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. 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 10-15 km/s can be accomplished using Solar Electric Propulsion (SEP) systems processing between 10 and 25 kW of 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 kW of power at Isp’s ranging from 7000 to over 14000 s. The burn times for these missions range from five to ten years. Future ion propulsion systems must therefore operate at higher power levels, higher Isp’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 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.
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 those ions 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 grids 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, as shown in Figure 2. 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 diameter carbon-carbon grids. 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. Finally,
FIGURE 2. Carbon grids have a much lower sputter yield than state-of-the-art molybdenum grids.

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. The focus of this paper is on the design and fabrication of the large, high Isp 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 simulation 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
- 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
FIGURE 3. NEXIS grid performance measured in subscale gridlet tests and predicted by the design codes.

summarized in Table 1. At these high voltages it is often difficult to design optics which operate over the large range of plasma densities that are 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 3 and 4. 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. These data were obtained by operating 10 cm diameter carbon-carbon gridlets containing 7 apertures each on a small ion source (ref). 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 dynamic range between these two limits is quite large and can easily be accommodated with careful discharge chamber design. The plots show the current limits predicted by the codes, which agree quite well with the measured limits.

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 \( I_{ap} \) 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:

- 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,
- the use of inexpensive, low modulus fibers during layup. The modulus is subsequently increased during processing to give very high strength,
- specialized tooling, processing and machining techniques to maintain the required tolerances, and
FIGURE 4. CETDP grid performance measured in subscale gridlet tests and predicted by the design codes.

- proprietary processing techniques to produce arc-resistant surfaces.

XXX-Unitape layup description...

The 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 prototype flat grids shown in Figure 5 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. 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, so this layup was used rather than the uniaxial tape layup to reduce fabrication costs. After curing at 350 F 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 high temperature graphitized to increase the fiber modulus. Grid panels were graphitized under flat fixture plate to ensure overall flatness of the grid panels. After inspection and further characterization, grid holes were mechanically drilled. A final proprietary process was used to improve the 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. 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 (ref).

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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REFERENCES


