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# Carbon-Based Ion Optics Development at NASA GRC

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# Carbon-based Ion Optics Development at NASA Glenn Research Center

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With recent success of the NSTAR ion thruster on Deep Space 1, there is continued interest in long term, high propellant throughput thrusters to perform energetic missions. This requires flight qualified thrusters that can operate for long periods at high beam density, without degradation in performance resulting from sputter induced grid erosion. Carbon-based materials have shown nearly an order of magnitude improvement in sputter erosion resistance over molybdenum. NASA Glenn Research Center (GRC) has been active over the past several years pursuing carbon-based grid development. In 1995, NASA GRC sponsored work performed by the Jet Propulsion Laboratory to fabricate carbon/carbon composite grids using a machined panel approach. In 1999, a contract was initiated with a commercial vendor to produce carbon/carbon composite grids using a chemical vapor infiltration process. In 2001, NASA GRC purchased pyrolytic carbon grids from a commercial vendor. More recently, a multi-year contract was initiated with North Carolina A&T to develop carbon/carbon composite grids using a resin injection process. The following paper gives a brief overview of these four programs.

## Introduction

Ion thrusters are increasingly being considered for long duration space propulsion applications.[1] Specific impulse of these devices is usually measured in thousands of seconds, with thrust efficiency typically greater than 50%. Thrust is usually limited to less than one Newton, requiring long periods of thrust to perform propulsive maneuvers. Many envisioned planetary missions require tens of thousands of hours of ion thruster operation. The high ion energies involved result in sputter erosion of electrode surfaces that can change electrode geometry and can ultimately cause structural failure. Molybdenum has been the most common ion thruster electrode material used to date due to its thermal stability, and relatively low sputter yield. It can be fabricated with common sheet metal forming techniques, and has a particularly low coefficient of thermal expansion. While molybdenum is a preferred metal to fabricate ion thruster electrodes, sputter erosion is still viewed as the life limiting factor in many ion thruster applications. There has long been a search for a significantly better material that could expand the capability of ion propulsion. Recent work has indicated that titanium may potentially improve grid life by about 50% over molybdenum, however this improvement is marginalized by less desirable thermal properties.[2]

Carbon has key material properties that exceed those of molybdenum. Graphite carbon has a very low coefficient of thermal expansion that is nearly zero within some temperature ranges. This is important in order to maintain precise geometric alignment between screen and accelerator aperture holes. High performance ion thrusters typically have large grid span-to-gap ratios that are vulnerable to thermal distortion. The high geometric stability of carbon materials may permit larger diameter thruster designs while still maintaining high beam density. Alternately, it may be possible to significantly increase the beam density of low power ion thrusters, improving applications on small spacecraft. The sputter erosion rate of graphite is much lower than any known metal. At some energy levels, it has been shown to have erosion rates an order of magnitude less than that of molybdenum. The use of carbon ion optics could drastically increase the life of ion thrusters by reducing electrode erosion that adversely affects aperture geometry. Carbon fiber is a very stiff material. It has an elastic modulus higher than that of most metals, but with a mass density lower than most metals. Components fabricated of carbon/carbon composites typically have very high natural resonant frequencies, and are more robust in high vibration launch vehicle environments. High material stiffness is also important to minimize ion optics distortion due to high voltage electrostatic attraction. Ion optics could be designed as flat panels in some situations, reducing fabrication cost, while maintaining aggressive span-to-gap proportions.

In recent years, several organizations have explored the potential of carbon-based materials for ion propulsion applications. Boeing and JPL have independently considered alternate aperture designs using carbon composites, such as slotted grids.[3,4] Fourteen cm dia. carbon composite grids were successfully fabricated in Japan by weaving resin impregnated fiber around pins.[5] Lockheed-Martin is presently serving as prime contractor for a USAF sponsored program to develop slotted grids.[6] The fabrication of ion optics from carbon-based materials has proven to be more challenging than for conventional metal construction. The diversified approach undertaken by NASA GRC is intended to maximize the probability of success at dramatically increasing the life of future ion thruster propulsion systems. The following paper reviews NASA GRC's carbon-based ion optics development program.

## Laminated Panels

In 1995, NASA LeRC sponsored work performed by the Jet Propulsion Laboratory to fabricate 30 cm diameter carbon/carbon composite ion thruster grids similar in geometry to those used on NSTAR.[7] The grids were slightly dished in order to increase structural rigidity and minimize grid-gap variation.

All grids began as identical blank panels without apertures. Six plies of unidirectional pre-preg tape were layed-up as $[0^o/+60^o/-60^o]s$ over a dish-contoured mandrel. The assemblies were then cured, carbonized, and graphitized. The dished blanks were then laser-machined under a jet of compressed air to form approximately 15 500 individual aperture holes per grid. Unexpectedly, the grid contours were found to be reduced after the laser machining process was completed. The extent of the contour deviation varied from about 0.35 mm with the accelerator grid, to about 1 mm with the screen grid. Unfortunately, this resulted in a mis-match among the three grid types, making it impossible to correctly adjust the grid gap of the ion optics assembly. If the center axis of the grids were gapped as with NSTAR, then the perimeter regions would be practically touching. To salvage the situation, the grids were ultimately installed onto the thruster in an inwardly dished configurations. This permitted more optimal grid spacing near the center, where the highest beam density occurs, but impairs performance near the grid perimeter. The screen to accelerator grid spacing was about 0.5 mm near the center axis, and about 1.1 mm near the perimeter. The decelerator grid, in most instances, was not used. See Figure 1.

Performance measurements were obtained in JPL facilities at background pressures ranging 2-4 x $10^{-3}$ Pa. At a beam current of 1.7 A, the perveance limit was 1.4 kV, as compared with 1.15 kV for molybdenum NSTAR grids. At this same current, the minimum accelerator voltage was found to be around –130 V, compared to -144 V for molybdenum NSTAR grids. These performance results were independently verified in tests performed at NASA GRC facilities. While the perveance for the carbon grids had been adversely affected by geometric distortions resulting from fabrication, there is no reason to believe that their performance could not match that of molybdenum if correct geometry had been tested.

There remains lingering doubts as to the structural robustness of machined carbon fiber grids. The screen grid appeared particularly fragile due to its high open area fraction. The laser machining process severed nearly every carbon fiber between adjacent aperture holes, and thus relied completely on inter-lamination shear strength to hold the grid together. The accelerator grid, however, had a lower open area fraction, resulting in better utilization of the carbon fiber as a load bearing structure. Alternate aperture configurations have been suggested as a means of correcting this concern, however the degradation in electrostatic performance has not been fully investigated.

## Chemical Vapor Infiltration

In 1999, NASA GRC initiated a contract with a commercial vendor for fabrication of carbon/carbon composite grids using a chemical vapor infiltration process.[8] The company planned to weave carbon fiber around aperture holes so that the fibers would not be severed, similar to a concept successfully implemented in Japan[5]. The ion optics design consisted of a screen grid and an accelerator grid with functional diameters of 8 cm. Both grids were to be flat, since dimensional stability was expected to be favorable at this small diameter. Two aperture arrangements were considered. The first was a hexagonal arrangement of circular apertures, similar to conventional metallic designs. An alternate square arrangement was also considered, which placed circular apertures in orthogonal rows and columns. Fabrication was to be performed with the aid of graphite mandrels. The mandrels were machined as a flat surface, with rows of posts present where apertures were desired. Tows of carbon fiber were laid down between the posts, and braided as needed to produce a uniform mesh-work. Difficulty was experienced with the screen grid since this required an open-area fraction of 67%, resulting in crowded regions where fibers crossed each other. The post height of only 0.38 mm made it very difficult keep fiber tows in position. Numerous set of grids were processed in the infiltration chamber using this technique, and all produced unsatisfactory results. Delaminations were common, and many carbon tows were not in the correct position, blocking aperture holes. Blame was placed on the short mandrel posts, which failed to hold the carbon fiber tows in the correct position. The posts were only 0.38 mm high, which corresponded to the desired grid thickness.

A revised attempt was made using temporary mandrel tooling. Plastic mandrels were fabricated using rapid prototyping techniques, and these mandrels had long pointed posts intended to facilitate fiber placement. Once all of the fiber tows were in the correct position, the entire assembly was coated with phenolic resin to bond everything in place. The objective was to transfer the bonded assembly to the original graphite mandrels for final thermal processing. Unfortunately, solvents in the phenolic resin partially disolved the plastic mandrel, making clean separation impossible.

Another variation of this approach was performed with a wax mandrel. Rapid prototyping techniques were used to fabricate a mandrel with long pointed posts, and utilizing a sacrificial wax material. The idea was to bond the braided assembly with phenolic resin as before, but then heat the assembly to melt away the sacrificial wax mandrel. The surface finish of the wax mandrel was excessively coarse, and did not permit easy braiding of the fiber tows. An assembly accident brought about a decisive end this attempt.

A final attempt was made using a wax mandrel with apertures in a square arrangement. This would permit carbon fiber tows to be laid in place without complex braiding. The fibers tows would cross each other at 90 degree angles, but span the entire diameter along a straight line. By this time, fabrication techniques for wax mandrels had been improved. Once bonded together by phenolic resin, the assembly was pyrolyzed between flat graphite plates. The hole-to-hole spacing of the apertures did not match the mandrel post spacing exactly, so the graphite mandrels could not be used. This last attempt produced an accelerator and screen grid that were intact, but geometric accuracy and precision were lacking. (See Figure 2.) The resulting grid set has not been tested to date.

A carbon/carbon composite mounting ring was also fabricated under contract with the same company. The ring was designed to be compatible with the NASA GRC 8 cm thruster that had previously been fabricated. This ring was subsequently use to position the pyrolytic carbon grids described elsewhere in this paper.

### Machined Pyrolytic Graphite

In 2001, NASA GRC established a contract with a commercial supplier to fabricate 8 cm and 30 cm diameter ion optics from pyrolytic graphite. Pyrolytic graphite is an attractive option over carbon-carbon grids for two reasons. First, although carbon/carbon has a higher elastic modulus due to continuous fibers in the composite, the pyrolytic graphite fabrication process is more straightforward because the material is relatively isotropic. Apertures can be arranged without concern for directional properties within the bulk material. Second, the pyrolytic graphite fabrication process typically results in a final material density that approaches the theoretical maximum density of carbon with minimal voids that typically result during the densification of carbon-carbon grids.

Pyrolytic graphite can be deposited on a flat surface for flat grids or on a domed surface for domed-shaped grids. The final grid shape and grid apertures are machined. To date, flat 8 cm diameter ion optics and associated mounting hardware have been successfully fabricated and are shown in Figure 3. Domed 30 cm ion optics are presently being fabricated.

### Resin Injection Molding

More recently, NASA GRC initiated a multi-year contract with North Carolina A&T to fabricate ion thruster grids using resin injection into a carbon fiber pre-form.[9] Several layers of finely woven carbon fabric are used to establish a pre-form. The pre-form is then pressed against a mold containing an array of precisely machined steel needles. The pre-form is then impregnated with resin and cured, to form a flat perforated panel. The composite grid is converted into carbon/carbon using the North A&T's patented carbon/carbon technology.

One key aspect of this process is that common mold hardware is used to fabricate both the screen and accelerator grids. This will ensure coaxial alignment of all grid apertures between all grid sets. The accelerator grid will have an open area fraction of 24%, achieved by shallow penetration of the conical needles when molding. The screen grid will have an open area fraction of 67%, achieved by deeper penetration of the conical needles when molding. All apertures will have a slight conic cross section that result from this procedure, but the divergence angle is expected to be only 7 degrees.

As of this writing, the mold was being fabricated, and the first grid set is scheduled for delivery in February of 2002. A series of mechanical and vibrational tests will follow, with possible scale-up to 30-cm diameter grids.

## Conclusions

With the success of the NSTAR Deep Space 1 program, there is continued interest in long term, high propellant through-put missions. This requires flight qualified thrusters that can operate for long periods at high beam density, without degradation in performance resulting from sputter induced grid erosion. Carbon-based materials have shown nearly an order of magnitude improvement in sputter erosion resistance over molybdenum. NASA GRC has been active over the past several years pursuing carbon-based grid development. In 1995, NASA GRC sponsored work performed by the Jet Propulsion Laboratory to fabricate carbon/carbon composite grids. A machined panel approach was used. In 1999, a contract was initiated with a commercial vendor to produce carbon/carbon composite grids using a chemical vapor infiltration process. In 2001, NASA GRC purchased pyrolytic carbon grids. More recently, a multi-year contract was initiated with North Carolina A&T to develop carbon/carbon composite grids using a resin injection process. The fabrication of ion optics from carbon based materials has proven to be more challenging than for conventional metal construction. The diversified approach undertaken by NASA GRC is intended to maximize the probability of success at dramatically increasing the life of future ion thruster propulsion systems.

## References

[1] Patterson, M.J., et al., "Ion Propulsion Development Activities at NASA Glenn Research Center," AIAA Paper 2000-3810, July 2000.

[2] Soulas, G.C., et al.,"Performance of Titanium Optics on a NASA 30 cm Ion Thruster," AIAA paper No. 2000-3814, July 2000.

[3] Meserole, J.S. and Rorabach, M.E., "Fabrication and Testing of 15 cm Carbon-Carbon Grids with Slit Apertures", AIAA Paper 95-2661, July 1995.

[4] Brophy, J.R., Mueller, J., and Brown, D.K., "Carbon-Carbon Ion Engine Grids with Non-Circular Hole Apertures", AIAA Paper 95-2662, July 1995.

[5] Kitamura, S., et al, "Fabrication of Carbon-Carbon Composite Ion Thruster Grids - Improvement of Structural Strength", IEPC Paper 97-093, October 1997.

[6] AFRL PRDA NR 00-08-MLK, "Topic 9-Reduced Erosion Materials for Electrostatic Thrusters", Spring 2000.

[7] Mueller, J., Brophy, J. R., and Brown, D. K., "Design, Fabrication and Testing of 30-cm Dia Dished Carbon-Carbon Ion Engine Grids," AIAA Paper 96-3204, July 1996.

[8] Patterson, M.C., "High Thrust Density Optics for Advanced Ion Propulsion, "Interim Contractor Report: C-75647-J, Ceramic Composite Inc., February 2001.

[9] Shivakumar, K.N., "An Innovative Manufacturing of Ion Thruster Grids by NC A&T's RTM Carbon/Carbon Composites Technology," Contract No. NAS3-01197 Progress Report, September, 2001.

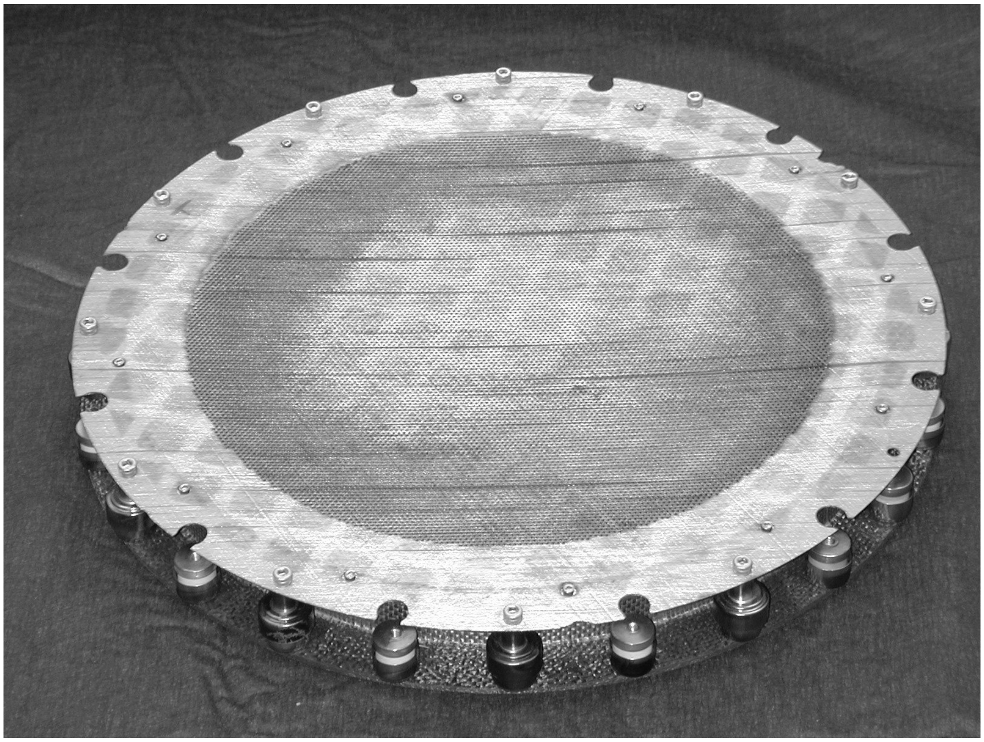

Figure 1.—Thirty cm carbon/carbon composite ion optics assembly fabricated by JPL.

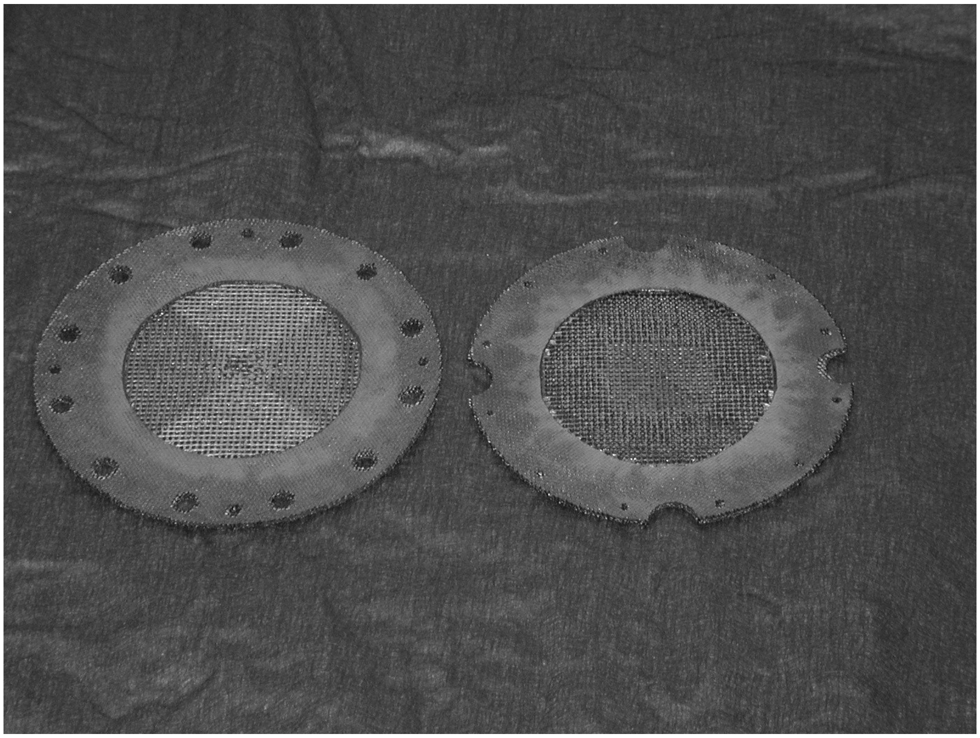

Figure 2.—Eight cm carbon/carbon composite accelerator and screen grids.

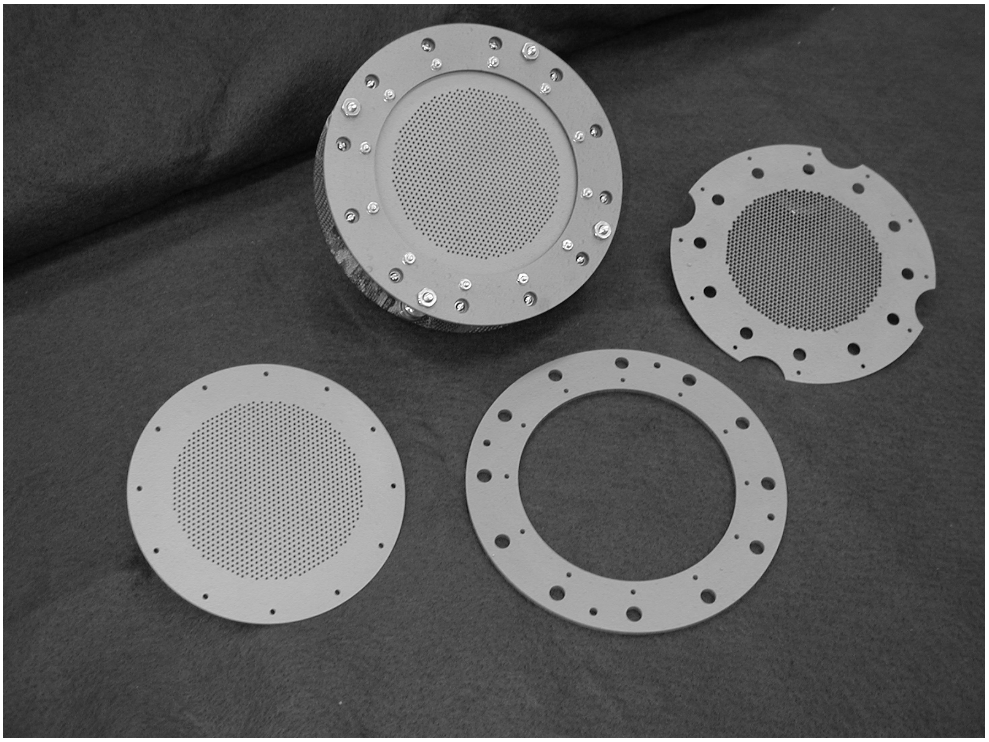

Figure 3.—Eight cm pyrolytic carbon grids and carbon/carbon composite isolated mounting structure.

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