CARBON/CARBON MATERIAL APPLICATION TO SOLID ROCKET MOTOR NOZZLES

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Current design requirements for Solid Rocket Motor (SRM) nozzles drive the nozzle volume envelope, cost, throat erosion and weight to the smallest reliable number and the exit cone thrust level to the highest reliable number.

In addition, the nozzle must support the highest SRM chamber gas pressure and temperature, and the lowest gas, surface wall material erosion and charring.

To successfully apply C/C composite billets to production missile programs the design and manufacturing engineer must know the following five major design application factors:

1. Fabrication and Processing

First, what is a 2-D or 3-D billet? A 2-D square block is a series of alternating layers of graphite cloth (composed of warp and fill graphite fiber yarn bundles) and an impregnating resin. The square block is subsequently cured (325° F and 200/1,000 psi), carbonized (1,500° F), and graphitized (4,500° F). No axial (Z) graphite fibers are used.

The graphite fiber cloth is processed by graphitizing rayon, polyacrylonitrile (PAN) or pitch cloth. The resin is an epoxy, phenolic or pitch material.

Other methods used to fabricate 2-D cones include tape wrapping or rosette layup.
A 3-D C/C square block is a woven, flexible grid of (X) warp - (Y) fill - (Z) axial graphite fiber, yarn bundles.

Fabricating the 3-D block flexible fiber grid is a manual operation. The axial graphite epoxy rods are in place in a holding jig, with the X (warp) and Y (fill) graphite fiber bundle layers manually inserted by hand and packed down for tight fiber layer spacing.

The 3-D cone mandrel is filled with manually inserted radial (Y) fill graphite-epoxy rods and the automated graphite is placed by hoop (X) warp helix winding and the axial (Z) polar winding by machine. The spacing between fiber bundles may vary from 0.040 to 0.125 inch.

An impregnating resin (epoxy - phenolic - pitch) fills the voids between fiber bundles and is subsequently carbonized and graphitized (similar to the 2-D block), rigidizing the block.

Densification of billets with resin char is done at 200 to 15,000 psi. For both the 2-D and 3-D blocks, the number of impregnating resin - curing - carbonization - graphitization cycles will determine billet density and porosity. The range of billet density is 1.45 to 2.05 gr/cc, with a goal of 10% porosity or less at 1.85-1.95 gr/cc density.

The 2-D and 3-D billet process parameters for fiber percent by weight in the finished block and the fiber distribution in the three planes is shown below:

C/C Type	Billet Fiber Weight-Percent		Percent Fiber Distribution X-Warp	Y-Fill	Z-Axial
2-D	50 - 60%		55%	45%	0%
3-D	40 - 50%	1	35%	10%	55%
		2	55%	10%	35%

2. Cost-Schedule-Size

The cost and delivery time for C/C billets will depend on:

1. Min-max diameter, length and radial thickness
2. Type of graphite fiber - high or low modulus
3. Spacing between fiber bundles in X-Y-Z directions.
4. Density of finished billet
5. Specification testing requirements

A cost, schedule and a current billet size limitation for 2-D and 3-D billets is listed in Table I.

Generally the 2-D C/C billets are used in nozzles as short inlet and throat rings and long exit cones, while 3-D C/C billets are used as a short one piece nose-inlet-throat (ITE) cone. Figure 1 shows typical submerged nozzles with design application areas - (nose-exit cone) listed.

3. Material Properties

A comparison of 2-D and 3-D material properties from cylinder or cone tag ends or blocks at room and elevated temperatures is listed in Table II. The 2-D billet is fabricated with low modulus/strength graphite fiber, while the 3-D billets are processed with a higher strength/modulus graphite fiber.

Quality control of the billets is achieved by density and X-ray inspection of the cured 2-D preform and 3-D woven fiber grid preform and after each 2-D/3-D impregnation-graphitization cycle. In addition, the billet is tested for mechanical-thermal properties to compare to specification requirements.

4. Design Application Examples

The material design application has been achieved by two routes.

1. Design and test of a complete 2-D C/C fixed submerged nozzle (Figure 1) with the ablative, insulative, and structural shells combined into a single function

material using rosette, flat laminate and tape wrap cloth processing.

2. Redesign of a current movable submerged nozzle for a 3-D C/C Integrated Throat-Exit (ITE) short cone and a standard tape wrapped carbon cloth phenolic reinforced plastic throat support, forward exit cone and submerged liner (Figure 2).

Both designs allow the design and manufacturing engineers to assess C/C nozzle costs, weight, reliability and erosion-char depth performance.

As for machining, bonding, aging and handling characteristics, the C/C composites act like reinforced plastics. For bonding C/C materials to RFP or metals, use an EA934 HySol epoxy. To bond C/C to itself, use C-34 Union Carbide carbon cement.

5. Static Test Performance

The static test performance of 3-D C/C material, while limited to cylinders or rings in the nose-inlet-throat area of nozzles in approximately 22 motor tests, has been 100% successful. No motor failures have been attributed to the 3-D C/C material. The erosion rates have been zero mils/sec minimum to a 9.0 mils/sec maximum. In addition, no delaminations or cracks have been noted in the postfired billets.

Considering 2-D C/C experience on more than 100 motor tests of approximately 200 2-D C/C rings tested as inlets, throats and exit cones - at least two inlet-throat rings and two exit cones have failed in static test. More 3-D C/C test experience is required to make an equal assessment of 2-D vs 3-D C/C future potential in all areas of the nozzle design.

A comparison of the 3-D C/C erosion performance in the inlet and throat vs 2-D C/C and PG and 2-D C/C vs carbon phenolic in the forward exit cone is given in Table III.

Summary

The application of extensive C/C composites to SRM nozzles will be easier with the five design application factors. The C/C design is lighter, simpler, and has smoother post-test wall surface and better structural integrity. However, C/Cs do cost more, need more tests, properties fabrication history, and lead purchase time.

The final decision to extensively use C/C composites in a production SRM missile program will be made by each manufacturer on the basis of the following items:

- Available development time and funding
- Design criteria requirements
- Design and manufacturing state-of-the-art
- SRM risk priority assessment

TABLE I

COST, SCHEDULE, SIZE LIMITATIONS

C/C Type	Max Dia (in.)	Max Length (in.)	Max Radial Thickness (in.)	Cost Range ($/lb)	Mfg Delivery Time (Months)
2-D Billets					
Blocks-Rings	40.0	2.0	2.0	100/600	4/6
Cylinders-Cones	72.0	96.0	1.5		
Suppliers - Carborundum - Kaiser - Polycarbon - Hitco					
3-D Billets					
Blocks-Rings	12.0	48.0	6.0	400/	6/8
Cylinders-Cones	30.0	56.0	6.0	1,500	
Suppliers - Avco - FMI - General Electric - McDonnell Douglas					

TABLE II

3-D/2-D C/C MATERIAL PROPERTIES

Type	Tensile Strength and Modulus X Warp	Tensile Y Fill	Tensile Z Axial	Compressive Strength and Modulus X Warp	Compressive Y Fill	Compressive Z Axial	Shear Strength and Modulus X Warp	Shear Y Fill	Shear Z Axial	Compression Poisson's Ratio XY/Z	Poisson's Ratio Z/XY	Coeff of Thermal Expansion X Warp	CTE Y Fill	CTE Z Axial	K Thermal Conductivity X Warp	K Y Fill	K Z Axial
1. 2-D C/C Ring SG = 1.55 T-50 Fiber Phenolic Resin RT	5,750 psi 1.68×10^6 psi		400 psi 0.47×10^6 psi	5,800 psi 1.30×10^6 psi		15,500 psi 0.25×10^6 psi	1,200 psi 0.74×10^6 psi		3,500 psi N/A	0.25	0.08	RT to 250°F 0.50		1.12	RT 54.0		23.4
3,000°F	7,750 psi 1.85×10^6 psi		650 psi 0.45×10^6 psi	8,000 psi 1.20×10^6 psi		22,300 psi 0.25×10^6 psi	1,200 psi N/A		N/A	0.25	0.08	RT to 1,800°F 1.12		1.95	at 1,500°F 27.0		12.2
	X-Hoop	Y-Radial	Z-Axial	X-Hoop	Y-Radial	Z-Axial	X-Hoop	Y-Radial	Z-Axial			X Hoop	Y Radial	Z Axial	X Hoop	Y Radial	Z Axial
2. 3-D C/C Rings-Blocks T-50 Fiber Pitch Resin SG = 1.90 RT	N/A	N/A	25,866 psi 19.53×10^6 psi	6,173 psi 6.65×10^6 psi	8,467 psi 6.56×10^6 psi	16,866 psi 16.36×10^6 psi	2,790 psi N/A	N/A	4,040 psi N/A	N/A	N/A	RT to 250°F -0.50		N/A	RT 117.0		99.0
3,000°F	N/A	N/A	23,600 psi 11.50×10^6 psi	N/A	N/A	15,500 psi N/A	N/A	N/A	N/A	N/A	N/A	RT to 1,800°F -0.35		N/A	at 1,500°F 52.5		46.0

NOTES 1. CTE Terms in./in.-°F x 10^{-6}
2. K terms BTU/ft-hr-°F

TABLE III

EROSION PERFORMANCE COMPARISON

Mtl	Inlet Erosion (mils/sec)	Throat Erosion	Forward Exit Erosion	Forward Exit Cone
2-D C/C	ϵ = 1.26 - 1.50 p = 689 - 1,100 psi 9.44 m/s	ϵ = 1.0 p = 550 - 1,100 psi 7.80 m/s avg 3 rings	ϵ = 1.10 - 1.17 4.05 m/s	ϵ = 2.0 1.31 m/s
3-D C/C	5.46 m/s avg 3 tests	3.87 m/s	2.30 m/s	--
PG	--	2.98 m/s	--	--
GCP/CCP	16.32 m/s	15.61 m/s	7.60 m/s	2.89 m/s

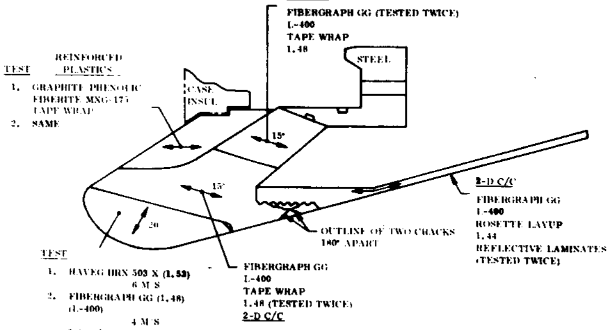

Figure 1. 2-D C/C Fixed Submerged Nozzle

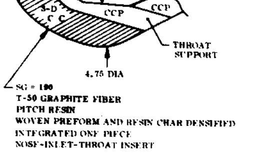

Figure 2. Reinforced Plastic - 2-D/CC - PG Redesign for 3-D C/C