Large Carbon-Carbon Grids for High Power, High Specific Impulse Ion Thrusters

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Abstract. NASA is investigating high power, high specific impulse propulsion technologies that could enable ambitious flights such as multi-body rendezvous missions, outer planet orbiters and interstellar precursor missions. Ion engines can efficiently operate at very high specific impulse, but accelerating voltages of many kV result in greater ion optics wear rates due to high energy ion bombardment. These lifetime issues can be addressed by the use of ion optics grid materials such as carbon with very low sputter yields and optics designs which minimize the flux and energy of ions to the grid surfaces. This paper reports performance and lifetime predictions based on numerical modeling and issues associated with fabrication of carbon-carbon composite grids for high power, high Isp grids.

INTRODUCTION

The demonstration of ion propulsion on the Deep Space 1 mission has paved the way for applications of advanced electric propulsion on more demanding future missions such as outer planet orbiters, multiple body rendezvous missions, sample return missions and interstellar precursor flights. However, these exciting missions place much greater demands on the propulsion system, as shown in Figure 1 (Noca, 2003). The chemical propulsion systems that have been used on most planetary missions to date have delivered ΔVs of a few km/s. Near-term missions demanding ΔVs of 10-40 km/s can be accomplished using Solar Electric Propulsion (SEP) systems processing between 10 and 25 kWe with specific impulses of 3000-5000 s. More ambitious missions require ΔVs ranging from 30 to over 100 km/s. To accomplish these missions with reasonable initial masses and tolerable trip times requires advanced Nuclear Electric Propulsion (NEP) systems capable of processing from 100 to 500 kWe of power at I_{sp}'s ranging from 7000 s to over 14000 s (Noca, 2003; Johnson, 1999). The burn times for these missions range from five to ten years. Future ion propulsion systems must therefore operate at higher power levels, higher I_{sp}'s and with longer lifetimes than state-of-the-art SEP systems.

One of the life-limiting components in ion thrusters is the ion accelerating system, composed of two grids with aligned apertures. The upstream screen grid is biased to a high positive potential and serves to extract ions from the discharge into individual beamlets that form the ion beam. These beamlets are focused through apertures in the downstream accelerator grid, which is biased negative of the ambient space potential and serves to prevent electrons from flowing upstream and minimize the loss of neutrals from the discharge chamber. Charge exchange reactions between the beam ions and those neutrals which do leak into the gap between the grids or downstream of the accelerator grid create ions which may not be focused properly. Some of these charge exchange ions strike the hole walls or the downstream surface of the accelerator grid, causing erosion by sputtering.

The erosion rate is determined by the energy of the ions striking the grid and the sputter yield of the material. The charge exchange ion energy depends on the potential in the location where they are created

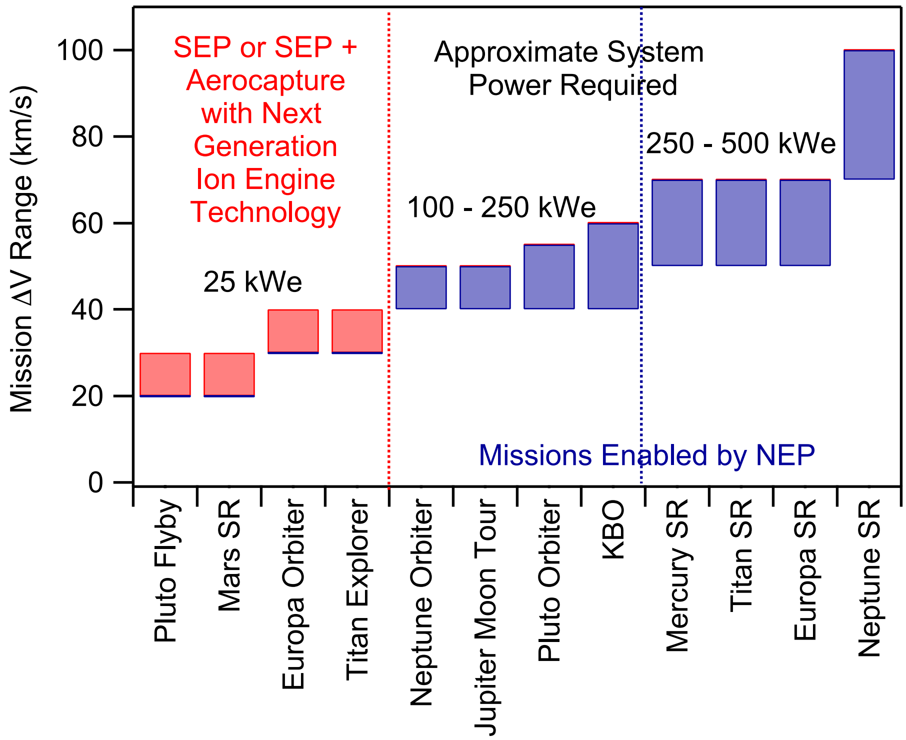

FIGURE 1. Future missions require much higher ΔV capability.

and the potential of the accelerator grid. Ions bombarding the hole walls are generally created in the interelectrode gap and are therefore accelerated through a potential difference which may be a large fraction of the total voltage difference between the grids. Ions which strike the downstream surface generally have lower energies because they are created at ambient ground potential or lower and are accelerated into the negative accelerator grid. The higher I_{sp}'s demanded by NEP applications are achieved by increasing the total accelerating voltage. This can aggravate grid erosion in two ways. First, the potential upstream of the accelerator grid is higher, increasing the energy of ions created between the grids which strike the hole walls. Second, the accelerator grid voltage must be more negative to prevent electron backstreaming, which increases the energy of ions hitting the hole walls and the downstream surface. This effect makes achieving the long thruster life required for NEP applications very challenging.

These lifetimes can be achieved through the use of advanced grid materials and design techniques. State-of-the-art thrusters for SEP systems use molybdenum grids. Carbon-carbon composite grids offer the potential for a significant increase in life because they have a sputter yield which is five to seven times lower than that of molybdenum (Deltschew, 2001; Meserole, 1993). Additional lifetime gains can be achieved by designing the grids to focus most of the charge exchange ions through the accelerator grid apertures and minimize the magnitude of the voltage required by the accelerator grid. The fabrication techniques for carbon-carbon composite grids are relatively less mature than the well-developed processes for molybdenum grid fabrication. Many of the fabrication challenges were addressed in the early 1990's at JPL for 15-cm and 30-cm diameter carbon-carbon grids (Mueller, 1993, 1995 and 1997). There are currently three development programs at JPL focused on scaling up the technology for larger engines. The Carbon-Based Ion Optics (CBIO) program is focused on developing 40-cm diameter grids as an upgrade for NASA's Evolutionary Xenon Thruster (NEXT), which is a part of the next generation ion propulsion system for SEP missions. These grids are designed to operate at 6 kWe and an I_{sp} of 4050 s. Carbon-carbon grids for far-term interstellar precursor missions are under development as part of the Cross Enterprise Technology Development Program (CETDP). These grids are 75 cm in diameter and are designed to operate at 14000 s I_{sp} and 30 kWe on an engine being built by the

NASA Glenn Research Center (Patterson, 2000; Rawlin, 2001). Finally, 65-cm diameter carbon-carbon grids are being designed for operation at 7500 s and 20 kWe for near-term NEP applications under the Nuclear Electric Xenon Ion System (NEXIS) program as part of NASA's Nuclear Systems Initiative. The focus of this paper is on the design and fabrication of the large, high I_{sp} grids for the latter two programs.

HIGH Isp GRID DESIGN APPROACH

The key to high power, high Isp thrusters is the grid design. Challenges include developing a geometry that extracts the required current density with proper beamlet focusing over the range of plasma densities produced upstream of the grids with a realistic electric field. Underfocusing in the high density regions in the center of the grid and overfocusing at the periphery can cause direct ion impingement on the hole walls in the downstream grid. In addition, the voltage on the downstream grid must be chosen to prevent electron backstreaming. The optics design must also properly focus the charge exchange ions created in the interelectrode gap to minimize hole wall erosion. Finally, the grids must be designed to minimize the dynamic loads encountered during launch.

A number of innovations allow these challenges to be met. New ion optics simulation tools and detailed structural modeling of grids fabricated from carbon-carbon composites have provided the insight to design long-life, high performance grids. The key features derived from these design tools include:

- use of relatively thick screen grids to improve the range of plasma densities over which proper focusing can be achieved,
- operation with large perveance margins (beam current densities low compared to those at which direct impingement due to underfocusing occurs) to minimize flux and energy of ions to the hole walls, and
- grid dishing and incorporation of very stiff mounting structures bonded directly to the screen grid periphery to minimize stresses from dynamic loads

The ion optics simulation tools described in (Katz, 2003) have been used to design 7500 s grids for the NEXIS application and 14000 s grids for the CETDP application. The resulting grid geometries are summarized in Table 1.

At these high voltages it is often difficult to design optics which operate over the large radial variation in plasma density that is typically produced upstream of the grids in the discharge chamber. However, the relatively thick screen grids in these designs offer a very high dynamic range, as shown in Figures 2 and 3. These plots show the ratio of accelerator grid impingement current to beam current as a function of beamlet current measured for the NEXIS and CETDP designs in subscale tests with xenon propellant. These data were obtained by operating 10 cm diameter carbon-carbon gridlets containing 7 apertures each on a small ion source at Colorado State University (Wilbur, 2001). The ratio of accelerator grid current to beam current rises at low beamlet currents (which corresponds to low upstream plasma densities) because of direct impingement due to overfocusing and at high beamlet currents (high densities) because of underfocusing. The peak beamlet currents required by the designs summarized in Table 1 are about 4–5 times higher than the crossover limits. These dynamic ranges can be accommodated by carefully designing the discharge chamber to achieve a relatively uniform plasma density profile. The plots also show the current limits predicted by the codes, which agree quite well with the measured crossover limits, but tend to underpredict the beamlet current at which the perveance limit is reached.

The plots in Figures 2 and 3 also demonstrate that the peak beamlet current for the two designs is significantly lower than the perveance limit. The benefit of this design approach is shown in Figure 4, in which the hole wall erosion rate predicted by the ion optics simulation code is plotted as a function of beamlet current for the CETDP grids operating on krypton. These simulations assume that the engine size increases as the peak beamlet current decreases to maintain a constant total beam current. As the engine

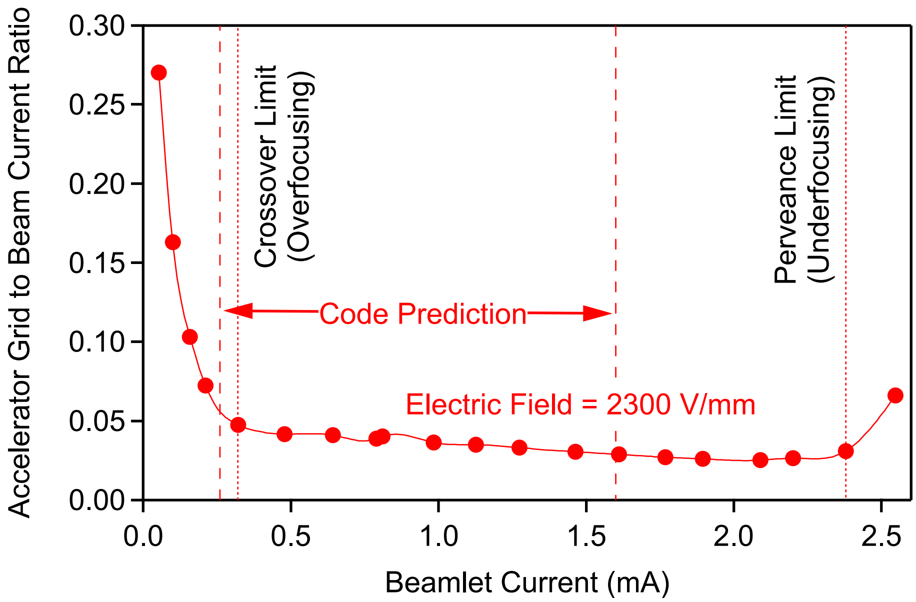

FIGURE 2. NEXIS grid performance measured in subscale gridlet tests and predicted by the design codes.

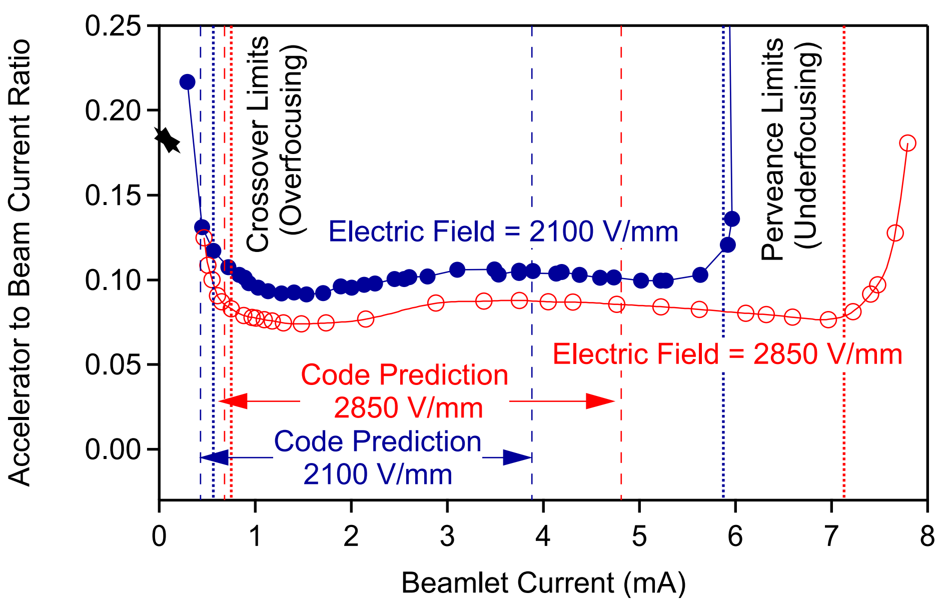

FIGURE 3. CETDP grid performance measured in subscale gridlet tests and predicted by the design codes.

Parameter	NEXIS	CETDP
Thruster		
Power (kWe)	19.9	30
I_{sp} (s)	7500	14000
Propellant	Xenon	Krypton
Thrust (N)	0.42	0.33
Efficiency	0.75	0.74
Screen Grid		
Maximum Voltage (V)	4870	13000
Thickness (mm)	2.00	4.00
Hole Diameter (mm)	6.83	12.1
Webbing Width (mm)	1.12	2.3
Open Area Fraction	0.67	0.64
Ion Transparency	0.75	0.65
Accelerator Grid		
Minimum Voltage (V)	-560	-850
Thickness (mm)	2.73	4.0
Hole Diameter (mm)	4.10	7.3
Open Area Fraction	0.24	0.24
Optics Assembly		
Active Beam Diameter (cm)	57	60
Peak Beamlet Current (mA)	1.38	2.38
Hole Spacing (mm)	7.94	14.4
Dish Depth (mm)	76	76
Grid Gap (mm)	2.36	6.6
Electric Field (V/mm)	2300	2150

TABLE 1: Geometry and Operating Conditions for NEXIS and CETDP Grids.

size grows, the density of neutral propellant that escapes from the engine decreases as well. Operating at current densities that are low compared to the perveance limit also causes most of the charge exchange ions formed between the grids (which have the highest energies) to be focused through the accelerator grid apertures, rather than striking the grids (Brophy, 2002). This effect combined with the reduced density of neutral atoms from which the charge exchange ions are created results in a dramatic reduction in the hole erosion rate as the beamlet current is decreased. At the erosion rate shown in Figure 4 for the design point, structural failure due to hole wall erosion ceases to be a credible failure mode. Structural failure due to erosion of the downstream surface is mitigated by the use of sputter-resistant carbon-carbon and very thick accelerator grids.

The key to surviving launch loads is the structural design. Three dimensional finite element models have been used to design the CETDP grids and are now being applied to the NEXIS design. The primary design variables are the dish depth and the screen grid boundary constraint. Conventional molybdenum grids are dished so that both grids buckle in the same direction as they get hot, helping maintain the desired grid gap. Carbon-carbon has a coefficient of thermal expansion near zero, so thermal buckling is not a concern. However, large carbon-carbon grids must be dished to increase their stiffness. The accelerator grid and the screen grid with its mounting system were modeled separately. These models did not include the apertures machined into the grids or the inherently non-isotropic properties of the composite material. Instead, the properties of the laminate were estimated using standard micromechanics methods and additional detailed finite element models of local regions of the grids including the apertures were used to determine the effect of the holes on the properties of the composite. These results were then used to define effective properties of an equivalent homogenous material with no apertures. The damping ratio used in the dynamic simulations was based on measurements of 30 cm diameter slotted grids. The simulations of loads that are representative of a Delta IV Heavy launch revealed that the screen grid is most susceptible to damage because its higher

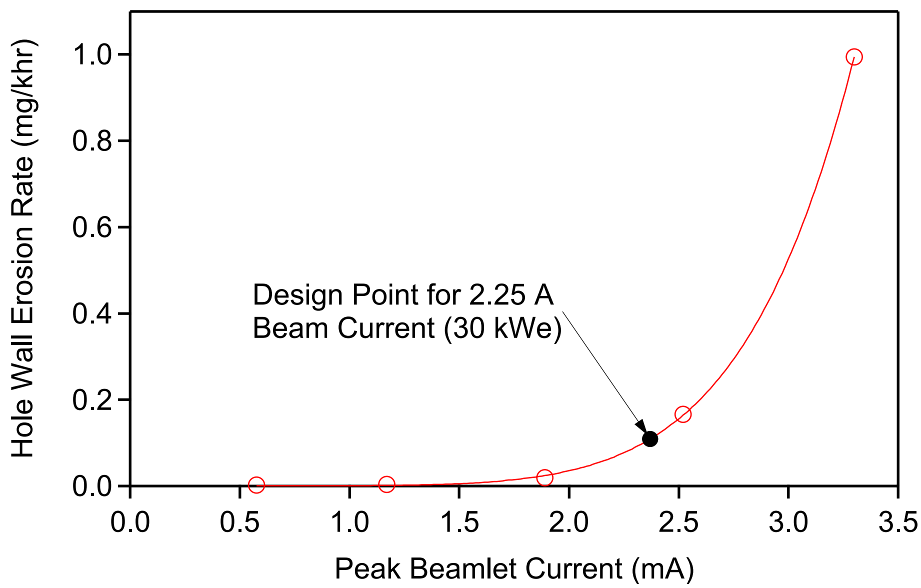

FIGURE 4. Hole wall erosion rates in the CETDP grid design increase dramatically as the beamlet current approaches the perveance limit.

open area fraction results in lower strength than the accelerator grid. A range of dish depths were studied, and for a 76 mm dish depth the modal analysis yielded 54 modes with frequencies between 388 and 2000 Hz. The one-sigma deflection was 0.25 mm for the screen grid, which corresponds to a 3-sigma stress level of 501 psi. The strength of the screen grid material adjusted for the high open area fraction is expected to be 896 psi, so the 76 mm dish depth gives a margin of safety, defined as MOS = (allowable stress - calculated stress)/calculated stress, of 0.78. This MOS should accommodate any uncertainties in loads and variability in manufacturing.

The constraints at the periphery of the screen grid were also varied, and the results showed that bonding the screen grid to a very stiff structure can significantly impact the results. The structure currently being used in the grids under development for the CBIO program are shown in Figure 5. It consists of a carbon-carbon box structure with radial ribs between two concentric cylindrical walls. A carbon-carbon ring is bonded to the upstream end of the cylindrical strucutre and serves as the interface between the optics assembly and the insulators that attach it to the engine body. An additional ring is bonded ot the downstream side of the structure and then the screen grid itself is bonded to that ring. The adhesive used in these bonds is carbonized at high temperature, so the resulting structure is exceptionally strong, lightweight and will not outgas at engine operating temperatures. A scaled-up version of this structure used in the finite element model of the CETDP grids is shown in Figure 6.

FABRICATION OF LARGE CARBON-CARBON GRIDS

Carbon-carbon grids offer a number of advantages over conventional grids, but there are challenges associated with fabricating large grids for high I_{sp} applications. The grids must be strong enough to survive the dynamic loads during the launch phase and be affordable. The completed grids must meet certain tolerances in curvature, aperture placement and aperture diameter and the assembly must meet tolerances for the grid gap. For high voltage applications the grids must have a sufficiently high quality surface finish to prevent excessive arcing.

All of these challenges are being addressed in the current programs. The innovations which make fabricating large carbon-carbon grids that can operate at high voltages include:

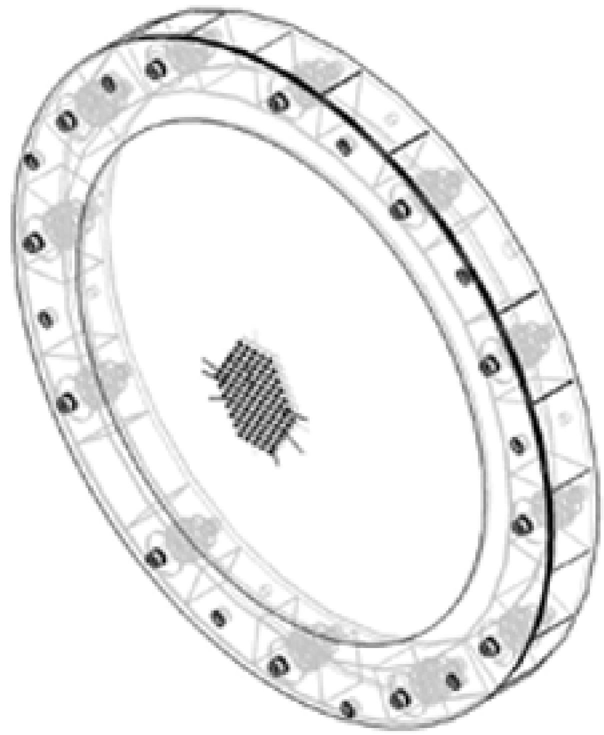

FIGURE 5. Ion optics assembly for the CBIO grids showing the screen grid bonded to a strong, lightweight carbon-carbon box structure.

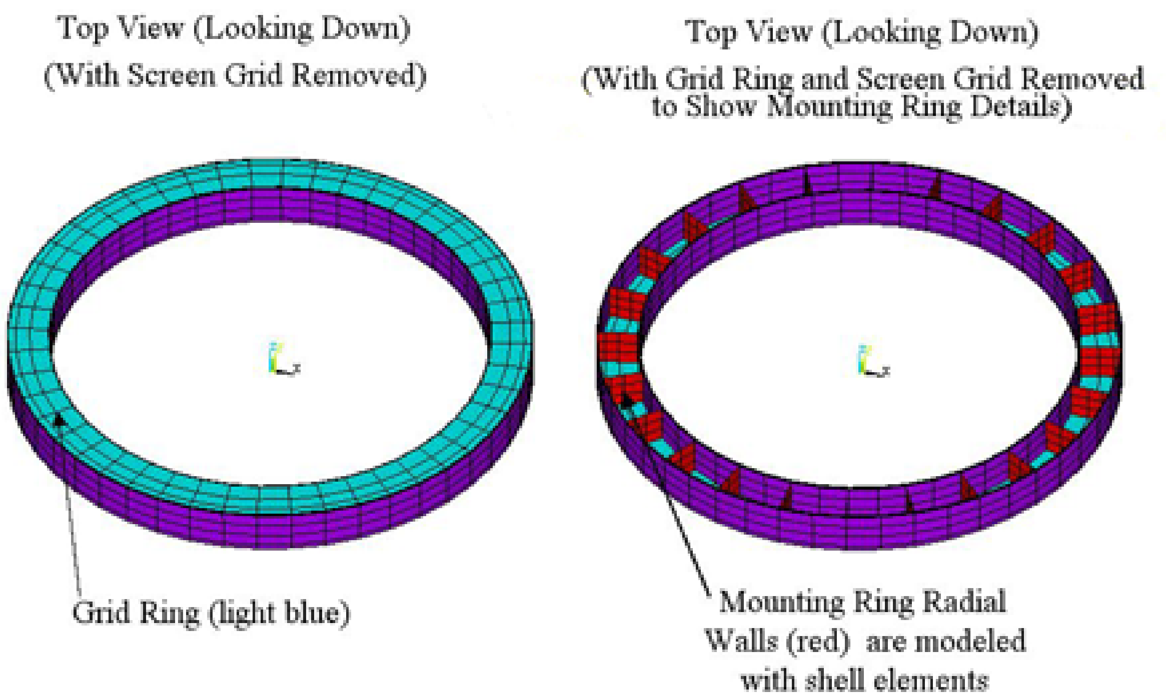

FIGURE 6. Mounting structure used in dynamic loads analysis of CETDP grids.

- the use of inexpensive, low modulus fibers during layup. The modulus is subsequently increased during processing to give very high strength,
- the use of uniaxial tape in a [0, +60, -60]s layup to maximize the fiber volume fraction and the number of continuous fibers with a hexagonal array of apertures,
- specialized tooling, processing and machining techniques to maintain the required tolerances, and
- proprietary processing techniques to produce arc-resistant surfaces.

A low-cost high-modulus carbon-carbon composite originally developed under Air Force sponsored programs was selected for these projects. This process uses low-modulus (25 msi or 175 Gpa) carbon fiber initially, which is significantly lower in cost than traditional high modulus carbon fiber (e.g. P100) and is very easy to weave with minimum fiber damage during weaving. The low modulus fiber is converted to 100+ msi (700 Gpa) in-situ during the standard C-C processing steps.

The 15-cm grid development program was extremely successful in demonstrating fabrication techniques for strong flat panels using plies of unidirectional tape (Mueller, 1993, 1995 and 1997). The [0/+60/-60]s layup consists of six plies with fibers aligned along the -60°, +60°, 0°, 0°, +60° and -60° directions in the different plies. The layup is symmetrical with respect to the center plane to prevent warpage. This particular layup was chosen because it allows a portion of the fibers in each ply to run between grid holes without being cut, thus increasing the strength of the grid. The key issues in panel development were strength, thickness, and flatness. The unidirectional tape layups have a very high fiber volume, which results in the strongest quasi-isotropic carbon-carbon material ever made. The critical structural property is the flexural modulus, because it determines how far the grid may bend due to electrostatic or vibrational (launch) loads. The [0/+60/-60]s layup yielded a flexural modulus in the 0 direction which is 80fabricated using this approach.

One of the critical steps in achieving the required tolerances is careful layup to produce a balanced composite. Misalignment of the plies can cause warping in the completed panel. The techniques required to avoid warping were developed under the 15-cm diameter grid development program, in which high yield fabrication of flat panels was demonstrated. These techniques are now being applied in the CBIO program for larger dished grids with excellent results. Another key to maintaining dimensional tolerances is proper fixturing during the processing. Male and female molds of the desired final grid shape are used in the initial layup, curing and carbonization. Supporting fixtures which have been designed to provide good gas flow to the panels are subsequently used for carbon vapor infiltration (CVI) densification. The original molds are used for the high temperature heat treatment to set the grid in the desired shape. Excellent tolerance control has also been achieved recently on four sets of 1 mm thick, 30 cm dished grids, demonstrating that improvements in fixturing and processing have eliminated problems with dish depth relaxation after machining that were encountered earlier (Mueller, 1997).

A proprietary process has been developed to improve the arc resistance of the optics assembly at very high voltages. A dramatic reduction in the probability of arcing between the grids was demonstrated in subscale tests of treated and untreated gridlets at Colorado State University. The untreated gridlets exhibited frequent arcing and operation at voltages above 10000 V with electric field strengths of 2100–2800 V/mm was impossible. With the treated gridlets, operation with total voltages between the grids as high as 13950 V and electric field strengths up to 2800 V/mm was achieved. No evidence of excessive arcing has been observed in testing of 30-cm diameter grids at up to 3000 V under the CBIO program.

The prototype flat grids shown in Figure 7 have been fabricated and machined for the CETDP program. Low-cost and low modulus P30 carbon fiber was procured from Cytec and woven into a balanced harness fabric. The fabric was prepreged with phenolic resin per Allcomp specification and then cut and laid up with [0/90, 45, 45, 90/0]s and [0/90, 45, 45, 90/0]2s ply orientation for the 2 mm and 4 mm thick grid panels. This layup was used rather than the uniaxial tape layup to reduce fabrication costs, because the flat grids are being used to prove the electrostatic design and are not required to have the high strength and stiffness to survive dynamic loads. After curing at 180° C under pressure to the desired thickness and fiber volume, the composite panels were inspected and characterized. The cured panels were further carbonized and CVI densified before a high temperature graphitization to increase the fiber modulus. The grid panels

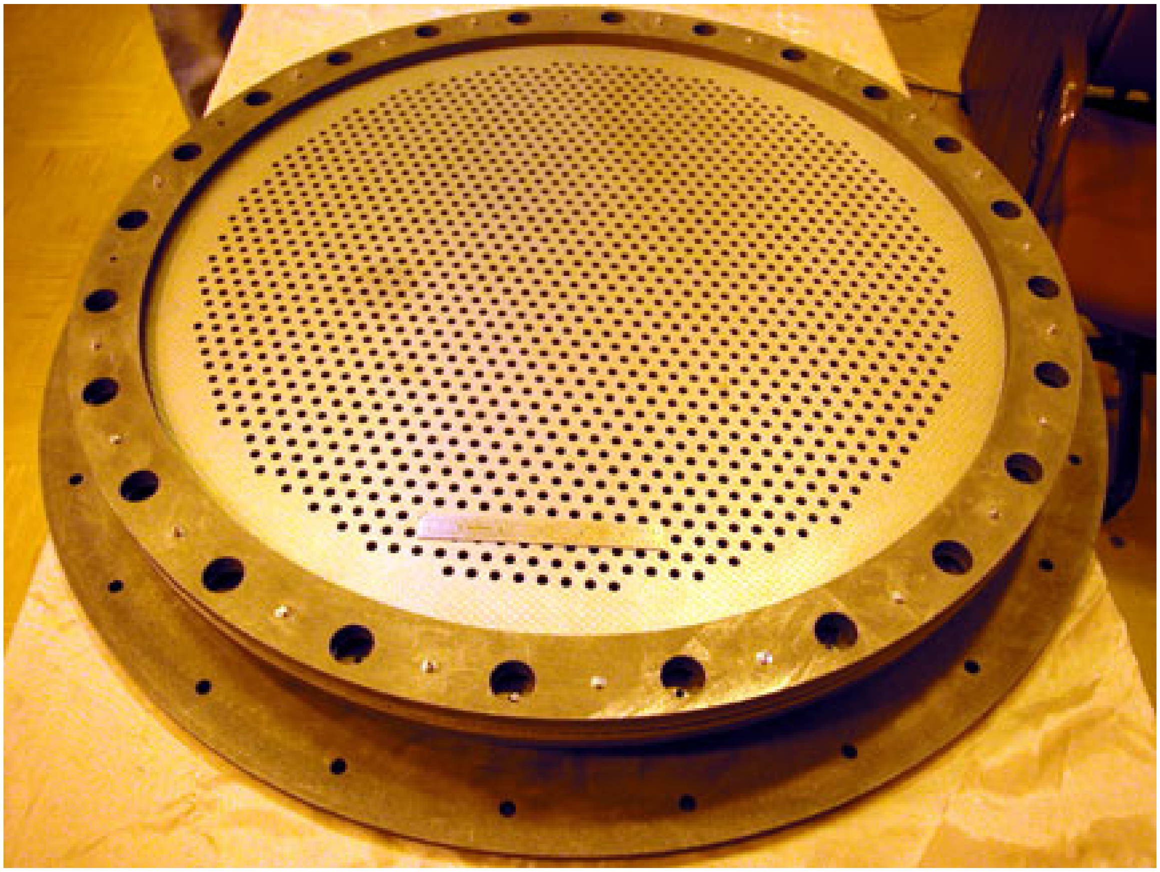

FIGURE 7. 75-cm diameter carbon-carbon grids designed to operate at 14000 s.

were graphitized under flat fixture plates to ensure overall flatness of the grid panels. After inspection and further characterization, grid holes were mechanically drilled. The grids were then treated to improve arc resistance.

The 80 cm diameter panels were flat to within 1.5-1.75 mm. After machining and final processing, the grids were mounted onto graphite adapter and stiffening rings and assembled with a nominal grid gap of 5.5 mm. The stiffening rings removed the small nonuniformities apparent in the original panels and resulted in a gap that was uniform to within ±4 percent. The optics assembly has been tested in vacuum at up to 15000 V with very little leakage current and no signs of excessive arcing. They are scheduled to be tested on the 75-cm diameter engine at NASA Glenn Research Center in the near future.

CONCLUSIONS

Future deep space missions require higher power levels, higher specific impulse and longer life from ion propulsion systems, placing great demands on the ion optics. These requirements can be met with advanced technologies such as carbon-carbon grids, but a number of design and fabrication challenges must be overcome. Recent improvements in ion optics modeling tools have resulted in grid designs which operate over a large range of plasma densities and focus most of the charge exchange ions through the accelerator grid apertures, which is the key to mitigating hole wall erosion. The performance benefits of these designs have been proven in subscale gridlet tests for I_{sp}'s of 7000 to 14000 s. An innovative mounting system design employing a carbon-carbon box structure bonded directly to the screen grid results in an assembly stiffness that greatly reduces stresses in the fragile screen grid from dynamic loads.

The critical fabrication issues for large, high I_{sp} carbon-carbon grids have also been addressed. Prototype flat grids up to 75-cm in diameter and 30-cm dished grids have been fabricated at low cost and have demonstrated very high strength, control of critical dimensions and excellent arc resistance. These results show that large, high I_{sp} grids can be developed for near-term NEP applications with relatively low technical risk.

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