

## REVIEW OF CARBON-BASED GRID DEVELOPMENT ACTIVITIES FOR ION THRUSTERS

John Steven Snyder\*  
*Jet Propulsion Laboratory  
California Institute of Technology  
Pasadena, CA 91109*

The primary life-limiting mechanism for state-of-the-art ion thrusters is erosion of the accelerator grid by charge-exchange ions produced in the plume of the thruster. Hence, significant reduction of the grid erosion rate should extend the useful life of a thruster. Carbon-based grids, because of their low sputter yields, provide an attractive means for increasing thruster lifetimes without requiring significant changes in well-characterized operating regimes, and are an enabling technology for high-specific-impulse, long-duration operation. Development of such grids, however, has presented many challenges. This paper reviews carbon-based grid development activities, specifically addressing grid manufacturing, optics performance, and launch and operational survivability. Development work has shown that carbon grids can be fabricated from 10 to 30 cm in diameter with clean aperture features, low coefficients of thermal expansion, and strength properties close to those of molybdenum. The optics performance has been shown to be essentially the same as for molybdenum grids. The sputter erosion rates, while dependent on fabrication methods, have been shown to be lower than those of molybdenum. Finally, although there have been significant problems with voltage standoff during some tests, carbon-based grids have proven the ability to stand off the voltages required for high-performance ion engines.

### INTRODUCTION

The major life-limiting mechanism for state-of-the-art ion thrusters with molybdenum grids is erosion of the accelerator grid. Hence, significant reduction of the grid erosion rate should extend the useful life of a thruster. Carbon-based materials are thus attractive for use as ion thruster grids because of their low sputter yields compared to molybdenum. In addition, they can have low or negative coefficients of thermal expansion. This property is also attractive because it could provide better control of the grid gap than can be achieved with molybdenum.

Although carbon-based grids hold much promise, there are also questions that must be answered. It must be determined if carbon grids can (1) provide the same or similar optics performance as state-of-the-art molybdenum grids, (2) provide increased lifetime, (3) stand off the required voltages for the life of the thruster, (4) survive launch loads, and (5) have sufficient process control to produce hardware to design specifications repeatedly.

---

\* Member of the Technical Staff, Advanced Propulsion Technology Group, Member AIAA

Most of the development work in the literature has been performed with carbon-carbon composites, although pyrolytic graphite has recently received attention. Thus, this paper will necessarily focus on the efforts and issues related to development of carbon-carbon composite ion thruster optics.

Development of carbon-carbon composites for ion thruster grids began in the early 1990's. Several research groups initiated programs within a few years of the first published reports. Several endurance tests, including one that lasted 18,000 hours, have been performed. Now, graphite grids are flying on RIT thrusters on the ARTEMIS satellite<sup>1</sup> and carbon-carbon grids on the MUSES-C spacecraft.<sup>2</sup>

### REVIEW

#### Manufacturing/Fabrication

Carbon-carbon (CC) composites can be fabricated from a dizzying array of design choices such as fiber type, fiber weave, curing resin, and laminate layup; processing methods such as carbonization, graphitization, liquid impregnation, chemical vapor infiltration (CVI), and chemical vapor deposition (CVD); and processing variables such as time, temperature, and pressure. All of these choices and variables have an effect on the final material properties

of the composite. Hence, CC manufacturing can be considered as much art as science.

Typical CC fabrication begins with a prepreg, i.e. carbon fibers that are preimpregnated with an uncured matrix resin.<sup>3</sup> Prepregs are laid-up in the desired form with the desired ply number and orientation then cured at elevated temperatures and pressures. A carbonization process performed at several hundred degrees Celsius drives non-carbonaceous material from the structure. A densification step then follows to increase the density of the material. This is usually done by CVI for ion thruster grids but can also be done by liquid impregnation. Graphitization at high temperatures (e.g. 2000-3000 °C) can be performed to pyrolyze and recrystallize the material which enhances the material properties. Of course, there are many variations of these processes. Some of these steps may be repeated multiple times to obtain the desired final composite properties.

Ion thruster grids pose an unusual problem for the CC manufacturer because of the unique requirements. The main obstacle in fabricating ion optics from CC material is forming thin composites that retain the desired mechanical properties and structural integrity after aperture machining to high open area fractions. This requires careful design choices and, as evidenced by the work in the literature, significant iteration or trial-and-error in CC grid development efforts. While important fabrication topics will be addressed here, an exhaustive review of the methods used by various research groups would not be particularly useful. The reader is referred to the literature for more detailed information.

The first CC grid developments were done with relatively thick (~1 mm), flat panels for smaller beam diameters (~10-15 cm).<sup>4-7</sup> These were made with square-woven fabric and ply orientation combinations of 0°, 45°, and 90°. Some warping of as-received<sup>4</sup> and planed<sup>7</sup> material was seen in those studies and also in subsequent layups of 0°/90° ply orientations with unidirectional tape prepreg.<sup>8</sup> This early work showed that a symmetric layup, i.e. one that is symmetric with respect to the center plane of the laminate, was important.<sup>8,9</sup>

Early work also showed that aperture machining had a very significant detrimental effect on the material properties of the panels because of the indiscriminate cutting of carbon fibers. In one study, machining of a 63% open area fraction into a square-woven fabric caused a 64% decrease in modulus.<sup>6</sup> This result directed researchers to attempt to fabricate panels that could be machined without such adverse effects on material properties.

Mueller et al.<sup>10</sup> first proposed CC layup with unidirectional tape in directions along the 0°, ±60° lines associated with hexagonal-packed circular apertures in

an attempt to retain the panel structural properties after aperture machining. This layup, depicted in Fig. 1, allows for continuous fibers along grid diameters parallel to rows of holes, except for grids with sufficiently large open area fractions.<sup>11</sup> The properties of these panels were significantly improved over the earlier 0°/90° panels, including less anisotropic behavior.<sup>12</sup> The improved strength and flexural modulus was considered necessary for larger-diameter grids.

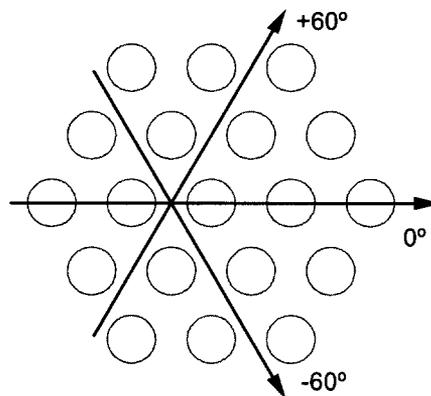


Fig. 1. Schematic of  $[0^\circ/+60^\circ/-60^\circ]$  Layup with Apertures.

In an attempt to increase grid strength and obtain quasi-isotropic materials properties, some research teams have investigated CC composites fabricated by various means from short, randomly oriented fibers in a felt or sheet matrix.<sup>13-17</sup> While an improvement over the first CC grids, these types of grids have been shown to have lesser strength and modulus than the 0/±60° layups with unidirectional fibers.<sup>14,17</sup> The 10-cm optics system of the MUSES-C thrusters employs this type of grid. Funaki et al.<sup>16</sup> extended the technique to 20-cm-dia. 1-mm-thick grids.

Grids with slotted apertures have been investigated as an alternative to hexagonal-packed circular hole patterns in order to maximize the number of uncut carbon fibers. This method, which relies on the strength of unidirectional fibers aligned parallel to the slots, can be used to produce relatively high strengths and flexural moduli in the direction of the slots. The properties were found to be much weaker, however, in the perpendicular direction<sup>18</sup> because the slot machining also maximizes the number of cut carbon fibers in that direction. One set of slotted grids were observed to have significant deflection under electrostatic loads.<sup>8</sup> Because of this designed large anisotropy in stiffness, it is not clear that slotted grids could survive launch loads.

Most CC developments have produced grid sets less than the 30-cm NSTAR size. Fabrication of sufficiently thin 30-cm or larger grids that can survive

launch loads requires material properties which appear achievable at this time only with the  $0/\pm 60^\circ$  unidirectional tape layup. Recent work<sup>19</sup> has shown the benefits of introducing additional CC stiffening and mounting structures as well as dishing of the grids to increase the vibration resistance. These add additional complications to the manufacturing process, however, and require greater process control. For example, the first set of 30-cm CC grids that were manufactured<sup>12,20</sup> had mismatched radii of curvature between the screen and accelerator grids, which resulted in large grid gap variations across the grid span. Finally, it should be noted that CC grids as thin as 0.3 mm have been successfully fabricated.<sup>21</sup>

Although most of the work in the literature is with CC materials, 8-cm flat pyrolytic graphite grids have been successfully fabricated and tested.<sup>22</sup> That work has been extended to 30-cm grids, also.<sup>23</sup>

#### Materials Properties

Two of the more important materials properties of CC composites for ion thruster grids, apart from the sputter yield, are the coefficient of thermal expansion (CTE) and the flexural modulus. Materials with a low or negative CTE are desirable because they could eliminate the dished-shape required of molybdenum grids to control the grid gap as they heat up and expand. Dished molybdenum grids are more difficult to align than flat grids, and it is also difficult to control the grid-to-grid spacing uniformly. Testing of several CC grid coupons has been performed and most have measured a CTE of the order of  $-1.0 \times 10^{-6}/K$  over the temperature range of interest<sup>4,6,8,17</sup> although there are some reports of positive CTE's.<sup>14,24</sup> For comparison, the CTE of molybdenum is about  $5 \times 10^{-6}/K$  at thruster operating temperatures. Thus, CC composites have the potential to provide much better thermomechanical properties than molybdenum and reduce or eliminate grid-gap control issues at operating temperatures.

The flexural modulus is a critical grid structural parameter because it describes how much the material bends due to loads applied by electrostatic or vibrational forces. A CC composite with a higher flexural modulus will be more rigid and will deflect less under load. Large deflections are undesirable because they could adversely affect the grid gap under

electrostatic load and could lead to catastrophic failure caused by grid-to-grid contact under vibrational loads.

The flexural modulus and other structural properties have been measured for many CC materials used for thruster grids. Almost all of this work has been done for panels that have not been weakened by aperture machining. The flexural modulus of a CC composite will depend on the type of materials used and their layup, and can be a strong function of direction for non-isotropic composites. This anisotropy is highlighted in Table 1 by a comparison of two different layup orientations for the same unidirectional fiber tape and same manufacturing processes.<sup>12</sup> The highest flexural modulus of 340 GPa is found for the  $[0^\circ/0^\circ/90^\circ]_s$  layup in the  $0^\circ$  direction (i.e. the direction parallel to the majority of the carbon fibers in the layup). This is very close to the flexural modulus of molybdenum (320 GPa).<sup>6</sup> This high value is offset by an order-of-magnitude lower modulus in the orthogonal direction. The  $0^\circ/\pm 60^\circ$  layup achieves a greater off-axis modulus at the expense of the  $0^\circ$  modulus. Reported flexural moduli for thruster grid panels range from 21 GPa<sup>14</sup> to 340 GPa.<sup>12</sup>

The Japanese Institute of Space and Astronautical Science (ISAS) has relied upon felt-type precursors to address composite anisotropy for many of its grid developments. The carbon felts, which consist of short randomly oriented carbon fibers, were used in the successful qualification of the MUSES-C ion optics. Although these materials lack the anisotropy of the unidirectional tape layups, they are not as strong as the latter composites. For example, the reported flexural modulus of the MUSES-C optics is 21 GPa,<sup>14</sup> while recent measurements with heat-treated composites have yielded only 35 to 45 GPa.<sup>17</sup> One development did achieve a flexural modulus of 68 GPa,<sup>16</sup> which is slightly larger than the  $90^\circ$  modulus of the  $0^\circ/\pm 60^\circ$  layup shown in Table 1, but still far below the 275 GPa in the  $0^\circ$  direction. Nonetheless, this type of CC composite has successfully passed vibration testing and is now flying on the MUSES-C spacecraft.

Although a high flexural modulus is in general desirable, there are many other design factors that affect the vibration response of a grid set. For example, although the MUSES-C grids have a relatively low flexural modulus, a rigid mounting ring was designed to

Table 1. Comparison of Materials Properties for Two Different Composite Layups (Data from Ref. 12).

Property	$[0^\circ/0^\circ/90^\circ]_s$ Layup		$[0^\circ/\pm 60^\circ/\pm 60^\circ]_s$ Layup	
	$0^\circ$ Direction	$90^\circ$ Direction	$0^\circ$ Direction	$90^\circ$ Direction
Tensile Strength (MPa)	754	414	486	NR
Tensile Modulus (GPa)	230	121	145	NR
Flexural Strength (MPa)	289	50	205	117
Flexural Modulus (GPa)	340	21	275	61

NR = not reported

increase the stiffness of the entire grid assembly.<sup>14</sup> Materials with higher flexural moduli are probably necessary for larger beam diameters (i.e. 30-cm or greater) while those with lesser moduli appear to be adequate for smaller geometries.

Only one study has presented results for materials properties before and after hole machining,<sup>6</sup> and those results are presented in Table 2. The layup of this grid, a 0°/45°/0° layup of square-woven fabric, was such that all carbon fibers in the active beam region were severed by aperture machining. A significant reduction in properties was found, with the flexural modulus scaling approximately with the open area fraction. This effect can be ameliorated by using a 0°/±60° layup with unidirectional fibers aligned with the rows of hexagonal-packed circular apertures. Although aperture machining in a 0°/±60° layup will undoubtedly reduce the flexural modulus to a value less than the original panel, the effect should be less than that seen in Table 2.

Table 2. Effect of Aperture Machining on Panel Properties (Data from Ref. 6).

Property	Panel No Holes	Panel 63% Open Area
Flexural Strength	180 MPa	28 MPa
Flexural Modulus	160 GPa	58 GPa

#### Hole Drilling

Several means have been investigated to machine apertures in carbon grids. Aside from the obvious mechanical drilling, researchers have used laser machining, electric discharge machining (EDM), ultrasonic impact grinding, air-turbine machining, waterjet etching, and sandblasting.

The first study of hole machining was performed by Garner and Brophy.<sup>6</sup> Their three-ply panels were fabricated from square-woven carbon fibers. Mechanical drilling was found to be difficult in general for large open area fractions and small hole diameters. The exit side of the grid webbing became damaged and fibers were pulled loose from the CC matrix. In addition, although it was not observed in this case it was noted that mechanical drilling can cause delamination between plies near the hole site.<sup>10</sup>

Mechanical drilling was investigated by Kitamura et al.<sup>7</sup> in PAN-based carbon fiber fabric with much better results. Clean hole features with no webbing breakage were achieved by drilling with tungsten-carbide bits when the CC panels were sandwiched between two graphite plates. Even with the hard tungsten-carbide coating, six bits were required to machine the 7000 holes in both screen and accelerator grids because of bit dulling. Mechanical drilling was also used on the MUSES-C carbon-fiber felt grids with good results.<sup>14</sup> Excellent results have been achieved

when drilling pyrolytic graphite.<sup>22</sup> It appears, then, that suitable hole quality can be achieved with proper care when mechanically drilling apertures.

Garner and Brophy<sup>6</sup> also investigated EDM for hole machining. Apertures machined with EDM showed no damage from the machining process, with good hole uniformity, no sidewall taper, and clean edge features. EDM was also successfully used for two other JPL grid developments.<sup>9,18</sup> Although it provides excellent hole quality, EDM is a relatively expensive technique.

Mueller et al.<sup>10</sup> presented the most complete study of aperture machining using test panels fabricated from carbon fiber layed-up in six unidirectional plies. Results obtained with ultrasonic impact grinding were excellent, similar to the EDM. Unfortunately, ultrasonic drilling is as expensive as EDM on a per-hole basis. Waterjet etching and sandblasting, while potentially less expensive, produced very poor results and thus were not considered further. Kitamura et al.<sup>7</sup> observed webbing breakage with ultrasonic rotary machining and poor hole features with air-turbine machining.

Hedges and Meserole<sup>4</sup> introduced laser machining of apertures for CC grids. Here, a small-diameter laser beam relative to the hole diameter "burns" a hole through the material and traces out the circumference of the aperture. Since this is a thermal process that melts and vaporizes the material to be removed, melting of the adjacent hole wall also occurs which could lead to undesirable hole features. The aperture machining was found to give clean, repeatable hole patterns with a 6° taper (the hole diameters were larger on the side of laser entry). Mueller et al.<sup>10</sup> showed high-magnification views of laser-drilled apertures with significant taper, melting, and out-of-round holes. These holes were drilled, however, with a "blast-through" method and not by tracing out the hole circumference.<sup>25</sup> A subsequent grid set machined by Mueller et al. with the tracing method produced "exceptional hole quality and outstanding accuracy and repeatability."<sup>20</sup> Laser drilling is significantly more cost-effective than EDM.<sup>10</sup>

One undesirable effect of machining apertures in CC grids is the weakening of the grid strength because of severed carbon fibers. Since much of the strength of CC materials results from the continuous fibers, alternatives to hole drilling have been investigated. Some research groups<sup>11,26</sup> have tried to address this problem by weaving carbon fibers around posts, arranged in the final hole pattern, on a mandrel. Although panels with continuous carbon fibers have been manufactured with this method, the layup is tedious, difficult with high open area fractions, and produces very poor apertures.

Although mechanical drilling of CC grids has been shown to produce good results, this has been done for

only flat, relatively small grids. Laser drilling may be preferable for larger, dished grids because of the additional tooling and labor costs required for the graphite “sandwich” parts required for mechanical drilling.

**Performance**

The optics performance of a grid set, e.g. perveance and electron backstreaming characteristics, is of critical importance for ion engines. The perveance of a grid set describes its ability to extract current from a thruster discharge chamber at a given voltage and is limited at lower voltages by direct impingement of beam ions on the accelerator grid. Electron backstreaming occurs when the accelerator grid voltage is sufficiently low for electrons downstream of the grid set to be accelerated back into the discharge chamber. Carbon-based grids will not be attractive for thrusters if their optics performance is significantly worse than for traditional molybdenum grids.

Optics performance measurements have been made with many different carbon grids and thrusters. While much data have been published, the results are not particularly useful in themselves; a comparison to molybdenum optics is necessary to determine the viability of carbon-based grids. Perveance and EBS measurements were made on a dished 30-cm CC grid set by Mueller et al.<sup>20</sup> The results were compared to measurements made on molybdenum optics but there were enough experimental differences to render the comparison inconclusive. A similar report was made by Kitamura et al.,<sup>7</sup> but in addition they noted that thruster performance was almost the same for both types of grids. Performance data for different slotted CC grid sets were obtained by Meserole<sup>8</sup> and by Brophy et al.<sup>18</sup> These data were compared with limited success to grids fabricated from molybdenum and CC, respectively, with circular apertures.

Three studies in particular have done detailed comparisons of carbon-based and molybdenum optics with similar geometries. The first, performed by Hedges and Meserole,<sup>4</sup> used flat 10-cm CC grids

machined to nearly the same hole pattern as a 10-cm dished molybdenum set. Differences between the two materials for perveance, EBS, and defocusing limit measurements were observed and it was concluded that those differences were consistent with those expected from the known differences in grid geometries, particularly grid thicknesses.

Mueller et al.<sup>9,12</sup> measured perveance and EBS characteristics in a 15-cm three-grid CC system. In the latter study at a 500-mA screen grid current, they found a perveance limit of about 1100 V for the CC grids, whereas a similar molybdenum set had a limit of 1000 V at the same operating conditions. The authors attributed the difference to the thickness of the CC accelerator grid which was a factor of 2.5 thicker than the molybdenum grid. Lack of control of the hot grid gap for molybdenum was also cited as a possible contributing factor. The authors concluded from this work that the perveance limit differences between CC and molybdenum were relatively small and were expected to be negligible with the use of thinner CC grids.

The most direct comparison of molybdenum and carbon-based grids was performed recently by Haag and Soulas<sup>22</sup> with pyrolytic graphite (PG). Details of the grids are shown in Table 3. Note that although the hole pattern was designed to be identical for each grid set, manufacturing limitations resulted in slightly different hole geometries as evidenced by the pin-gage open area fraction measurements. Performance of each grid set was measured on a masked-down 30-cm thruster. A direct comparison of perveance measurements with the two grid materials operating at the same conditions is shown in Fig. 2. On average, the PG grids required only 2% more total voltage to extract the same beam current. This result could easily be explained by differences in hole geometry, alignment, or hot grid gap between the two grid sets. The results of EBS measurements showed a greater difference between molybdenum and PG, with 20 to 57 additional volts required by molybdenum to prevent backstreaming depending on the beam current. Several

Table 3. Comparison of Grid Designs Tested by Haag and Soulas.<sup>22</sup>

Parameter	Pyrolytic Graphite	Molybdenum
Beam Diameter	8 cm	8 cm
Number of Apertures	1159	1159
Screen Grid Thickness	0.4 mm	0.4 mm
Accelerator Grid Thickness	0.5 mm	0.5 mm
Grid Dish Depth	Flat	3 mm (inward)
Design Hole Pattern	Nearly same as NSTAR	Identical to PG
Measured Open Area Fraction Of Screen Grid	64%	69%
Measured Open Area Fraction Of Accelerator Grid	22%	26%

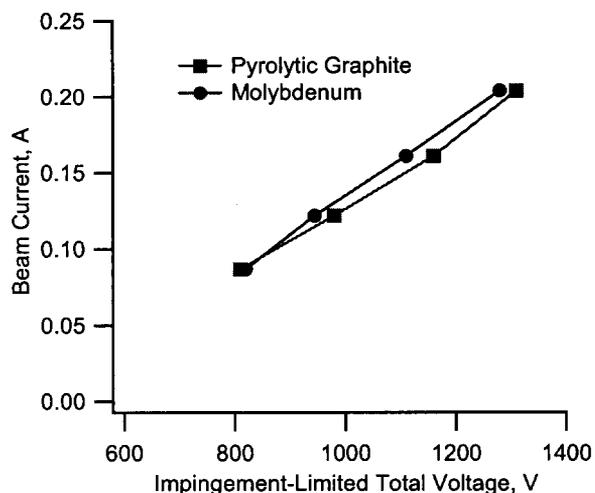


Fig. 2. Comparison of Perveance Limit of Pyrolytic Graphite and Molybdenum Optics (Data from Ref. 22).

factors were cited as possible contributors to the EBS difference. Results of screen grid transparency measurements showed that the PG transparency was less than the molybdenum transparency by less than 10% for all beam currents investigated, which is consistent with the smaller open area fraction of the PG screen grid. Overall, these experiments appear to confirm that carbon-based ion optics can provide equivalent optics performance to molybdenum grids.

#### Vibration

Although the ability of carbon-based grids to survive launch loads is legitimately a major concern, very little work focusing on this problem has been published. The only experimental data are from the development testing of the 10-cm CC ion optics for the MUSES-C thrusters.<sup>14,28</sup> This is a three-grid CC system where each grid is 1-mm thick and each grid gap is 0.5 mm. The panels were fabricated from pitch-based carbon felt and densified by CVI. The strength and flexural modulus of the resulting panel are much less than for molybdenum. Concern for launch survivability of the grids led to the design of a fairly thick, rigid aluminum grid mounting ring.

Vibration testing was performed for the CC grid and aluminum mounting ring system. Sinusoidal sweep tests showed that the natural frequencies were 265 Hz, 337 Hz, and 325 Hz, respectively, for the screen, accelerator, and decelerator grids.<sup>28</sup> Random vibration testing was performed according to specifications for the M-5 launch vehicle, in 3 axes each at a level of 26.8 Grms<sup>14</sup> (for reference, the NSTAR ion engine was vibrated during qualification testing to only 9.0 Grms). Accelerations on the grid centerline were measured at 112-129 Grms.<sup>28</sup> Grid-to-grid contact was observed

during the testing, but inspection showed no damage to the grids. It was decided that the grid collision would be allowed and that the grid design should not be changed to prevent grid-to-grid contact.

As a part of property measurements of new CC materials under investigation, Shimizu et al.<sup>17</sup> performed a structural analyses for a 20-cm flat grid design. The materials under study were fabricated from short pitch-based carbon fibers, which were heat-treated to either 2000 °C or 3000 °C. The flexural moduli of these materials were both higher than that used in the MUSES-C grids.<sup>14</sup> The analyses predicted a first natural frequency of 150 Hz for the accelerator grid.<sup>17</sup>

Recently, JPL has performed vibration testing and modeling of newly developed 30-cm dished CC grids.<sup>19</sup> The screen and accelerator grids were specifically designed to survive NSTAR-level launch loads. Results of random vibration testing of the accelerator grid to levels of 18.6 Grms are reported in Ref. 19. The grid survived the test with no visible damage. In addition, it was shown that dynamic models of the grid response correlate with the test data to within a few to several percent.

#### Arcing/Voltage Standoff

Much of the reported experience with voltage standoff and arcing of CC grids is similar to that observed with metallic surfaces. Specifically, initial application of high voltage causes arcs in seemingly random locations, and the arc rate decreases with time as the surface is conditioned. Arc conditioning smoothes the initially rough surface and the conditioned surface is able to hold off more voltage. Relatively clean and smooth surfaces condition more quickly; rougher surfaces, such as carbon fiber composites with stray fibers, may take longer. An example of this type of behavior is described for CC grids in Ref. 4 where no visible damage to the grids was observed. In another experiment, very little arcing was seen at all on CC grids.<sup>9</sup>

Extreme cases of arcing with CC grids have also been reported. Reference 13 describes the first 144 hours of a 300-hour demonstration test of CC technology. Arcing was so frequent in the first several hours that no beam could be extracted. The total voltage between the screen and accelerator grids was slowly increased until reaching the final value of 1250 V after 47 hours. After several tens of hours of operation the arcing disappeared because, according to the authors, stray carbon fibers had been cleaned off of the surface. The remainder of the test finished without further problems with arcing.<sup>29</sup>

In a separate test, arcing between CC grids with rough surface texture limited initial work to an extraction voltage of 1800 V over a 1-mm gap.<sup>27</sup> Additional study indicated that the breakdown voltage

of CC composites depends strongly on the manufacturing process.

One of the most problematic results from the standpoint of application of CC technology was the termination of a recent endurance test of 14-cm CC grids because of excessive arcing.<sup>15</sup> Arcing caused so much damage to the grids in this case that the total voltage of 1200 V could not be sustained and the test was halted after 3814 hours. Inspection of the grids after the test showed a discolored area with localized grid damage. The screen grid in this area "rose slightly" and had many cracks as evidenced in the published photographs. The accelerator grid also had many cracks and "parts of the grid fell off." Based on these descriptions it is likely that the damaged grid area had an appreciably smaller gap than the rest of the grid, and hence a higher electric field strength. This, coupled with the sharp edges of the cracks, would have increased the probability of arcs in this location compared to the rest of the grid and concentrated the damage locally. The authors suggested that the test equipment must be reconfigured to reduce the time between arc initiation and supply shut down in order to reduce the deposited energy. In addition, they noted that grid arcing appeared to be correlated with the failure of a triac associated with the beam supply and with tripping of an input-power circuit breaker, and suggested that noise currents could have caused the power supply problems. There was little description of the CC fabrication, so it is difficult to tell if arcing was caused or aggravated by any inherent material property.

An earlier study by the same authors of Ref. 15 also reported grid damage caused by frequent arcing. Here, with 14-cm grids and a cold grid gap of 0.5-0.6 mm, the planned total voltage of 1400 V could not

be achieved.<sup>7</sup> Frequent arcing did not subside with time. The grids were then re-gapped to 0.9 mm and were able to run at 1400 V. Post-test inspection shows cracks and erosion ostensibly caused by arcing, and carbon fibers were found jutting out from the grid holes that were not observed before the testing. Again, these damaged areas have greater probability of arcing and repeated damage because of locally enhanced electric fields caused by sharp edges. These grids were manufactured from PAN-based fibers whereas most other CC developments used pitch-based fibers. The apertures were mechanically drilled with tungsten-carbide bits. Mechanically drilled CC has, in other studies, been shown to produce more stray fibers that could serve as arc initiation sites.<sup>6</sup>

An important factor in determining optics performance is the electric field that is sustained by the grids across the grid gap. A non-exhaustive summary of inferred electric fields used in carbon-based grid testing is provided in Table 4. For comparison, the intra-grid electric field for the NSTAR thruster operating at full power is about 2100 V/mm. Many of the carbon-based grid tests have achieved or exceeded this level in sustained laboratory testing. In addition to the 6400 V/mm demonstrated during thruster operation, Meserole<sup>4</sup> demonstrated standoff of 8600 V/mm in vacuum.

#### Sputtering/Erosion

Reduced sputter erosion compared to molybdenum is the primary attractive quality of carbon materials for ion thruster grids. Bulk carbon has a sputter yield that is five to seven times lower than molybdenum for xenon ion energies of interest for accelerator grids.<sup>32</sup> Sputter yields of materials are functions of surface

Table 4. Reported Voltage Standoff of Carbon-Based Grids During Thruster Operation.

Total Voltage (V)	Cold Grid Gap (mm)	Inferred Electric Field (V/mm)	Avg. Current Density (mA/cm <sup>2</sup> )	Ref.	Notes
1400	0.9	1500	3.1	7	Voltage limited by arcing
1800	1.0	1800	NR	27	Voltage limited by arcing
1250	0.64	2000	2.8	8	Slotted grids, 220 hours operation
1350	0.64	2100	3.1	12	700 hours operation
1050	0.5	2100	1.1	13, 29	300 hours operation
1600	0.64	2500	2.8	9	
1300	0.5	2600	1.5	14	2700 hours operation
2400	0.85	2820	2.8	30	
1750	0.61	2870	3.2	18	Slotted grids
1450	0.5	2900	2.5	20	30-cm dished grids
1800	0.5	3600	1.4	14	15,300 hours operation
1850	0.35	5290	1.8	31	
1280	0.2	6400	2.2	4	

NR = Not Reported

roughness and especially binding energy among other parameters,<sup>33</sup> so it can be expected that the sputtering behavior of CC composites will be complex. Yields will vary somewhat depending on the materials and processes used in fabrication. Additionally, the carbon fibers in CC composites have a much higher binding energy than the weaker carbon matrix surrounding them, so they will sputter at a lower rate than the matrix. This will change the surface morphology and relative fiber/matrix concentrations from the original material until some equilibrium state is reached.<sup>34</sup> Hence, caution must be exercised when comparing the measured sputter yields of different CC materials. Estimates of material lifetime in sputtering environments should only be made from carefully controlled yield measurements using the same material.

Initial comparison of the erosion rates of CC and molybdenum was performed during thruster tests and, though results were affected to some degree by background gases, the CC erosion rate was shown to be less than molybdenum in both cases.<sup>5,6</sup> Meserole concluded that the erosion rate of his CC material was between one-eighth and one-ninth that of molybdenum.<sup>5</sup> CC grid erosion has been characterized by mass-loss and dimensional measurements by Mueller et al.<sup>12</sup> in a 700-hour endurance test and Funaki et al.<sup>14</sup> for the 18,000-hour MUSES-C endurance test. In the latter test, the accelerator grid eroded at an estimated net rate of 28-60  $\mu\text{g/hr}$ .

Four groups have performed controlled sputter yield measurements of CC materials and reported their findings. Deltschew et al.<sup>35</sup> used a PAN-based fiber in

a biaxial weave, heat treated at above 2500 °C. Blandino et al.<sup>36</sup> tested panels of pitch-based DuPont E55 fiber layed-up in six plies of unidirectional tape described in Ref 9.<sup>37</sup> Multiple carbonization and graphitization steps were used in this fabrication. A random fiber matrix made in the preformed yearn method was used by Kuninaka et al.,<sup>13</sup> and Funaki et al.<sup>16</sup> tested grid material made from plies of thin fiber sheets containing short pitch-based carbon fibers.

The results of these sputter yield measurements are shown in Fig. 3 along with yields for molybdenum and bulk carbon<sup>32</sup> for reference. It can be seen that there are considerable differences in the data, with the Blandino and Deltschew data differing by a factor of about three to four. The Blandino data have a lower sputter yield than bulk carbon at some energies, which is in contrast to the findings of Deltschew.<sup>35</sup> The Deltschew data, however, do not show the expected reduction in sputter yield compared to molybdenum at lower energies. The Kuninaka data fall well within the carbon and molybdenum data and have a similar trend.

Some of the scatter in the data of Fig. 3 are likely a result of materials differences as discussed earlier, but it is possible that some of the results may be affected by experimental conditions. Only Blandino and Deltschew gave estimates of experimental uncertainties. Both Kuninaka and Blandino reported molybdenum yields in addition to CC yields, and there were differences between those and the Rosenberg and Wehner data (about a factor of two for Kuninaka, and less than 30% for Blandino). Deltschew et al. measured graphite sputter yields and the data they report compare

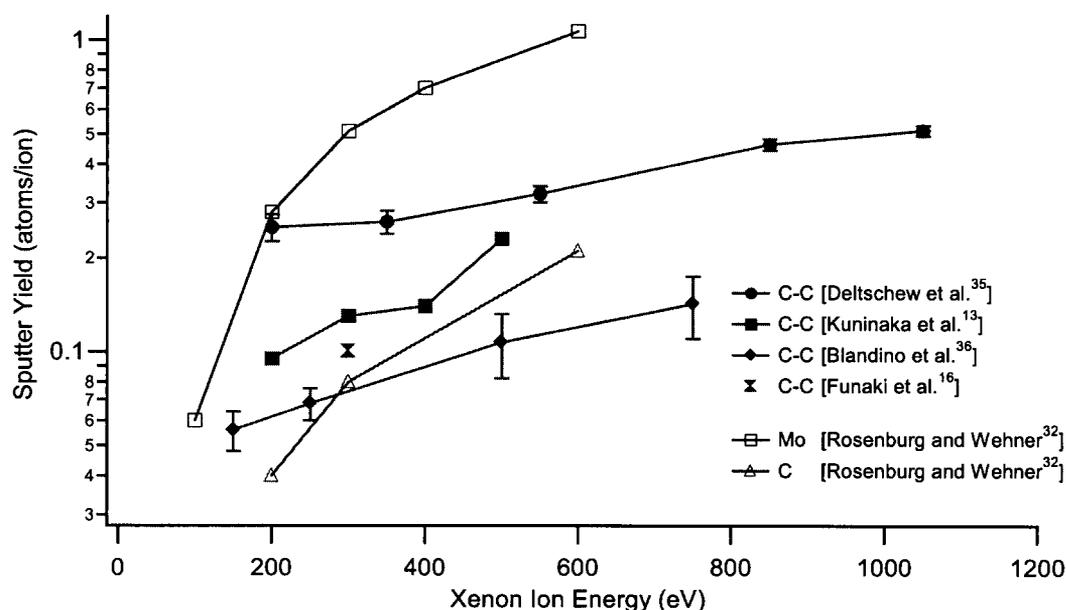


Fig. 3. Sputter Yield Measurements for Carbon-Based and Molybdenum Grid Materials.

reasonably well to other published data. The reader is encouraged to consult the references for more details on the sputter yield measurements.

In addition to sputter measurements at normal incidence, Deltshew et al.<sup>35</sup> measured CC and graphite sputter yields as a function of incidence angle up to 80°. Those results are reported in Ref. 35 as well as interesting photographs of CC surface morphology as a function of time and incidence angle. Because of the complex nature of CC sputtering, these results are probably applicable only for the particular material used in that study.

Measured sputter yields of CC do not completely describe the erosion resistance of these materials relative to molybdenum, however, because the CC atom number densities are larger and the erosion rate is proportional to the sputter yield divided by the atom number density. The number density of atoms in molybdenum is determined from the density (10.2 gm/cm<sup>3</sup>) divided by the atomic mass (95.94 amu). When this value is compared with that for a typical CC composite (1.7 gm/cm<sup>3</sup> and 12.0 amu) it is seen that the composite has approximately 33% more atoms per unit volume than molybdenum. For example, the CC sputter yield data of Funaki<sup>16</sup> are a factor of five less than the molybdenum data of Rosenberg and Wehner<sup>32</sup> at 300 eV, hence the CC erosion rate would be a factor of 6.7 less than for molybdenum. This makes CC composites even more attractive for thruster grids.

### PRESENT ACTIVITIES

There is presently a significant amount of activity with carbon-based grid development. ISAS is continuing the development and test of 20-cm grids<sup>17,38</sup> following the successful MUSES-C program including the launch this year of the first set of CC ion optics. NASA GRC is building on the successful fabrication and test of 8-cm pyrolytic graphite grids<sup>22</sup> with a 30-cm grid effort.<sup>23</sup>

The Jet Propulsion Laboratory is currently developing 30-cm dished CC grids for high-specific impulse operation as a part of the Carbon-Based Ion Optics (CBIO) program. Boeing Electron Dynamic Devices, Inc., is developing 30-cm pyrolytic graphite grids for the same program.<sup>19</sup>

The successes and lessons learned from previous development programs have led to even more ambitious work. JPL is now fabricating 65-cm dished CC grids for the NEXIS program<sup>39</sup> and has recently successfully fabricated 75-cm flat CC grids. The 75-cm grids are designed for operation at a specific impulse of 14,000 sec.

### CONCLUSIONS

Carbon-carbon grids have gone from initial development to flight in a decade. The properties of carbon-based grids that were initially attractive, low sputter yield and low or negative coefficient of thermal expansion, have been verified by many tests. Initial concerns about the material, such as the ability to hold off voltage and survive launch loads, have been dealt with by test and design. Greater understanding of the material behavior as it relates to ion thruster requirements has been achieved and greater design tools have been developed for present and future use. Additionally, preliminary testing with pyrolytic graphite has yielded encouraging results. These successes and lessons learned have led to ambitious new developments for 30-cm pyrolytic graphite grids and to 30 to 75-cm carbon-carbon grids.

### ACKNOWLEDGEMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. Funding was provided by the In-Space Transportation Program managed by Les Johnson at the NASA Marshall Space Flight Center. This work was performed as a part of the CBIO program, which is managed by Randy Baggett. Their support is gratefully acknowledged.

### REFERENCES

1. R. Killinger, R. Kukies, M. Surauer, L. van Holtz, and A. Tomasetto, "Orbit Raising with Ion Propulsion on ESA's ARTEMIS Satellite," AIAA 2002-3672, 38<sup>th</sup> Joint Propulsion Conference, Indianapolis, IN, July 2002.
2. K. Toki, H. Kuninaka, K. Nishiyama, and Y. Shimuzu, "Flight Readiness of the Microwave Ion Engine System for MUSES-C Mission," IEPC 2003-98, 28<sup>th</sup> International Electric Propulsion Conference, Toulouse, France, March 2003.
3. "Fabrics and Preforms," appears in *Constituent Materials*, ASM Handbook Vol 21, Composites, ASM International, Material Park, Ohio, 2001.

4. D.E. Hedges and J.S. Meserole, "Demonstration and Evaluation of Carbon-Carbon Ion Optics," Journal of Propulsion and Power, Vol. 10, No. 2, Mar-Apr 1994, pps. 255-261.
5. J.S. Meserole, "Erosion Resistance of Carbon-Carbon Ion Optics," Journal of Propulsion and Power, Vol. 17, No. 1, Jan-Feb 2001, pps. 12-18.
6. C.E. Garner and J.R. Brophy, "Fabrication and Testing of Carbon-Carbon Grids for Ion Optics," AIAA 92-3149, 28<sup>th</sup> Joint Propulsion Conference, Nashville, TN, July 1992.
7. S. Kitamura, K. Miyazaki, Y. Hayakawa, Y. Nakamura, and S. Yamaguchi, "Fabrication and Testing of Carbon-Carbon Composite Grids for a 14-cm Ion Thruster," IEPC 95-93, 24<sup>th</sup> International Electric Propulsion Conference, Moscow, Russia, 1995.
8. J.S. Meserole, "Fabrication and Testing of 15-cm Carbon-Carbon Grids with Slit Apertures," AIAA 95-2661, 31<sup>st</sup> Joint Propulsion Conference, San Diego, CA, July 1995.
9. J. Mueller, J.R. Brophy, D.K. Brown, and C.E. Garner, "Performance Characterization of 15-cm Carbon-Carbon Composite Grids," AIAA 94-3118, 30<sup>th</sup> Joint Propulsion Conference, Indianapolis, IN, June 1994.
10. J. Mueller, D.K. Brown, C.E. Garner, and J.R. Brophy, "Fabrication of Carbon-Carbon Grids for Ion Optics," IEPC 93-112, 23<sup>rd</sup> International Electric Propulsion Conference, Seattle, WA, Sept. 1993.
11. S. Kitamura, Y. Hayakawa, Y. Kasai, and T. Ozaki, "Fabrication of Carbon-Carbon Composite Ion Thruster Grids – Improvement of Structural Strength," IEPC 97-093, 25<sup>th</sup> International Electric Propulsion Conference, Cleveland, OH, 1997.
12. J. Mueller, J.R. Brophy, and D.K. Brown, "Endurance Testing and Fabrication of Advanced 15-cm and 30-cm Carbon-Carbon Composite Grids," AIAA 95-2660, 31<sup>st</sup> Joint Propulsion Conference, San Diego, CA, July 1995.
13. H. Kuninaka, S. Satori, and Y. Horiuchi, "Continuous Operation Test of Microwave Discharge Ion Thruster System," AIAA 95-3070, 31<sup>st</sup> Joint Propulsion Conference, San Diego, CA, July 1995.
14. I. Funaki, H. Kuninaka, K. Toki, Y. Shimizu, K. Nishiyama, and Y. Horiuchi, "Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster," J. of Propulsion and Power, Vol. 18, No. 1, Jan-Feb 2002, pps. 169-175.
15. Y. Hayakawa, S. Kitamura, and K. Miyazaki, "Endurance Test of C/C Grids for 14-cm Xenon Ion Thrusters," AIAA 2002-3958, 38<sup>th</sup> Joint Propulsion Conference, Indianapolis, IN, July 2002.
16. I. Funaki, K. Nishiyama, H. Kuninaka, K. Toki, Y. Shimizu, and H. Toki, "20 mN-class Microwave Discharge Ion Thruster," IEPC 01-103, 27<sup>th</sup> International Electric Propulsion Conference, Pasadena, CA, Oct. 2001.
17. Y. Shimizu, H. Kuninaka, K. Nishiyama, and K. Toki, "Evaluation of New Carbon-Carbon Composite Material for a 20 cm Ion Engine," IEPC 2003-97, 28<sup>th</sup> International Electric Propulsion Conference, Toulouse, France, March 2003.
18. J.R. Brophy, J. Mueller, and D.K. Brown, "Carbon-Carbon Ion Engine Grids with Non-Circular Apertures," AIAA 95-2662, 31<sup>st</sup> Joint Propulsion Conference, San Diego, CA, July 1995.
19. J.S. Snyder, J.R. Brophy, D.M. Goebel, J.S. Beatty, and M.K. De Pano, "Development and Testing of Carbon-Based Ion Optics for 30-cm Ion Thrusters," AIAA 2003-4716, to be presented at the 39<sup>th</sup> Joint Propulsion Conference, Huntsville, AL, July 2003.
20. J. Mueller, J.R. Brophy, and D.K. Brown, "Design, Fabrication, and Testing of 30-cm Dia. Dished Carbon-Carbon Ion Engine Grids," AIAA 96-3204, 32<sup>nd</sup> Joint Propulsion Conference, Lake Buena Vista, FL, July 1996.
21. H.J. Leiter, H.W. Loeb, and K.H. Schartner, "RIT15S and RIT15LP – The Development of High Performance Mission Optimized Ion Thrusters," AIAA 99-2444, 35<sup>th</sup> Joint Propulsion Conference, Los Angeles, CA, June 1999.
22. T. Haag and G. Soulas, "Performance of 8-cm Pyrolytic-Graphite Ion Thruster Optics," AIAA 2002-4335, 38<sup>th</sup> Joint Propulsion Conference, Indianapolis, IN, July 2002.
23. T. Haag and G. Soulas, "Performance of 30-cm Pyrolytic Graphite Ion Thruster Optics," AIAA 2003-4557, to be presented at the 39<sup>th</sup> Joint Propulsion Conference, Huntsville, AL, July 2003.

24. H. Kuninaka and S. Satori, "Development of Microwave Discharge Ion Thruster for Asteroid Sample Return Mission," AIAA 96-2979, 32<sup>nd</sup> Joint Propulsion Conference, Lake Buena Vista, FL, July 1996.
25. Personal Communication, J. Mueller, July 2003.
26. T. Haag, M. Patterson, V. Rawlin, and G. Soulas, "Carbon-Based Ion Optics Development at NASA GRC," IEPC 01-94, 27<sup>th</sup> International Electric Propulsion Conference, Pasadena, CA, Oct. 2001.
27. K.H. Groh, H.J. Leiter, and H.W. Loeb, "Design and Performance of the New RF-Ion Thruster RIT15," AIAA 98-3344, 34<sup>th</sup> Joint Propulsion Conference, Cleveland, OH, July 1998.
28. I. Funaki, H. Kuninaka, Y. Shimizu, K. Toki, S. Satori, and K. Nishiyama, "Verification Tests of 10-cm-diam. Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster," IEPC 99-164, 26<sup>th</sup> International Electric Propulsion Conference, Kitakyushu, Japan, Oct. 1999.
29. S. Satori, H. Kuninaka, and K. Kuriki, "300 Hours Endurance Test of Microwave Ion Thruster," IEPC 95-89, 24<sup>th</sup> International Electric Propulsion Conference, Moscow, Russia, 1995.
30. H.J. Leiter and D. Feili, "RIT 15S – A Radio Frequency Ion Engine for High Specific Impulse Operation," AIAA 2001-3491, 37<sup>th</sup> Joint Propulsion Conference, Salt Lake City, UT, July 2001.
31. S. Tamaya, I. Funaki, M. Murakami, and H. Kuninaka, "Plasma Production Process in an ECR Ion Thruster," AIAA 2002-2196, 33<sup>rd</sup> AIAA Plasma Dynamics and Lasers / 14<sup>th</sup> International MHD Conference, Maui, HI, May 2002.
32. D. Rosenberg, and G.K. Wehner, "Sputtering Yields for Low Energy He<sup>+</sup>, Kr<sup>+</sup>, and Xe<sup>+</sup> Ion Bombardment," J. Applied Physics, V. 33, n. 5, May 1962, pp. 1842-1845.
33. V.S. Smentkowski, "Trends in Sputtering," Progress in Surface Science, Vol. 64, 2000, pps. 1-58.
34. G. Betz and G.K. Wehner, "Sputtering of Multicomponent Materials," appears as Chap. 2 of Sputtering by Particle Bombardment II, ed. R. Behrisch, Springer-Verlag, Berlin, 1983.
35. R. Deltschew, M. Tartz, V. Plicht, E. Hartmann, H. Neumann, H.J. Leiter, and J. Esch, "Sputter Characteristics of Carbon-Carbon compound Material," IEPC 01-118, 27<sup>th</sup> International Electric Propulsion Conference, Pasadena, CA, Oct. 2001.
36. J.J. Blandino, D.G. Goodwin, and C.E. Garner, "Low energy sputter yields for diamond, carbon-carbon composite, and molybdenum subject to xenon ion bombardment," Diamond and Related Materials, Vol. 9, 2000, pps. 1992-2001.
37. Personal Communication, C.E. Garner, July 2003.
38. K. Nishiyama, H. Kuninaka, Y. Shimizu, and K. Toki, "30mN-Class Microwave Discharge Ion Thruster," IEPC 2003-62, 28<sup>th</sup> International Electric Propulsion Conference, Toulouse, France, March 2003.
39. J.E. Polk, "An Overview of the Nuclear Electric Xenon Ion System (NEXIS) Program," AIAA-2003-4713, to be presented at the 2003 Joint Propulsion Conference, Huntsville, AL, July 20-23, 2003.