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Carbon Ion Engine Technology- Executive Summary

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1 Introduction

1.1 Scope and purpose of the project

This programme of work is targeting the application of carbon technology in order to enable extended lifetime and higher thrust operation of a T6 Gridded Ion Engine (GIE). The development programme addresses the design, analysis, manufacture, and test of a carbon screen grid. The full scope of the project is shown in Figure 1.

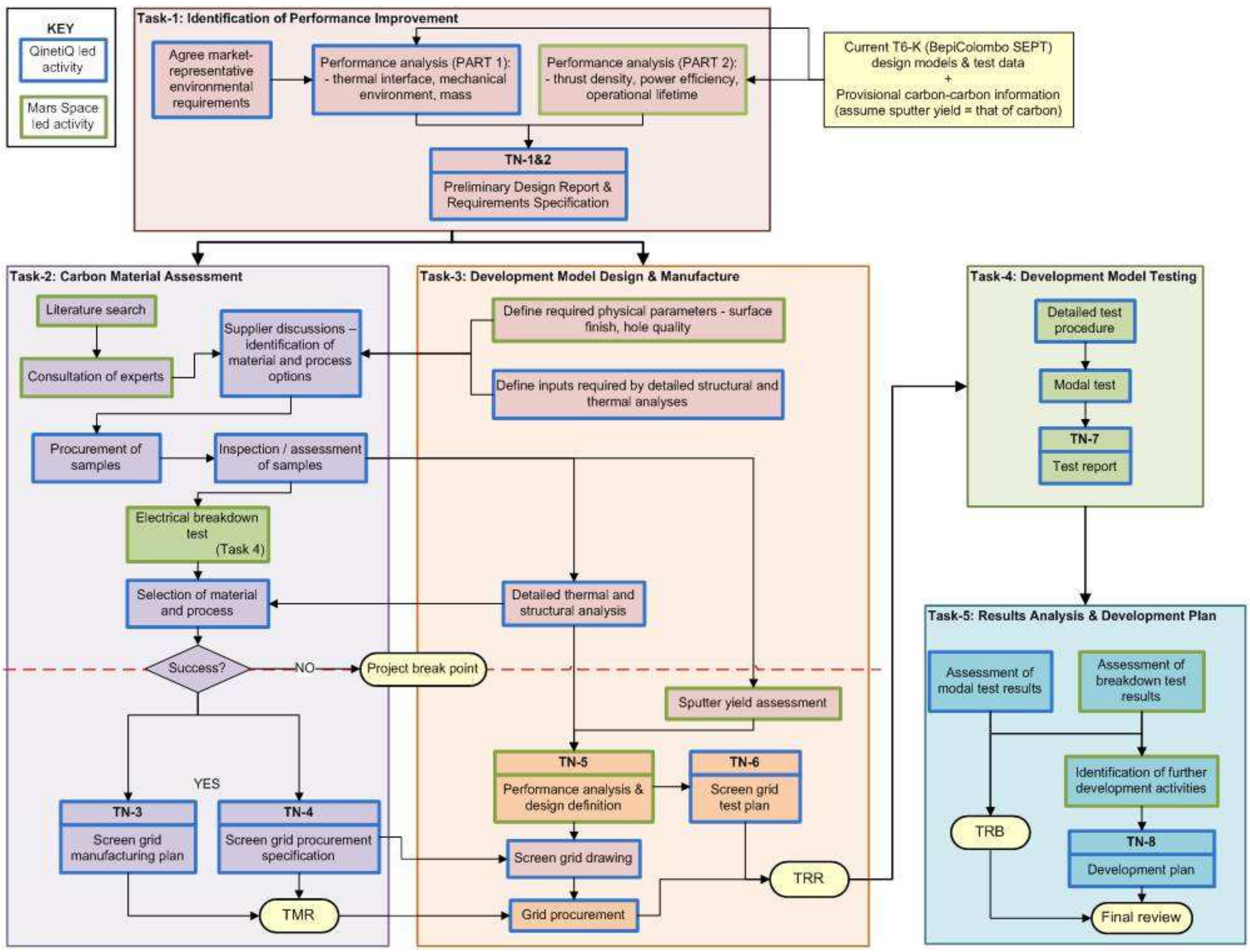


Figure 1: Study logic for the carbon ion engine technology programme

2 References and Abbreviations

2.1 Applicable documents

AD	Document Number	Document Name
AD-01	TS/NTB/TN1403175 Issue 1, rev 1	Preliminary Design Report & Thruster Requirements Specification
AD-02	QinetiQ/TS/NTB/TN1500097 Issue 1.0	Development Model plan & Carbon Material Procurement Specification
AD-03	MSL-CC-TN-003 Issue 01-00	Breakdown Voltage Characterization Test Report
AD-04	MSL-CC-TN-004 Issue 01-00	Gridset Lifetime Assessment with Pyrolytic Graphite Screen Grid
AD-05	QINETIQ/EMEA/SPACE/TN1600042 Issue 01-00	Performance Analysis & Design Definition
AD-06	QINETIQ/EMEA/SPACE/ TN1800053 Issue 2.0	Inspection photos of pyrolytic graphite screen grid mk2
AD-07	QINETIQ/EMEA/SPACE/TSTR1800070 Issue 1.0	T6 Pyrolytic graphite screen grid qualification vibration test report
AD-08	QINETIQ/TS/NTB/Bid/1401653 Issue 2.0	Assessment of carbon ion engine technology
AD-09	QINETIQ/KI/SPACE/TN040807 Issue 1.0	Characterisation testing and performance analysis of graphite T6 Gridded Ion Engine

Table 1: Applicable Documents

2.2 Abbreviations

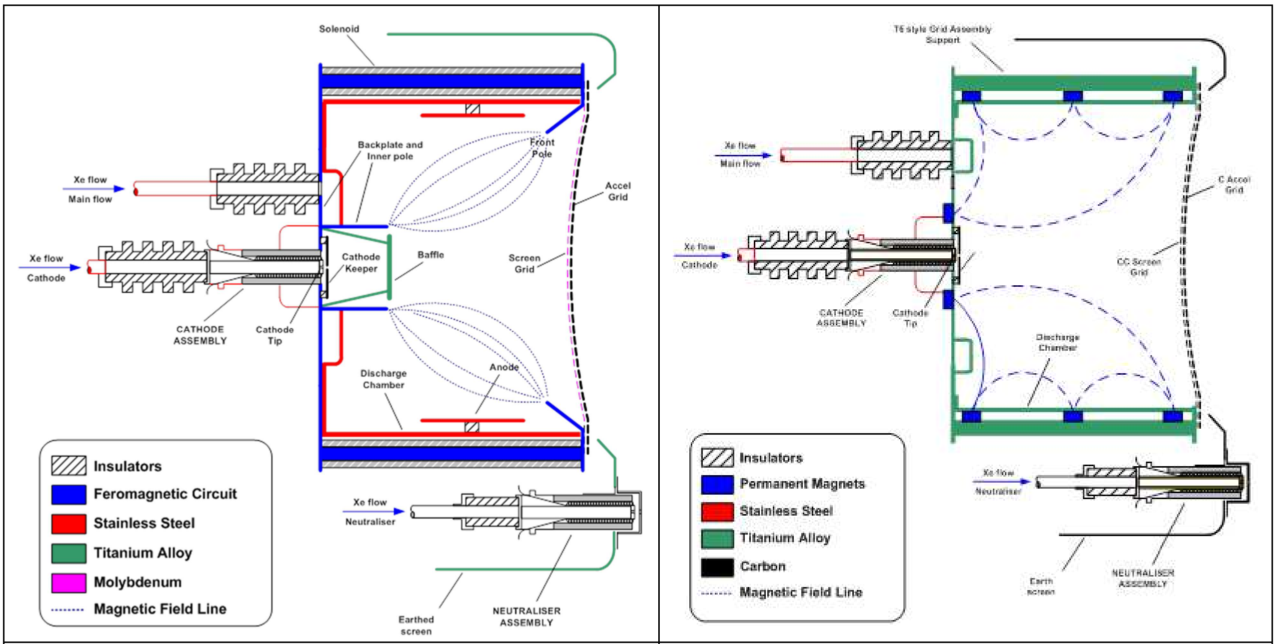
Abbreviation	Description
AD	Applicable Document
BOL	Beginning Of Life
CFRC	Carbon Fibre Reinforced Carbon
CTE	Coefficient of Thermal Expansion
CVD	Chemical Vapour Deposition
CVI	Chemical Vapour Infiltration
EDS	Energy Dispersive Spectroscopy
EGEP	European GNSS Evolution Programme
EQM	Engineering Qualification Model
ESA	European Space Agency
GIE	Gridded Ion Engine
HV	High Voltage
PG	Pyrolytic Graphite
PPU	Power Processing Unit
SOW	Statement of Work

Table 2: Abbreviations

3 Background

3.1 Kaufman and Ring Cusp Designs

QinetiQ's mature T-series thrusters, including the T5 thruster qualified for the GOCE mission and the T6 thruster qualified for the BepiColombo mission, have adopted a Kaufman configuration. In this configuration the ionisation process is fine-tuned by applying a variable magnetic field via solenoids positioned around the discharge chamber. More recently QinetiQ has started to develop Ring Cusp thrusters. In this configuration, permanent magnets are positioned around the discharge chamber instead of solenoids. This arrangement reduces the ability to finely control the thrust level, but offers improved ionisation efficiency which reduces the power demand for a given thrust, and reduces the power dissipated in the discharge chamber leading to lower operating temperatures. In addition the anode voltage is reduced, which extends the screen grid lifetime.



Kaufman T6	Ring Cusp T6

Figure 2: QinetiQ T6 ion thrusters

4 Performance objectives

Table 3 identifies the target performance improvements and the potential to achieve these objectives, accounting for evolved mission requirements since the Statement of Work (SOW) was generated.

SOW Performance Objectives	Commentary
Physically smaller thruster capable of delivering 150mN or more.	T6 capability currently generates up to 145mN for 5kW (22cm baseline) Market requirements for Navigation (G2G) are now >180mN for 3.5kW Market requirements for Telecoms (GIESEPP) are now 215mN for 5.5kW (30cm baseline)
High thrust density resulting in increased thrust at lower operating temperatures.	The T6 has previously been operated up to 230mN with a Molybdenum screen grid but lower operating temperatures would require a carbon discharge chamber or a Ring Cusp engine
Lower dry mass (2kg saving)	The T6 Kaufman engine mass is 8.5kg. The Molybdenum screen grid mass is only 69g, and the carbon grid is 24.8g, so introduction of carbon components will not reduce mass significantly
Lower production costs	The difference in screen grid cost for carbon compared with Molybdenum is not significant on its own. A carbon discharge chamber may lower temperatures sufficiently to enable a simplified thermal design.
Longer life screen grid to >25MNs	T6 capability currently ~7.3MNs (G2G operations including 2483 cycles) G2G and GIESEPP requirements are 5 and 9MNs respectively excluding qualification margin
Trade-off between high thrust and high specific impulse	T6 achieves 3890-4261s at 145mN with a beam voltage of 1850V Ring Cusp engine with a beam voltage of 1000V reduces the Isp to ~3100s with a lower specific power of ~25W/mN Isp requirement for G2G is >1500s Isp requirement for GIESEPP is 3000s (orbit raising) – 4000s (stationkeeping)

Table 3: Carbon ion engine technology performance objectives

5 Material Selection

5.1 Introduction

A comprehensive literature search has been performed to establish a list of suitable carbon materials and processing methods for use as grid components within GIEs. Many potential suppliers were consulted. Based on TN-1/2 (AD-01) and supporting design data from existing thrusters, each candidate material has been assessed, including applicable processing methods to establish a short list of candidate materials.

Samples were obtained for mechanical drilling, and high magnification microscopy.

5.2 Carbon Fibre Reinforced Carbon (CFRC)

CFRC material is laid up in a mould in its intended final shape, with carbon filament and/or cloth surrounded by an organic binder such as phenolic resin. The phenolic matrix holding the fibres together is reduced to relatively pure carbon by high temperature firing in an oxygen-free atmosphere. This carbonisation process drastically reduces the strength and mass of the laminate in the process forming voids, requiring subsequent densification to raise density and structural integrity. The voids are gradually filled by forcing a carbon-bearing gas such as acetylene through the material. In this Chemical Vapour Infiltration (CVI) process, the carbonised laminates are processed for an extended period (~200 hours) in a vacuum at high temperature in the presence of the carbon-bearing gas. This is a time consuming and expensive process. In addition, mechanical drilling inevitably breaks the fibres, leading to a reduction in the material strength, and exposing fibre ends in the holes.

Figure 3 shows examples of the voids and broken fibres. N.B. ragged edges to perforation holes will reduce the voltage standoff potential and prolong thruster qualification testing by extending the grid burn in period before stabilisation of the accel grid current.

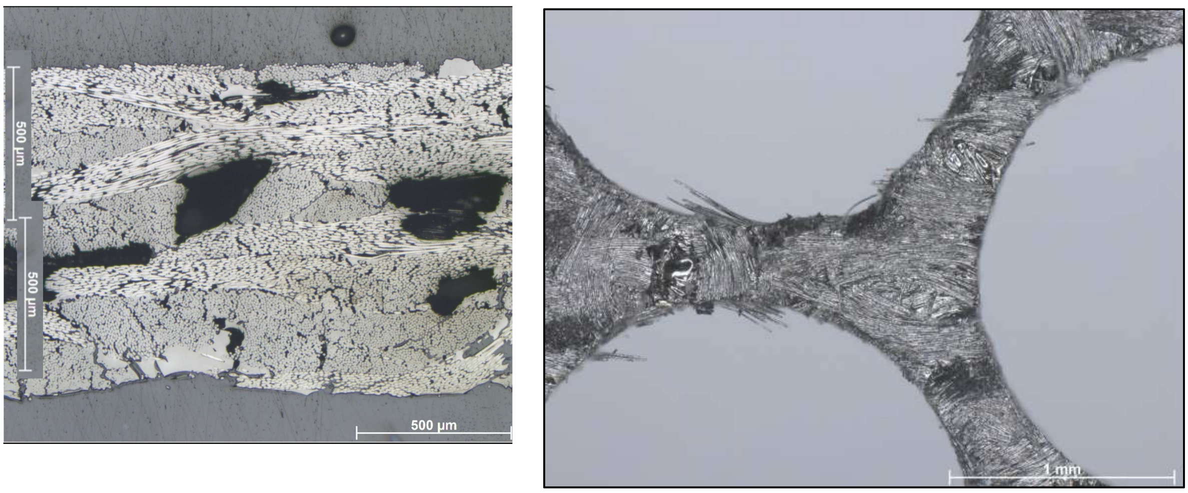


Figure 3: CFRC sample photographs

5.3 Pyrolytic Graphite (PG)

Pyrolytic Graphite is a synthetically manufactured form of graphite. PG is made in a single stage by high temperature decomposition of hydrocarbon gases (e.g. acetylene) in vacuum followed by deposition of the carbon atoms onto a substrate surface, i.e. Chemical Vapour Deposition (CVD). The resulting material is ultra-pure anisotropic graphite possessing near theoretical density of 2.22 g/cm^3 (no pores), with excellent thermal conductivity and high strength. The processing time is reduced compared to the multi-stage processing required for densified CFRC materials. Drilled apertures are clean, as shown in Figure 4.

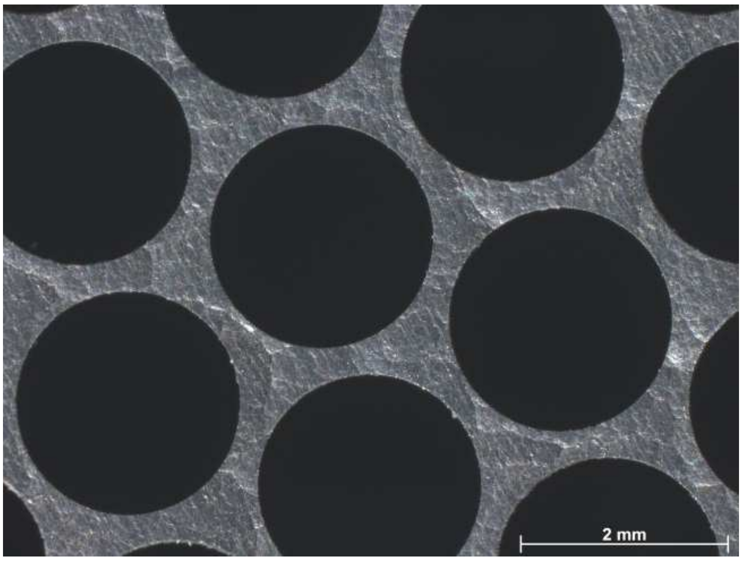


Figure 4: T5 Carbon screen grid

5.4 Comparison of materials

Table 3 presents an overall comparison of CFRC & PG materials for this application. As a consequence it was agreed to proceed with manufacture of a pyrolytic screen grid.

Factor	CFRC	Pyrolytic Graphite
Cost	High	Medium
Porosity	Poor	Excellent
Uniformity, consistency and surface finish	Poor	Good
Aperture definition	Poor	Good
Mechanical robustness	Unknown (non-homogenous, therefore cannot be modelled)	Low (compared with Molybdenum)

Table 4: Comparison of candidate carbon screen grid materials

6 Manufacturing Approach

6.1 PG screen grid

The approach for manufacturing a screen grid from pyrolytic graphite is described here, noting the need for repeatable and cost effective manufacture without high scrap rates due to defects.

The PG grid was manufactured by Kennametal by machining a block of material into a dome shape, i.e. the convex surface. A sacrificial mandrel was manufactured to fit the convex surface of the grid and then the concave side of the PG component was machined to provide a grid with a thickness of 0.5mm. A thinner screen grid thickness would be beneficial for ion optic performance, but matching the molybdenum screen grid thickness of 0.3mm was considered high risk for manufacture at this stage. Mechanical drilling of the holes was performed from the concave surface to the convex surface of the grid. The screen grid for a T6 size thruster has approximately 7300 perforations. The first attempt by Kennametal to drill these perforations in the machined PG blank led to breakthrough of the web material between adjacent holes in 3 locations, see Figure 5.

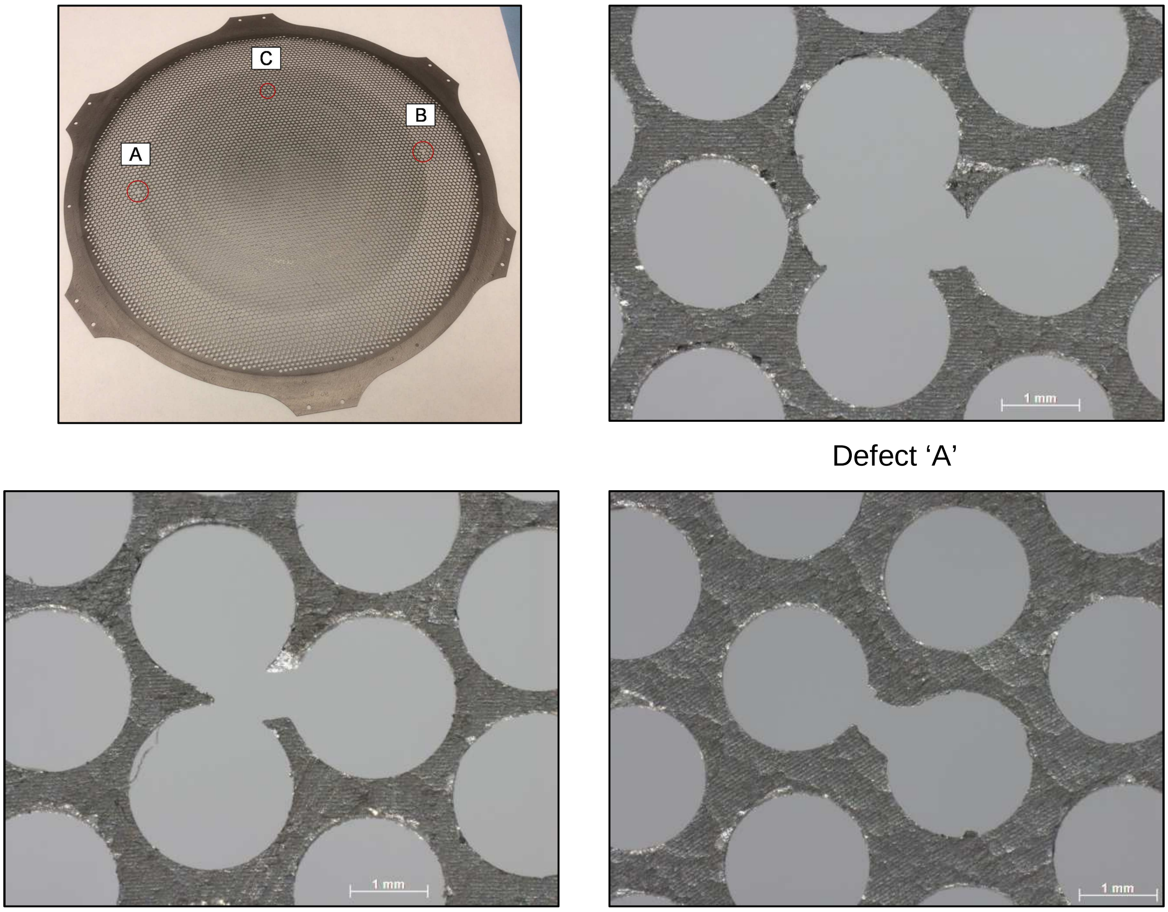


Figure 5: Upstream surface of pyrolytic graphite screen grid with defects & locations

During a second attempt at manufacture by Kennametal, the number of operations for each drill bit was decreased from 250 holes per drill bit to 100 holes per drill bit to avoid blunting, and the holes were drilled from the opposite direction (i.e. from the convex surface to the concave surface). This resolved the breakthrough problems and the profile of the screen grid was found to be within specification.

6.2 Alternative drilling techniques

Laser drilling has been considered as an alternative having the advantage of minimal cutting force to disrupt the delicate webs between holes. Fragments from a grid made from pyrolytic graphite previously were sent to Precision Laser Processing Ltd for trial laser drilling. A very small diameter laser beam has been used to 'trepan' these holes in the pyrolytic graphite coupons. The laser is first directed at the centre of the circular area of material to be removed; point 'A' in Figure 6. The laser is then traversed to point 'B' and then around the circumference of the required hole, back to point 'B'. Cutting forces are non-existent.

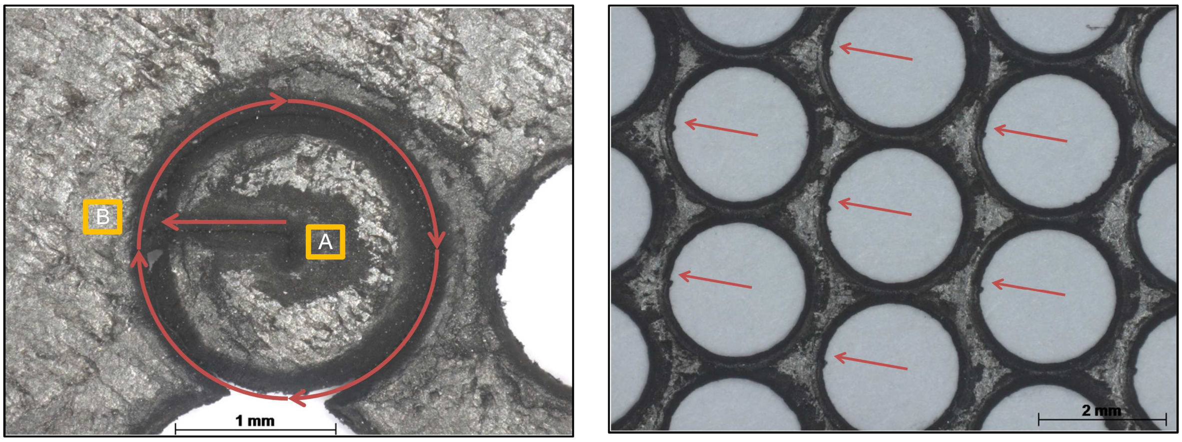


Figure 6: Laser 'drilling' process (top side)

Repeatability of the cutting process looks to be good as a 'pip' at the start/finish of each trepanning operation appears on every hole at the same position on the circumference. These pips may not be a concern if they are 'burnt off' in initial thruster commissioning. Hole to hole positioning was not consistent – possibly more of an issue related to the positioning system used than the laser itself.

Further examination with a scanning electron microscope shows chamfering and edge details for a cut hole. Figure 7.

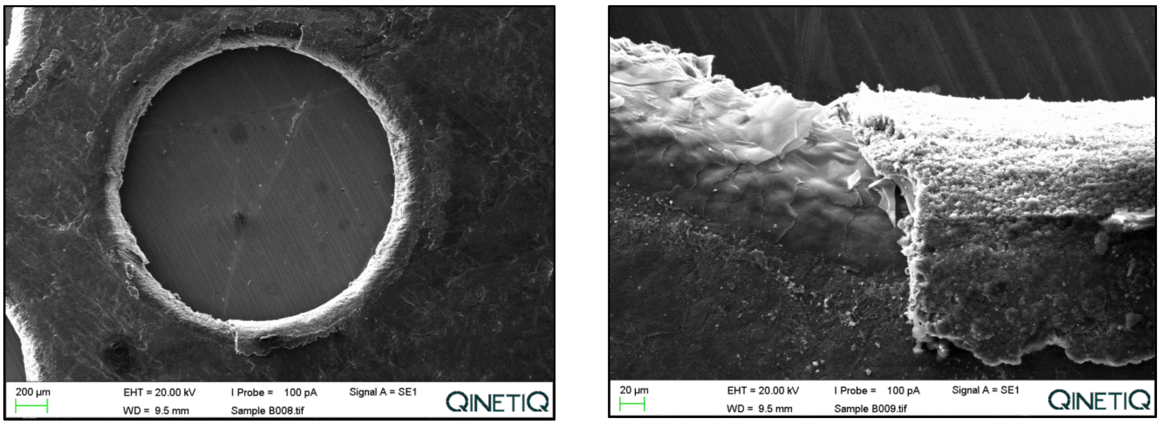


Figure 7: SEM images of laser drilled sample

There appears to be a ‘deposit’ around the edge of the hole that has fallen off in a number of places. Energy Dispersive Spectroscopy (EDS) analysis of the deposit reveals the presence of aluminium as a minor addition to a mostly carbon deposit composition. Since there is no aluminium in the parent pyrolytic graphite material, it is assumed that the aluminium originates from an underlying support plate for the sample, which has vaporised and mixed with the vaporised graphite, partially recondensing as the cut progresses.

Improvements in this laser ‘drilling’ process may be possible through fine-tuning the cutting parameters. Manufacture repeatability and costs for production of a T6 pyrolytic graphite grid in this way have not been established. Therefore, whilst mechanical drilling was maintained for the carbon screen grid for this project, laser drilling grid holes in a PG grid appears to offer a potential alternative.

7 Mechanical and thermal performance

7.1 Mechanical analysis

The T6 Finite Element (FE) model was updated based upon studies using separate high definition finite element models of grids (2.8 million plate elements). Sensitivity analyses were performed for critical damping, screen grid thickness, and dish depth. Modal testing of the grids was also performed to provide greater accuracy to the damping parameter. The FEM was used to predict results for various random loading cases applied along each coordinate axis. The results suggested that the grid assembly would survive testing at BepiColombo levels (7.19g_{RMS}) and intermediate levels (12.60g_{RMS}), but would fail for HPEPS levels (18.43g_{RMS}).

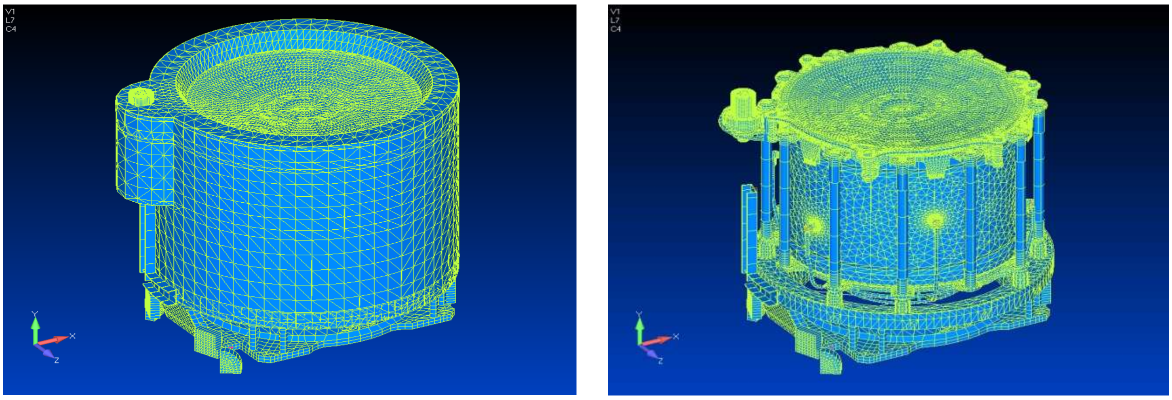


Figure 8: Finite element model shown with & without earth screen

7.2 Mechanical testing

A reduced thruster assembly was then created consisting of the dual grid and a partial backplate assembly including the discharge chamber, solenoids and mounting ring, so that representative mechanical loads would be transmitted to the grids.

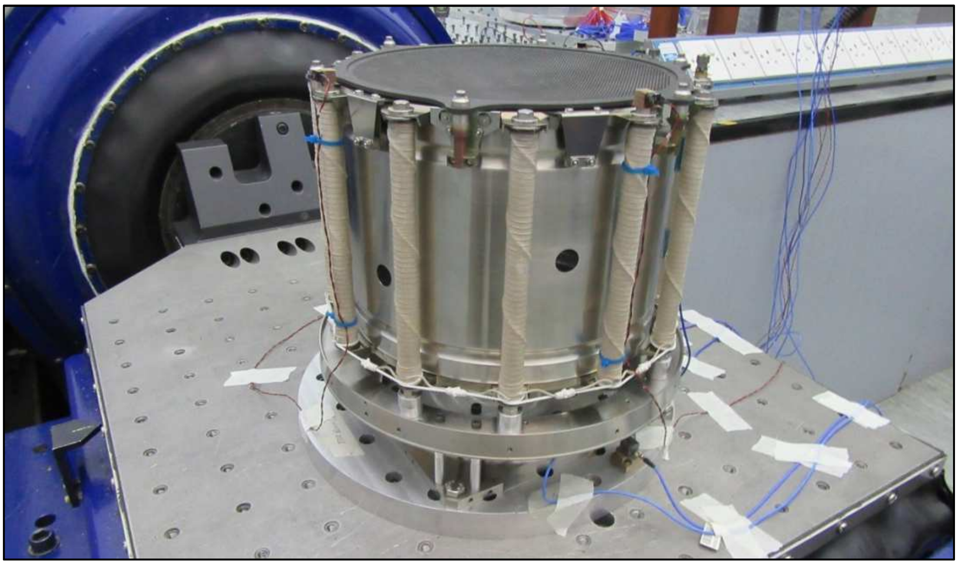


Figure 9: Thruster assembly on vibration shaker slip table for lateral excitation

This reduced thruster assembly was subjected to vibration testing as described in TN7 (AD-07). Mechanical robustness was found to be better than expected from earlier modelling work and demonstrated that the all carbon T6 sized gridset successfully survived random vibration up to Telecommunications levels (2 minutes at 18.4 g_{RMS})

7.3 Thermal and thermoelastic analysis

The T6 design is constrained by the low temperature limit for the Gore High Voltage cable. This has required complex thermal breaks to be designed to maintain an acceptable cable temperature. Consequently, a simplified thermal design could be achieved if either the cable temperature is reduced, or the cable temperature limit is improved. Although modelling predicts the implementation of a PG screen grid will lower the screen grid temperature by up to 60°C at 145mN, the impact on other elements of the assembly is minimal. However, temperature reductions of between 30ºC (front pole) and 55ºC (discharge cathode mounting flange) have been demonstrated with a carbon discharge chamber (AD-09) for a thrust of 217mN, and further reductions can be achieved with a Ring Cusp design due to the higher ionisation efficiency. Switching HV cable from Gore (qualified to 199°C) to Axon (280°C) will provide additional margin to enable higher thrust densities to be achieved with a simplified thermal design.

Screen grid thermoelastic behaviour is dominated by the grid mounting arrangement. The screen grid is held in intimate contact with the front pole by the screen grid legs and the screen grid rim guides. The front pole component forms part of the magnetic circuit for a Kaufman thruster and is therefore manufactured from soft magnetic iron which has a high Coefficient of Thermal Expansion (CTE).

Figure 10: Grid assembly and front pole

AD-03 identified a minimum gap of 0.3mm is required to prevent electrical breakdown for an all carbon gridset. This minimum gap needs to be maintained under all operating conditions e.g. initial start-up and steady-state conditions at maximum thrust. However, AD-05 identified the predicted thermal expansion behaviour of the all carbon gridset when assembled with a T6 Kaufman engine. When operating, the screen grid has an elevated temperature with a large thermal gradient from the centre to the outer periphery. Thermal expansion of the molybdenum screen grid under this loading causes dishing of the grid to increase, i.e. the screen grid moves away from the accel grid.

Simultaneously, the iron front pole which is present on the Kaufman grid assembly configuration is heated and increases in diameter. The coefficient of thermal expansion for iron is greater than that for molybdenum. At the interface between the front pole and the screen grid, the temperatures and CTEs of these components mean that, in isolation, the radial growth of the front pole is greater than the screen grid. The screen grid legs and the rim guides, in conjunction with the front pole, drag the periphery of the screen grid with the expanding front pole. This has the effect of tensioning the screen grid, thus reducing the dishing. It should be re-emphasised that the grid gap changes are not simply due to material CTE differences. Temperature differences and temperature profiles for the accel grid and the screen grid are also major contributory factors in evolution of the grid gap.

With the current molybdenum screen grid, it is known that the grid gap reduces when the thruster is operating (hot), but that the reduction in grid gap is not sufficient to lead to the minimum gap of 0.3mm. In the absence of any other changes, direct substitution of the molybdenum screen grid with a pyrolytic graphite version could lead to the grids touching at temperature. This is due to the lower CTE of PG compared to molybdenum. However, this prediction is based on FE modelling that has not been validated. Actual measurements of the assembly under thermal loading need to be performed to confirm the FE prediction. With a Ring Cusp engine the grid mount can be manufactured from any material, potentially allowing more design flexibility to accommodate the required thermoelastic behaviour to maintain the desired hot grid gap.

8 Performance and Lifetime

A preliminary performance and lifetime assessment of the pyrolytic screen grid has been reported in AD-04.

Simplistically, if the operating conditions are kept consistent, then the use of carbon in place of molybdenum reduces the sputter yield and hence significantly extends the life of the screen grid by at least 57% at 145mN with a beam voltage of 1850V and an accel voltage of -265V. Effectively we can utilise the lower sputter yield of carbon to drive the discharge harder, thereby achieving higher thrust densities without compromising screen grid lifetime. However other operating constraints such as thermal limits (addressed in section 7.3) and grid perveance also need to be addressed. Reducing the beam voltage improves the W/mN figure, but an increase in accel grid voltage is also required to ensure that a higher maximum thrust is achievable. Figure 11 indicates the predicted T6 thrust capability at 1000V beam voltage across a range of accel voltages.

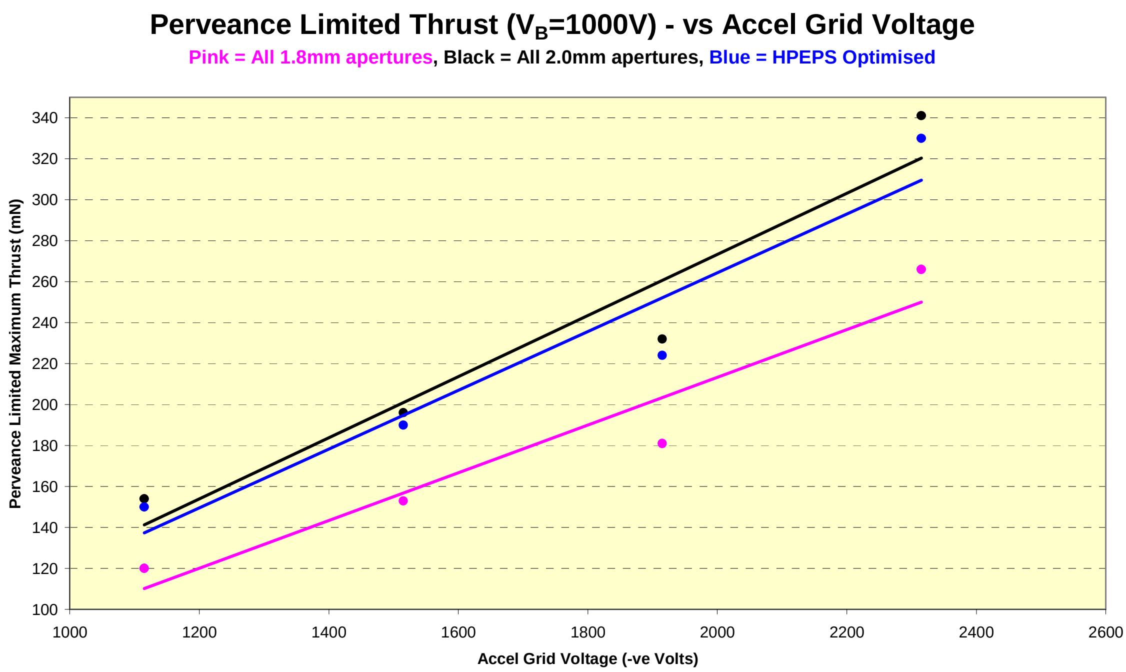


Figure 11: T6 thrust limit at a range of accel voltages (beam voltage = 1000V)

9 Conclusions and further developments

9.1 Development Strategy

The carbon ion engine technology project has now addressed the two main development risks that had previously been identified by QinetiQ: the ability to successfully manufacture a carbon screen grid, and the survival of the carbon screen grid under vibration loads for a T6 sized thruster. These were considered the main barriers to the adoption of a carbon screen grid as part of QinetiQ's thruster designs. Removal of these barriers makes the continued development of the carbon screen grid an attractive proposition.

The use of carbon as the screen grid material has the potential to benefit all Gridded Ion Engines by extending lifetime. The thrust range could also be extended. This will increase the temperature at the HV cable, but this can be mitigated by a carbon discharge chamber with higher emissivity, and by switching to the Axon cable. These changes may also enable a simplified thermal design for the thermal breaks with subsequent cost reductions. A Ring Cusp design will also reduce temperatures by virtue of the higher ionisation efficiency.

There remains a possibility of electrical breakdown due to differential thermal expansion of the grids, although this has yet to be demonstrated. In order to maintain a suitable grid gap over the full thrust range, a revised interface which decouples the screen grid from the front pole could be implemented for a Kaufman engine, whereas for a Ring Cusp thruster the front pole can be replaced with another material of different CTE since it does not form part of the magnetic circuit.

9.2 Development Roadmap

Figure 12 shows a simple roadmap for the continued development of carbon technology and incorporation into QinetiQ's GIE products.

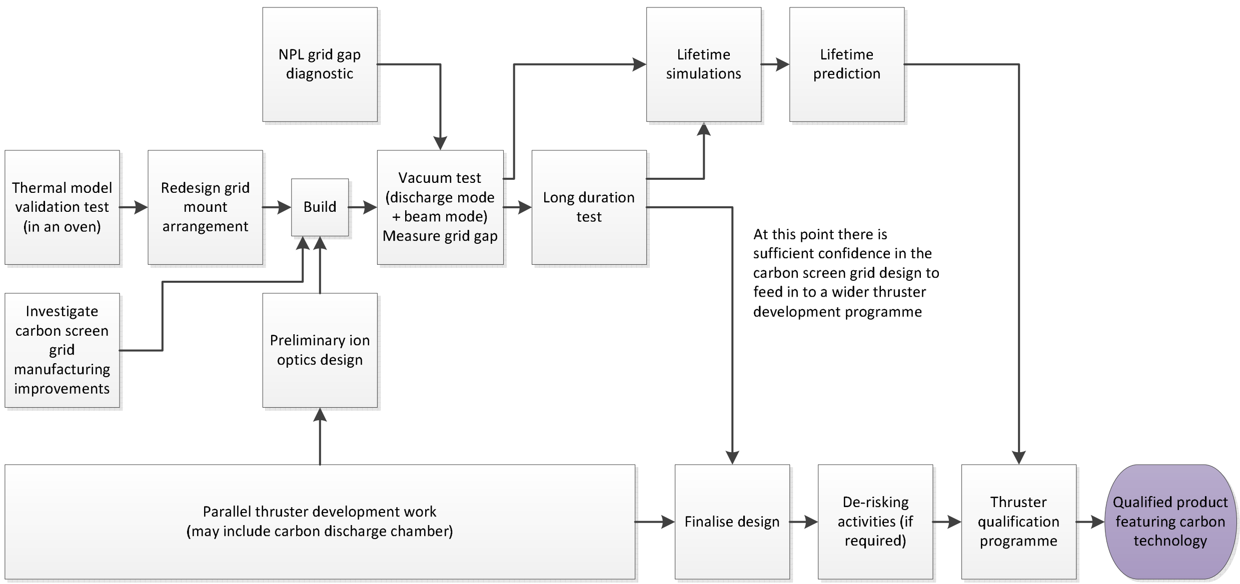
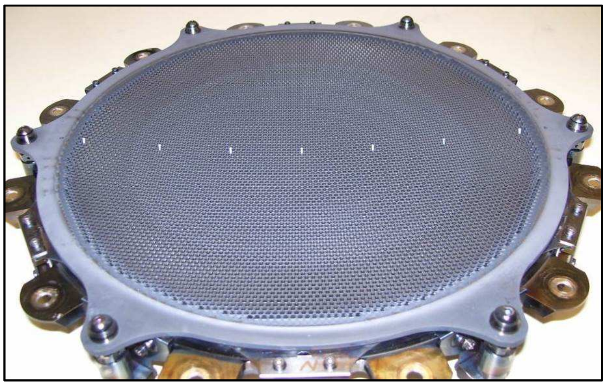


Figure 12: Carbon Technology Development Roadmap

Confirmation of the grid thermal expansion behaviour can be achieved in several stages. A simple test can be performed in an oven with a series of pins mounted on the screen grid but protruding through the accel grid to measure the change to the grid gap. Changes to the screen grid mounting arrangement may be possible from this test which could then be implemented before thruster operation under vacuum.

Grid thermal expansion can then be determined under operational conditions by use of a remote laser technique developed by NPL under the BepiColombo programme.



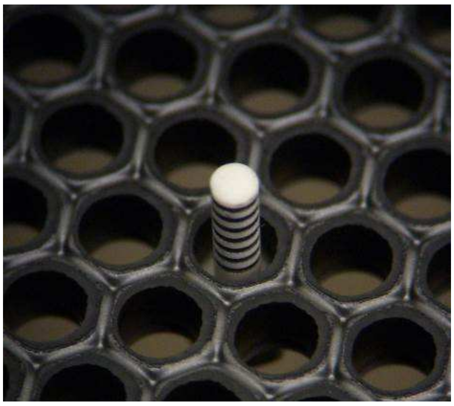


Figure 13: Ceramic pin arrangement for grid gap measurement

Overall, improvements in the lifetime, thrust density, and specific impulse can be realised by the adoption of a carbon screen grid ideally in conjunction with a carbon discharge chamber, Axon HV cable, and revised beam and accel voltages. These benefits are potentially extended by adoption of a Ring Cusp design, with higher ionisation efficiency and flatter radial plasma distribution thereby enabling simplified ion optics and thermal breaks, as well as elimination of solenoids, anode, ceramic isolators, sputter shields, rigid harness, and front pole to provide mass and cost reductions.

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