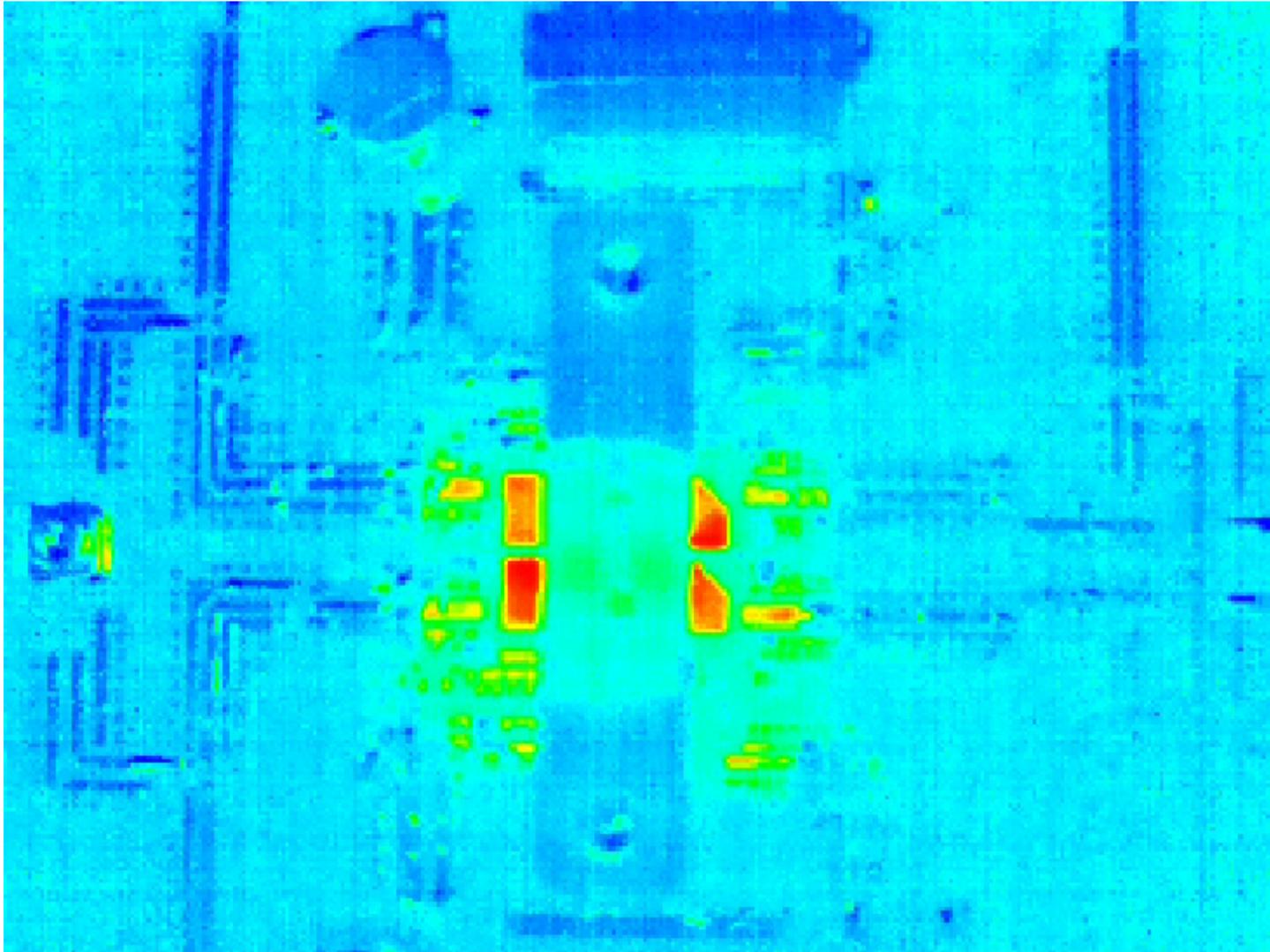
	Pout	Common DC	Peak DC	Avg DC	48 Modules
	[W]	[W]	[W]	[W]	[W]
GaN	240	8.55	405	46.7	2241.6
Bipolar	230	8.55	563	62	2976
GaN Improvement	10	0	-158	-15.3	-734.4

Note: Both (GaN and bipolar) were measured in laboratory in fully saturated mode.



180W GaN Power Amplifier (1260MHz)

~65% efficiency, 78usec PW, 1200 Hz PRF, 240W out





New Chassis Material: Improved CTE Matching

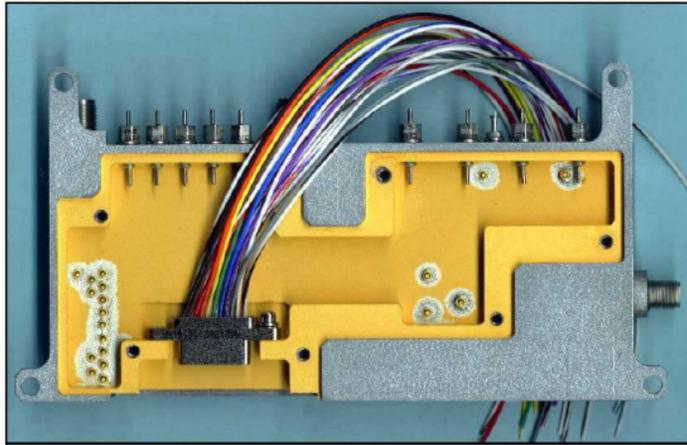
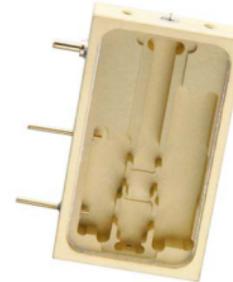


Fig. 1. Fully manufactured base of a CE11 package (courtesy of Pacific Aerospace and Electronics, an Sandvik Materials Technology Raytheon Space and Airborne Systems)

Hermetic Ka Band Amplifier Housings Tyco Space – (ESA Herschel/Plank) satellite



	Kovar®	Osprey CE11 50% Al - Si
Density g/cc	8.42	2.5
CTE - ppm/deg C	5.9	11
Thermal Conductivity W/mK	17	140

 SANDVIK



Microelectronic Circuit Housing Artis 4 satellite - L- and S-band Solid State Power Amplifier



	Kovar®	Osprey CE9 60% Al - Si
Density g/cc	8.42	2.5
Thermal Conductivity W/mK	5.9	130
CTE ppm/deg C	5.9	9

Attempts to qualify AlSiC equivalents have been unsuccessful

Sandvik Materials Technology

 SANDVIK

Defense/Aerospace Hermetic Packages Raytheon Space and Airborne Systems



	Al6061	Titanium CP-1	Osprey CE11 50% Al - Si
Density g/cc	2.86	4.51	2.5
CTE - ppm/deg C 25 - 100 deg C	24	8.9	11
Thermal Conductivity W/mK	167	17	150

Sandvik Materials Technology

 SANDVIK

11 • Courtesy of Sandvik, with technologies from Pacific Aerospace, Tyco Space, EADS Astrium, and Raytheon



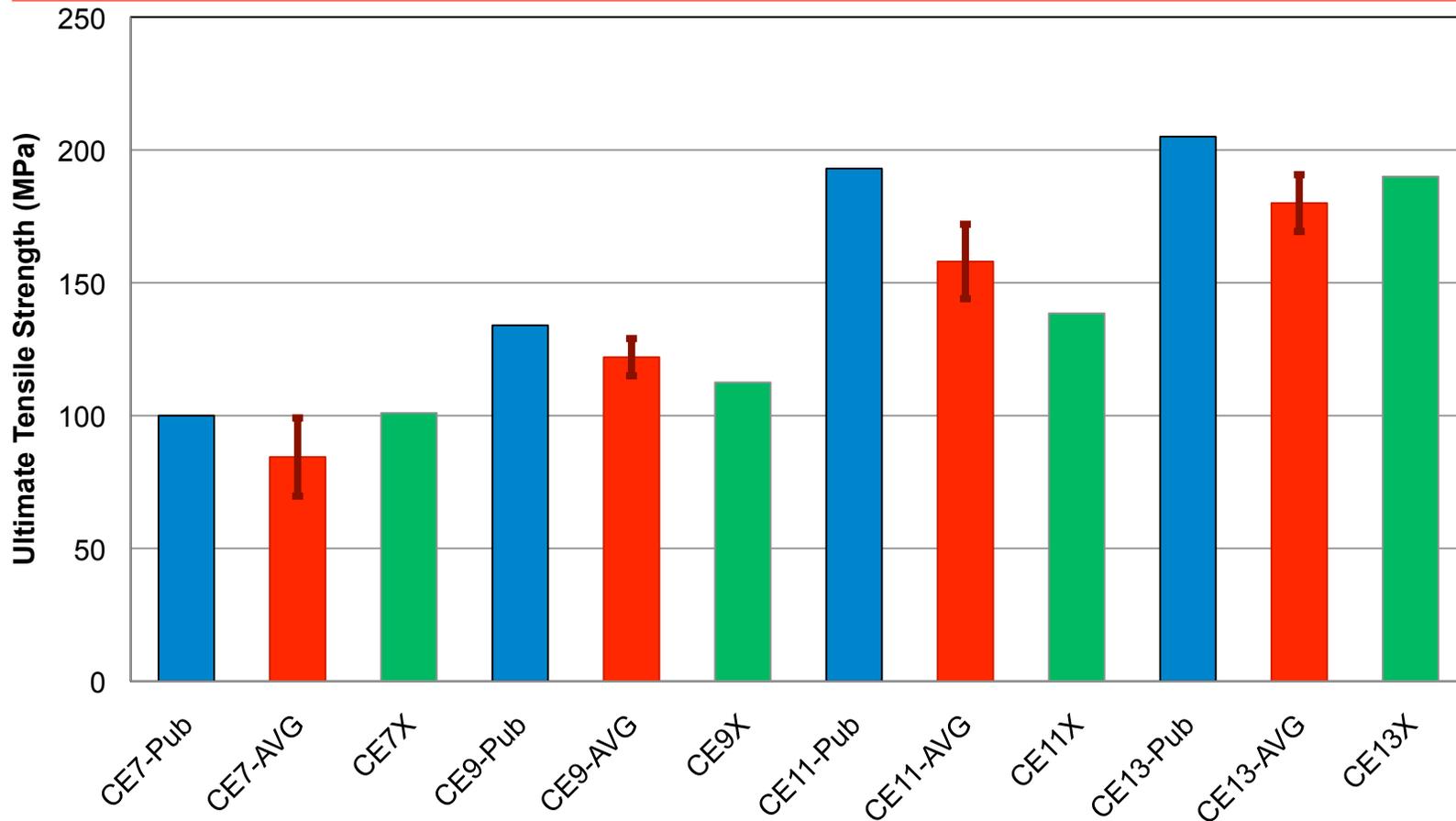
Materials Selection-Housing

Material	CTE (x-y) (ppm/°C)	Thermal Cond. (W/m-K)	Density (g/cm ³)	Elastic Modulus (GPa)
Si	2.5	124	2.3	
GaAs	5.4	50	5.3	
Rogers 4003	11-14	0.64	1.78	
Rogers 6002	16	0.60	2.1	
Stablcor ST10 387	4-6.5	200	1.58	
Cu	16.4	398	8.93	
Kovar	5.9	17.3	8.36	138
6061 Al-T6	23.6	167	2.7	70-80
CE7 (70Si/30Al)	7.2	120	2.42	129
CE9 (60Si/40Al)	9.1	129	2.46	123.5
CE11 (50Si/50Al)	11.4	149	2.51	121
CE13 (42Si/58Al)	12.8	160	2.6	102

- The role of the housing material is to protect the inside electronics from the external environment, while providing a means of signal transmission.
- 6061 Al and Kovar are currently the most utilized housing materials for space based applications. Kovar is used due to its low coefficient of thermal expansion (CTE), which is close to that of GaAs, and 6061 Al is used due to its low density and high thermal conductivity. CuMoCu tabs are often utilized between the die and the housing to compensate for the CTE mismatch.
- The CE alloys evaluated within this project combine low CTEs with low density and relatively high thermal conductivity. The use of CTE matched materials will eliminate the need for the additional interface and potential site for failure.



Tensile Behavior



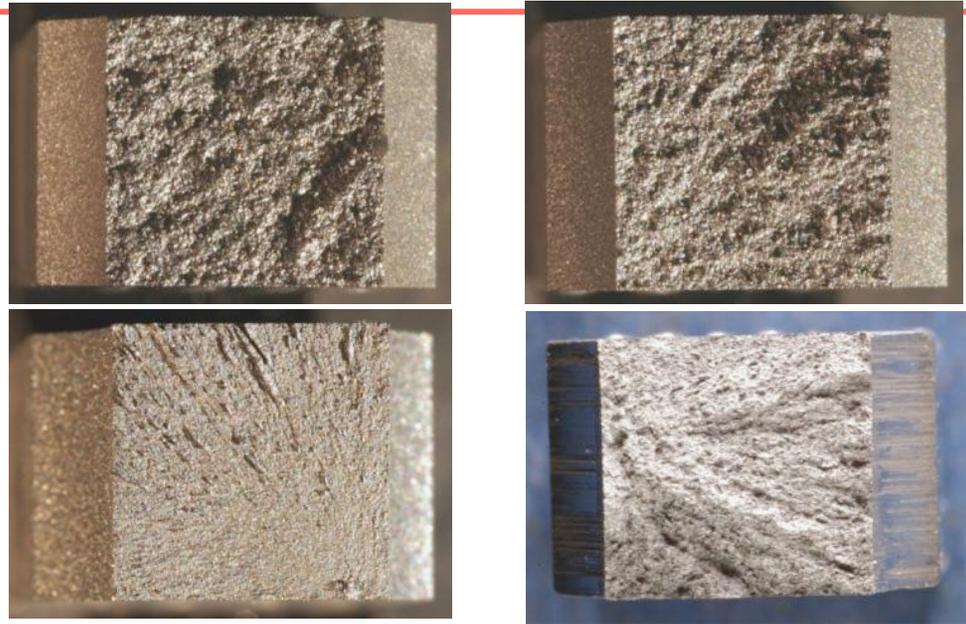
- The above plot summarizes published and measured values for the Ultimate Tensile Strength of CE7, CE9, CE11 and CE13.
- For each of the materials, measured values were lower than those published by the company.



Tensile Behavior



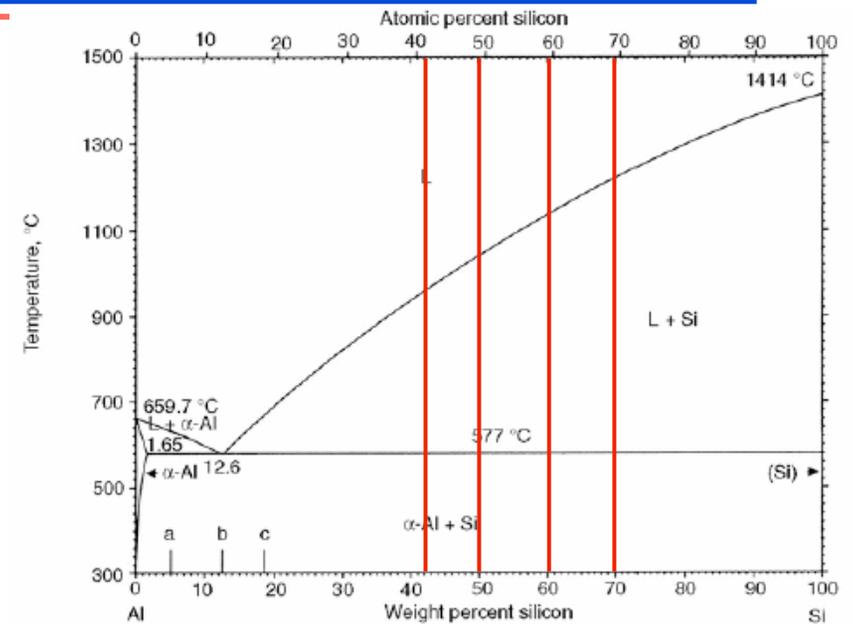
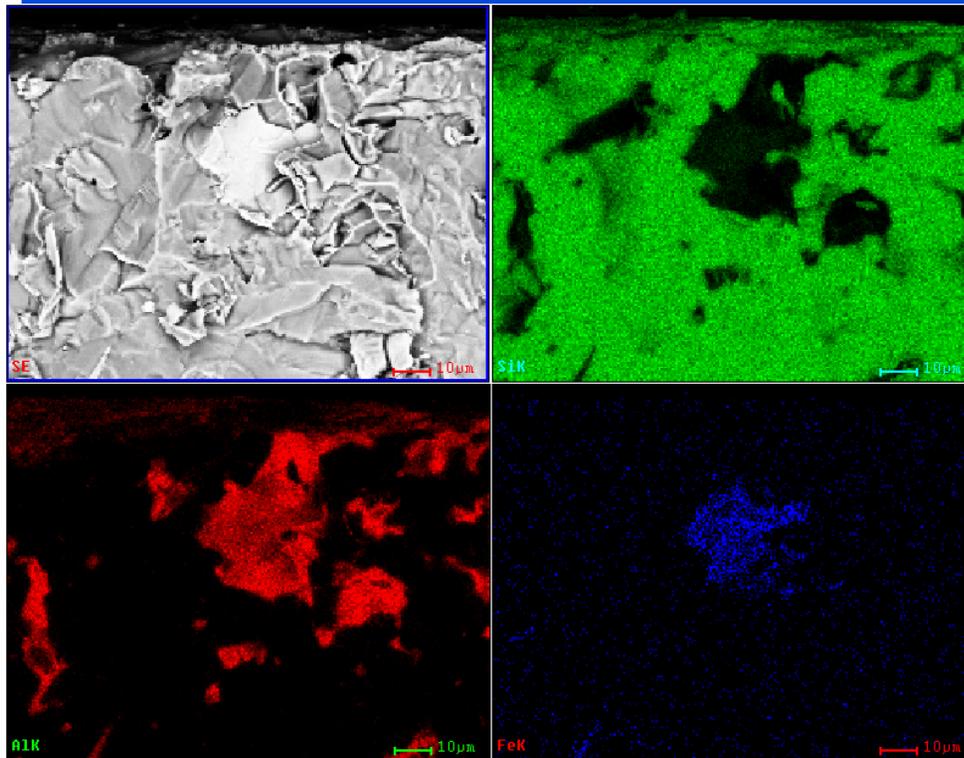
Examples of samples that failed within the grips or at the machined radius.



- Due to their high Si content, each of the CE alloys exhibited the characteristics of a brittle material.
- The materials are highly sensitive to flaws in machining and compression against sharp objects.
- This characteristic was clear due to the number of samples that failed within the grips (test fixtures) and at the machined radius of the test coupons.
- Following a discussion of results with the manufacturer, it was determined that the use of bending tests (traditionally for ceramics) may be a better way of obtaining valid test results for comparison at various temperatures.
- Bend test samples are currently being fabricated and the test facility has been identified.



SEM Fractography



- The presence of continuous Si , with small islands of the Al-rich phase, is clear from the phase diagram and the fracture surface composition map.



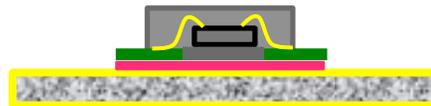
Packaging Configuration



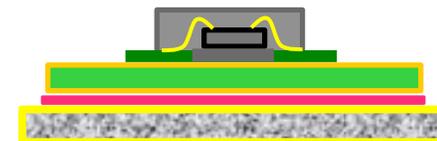
Phase IA



Phase IB



Phase II

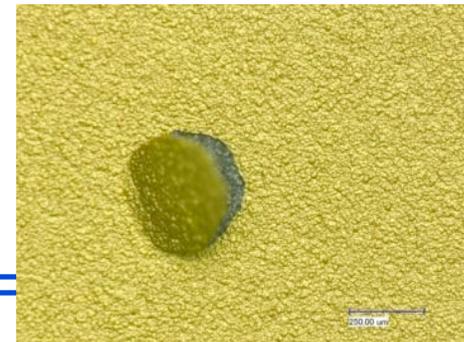
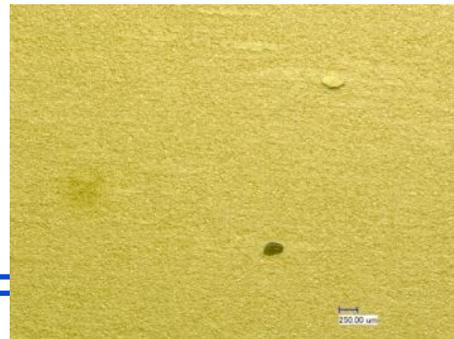
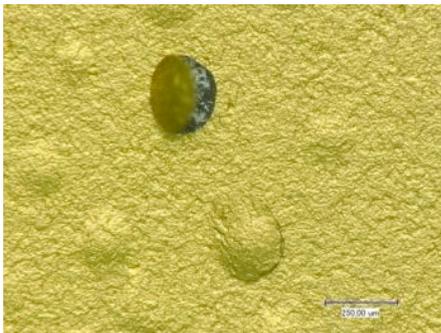
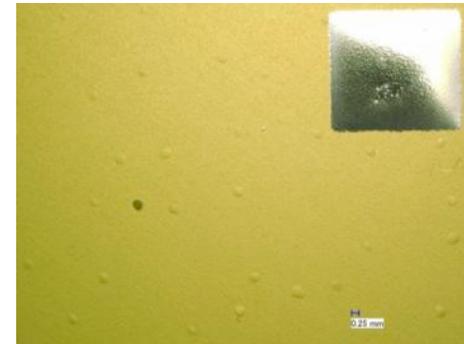
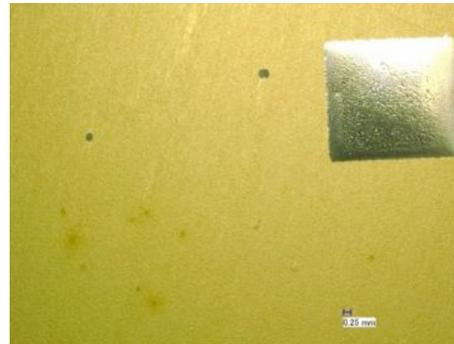


- The direct attachment of bare die to the housing is being evaluated first due to the delicate nature of bare devices and the significant influence of substrate expansion characteristics on device failure.
- In addition, the evaluation of packaged devices attached to the substrate is underway.
- The attachment of substrates/printed circuit boards will be evaluated once the test boards arrive.



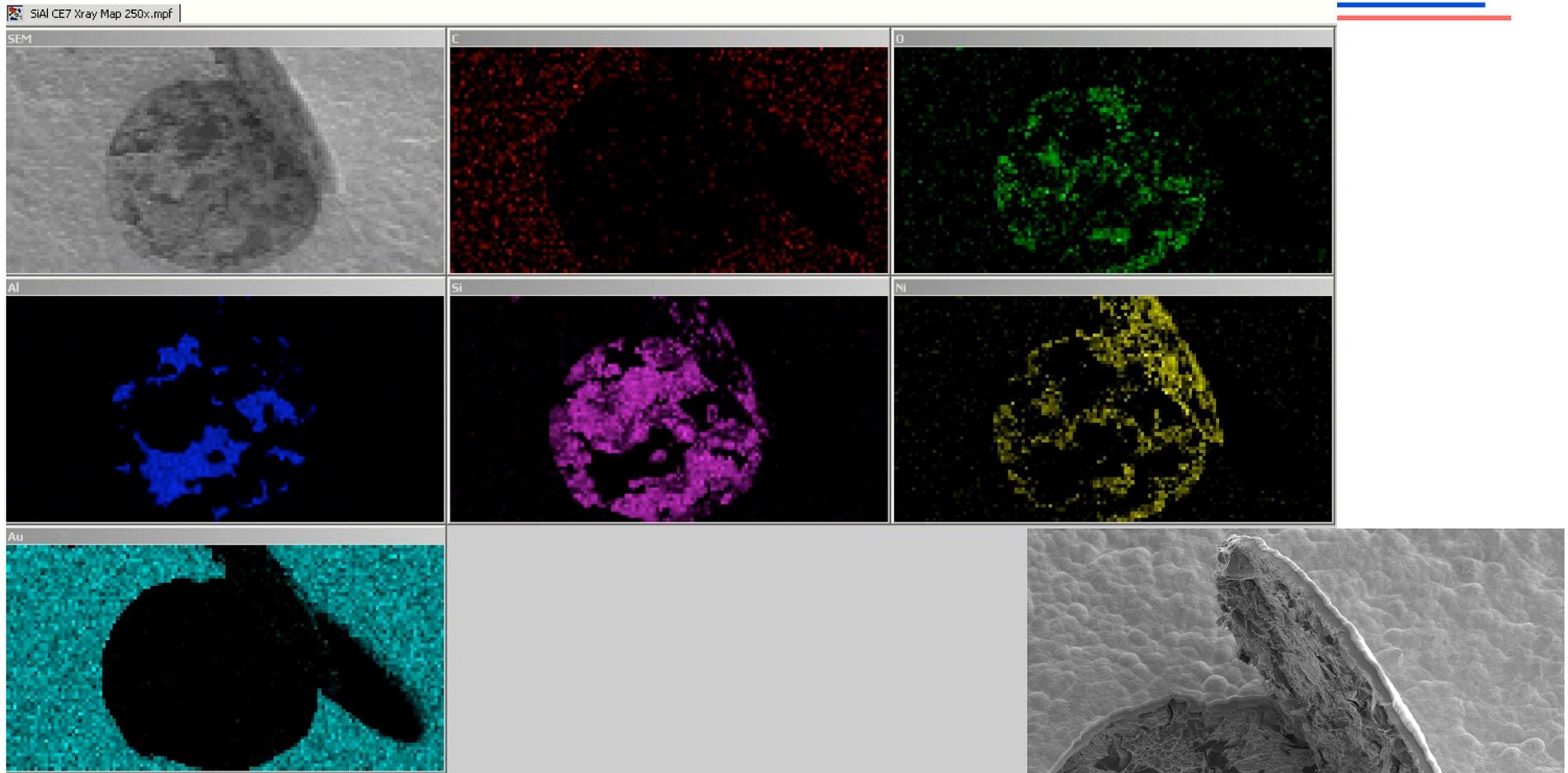
AuSn Die Attach

- CE Alloys with AuSn die attach and GaAs die.
 - For the first set of materials evaluated, Ni-Au plating blisters following exposure to 80Au20Sn reflow temperature (<math><280^{\circ}\text{C}</math>).
 - Blistering may reduce the reliability of the die attach connection.





Die Attach – Initial Results

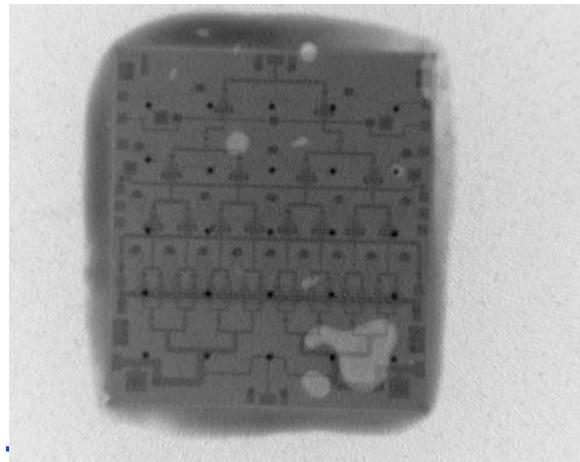
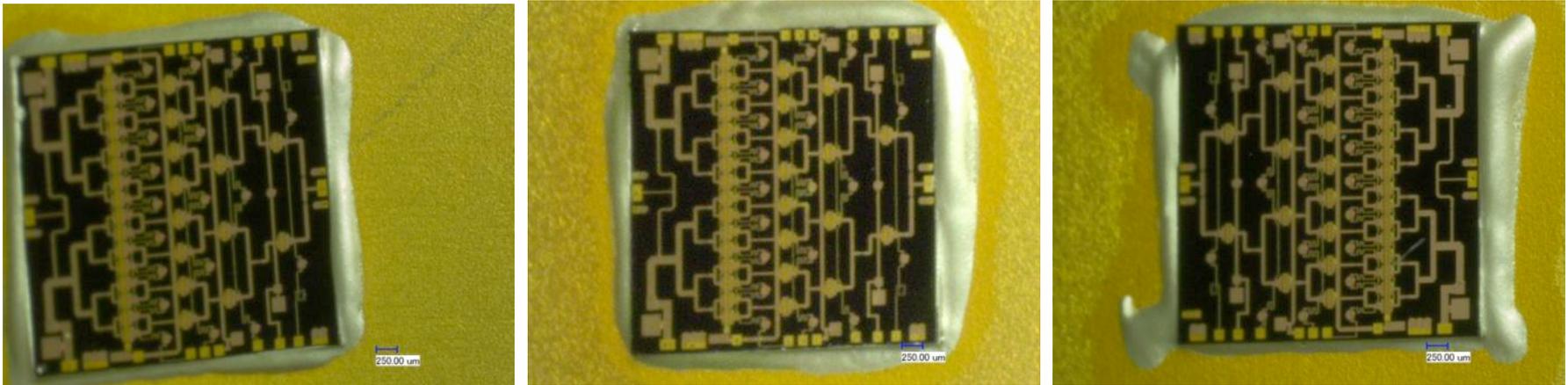


- Detailed investigation of plating blisters revealed that separation occurred within the Ni layer.
- No blistering was observed for the conductive epoxy attachment, which was processed at 150°C.

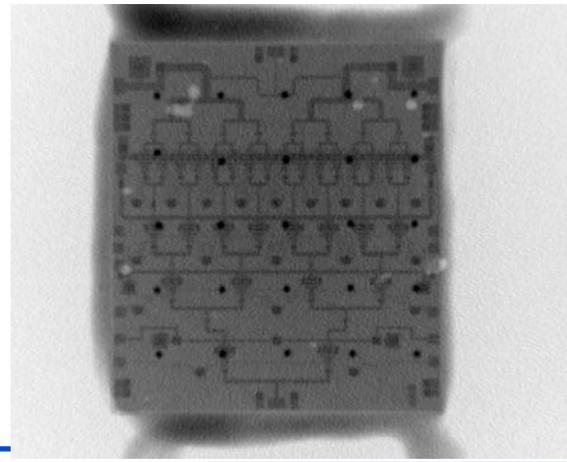


Die Attach-Conductive Epoxy

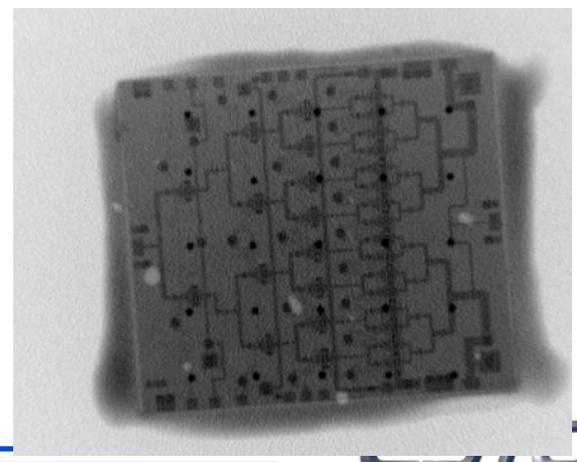
- X-ray analysis of conductive epoxy assemblies revealed minimal porosity within the epoxy die attach.
- Assemblies were exposed to 100 temperature cycles (-55 to +125°C) with no signs of degradation.



CE7



CE9



CE11 Earth Science Technology Office

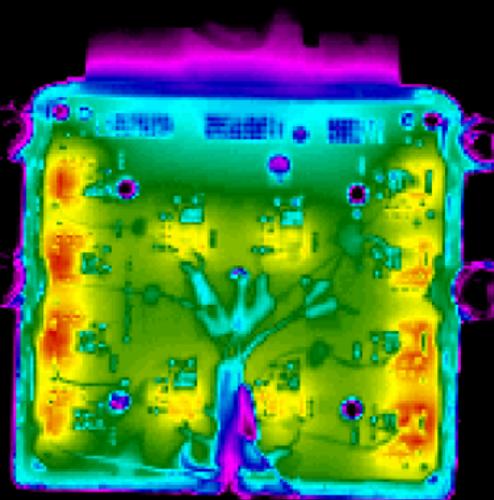


New PC Board Materials: Local Heat Dissipation

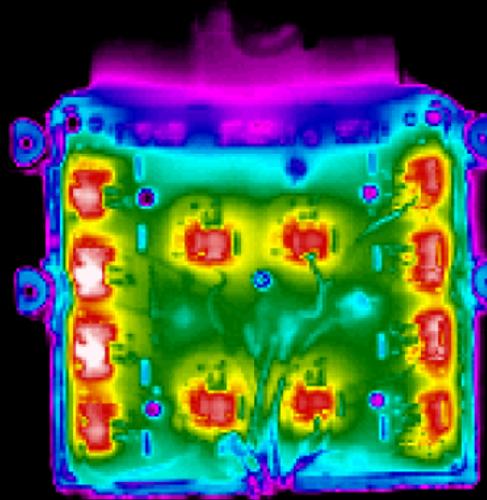


CASE STUDY – Thermal at 40W, ST325

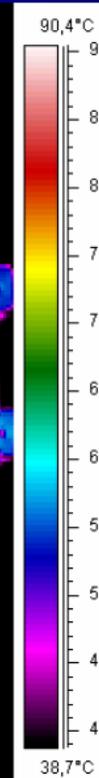
NATURAL CONVECTION
40Watt



STABLCOR®
ST325+FR4



FR4 PCB



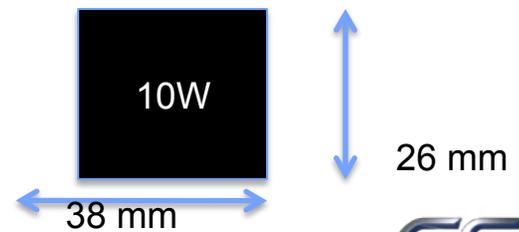
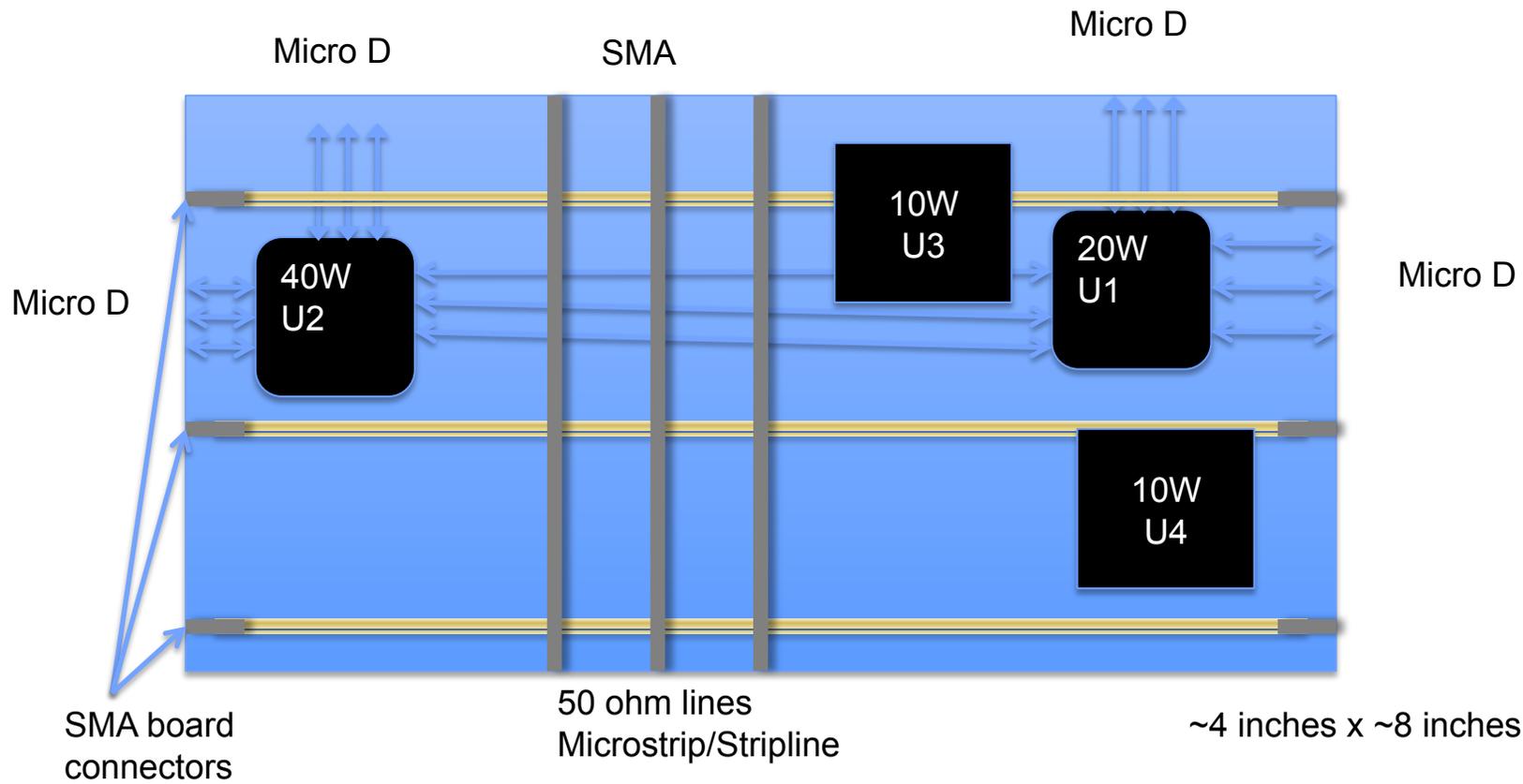
Customer Quote:

With the STABLCOR we can say that hot spots are practically eliminated

ST325 represented a 15% to 20% temperature reduction compared to FR4

40Watt, Natural Convection, STABLCOR PCB running 16.4°C Cooler

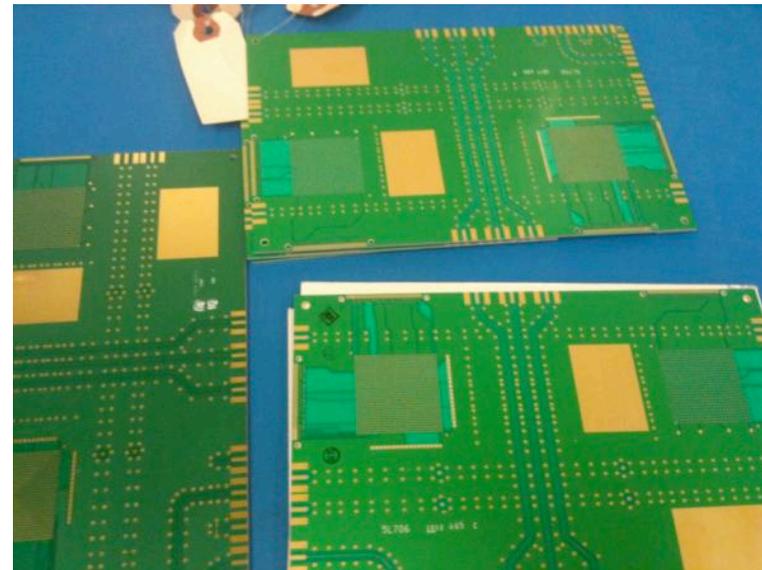
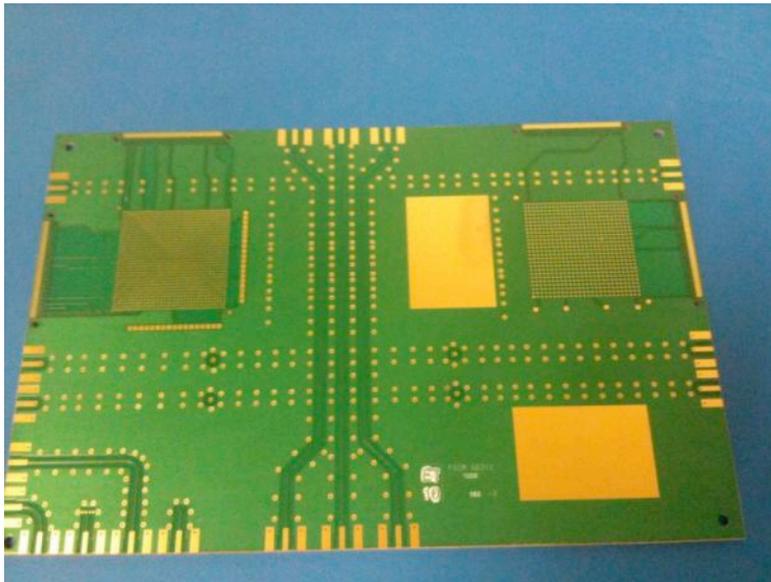
Courtesy: CONTINENTAL Automotive France SAS, Mr. Loic Bertrand





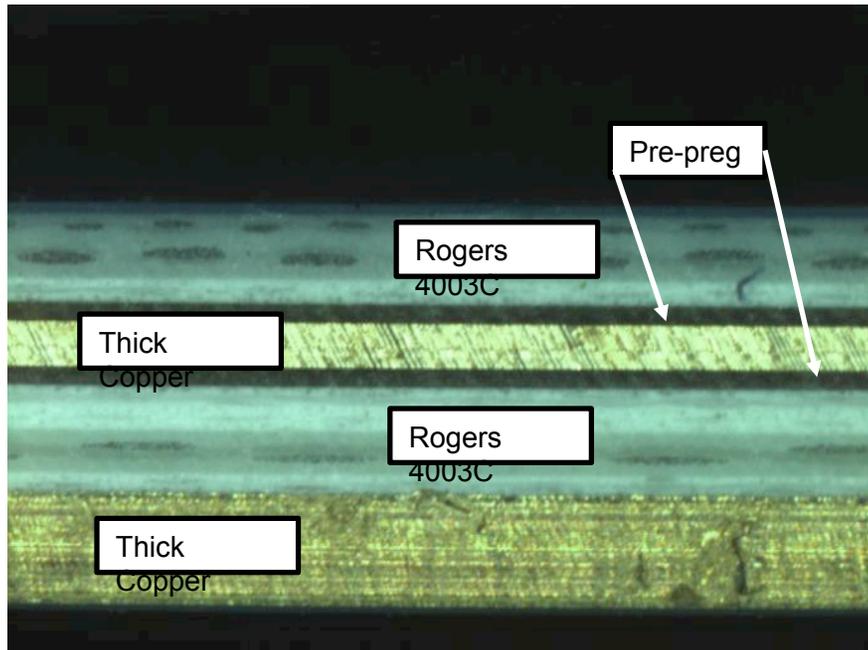
PCB Fabrication and Testing

- Per the earlier discussion on the PCB delays, this task is behind, but all materials have now arrived in the last two weeks (early April 2010)
- Assembly is underway
- Below are photos of the overall board, along with side by side of the three different boards (Rogers 6002, Rogers 4003, and 4003 with Stablcor)

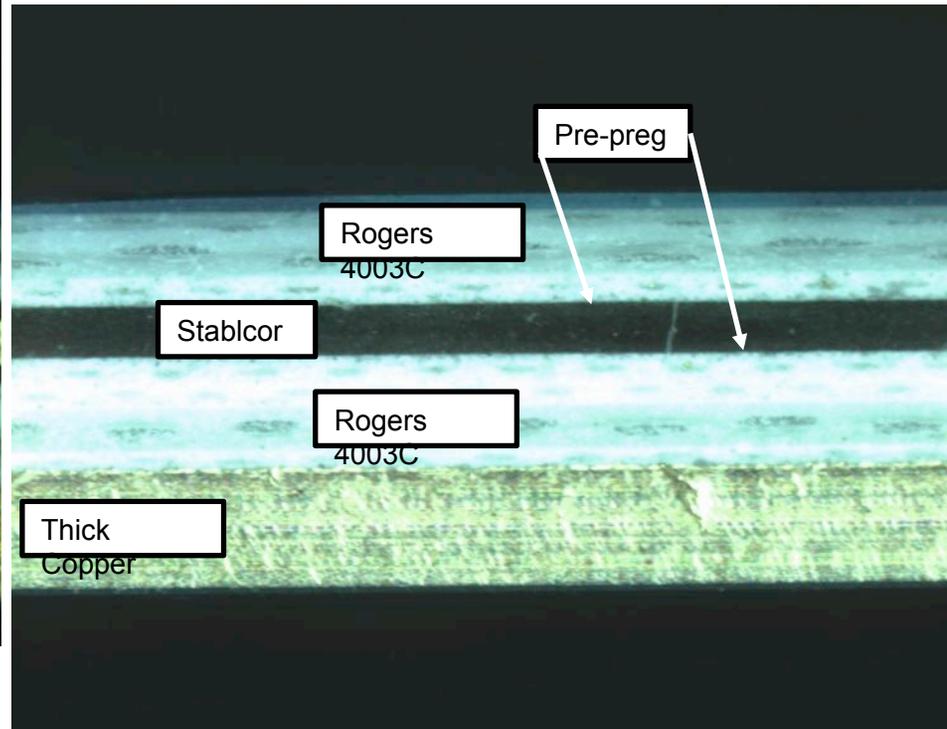




PCB Microphotograph Cross-sections



Standard best practice:
Rogers 4003C RF PCB material with thick-clad bottom and embedded thick copper heat spreader in center. The embedded copper is sandwiched between layers of prepreg (the glue), which appears black.



Stablcor:
Rogers 4003C RF PCB material with thick-clad bottom and embedded Stablcor heat spreader in center. The Stablcor and prepreg layer (the glue) are both black and in the center.



Lot Yield Information

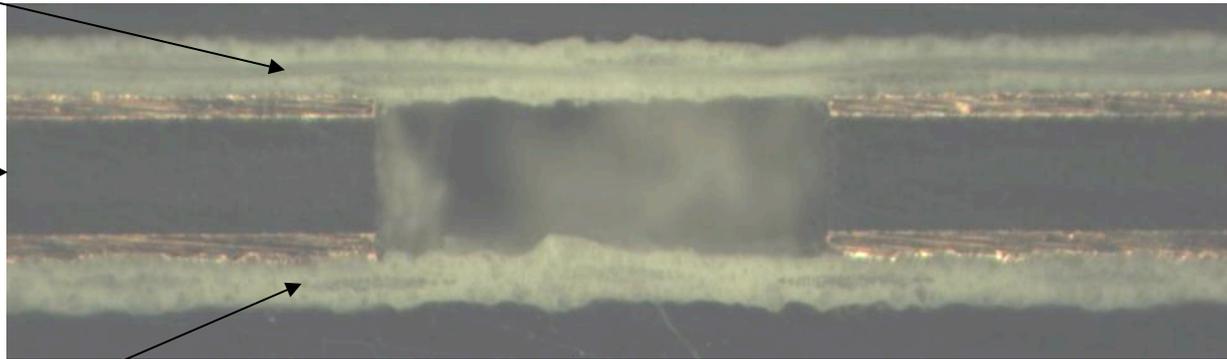
- Started 3 panels(9 pcs) on each build. 1 panel(3 pcs) was used as a test vehicle to try laminating the .008” core with only the RO4450F prepreg.
- Glass reinforced hydrocarbon/ceramic laminates
 - 1A –Stablcor Version
 - Yielded 2 pcs out of 6
 - 3 pcs scrap for lifted/damaged traces(see photo)
 - 1 pc scrap for reduced trace(see photo)
 - 2A – Copper Core Version
 - Yielded 5 pcs out of 6
 - 1 pc scrap for reduced trace(see photo)
- 3—Fusion Bonded Durioid
 - Yielded 4 out of 6 (actually 1/3 and then 3/3 once process vetted)
- Note: noticed some delam on some sections between the polyimide prepreg and the rogers 4450 prepreg



RO4450F no prelam test

RO4450F

.008" Stablcor

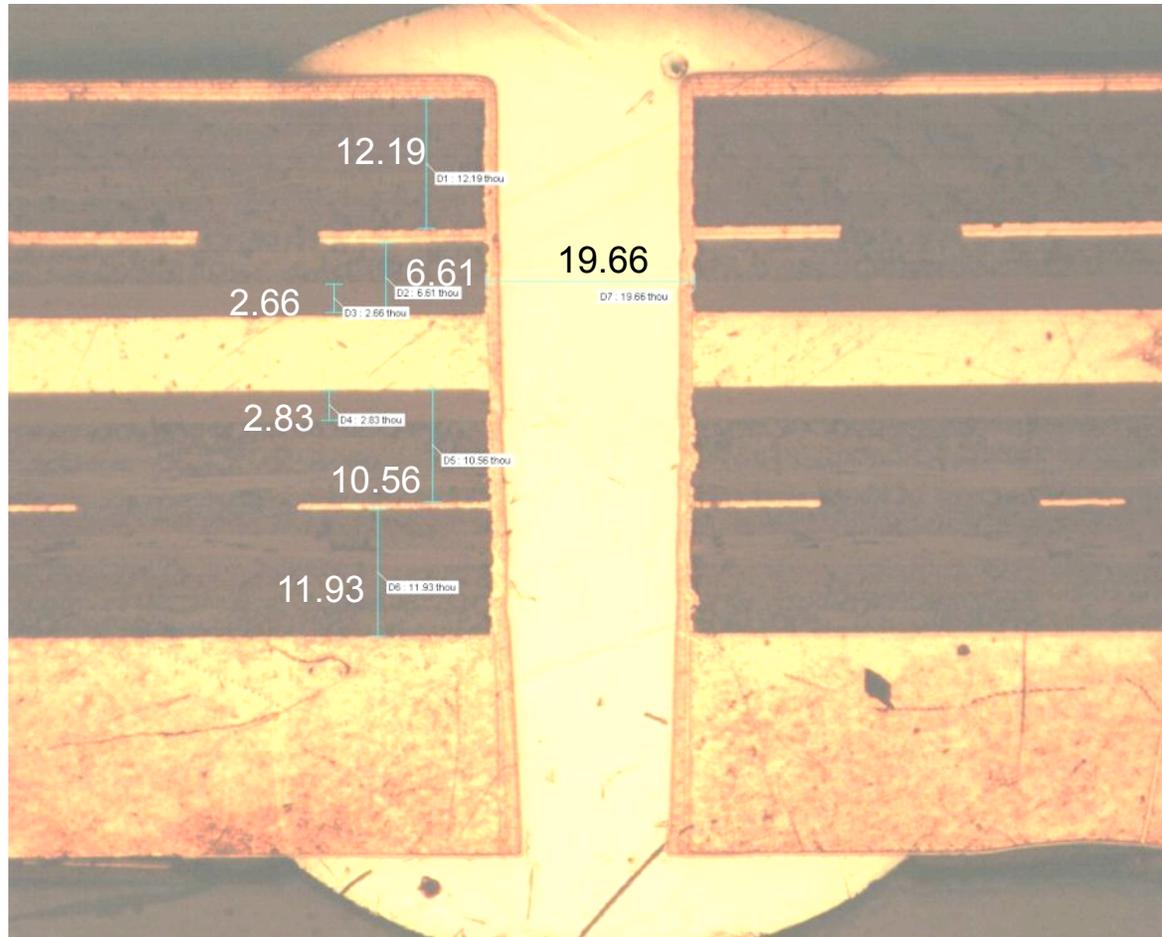


RO4450F

RO4450F prepreg did not flow into holes of .008" cores

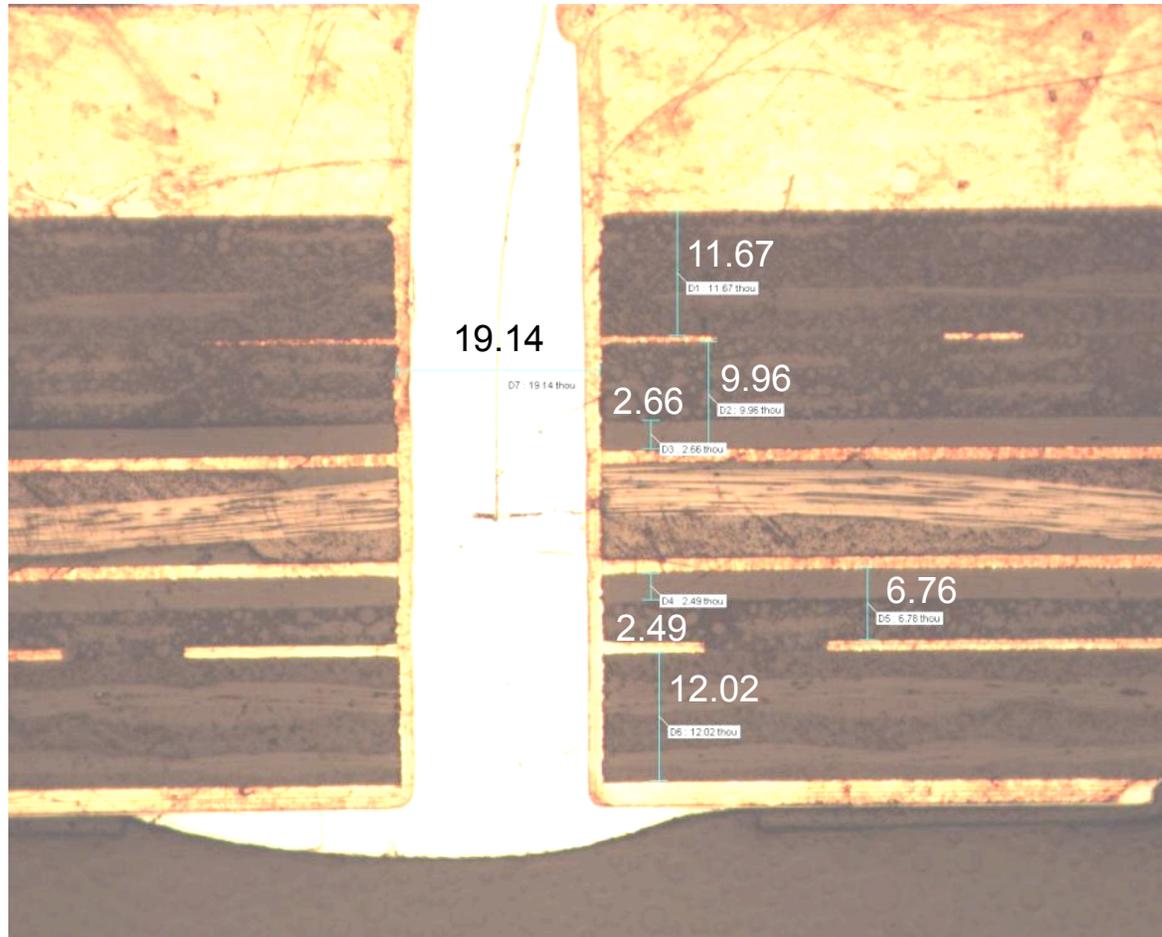


2A Cu Core Build – Thru Hole



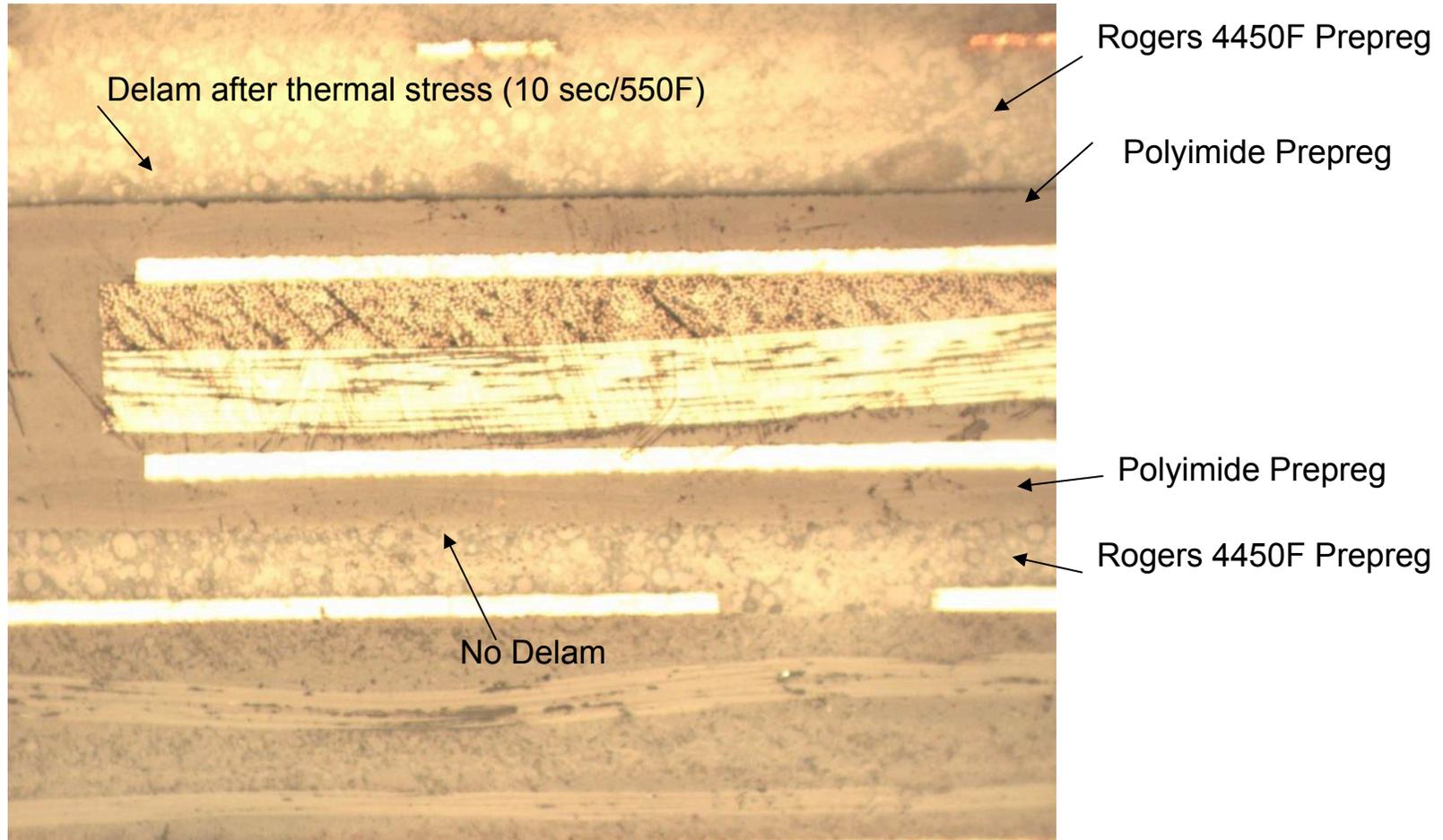


1A Stablcor Core Build – Thru Hole





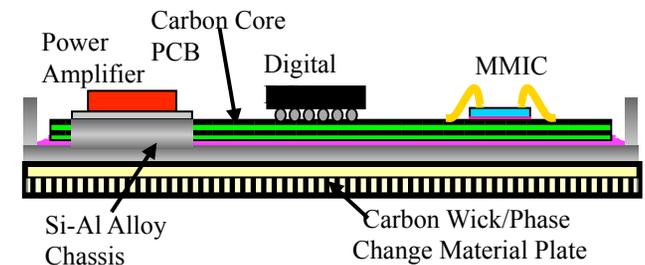
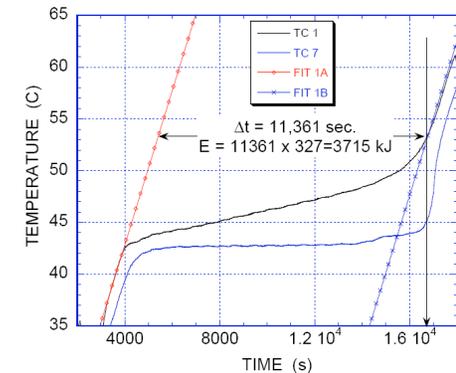
Delam





New Thermal Capacitor: Reduced Thermal Cycling

- PCM (Phase Change Material) behaves as a thermal capacitor, absorbing heat until the material transitions states completely (melts)
- PCM will constrain temperature variability assuming an appropriate thermal interface between the electronics and the PCM
- Flight heritage for PCM: 1kWh heat sink (CRYOTSU, STS-95)
- We are adapting PCM to small format/localized use
- Incorporates PCM into multi-stage thermal package to mitigate localized hot spots and total heating
- Carbon-Fiber PCB moves heat out of hot areas quickly, improving reliability—especially for BGA packages
- Silicon Aluminum alloy chassis reduces CTE mismatches between electronics and chassis, improving reliability
- Incorporates PCM to constrain total module heating
- Combination reduces local heating, total heating, and parts (mechanical) stress





PCM Unit

- The Phase Change Material (PCM) package was built by Energy Science Laboratory Inc. (ESLI) for the thermally stabilized T/R RF Module project.
- Eicosane paraffin wax is used as the PCM because of its high latent heat capacity & melting point temperature (36 C) for the T/R RF module operation.
- Because of the low thermal conductivity of the wax, carbon fibers are impregnated into the wax to provide added conductivity.
- The paraffin wax is stored in the cells of a honeycomb structure that forms the core of the PCM unit. Carbon fibers are distributed in the cells to provide high thermal conductivity along the thickness of the unit. The lateral in-plane thermal conduction is two orders of magnitude lower for the current PCM package design.





PCM Package Test Set Up

- The PCM package and a heater plate is enclosed in an insulated box for this test, The insulated box significantly reduces the convective and radiative parasitic heat losses.
- The heater plate is a ¼” thick aluminum plate (about the same foot print as the PCM unit) with a film heater attached on one side. A thermally conductive interface material is used between the plate and the PCM unit to improve the heat transfer.
- Temperature data is taken at the top and bottom sides of the encapsulated PCM to find its energy storage capability.

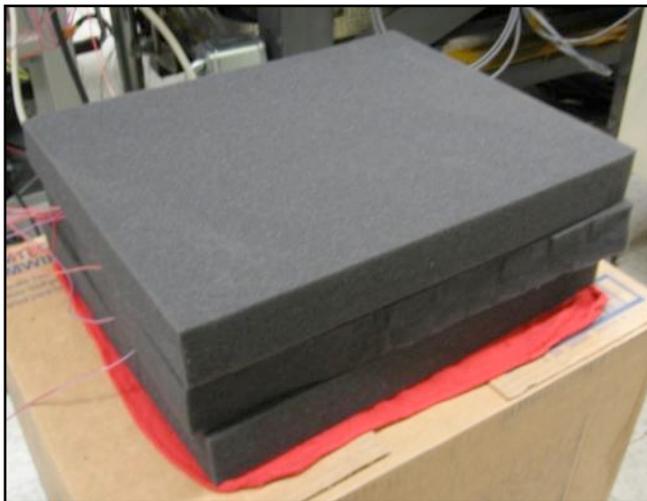


Image 1: Insulated Test Setup

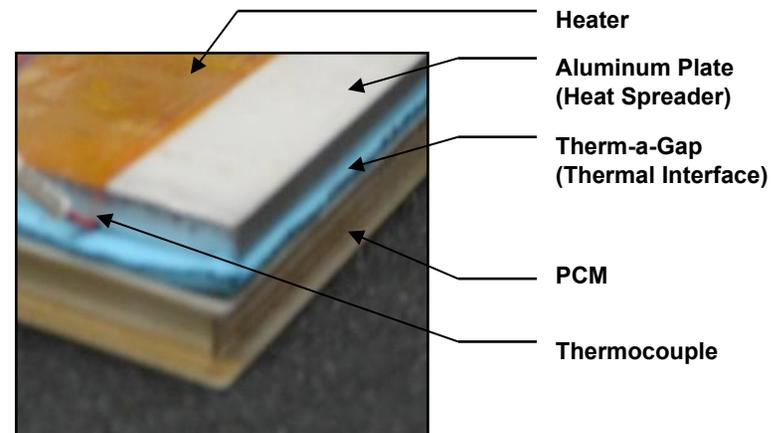


Image 2: PCM Stackup

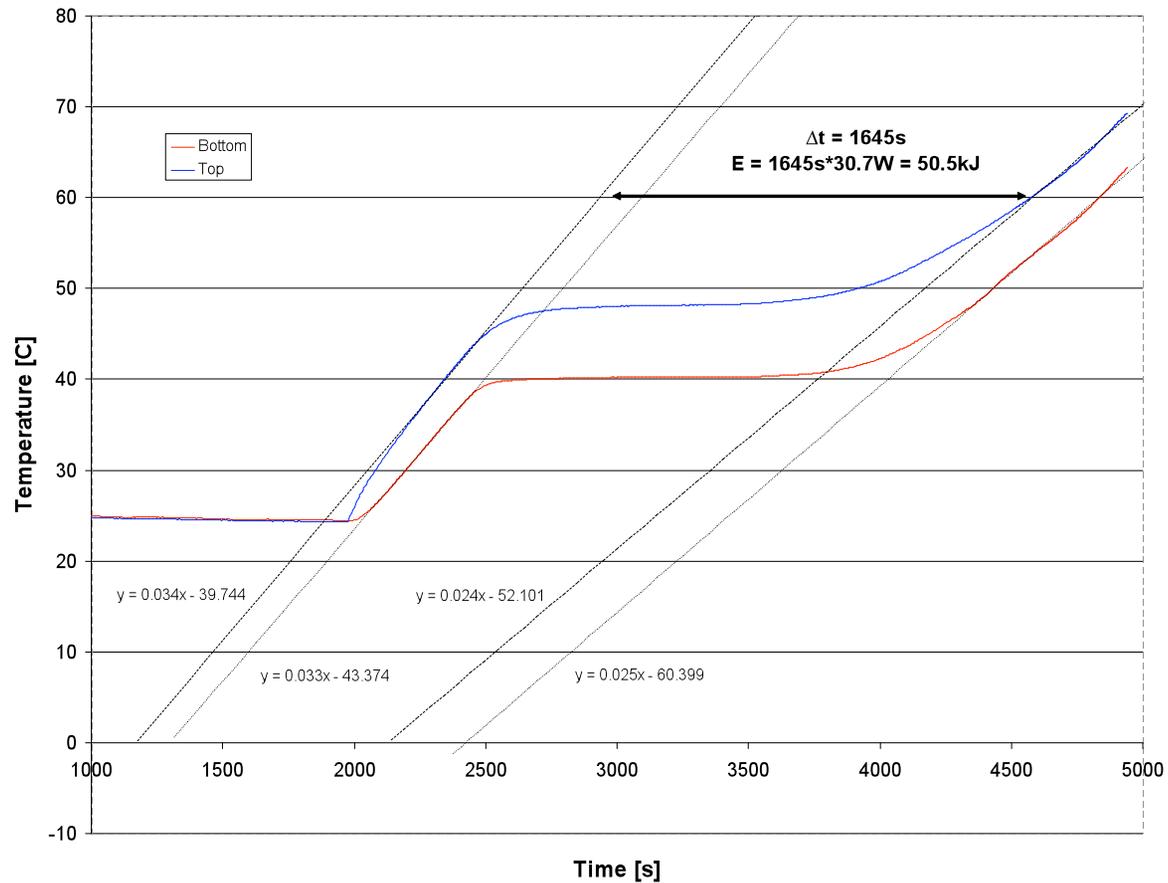


PCM Thermal Capacity

- The thermal capacity of the PCM unit is experimentally determined by melting the PCM in the unit and monitoring the unit temperature over the time.
- The heat is absorbed as the sensible heat by the wax till it reaches its melting point and the subsequent heat melts the wax and the temperature remains at its melting point until all the wax is melted.
- The product of the time duration the wax remains at its melting point and the heater level is the latent heat thermal capacity of the PCM unit.
- The temperature data was graphed and the latent heat energy storage capability, found here to be 50.5 kJ (compared with the data sheet approximating 48.7kJ).
- The offset between the top and bottom temperatures can be attributed to the resistance of the thermal interface material. The initial and final temperature slopes are approximately even for both surfaces, the steeper profile found at the end due to a higher specific heat in the liquid phase.
- Repetitive testing and data at various locations would allow a more precise number to be found.

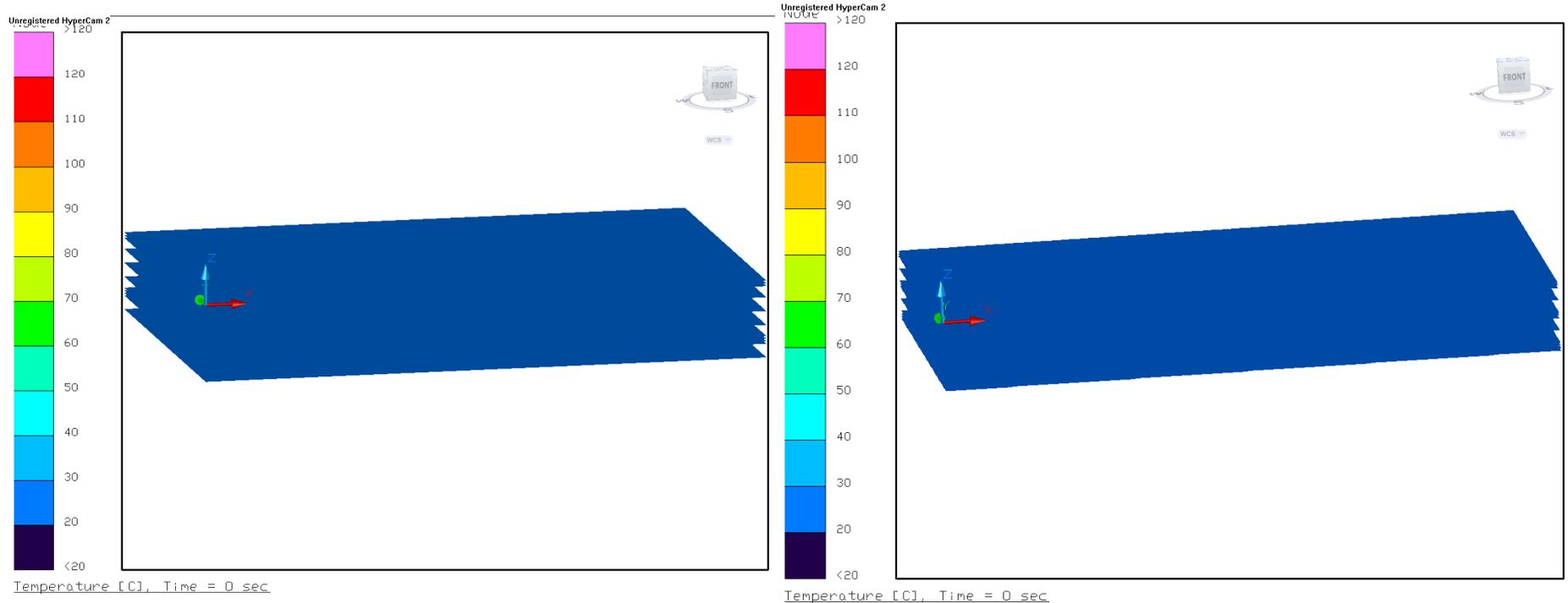


Thermal Capacity of the PCM Unit





Test Structure Model/Impact of PCM



Thermal model of PCB stackup testboard. PCM interface at “bottom”. Orange coloring on board surface indicates no margin for maximum junction temperature of 125C (>100C ambient plus 25C for junction temperature).

Thermal model of PCB stackup testboard. Standard thermal interface. Orange coloring on board surface indicates no margin for maximum junction temperature of 125C (>100C ambient plus 25C for junction temperature). Red violates flight requirements.



PCM Testing: Uniform Heat Distribution

- A larger heater spreads the heat and prevents hot spots in the PCM.
- Utilizing some form of a heat spreader will create a uniform temperature distribution and ensure an even melting profile in the paraffin. Uneven melting within the PCM will cause the PCM to be underutilized and temperature to rise more quickly than predicted.



Image 5: Top View of the PCM with Large Heater

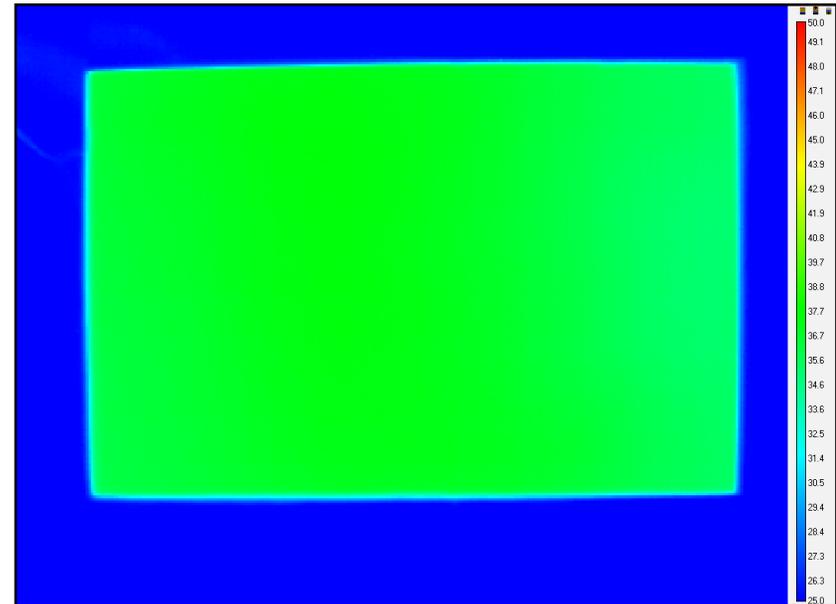


Image 6: Bottom View of the PCM with Uniform Temperature Distribution



PCM Testing: No Heat Spreader

- As shown below, a concentrated heat source conducts only in the vertical direction with little horizontal conductivity creating a hot spot. A heat spreader between the heat source and the PCM would be required to distribute the heat and ensure that the PCM melts uniformly.

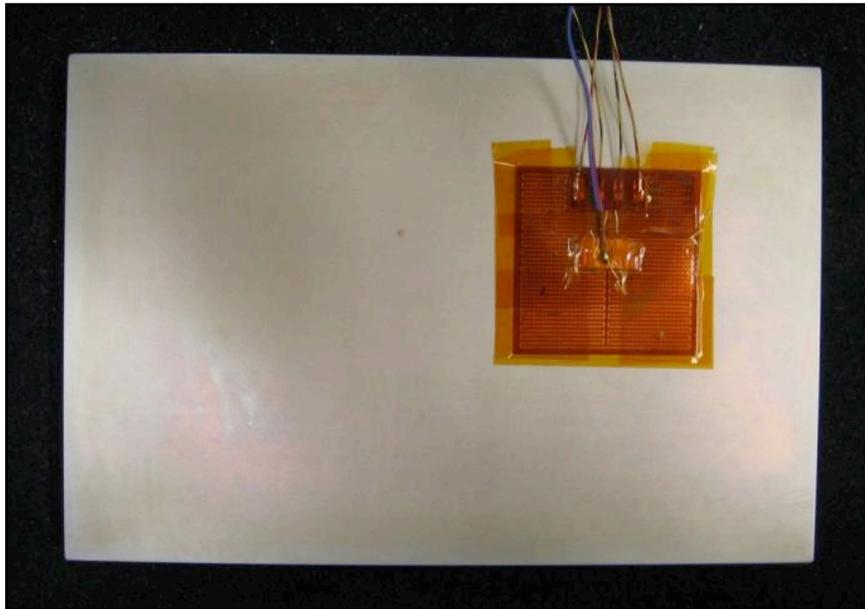


Image 3: Top View of the PCM with Heater

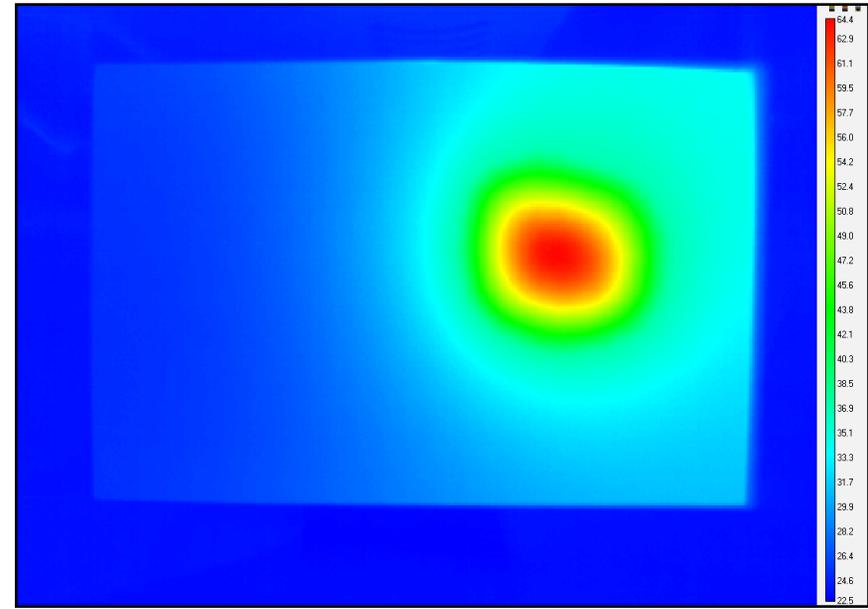
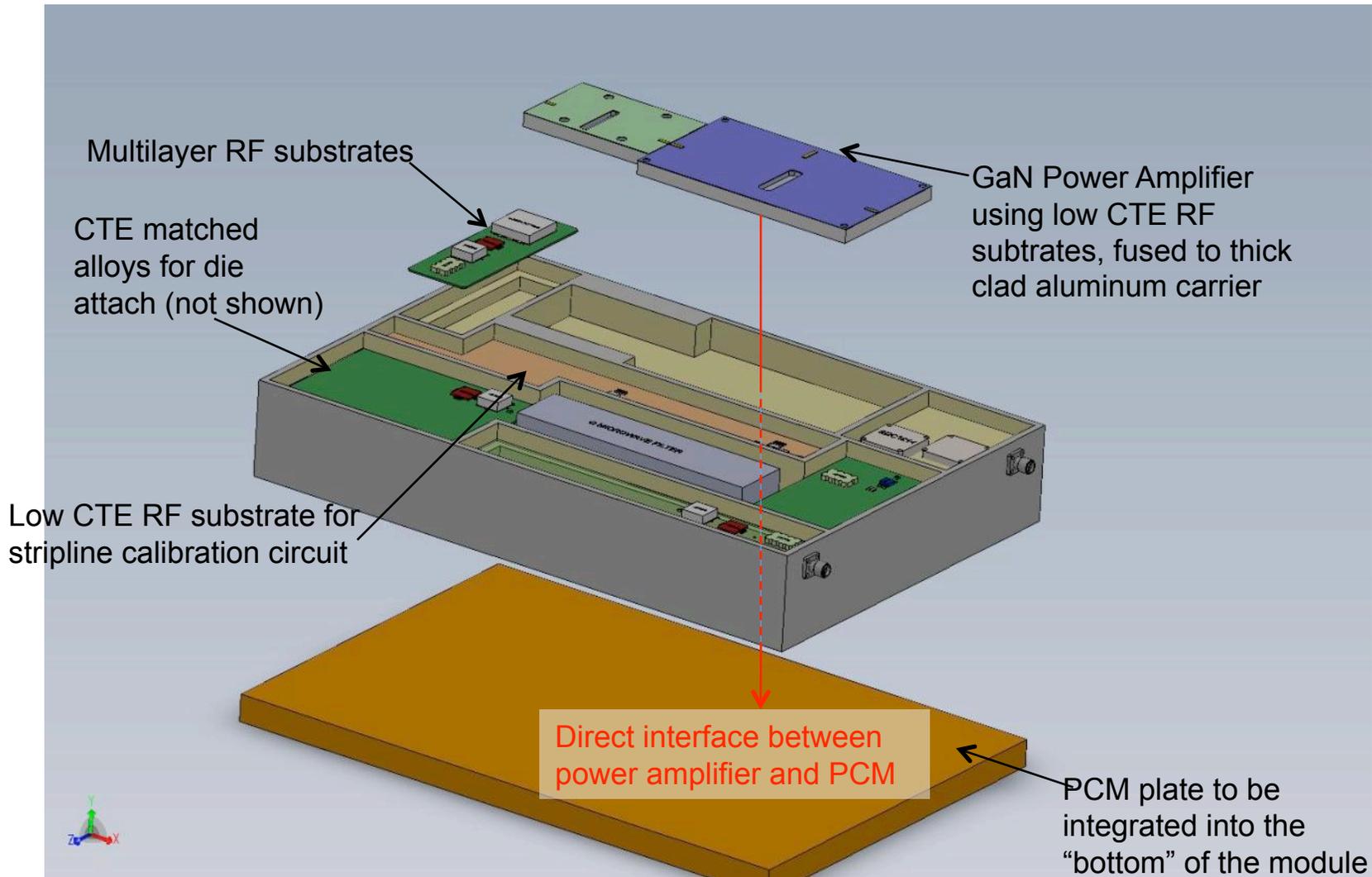


Image 4: Bottom View of the PCM with Hot Spot



TR Module Integration





Conclusions

- Evaluation of target technologies/materials nearing completion
- Three of the technologies (GaN, point-of-load regulators, CE alloys) are currently being evaluated for insertion into flight
- Advanced PCB manufacturing (for RF) remains markedly more challenging than standard techniques and the marginal advantages are TBD
 - Stablcor presents challenges for RF materials, requires significantly more hands-on fabrication and appears to have lower yield
 - Compared to high quality RF materials (with low temperature coefficients), the improvements might be marginal (TBC)
- PCM is showing promise for appropriate applications (instruments with periodic changes in heat dissipation, ie, spot-light SAR, high capacity comm, fly-bys)
- Overall progress TR module technologies and design indicate that a module with integrated thermal technologies is plausible and can be selected as required