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Presentation Title: “High Thermal Conductivity Polymer Matrix Composites (PMC) for Advanced Space Radiators”

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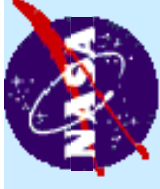
ABSTRACT

High temperature polymer matrix composites (PMC) reinforced with high thermal conductivity (~ 1000 W/mK) pitch-based carbon fibers are evaluated for a facesheet/fin structure of large space radiator systems. Significant weight reductions along with improved thermal performance, structural integrity and space durability toward its metallic counterparts were envisioned. Candidate commercial resin systems including Cyanate Esters, BMIs, and polyimide were selected based on thermal capabilities and processability.

PMC laminates were designed to match the thermal expansion coefficient of various metal heat pipes or tubes. Large, but thin composite panels were successfully fabricated after optimizing cure conditions. Space durability of PMC with potential degradation mechanisms was assessed by simulated thermal aging tests in high vacuum, $1-3 \times 10^{-6}$ torr, at three temperatures, 227 °C, 277 °C, and 316 °C for up to one year. Nanocomposites with vapor-grown carbon nano-fibers and exfoliated graphite flakes were attempted to improve thermal conductivity (TC) and micro-cracking resistance. Good quality nanocomposites were fabricated and evaluated for TC and durability including radiation resistance. TC was measured in both in-plan and thru-the-thickness directions, and the effects of microcracks on TC are also being evaluated.

This paper will discuss the systematic experimental approaches, various performance-durability evaluations, and current subcomponent design and fabrication/manufacturing efforts.

KEY WORDS: High temperature polymer composite, Pitch-based carbon fiber, Facesheet/Fin, Space Radiator, Thermal conductivity, Thermal expansion, Space durability, Nano-composites



High Thermal Conductivity Polymer Matrix Composites for Advanced Space Radiators

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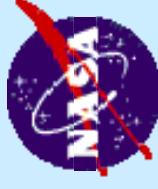
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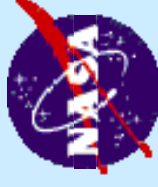
Contributors

- Jane Manderscheid, GRC: Radiator sub-panel design
- Derek Quade, GRC: PMC panel & radiator sub-panel fabrication
- Dave Kowalski, GRC: PMC vacuum Thermal aging
- Michelle Cybulski, U.of Dayton-summer intern
- Dan Scheiman, ASRC/GRC: PMC thermal properties; Vac. Thermal aging
- Rohit Mital, OSU-summer intern: PMC thermal conductivity & Image analysis
- Richard Martin, CSU/GRC: IR Thermography NDE of radiator sub-panels
- Demetrios Papadopoulos, U. of Akron/GRC: PMC mechanical properties
- Linda McCorkle, OAI/GRC: PMC SEM Micrographs; thermal conductivity
- Linda Inghram, OAI/GRC: PMC NDE & acid digestion
- Chris Burke, ASRC/GRC: Thermal cycling test of radiator sub-panels
- Don Jaworske, GRC: Radiation testing
- Tim Ubienski, Joe Lavelle, SLI/GRC: PMC machining & test fixture fabrication
- Sangwook Sihm, UDRI-AF: PMC panel lamination lay-up analysis
- Paul Biney, Prairie View A&M U.: Thermal spiking experiment
- UDRI and Nanospense, MRI: Nano formulation and compounding
- YLA, Inc.: PMC prepregging
- Canyon composites: PMC panel fabrication

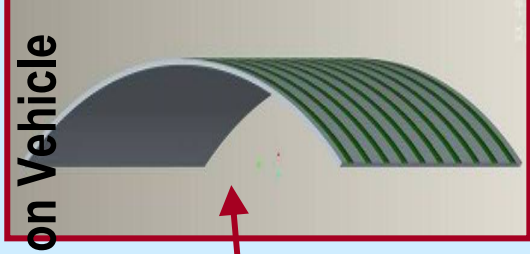
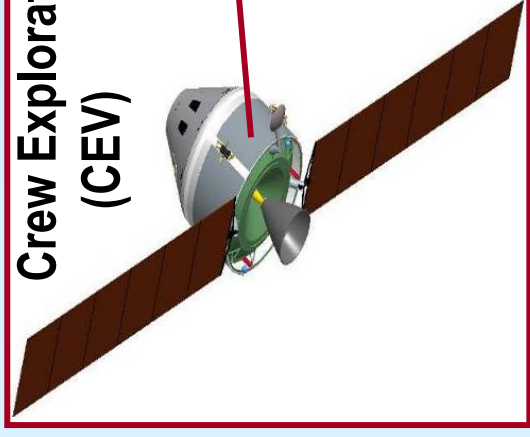
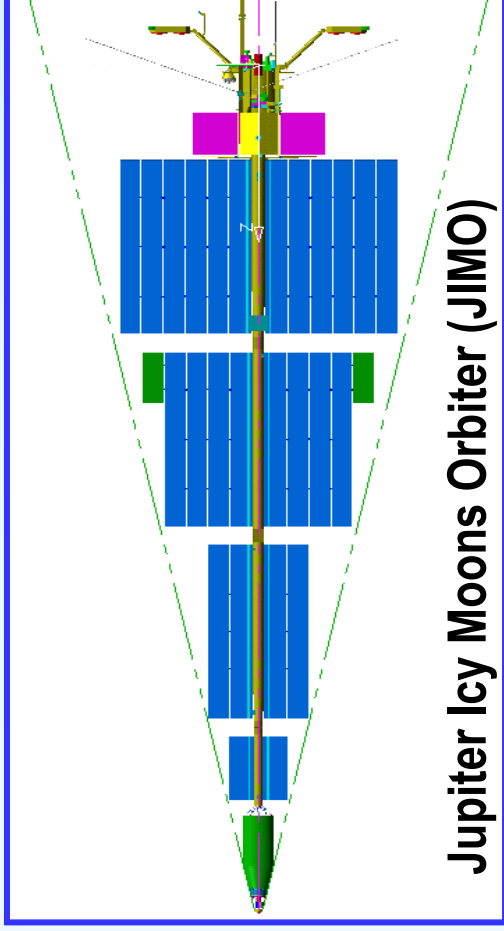


Subject Matter

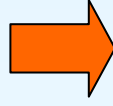
- ❑ Background
- ❑ PMC Radiator Panel Design & Material Selection
- ❑ PMC Facesheet Design and Fabrication
- ❑ PMC Performance & Feasibility Evaluation
 - Thermal conductivity and Nano-composites
 - Effects of micro-cracks
 - Vacuum thermal aging
 - Radiation hardness
- ❑ PMC Radiator Sub-Panel Fabrication
 - Overwrap co-cure vs. 2ndary bonding
 - Thermal performance
 - HT-PMC bonding evaluation
- ❑ Summary and Future work plan



Background



- ✓ Larger area, significant mass driver
- ✓ Wider range of temperatures (200 – 550°F)
- ✓ Sophisticated deployment, possibly similar to ISS



PMC with high thermal conductivity carbon fibers
(Coal tar pitch-based w/ up to 1000 W/mK)
→ Higher potential!

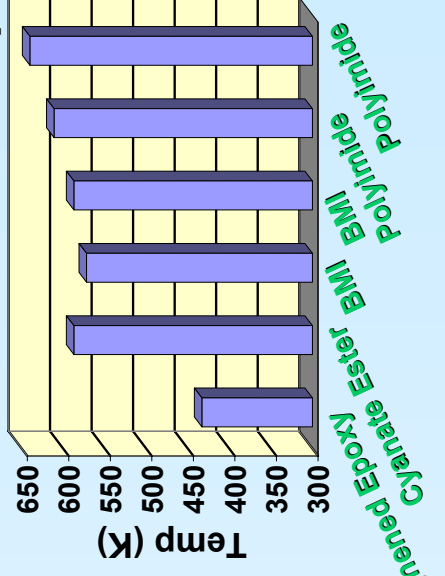


Polymer Matrix Composites

DESCRIPTION

- ❑ Varieties of material choices; fibers, resins
- ❑ Commonly used for spacecraft structural members and lower temperature radiators
- ❑ Inherently low resin thermal conductivity; but improved by the use of nano-fillers → transferable to continuous fiber PMCs?

Resin Glass Transition Temperatures



ROM PROPERTIES

K11100/polymer 60% Fiber Vol	Axial	Trans.	0° ± 30°
CTE (μm/mK)	-1.2	~40	-
RT Density (g/cm ³)	1.8	1.8	1.8
RT Conductivity (W/mK)	600	~1	300
Strength (GPa)	2	-	1.3
Modulus (GPa)	590	-	400

PROS AND CONS

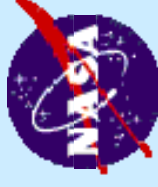
- (+) High specific stiffness & strength
- (+) Least expensive composite form
- (+) Tailorable CTE, thermal conductivity, mechanical properties
- (+) Established manufacturing base
- (-) Durability insufficiently characterized
- (-) Poor thru-thickness T conductivity
- (-) Highly anisotropic properties
- (-) Bonding challenges w/ metal HP/HT



Background

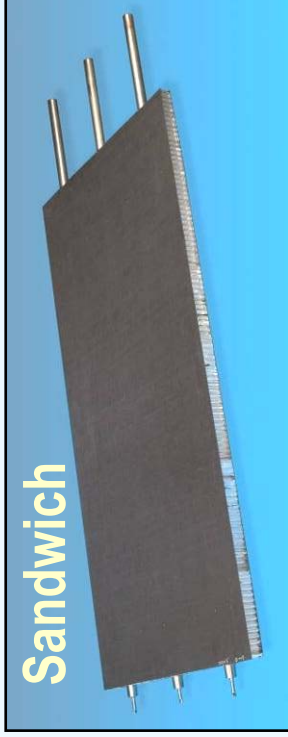
Technology Development Required for PMC

- Low thru-thickness thermal conductivity
- Effect of cracking defects on thermal conductivity
- Temperature limits for long-term application
- Component specific fiber architecture optimization
- Component specific design data and fabrication experience



PMC Radiator Panel Designs

Variables



- ✓PMC material
- ✓Saddle matr'l & design
- ✓Adhesive material
- ✓Core material & type



- ✓PMC material
- ✓HT material; Al, SS, Ti
- ✓HT radius
- ✓PMC f/s Thickness
- ✓Adhesive material



- ✓PMC material
- ✓HT materials; Al, SS, Ti
- ✓Adhesive material
- ✓Adhesive thickness

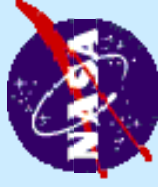
PMC Material Selection

□ Matrix materials:

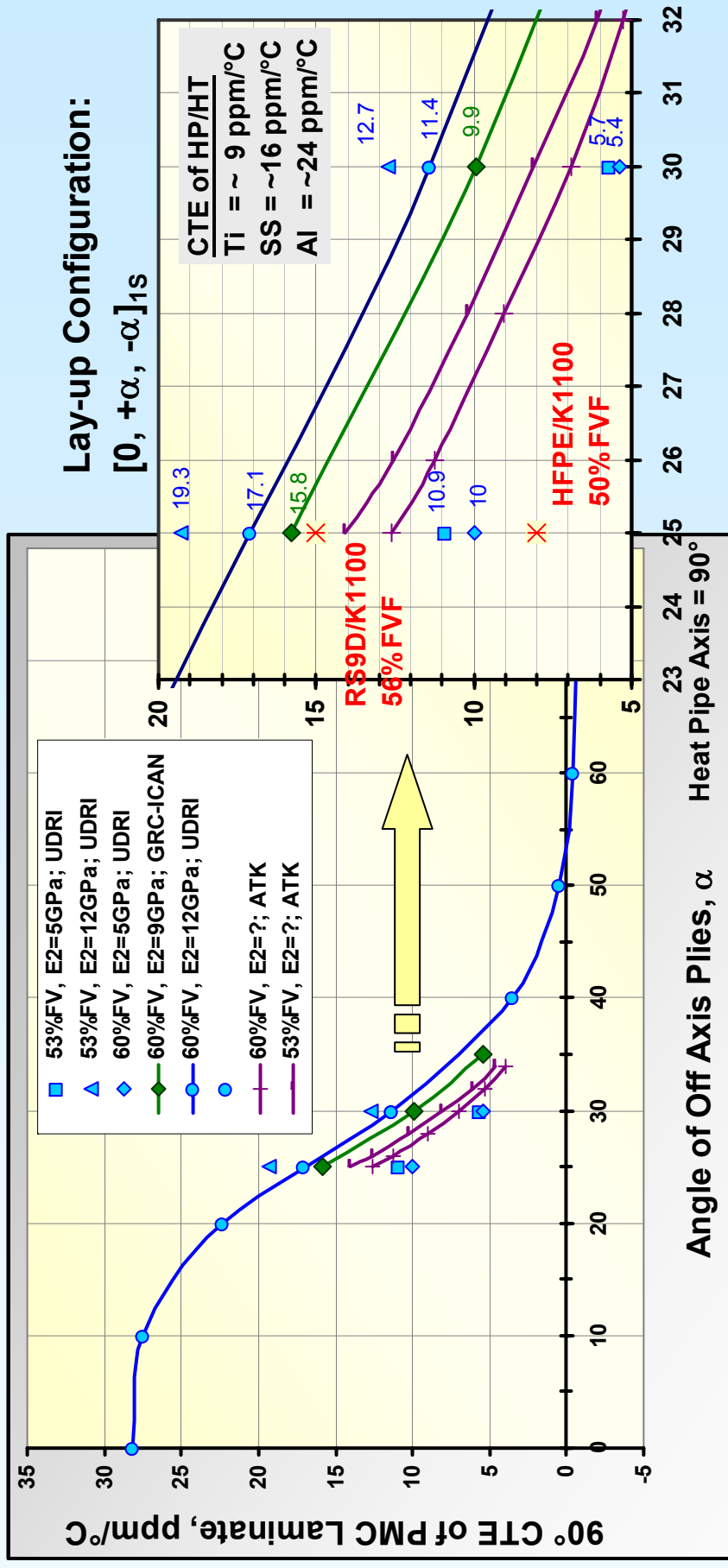
- RS9 (Cyanate ester), YLA
- EX1551 (Cyanate ester), Bryte
- Cycom 5250-4 (Bismaleimide), Cytec
- HFPE-II-52 (6-F polyimide), Maverick

□ Pitch-based carbon fibers: K13D2U (Mitsubishi) and K1100 (Amoco/Cytec) in 2K tow

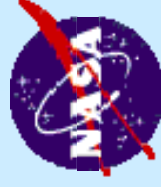
- 800~1000 W/mK in-plane vs. ~20 W/mK out-plane TC
- Axial CTE \sim - 1.5 ppm/°C; elongation to failure < 0.4%



PMC Facesheet Design – CTE matching



PMC f/s lay-up configurations to match CTE of metal HP/HT via various analytical solutions based on lamination theory: $[0/15/-15]_n$ for aluminum vs. $[0/25/-25]_n$ for stainless steel vs. $[0/30/-30]_n$ for Titanium



PMC Facesheet Fabrication

- ❑ Hot-melt prepregging (YLA); 12" wide, 37w% resin, 67 gsm FAW → 0.0025 inch thick after cure, 60 v% FVF targeted
- ❑ Panel fab (GRC or Canyon); Hand lay-up (12"x12" or 24"x36" or 36"x44"; 6-ply) → optimized vacuum bagging → autoclave cure w/

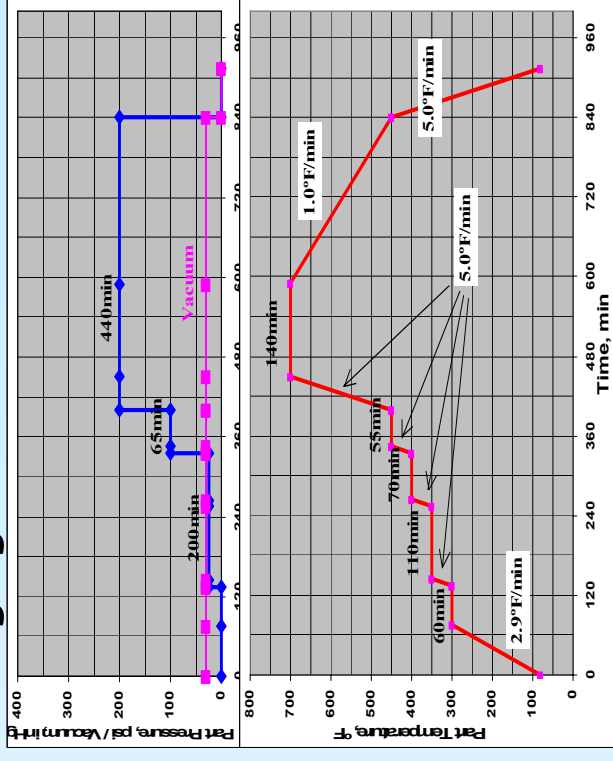
RS-9D cure

- Apply 28 in/Hg vac & 80 psi P
- Heat to 390 °F @ 3 – 5 °F/min
- Hold at 390 °F for 127 min
- Cool to RT @ ~ 3°F/min
- Postcure at 600 °F for 4 hrs free standing in air

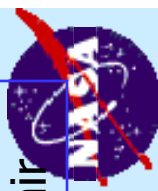
- ❑ C-scan and QC testing (GRC)

HFPE-II-52 cure

- B-staging @ 400°F for 1 hr



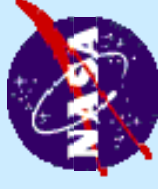
- Postcure @ 700°F for 16 hrs in air



Thermal conductivity and Nano-composites

- Material Selections

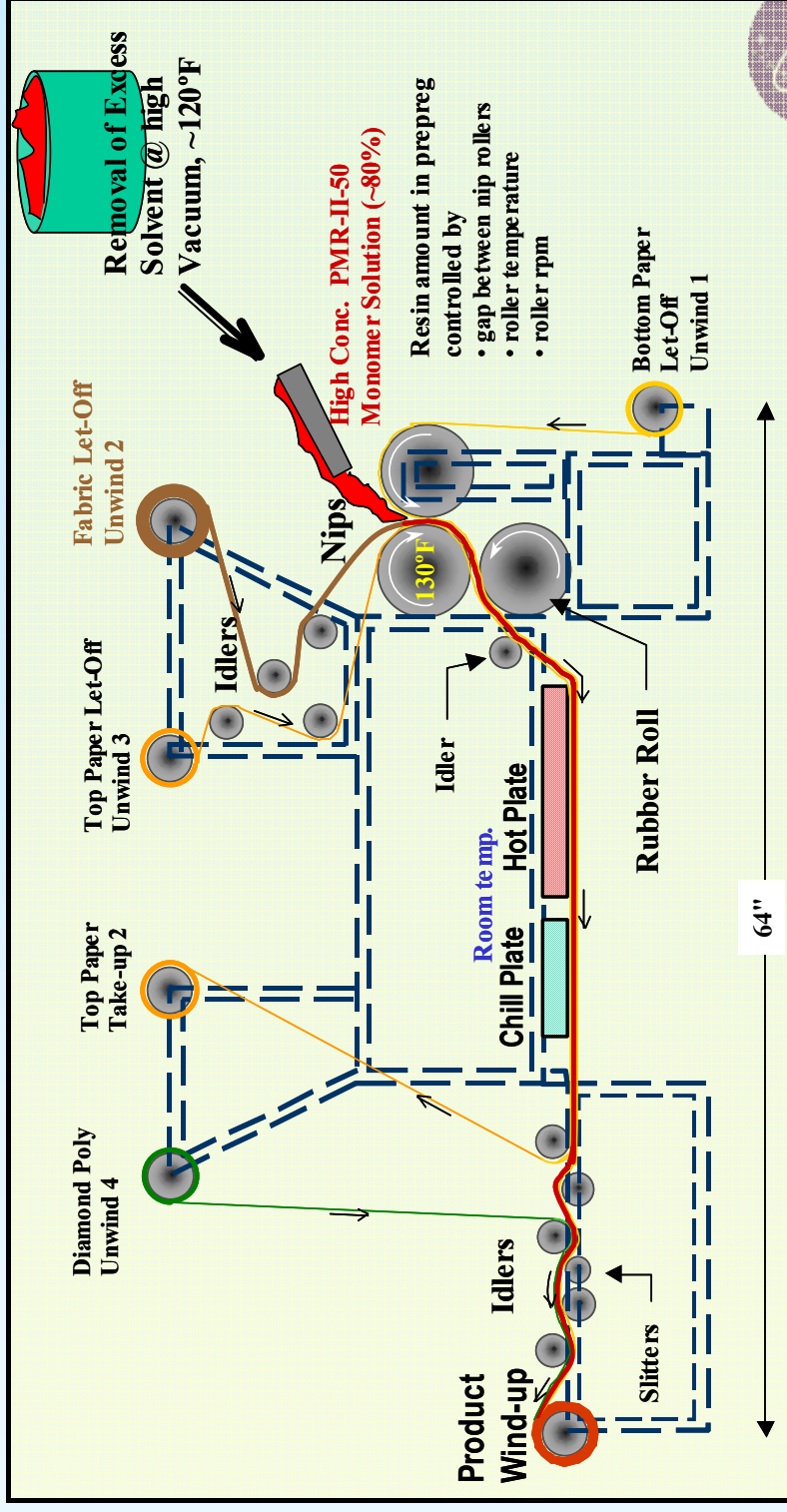
- High thermal conductivity nano fillers studied;
 - ❖ Vapor grown carbon nano fibers (VGCNF) --- high temperature grade: PR24HHT, ASI
 - density = ~ 1.8 g/cc, a tube structure of graphite w/ variable morphology and densities
 - Average diameter = ~ 100 nm (10 nm - 500 nm in distribution), aspect ratio = ~ 500
 - ❖ Exfoliated graphite flakes (ExGf) --- exfoliated by UDRI patented process
- RS-9D Cyanate ester resin (YLA) + K13D2U C-fiber (Mitsubishi) composite system



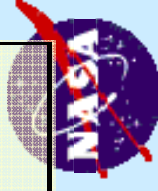
Thermal conductivity and Nano-composites

- Processes

- Nano filler-resin mixing, compounding (20wt% filler) by UDRI/NanoSpense/MRI for optimum dispersion → Uni-tape PMC prepreg by Hot-melt process at YLA (10wt% filler) → composite panel fabrication w the optimized cure cycles at GRC (12"x12") and Canyon (24"x36")



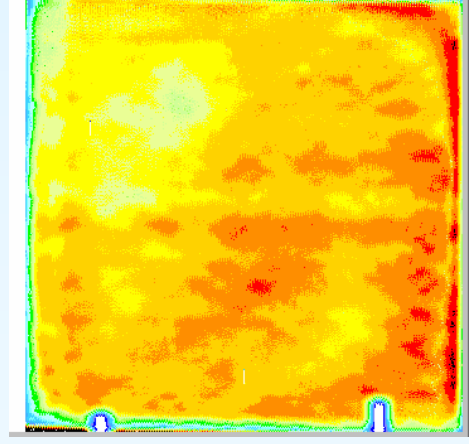
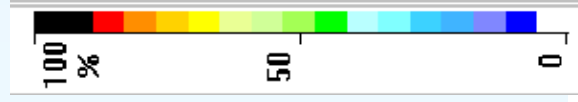
YLA Prepregging Set-up



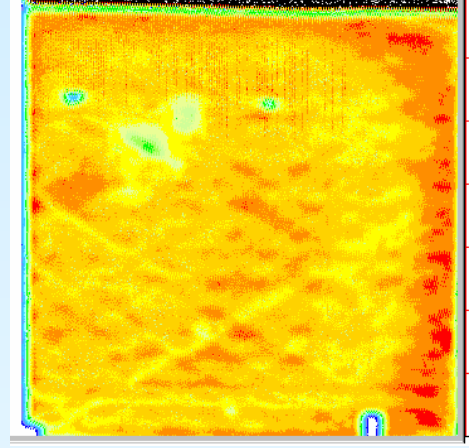
Thermal conductivity and Nano-composites

- Preliminary Results

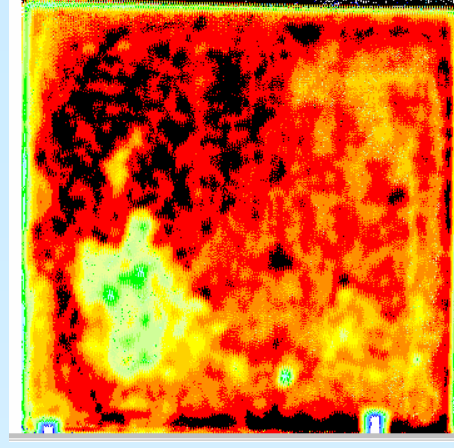
- 12-ply, [0/+30/-30/+30/0]_{1s} to match CTE of Ti heat pipe (HP);
12"x12"x0.028"
- Cured @ 380 °F, 80psi, 28 in/Hg vacuum for 2 hrs w/ optimized bagging →
Postcured at 600 °F for 4 hours
- C-scan NDE



Straight resin



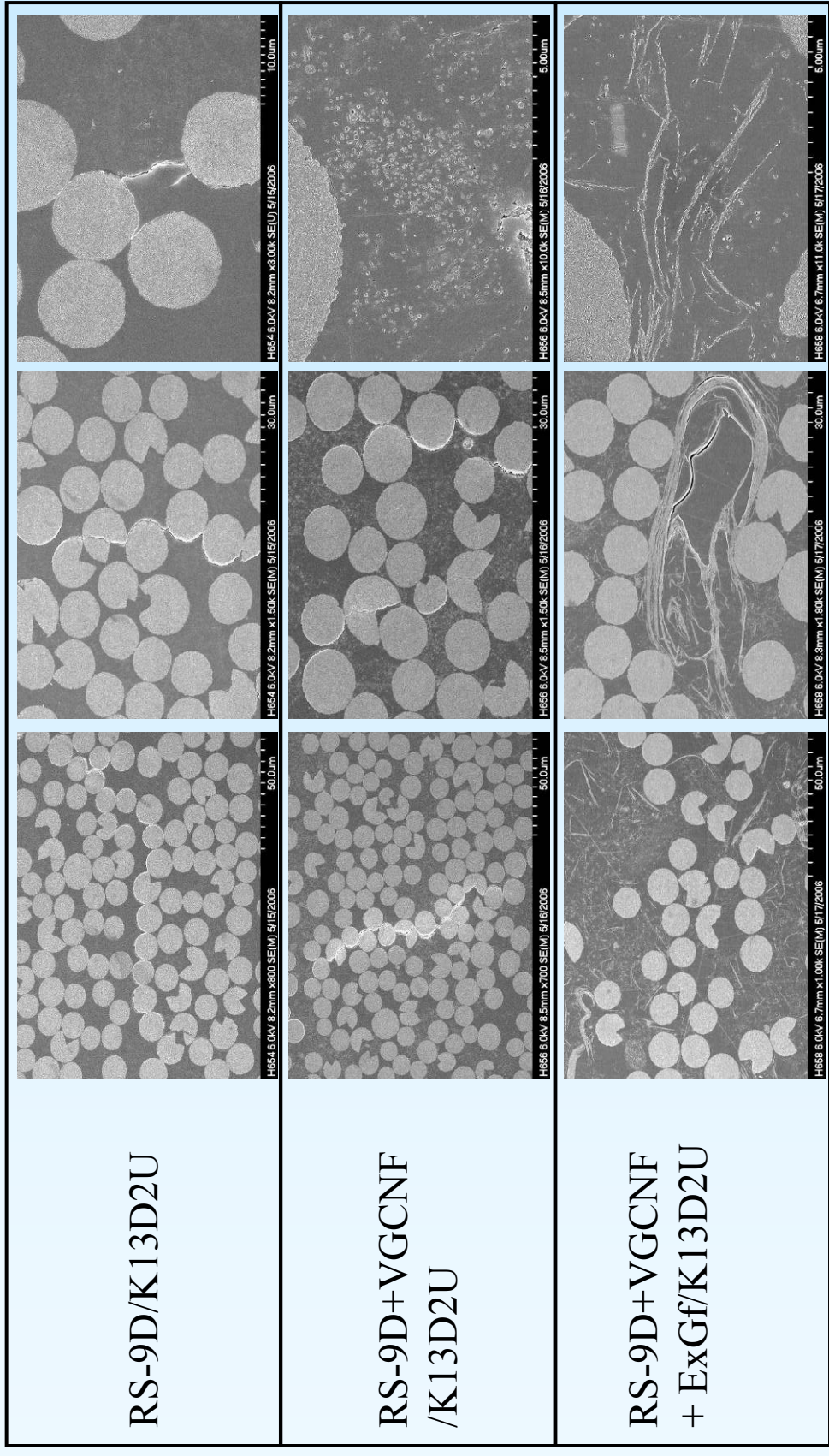
Resin + VGCNF (10wt%)



Resin + VGCNF (5wt%)
+ ExGf (5wt%)

Thermal conductivity and Nano-composites

- Preliminary Results



Typical SEM micrographs of RS-9D/K13D2U PMC in terms of nano-modification showing fiber/filler distribution-connectivity and defects

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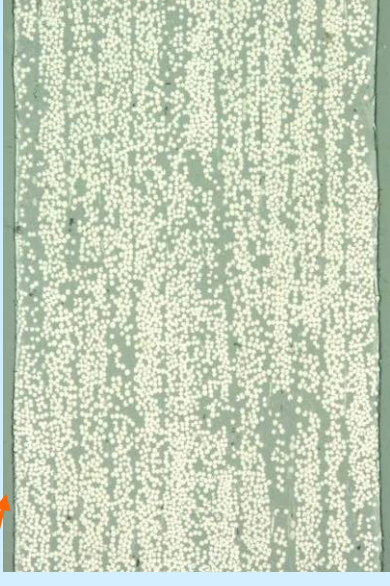
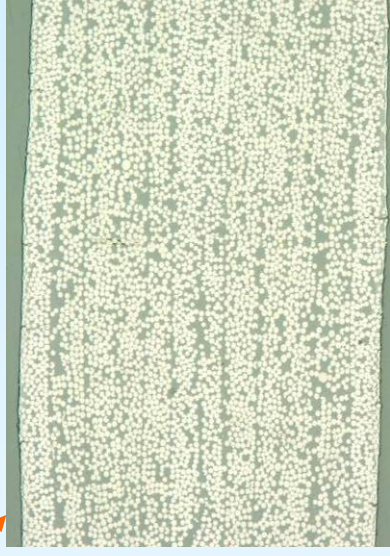
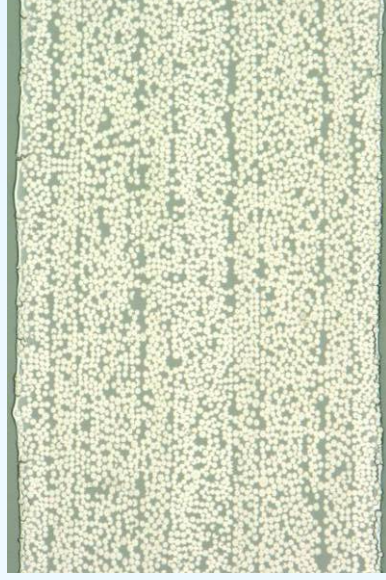
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Thermal conductivity and Nano-composites

- Preliminary Results

Properties PMC Laminate type	F.V.F* , %	Tg, °C (by DMA)		Td, °C (TGA in N ₂)
		G' onset	Tan δ	
Straight resin	57.3	368	423	410
Resin+VGCNF	54.2	309	411	408
Resin+VGCNF+ExGf	46.0	330	413	410

* F.V.F was determined by optical image analysis in Keyence high power (500x) digital microscope system (Note: nano filler volume counted in resin volume)



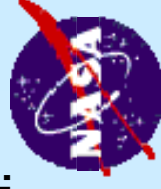
Thermal conductivity and Nano-composites

ME/TZSGH/LFA 447

- Preliminary Results

	Density g/cc	Specific heat capacity, J/g °C		Diffusivity, mm ² /sec			Conductivity, W/mK			
		20 °C	150 °C	300 °C	20 °C	150 °C	300 °C	20 °C	150 °C	300 °C
RS-9D Straight/K13D2U laminate										
0°					212	138	88	299	240	206
90°	1.75	0.81	1.00	1.34	42	29	20	59	51	47
Z-dir.					1.00	0.78	0.62	1.42	1.37	1.44
RS-9D+VGCNF/K13D2U laminate										
0°					179	121	86	241	223	213
90°	1.72	0.79	1.08	1.45	42	27	18	56	50	45
Z-dir.					1.01	0.79	0.61	1.36	1.46	1.51
RS-9D+VGCNF+ExGf/K13D2U laminate										
0°					166	108	74	198	180	166
90°	1.70	0.70	0.98	1.32	35	23		42	37	
Z-dir.					1.09	0.86	0.66	1.30	1.43	1.47

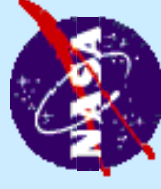
* Thermal diffusivity by Laser Flash Analysis (LFA 447), ΔCp by mDSC, density by dim.



Thermal conductivity and Nano-composites

- Preliminary Results

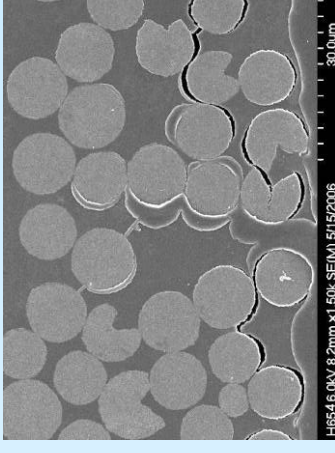
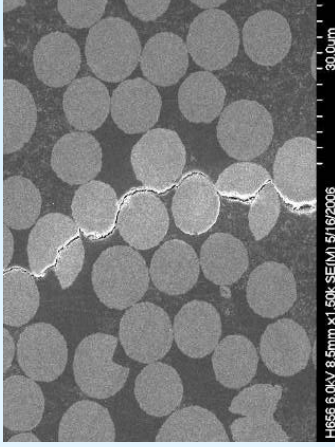
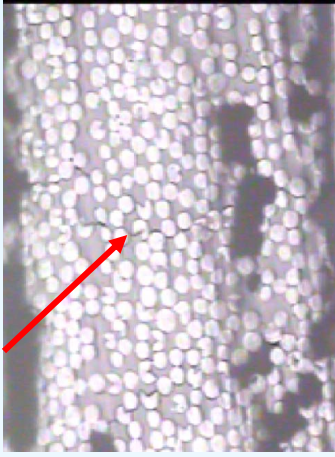
	Density g/cc	Specific heat capacity, J/g °C		Diffusivity, mm ² /sec		Conductivity, W/mK				
		20 °C	150 °C	300 °C	20 °C	150 °C	300 °C			
RS-9D Straight/K13D2U laminate										
Z-dir.	1.75	0.81	1.00	1.34	1.00	0.78	0.62	1.42	1.37	1.44
RS-9D+VGCNF/K13D2U laminate										
Z-dir.	1.72	0.79	1.08	1.45	1.01	0.79	0.61	1.36	1.46	1.51
RS-9D+VGCNF+ExGf/K13D2U laminate										
Z-dir.	1.70	0.70	0.98	1.32	1.09	0.86	0.66	1.30	1.43	1.47
HFPE-II-52 Polyimide/K13D2U lamiante										
Z-dir.	1.34	0.86	0.98	1.33	1.98	1.44	1.16	2.28	1.90	2.08



Effects of Microcracks

- Preliminary Results

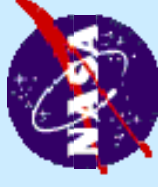
Objective: Determine effects of microcracks on thermal conductivity



- Thermal spiking preconditioning experiments (Prairie View A&M facility)
 - RS-9D/K13D2U: [0/30/-30]1s vs [0/30/-30/-30/30/0]1s vs [0/60/-60/-60/60/0]2s
 - LN₂ ⇔ 177 °C (350°F)
 - Density of microcrack measured, #/mm
 - TC measurements in thru-thickness direction, W/mK

	450 cycles	750 cycles	950 cycles	1250 cycles
12-ply	3.0±1.8	5.0±1.4		6.1±1.4
24-ply	4.4±1.7	6.9±1.2	7.6±1.9	7.0±0.5

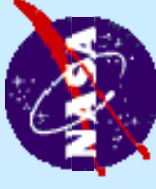
	0 cycle	1250 cycles
12-ply	1.975±0.13	1.937±0.07
24-ply	1.739±0.19	1.404±0.02



Effects of Microcracks

- Current Work Plan

- RS-9D/K13D2U vs. RS-9X1 (VGCNF-PR24HHT)/K13D2U vs. RS-9X2 (VGCNF+ExGf)/K13D2U
 - Also, effects of nano-modification on microcracking
- All 12-ply [0/30/-30/30/0]1s
- Thermal spiking preconditioning experiments (Prairie View A&M facility)
 - LN2 \leftrightarrow up to 232 °C (450°F), automated cycle @ 4 cycles/hr up to 2,000 cycles
- TC measurements: 0° and 90° in-plane directions vs. thru-thickness direction

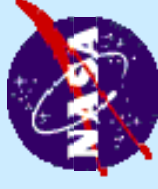


Vacuum Thermal Aging

- ❑ To assess PMC space durability by the accelerated thermal aging under high vacuum in simulating space environments
- ❑ To down-select most durable PMC candidate system
- ❑ To identify PMC degradation modes and mechanisms

PMC Candidates	Dry Tg, °C	Max. use T, °C
A: HFPE/K13D2U	390	~ 316
B: HFPE/K1100	404	~ 316
C: RS-9D/K13D2U	~ 349	232 - 288
D: RS-9D/K1100	361	232 - 288
E: RS-9X1 (VGCNF)/K13D2U	~ 366	>288
F: RS-9X2 (VGCNF+ExGf)/K13D2U	~ 371	>288

✓ All test panels: 6-ply [0, +30, -30]_{1s}



Vacuum Thermal Aging

- Experimental set-up

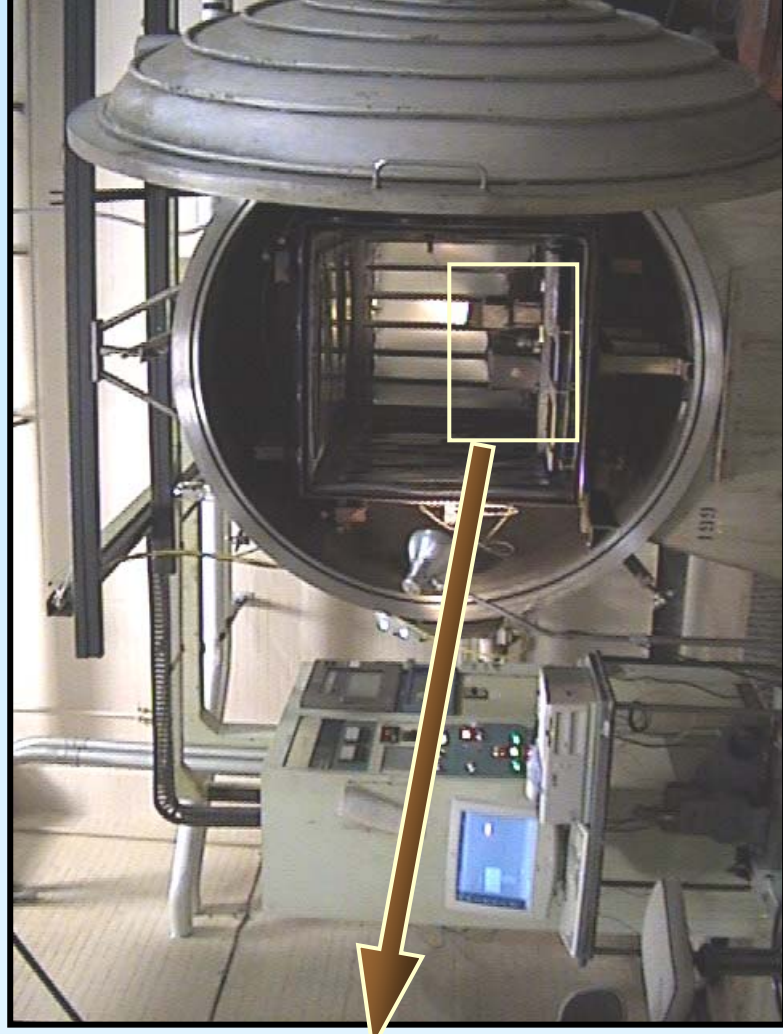


❖ 227 vs 277 vs 316 °C
(440 vs 531 vs 600 °F)

❖ 10⁻⁶ torr

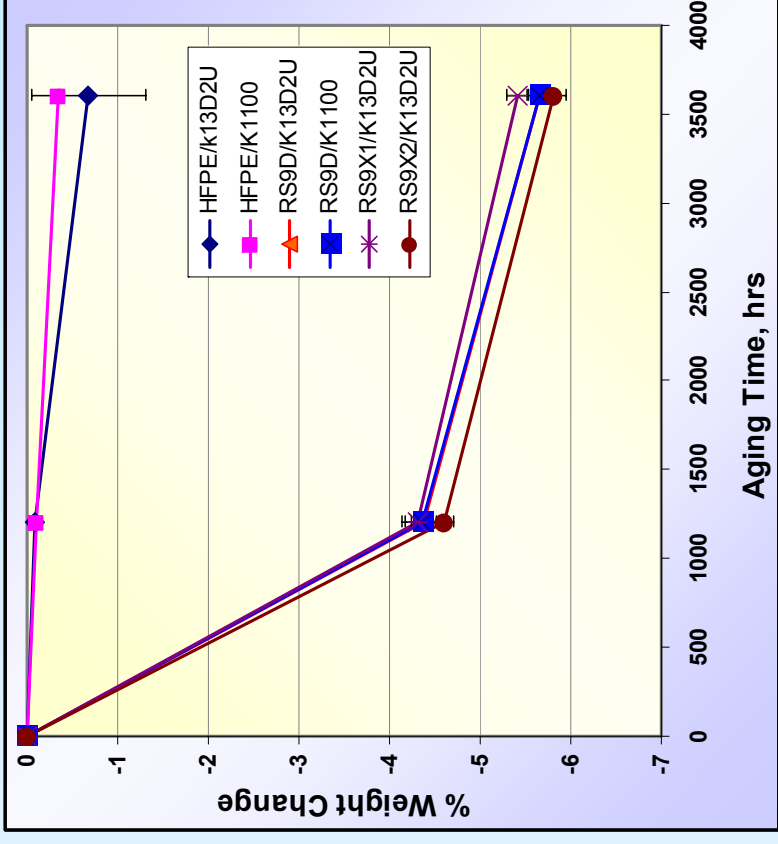
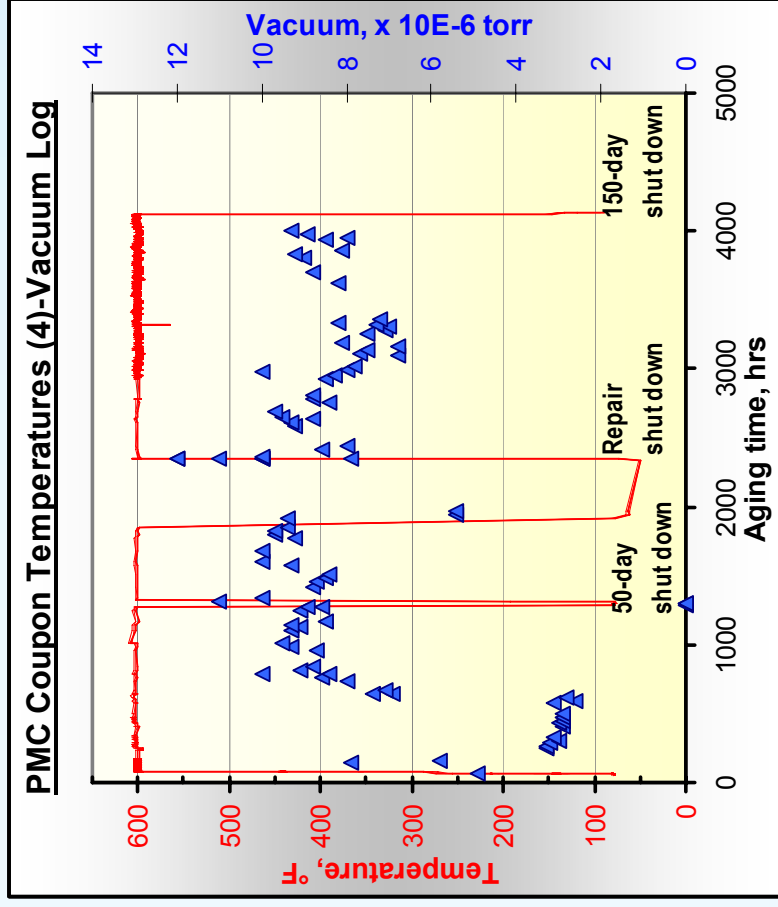
❖ Up to 10,000 hrs --- 0; 50; 150; 250; 417 days

- Total 48 3"x3"; 18 6"x4"; 18 4"x6" arranged for radiation heat
- Δ Wt, T_g , T_d , Cp, CTE, TC, FVF, void cont, FT-IR, damage evolution, and axial & transverse tensile properties to be monitored



Vacuum Thermal Aging

- Initial Results



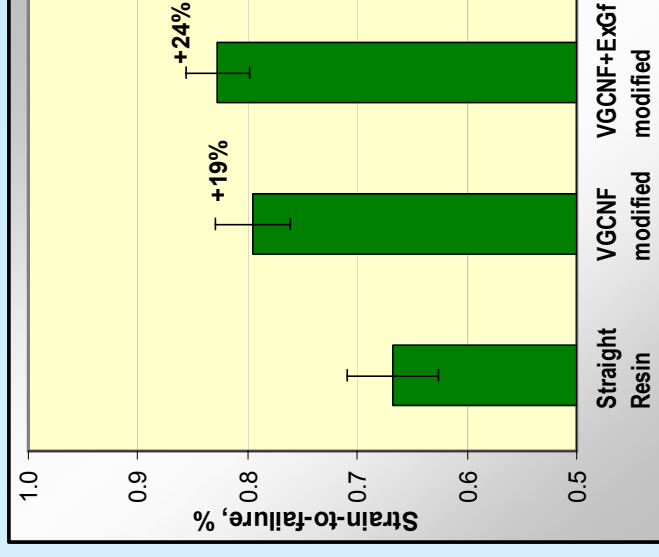
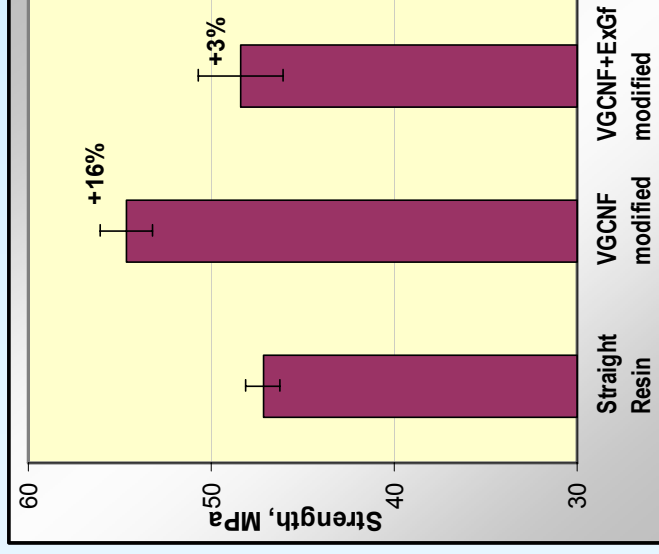
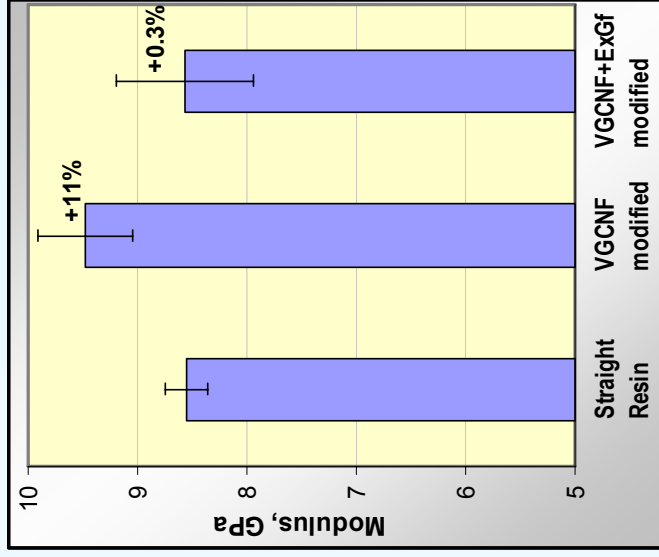
➤ Significant outgassing from Cyanate ester systems

Vacuum Thermal Aging

- Initial Results

RS-9##/K13D2U composites, 6-ply [0, +30, -30]_{1s} panels

Transverse (90°) Tensile Properties (Not normalized by F.V.F)
Baseline control at RT @ t=0



➤ Positive effects of nano-modifications on mechanical property

Vacuum Thermal Aging

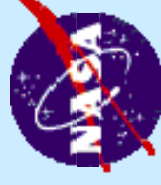
- Initial Results

RS-9##/K13D2U composites, 6-ply [0, +30, -30]_{1s} panels

Baseline control properties at RT @ t=0
 (Tested by Material Innovations Inc (MII); Not normalized by F.V.F)

PMC Laminate type and test direction	Conductivity*, W/mK			
	30 °C	100 °C	150 °C	
RS-9D Straight/ K13D2U laminate	0°	345	322	300
	90°	91	88	84
	Z-dir.	1.3	1.2	1.2
RS-9D+VGCNF/ K13D2U laminate	0°	346	326	304
	90°	93	90	88
	Z-dir.	1.7	1.7	1.6
RS-9D+VGCNF+ExGf/ K13D2U laminate	0°	322	297	281
	90°	83	79	77
	Z-dir.	2.2	2.2	2.1

*MII internal Steady State Thermal Conductivity Method

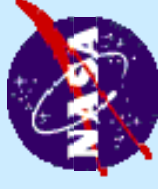


PMC Radiation Hardness

- ❑ High energy radiation can lead to chain scission (softening) or cross-linking (hardening) in polymers
- ❑ Electron Beam (β particle) is a cost effective & safe way to survey the radiation sensitivity of materials & components
- ❑ PMCs exposed to 20, 200, & 400 Mrad from 4.5 MeV e-beam
 - A:HFPE/K13D2U, C:RS-9D/K13D2U, F:RS-9X (VGCNF+ExGf)/K13D2U
 - Exposure led to no measurable weight loss, a good indication that there was no significant changes in chemistry

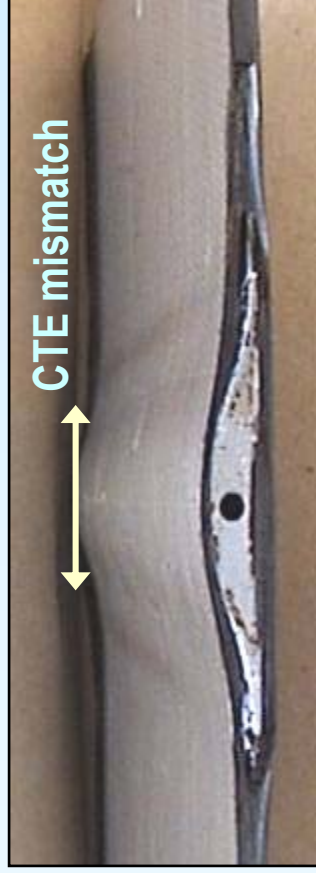
PMC	20 Mrad	200 Mrad	400 Mrad
A	-0.046 ± 0.053	-0.106 ± 0.190	-0.013 ± 0.086
C	0.131 ± 0.102	0.019 ± 0.310	0.194 ± 0.218
F	0.053 ± 0.112	-0.089 ± 0.386	0.134 ± 0.208

- Other evaluations (e.g., Tg, Td, Cp, CTE, TC, axial & transverse tensile properties, FVF, and void content etc) are underway



PMC Radiator Sub-Panel Fabrication

- Overwrap Concept: Co-cured



- ✓ RS-9D/K13D2U PMC f/s
- ✓ Aluminum HT
- ✓ HT radius?
- ✓ PMC f/s Thickness?
- ✓ RS-4A film Adhesive

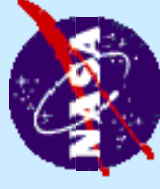
□ Benefits:

- Larger contact area to HT/HP, thus more efficient heat transfer
- More robust structure, better protected HT/HP

□ Challenges:

- Brittleness of pitch-based C-fibers, limited bend radius of 2.0 inch?
- Potentially heavier weight penalty
- Greater CTE mismatch between HT/HP and f/s in transverse direction
- Vacuum bagging and cure conditions optimized to minimize resin squeeze-out and to reduce CTE mismatch

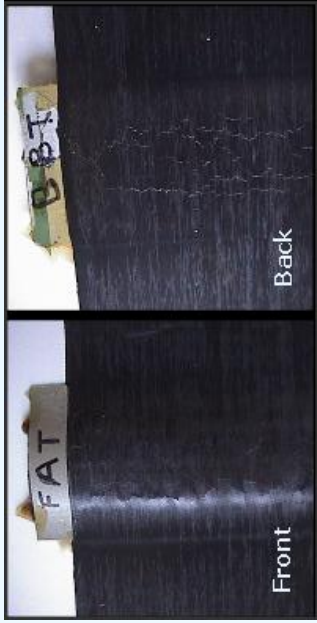
➔ Cure @ 177°C for 3 hrs, then postcured @ 204°C for 6 hrs



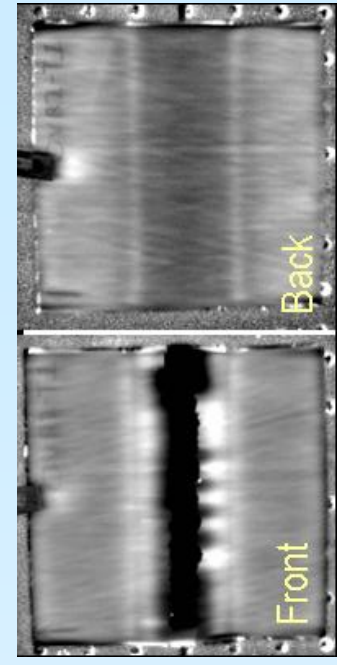
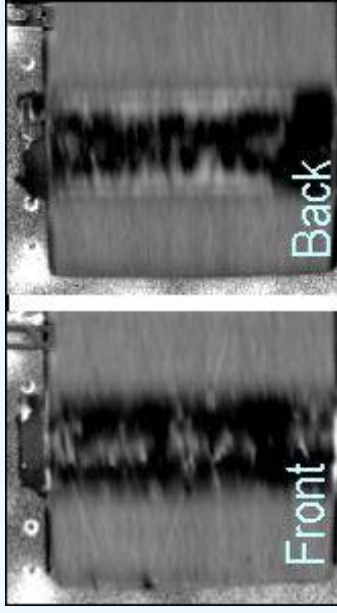
PMC Radiator Sub-Panel Fabrication

- Overwrap Concept: Co-cured

[0/15/-15/0]-HT(R1.75")-[0/15/-15/0]



[0/15/-15/0]_{1s}-HT(R1.5")-[0/15/-15/0]_{2s}



IR Thermo-graphs;
 Darker area
 → slower cooling
 → cracks, delam,
 or debonding etc.

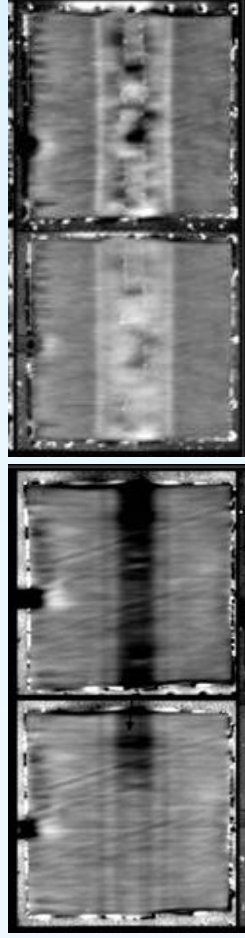
- ✓ Cracks due to CTE mismatch, not by HT curvature since both side cracked
- ✓ Poor bonding due to lack of resin + CTE mismatch

- ✓ Cracks on front 8-ply f/s, also delaminated and/or debonded
- ✓ 16-ply → Crack-free and good bonding!
- ✓ Role of HT curvature?

PMC Radiator Sub-Panel Fabrication

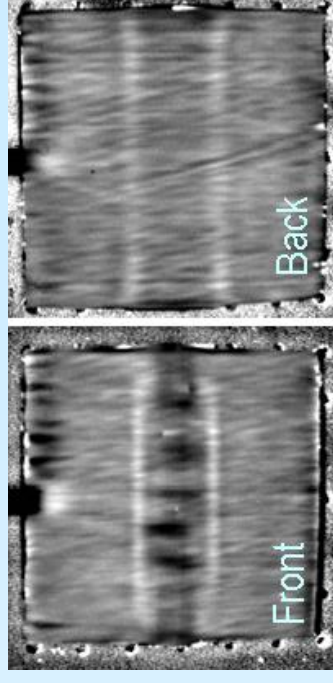
- Overwrap Concept: Co-cured

$[0/15/-15/0]_{2S}$ -HT(R1.5")- $[0/15/-15/0]_{1S}$ $[0/15/-15/0]_{2S}$ -[RS4A]₂-HT(R1.0")-[RS4A]₂- $[0/15/-15/0]_{2S}$



Cured Postcured Cured Postcured

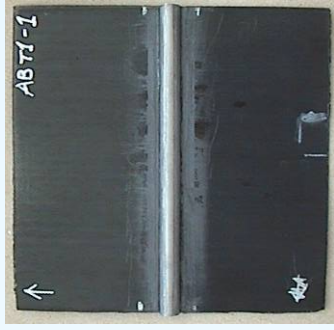
- ✓ No cracks on 16-ply despite of curvature, but debonded after PC due to curvature
- ✓ Cracks on 8-ply due to CTE mismatch, and localized delam and/or debonding



- ✓ Thin single crack on both 16-ply f/s
- ✓ Additional crack & localized delam/debond after PC on front f/s due to curvature
- ✓ Strong/rigid adhesive bond caused greater CTE mismatch?

PMC Radiator Sub-Panel Fabrication

- Adhesive-Bonding Concept



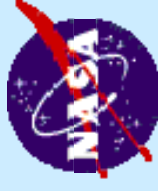
- ✓ RS-9D/K13D2U PMC f/s
- ✓ HT materials: SS vs. Al
- ✓ RS-4A film Adhesive (0.031 psf)
- ✓ Adhesive thickness?

□ Benefits:

- Easier fabrication, Lighter, and good manufacturability

□ Challenges:

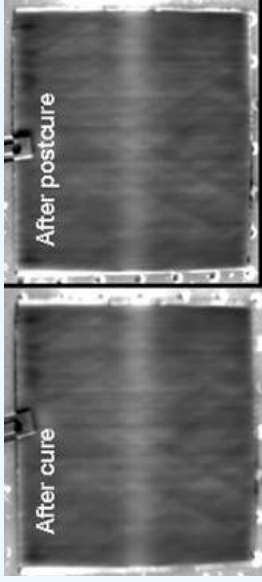
- Thru-thickness thermal conductivity
 - Strong and robust bonding
 - Vacuum bagging and cure conditions (autoclave) optimized to minimize resin squeeze-out and to reduce CTE mismatch
- ❖ PMC f/s cured @ 193°C for 2 hrs → stand. Surface prep → HT bonded & cured @ 177°C for 3 hrs → all postcured @ 204°C for 6 hrs



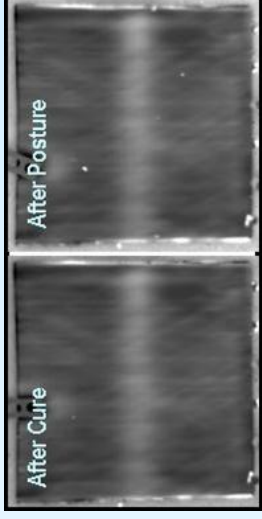
PMC Radiator Sub-Panel Fabrication

- Adhesive-Bonding Concept

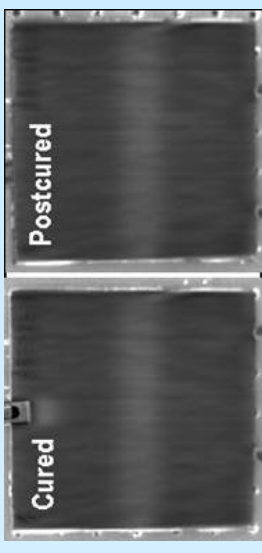
SS HT-[RS4A]₁-[0/25/-25/0]₁S



SS HT-[RS4A]₃-[0/25/-25/0]₁S



AL HT-[RS4A]₃-[0/25/-25/0]₁S

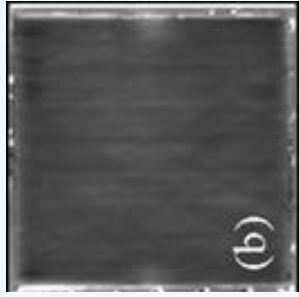


- ✓ Cured-postcured panels → No visual damage on PMC f/s and reasonable bonding regardless of HT type or bondline thickness
- ✓ 3-layer adhesive → more resin fillet formed at HT edges

PMC Radiator Sub-Panel Fabrication

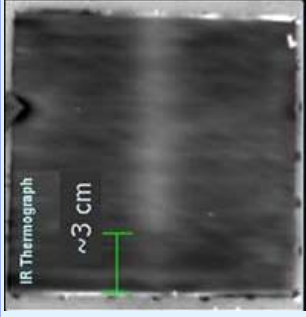
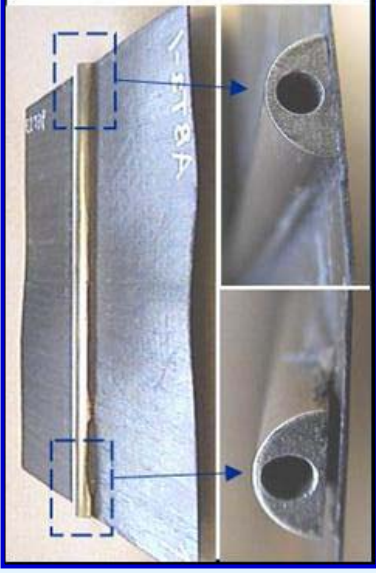
- Thermal Performance: 43°C ⇔ -153°C, 10-20 cycles

SS HT-[RS4A]₁-[0/25/-25/0]₁S



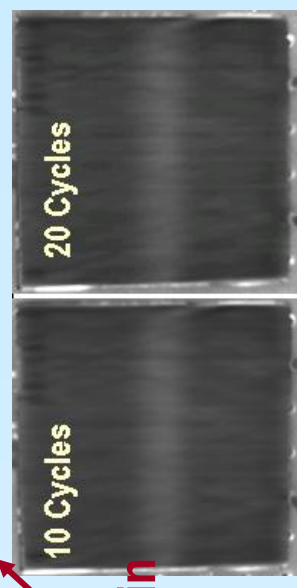
Heating/cooling rate not controlled

SS HT-[RS4A]₃-[0/25/-25/0]₁S

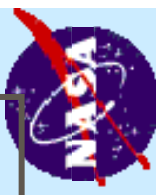


10°C/min

AL HT-[RS4A]₃-[0/25/-25/0]₁S



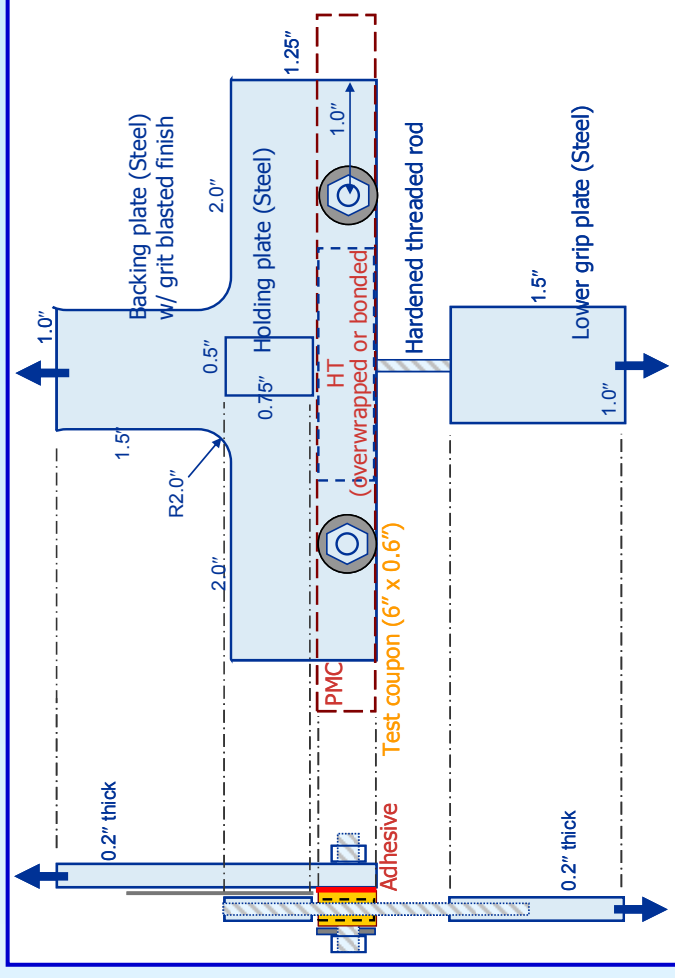
- ✓ SS HT panels under severer thermal cycling → 1-layer adhesive failed, but 3-layer survived w only edge debonding
- ✓ 100% adhesive failure on PMC f/s
- ✓ Under controlled rate, AL HT w 3-layer adhesive survived 20+ cycles



PMC Radiator Sub-Panel Fabrication

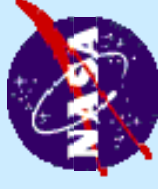
- HT-PMC bonding evaluation

- Sub-panel to be sectioned into ~0.6" wide test coupons
 - Both overwrap and adhesive-bonded panels
 - Optimized sectioning w/ a low speed diamond saw not to damage bondline
- Tested in lap-shear mode;
- Test fixtures designed and fabricated
- Tested at RT and 177°C (350°F)



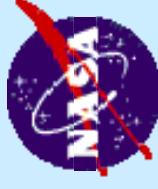
Summary

- ❑ Design and candidate material selection were made for PMC radiator development; and design and fabrication of PMC f/s panels were completed
- ❑ Nano-composites w/ two conductive nano fillers were evaluated for TC enhancement, but the improvement was very limited yet
- ❑ Performance and durability evaluations of PMC f/s including vacuum thermal aging, radiation hardness, and microcrack-TC relation were initiated
- ❑ For overwrap concept, the radius of HT curvature should be greater than 4.45 cm (1.75 in). PMC facesheet should be 16 plies or higher on both front and back side of the HT overwrap section. Then, weight saving concern? Micro slots or holes to reduce weight of HT
- ❑ Combination of overwrap and adhesive bonding is still persuasable option, but more ductile/soft adhesive systems with reasonable bond strength, good thermal conductivity, and high temperature capability, e.g., conductive nano-modified silicon based adhesive would be more suitable for the application?
- ❑ For the adhesive-bonding concept, the RS-4A Cyanate ester film adhesive performed well for both SS and Al HT with RS-9D/K13D2U PMC f/s.
- ❑ Thicker adhesive layer, ~0.04 cm (0.016 in), was recommended for the adhesive-bonding option based on thermal performance, and sizable resin fillet formed at the edges of HT would improve bonding integrity
- ❑ HT-PMC f/s bonding integrity will be quantitatively evaluated



Future Work Plan

- ❑ Complete vacuum thermal aging at all three Ts
- ❑ Complete microcrack-TC relations
- ❑ Complete bond strength evaluation
- ❑ Down-select and optimize material, design and process
- ❑ Develop fabrication-manufacturing specifications for a full-size component scale PMC radiator panels
- ❑ Continue nano-modification for thru-thickness TC improvement based on “cocktail Design” approach

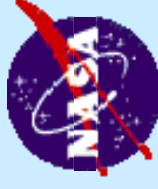


Future Work

- “Cocktail Design” Approach

Maximize/optimize the thru-thickness thermal conductivity of continuous fiber reinforced PMC, specifically focusing on

- ❖ **Synergistic chemical, physical, and structural modifications from molecular level to nano, micro, and macro scales including,**
 - Selection of high TC constituent Materials,
 - Molecular modifications of matrix resin system
 - High TC filler reinforcement but via cocktail design from nano to macro scale to maximize connectivity/architectural interactions
 - Filler loading ratio optimized in terms of connectivity, processability, and weight/density control
- ❖ Material-process selection based on performance prediction/theoretical modeling
- ❖ Optimizing material processing (mixing/dispersing) and structure (design and fabrication)
- ❖ Optimizing filler surface treatment for improved wetting and bonding w/ matrix resin
- ❖ Multi-functionalization; in addition to high TC, improve electrical conductivity and EMI shielding as well as good mechanicals



Future Work

- “Cocktail Design” Approach

Cocktail Modification Concept for Z-

Thermal Conductivity Improvement

Dimensions

Fibers:

K13D2U or K1100: ~10 μm dia

M40J & M60J: 5 μm dia

Matrix:

Molecular modifications for high TC;

Epoxies, Cyanate esters, Polyimides

Fillers:

Metal Flakes/Fibers/Spheres (MF) etc:

~ 1 mm L x ~0.5 mm W x ~25 μm Th

Chopped Fibers (CF): 3 – 5 μm Ø x ~ 50 μm L

Carbon Blacks (CB): ~ 3 – 8 μm Ø

Exfoliated Graphite Flakes (EGf):

~ 30 μm L x ~ 10 μm W x sub- μm Th

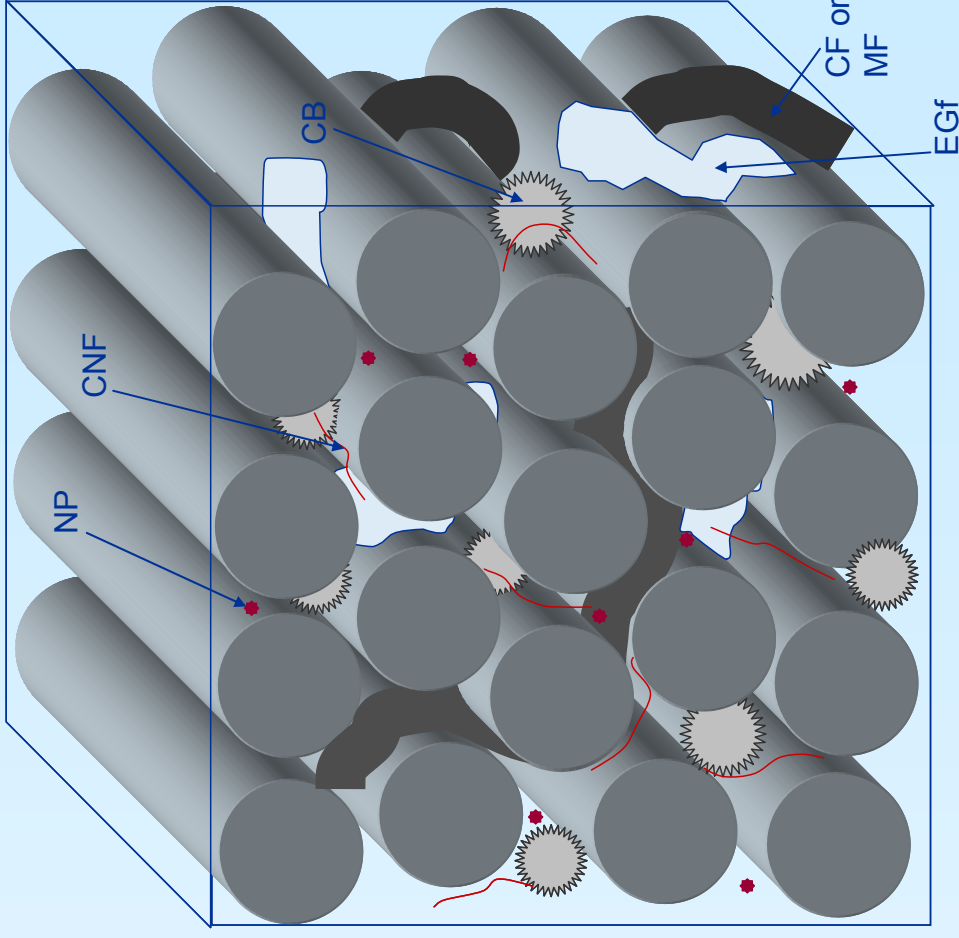
Carbon Nano Fiber (CNF):

~ 0.02 μm Ø x ~ 5 - 10 μm L

Nano-particulates (NP; metallic/ceramic):

~ 10 – 100 nm Ø

Optimize filler loading ratios, shape factors, and total amount in terms of thermal conductivity, processability, and composite performance and properties



e.g., Composite w/ 60 % FVF
+ total up to 20 wt% Filler loading