A SUMMARY OF THE QINETIQ HOLLOW CATHODE DEVELOPMENT PROGRAMME IN SUPPORT OF EUROPEAN HIGH POWER HALL EFFECT AND GRIDDED THRUSTERS

H.B.Simpson, N.C.Wallace, D.G.Fearn and M.K. Kelly
QinetiQ, Farnborough, Hampshire, GU14 0LX, The United Kingdom.

INTRODUCTION

QinetiQ has extensive experience with the design, development, qualification and testing of hollow cathodes. This expertise stems from three decades of development and testing of hollow cathodes for the T1[1], T2[2], T4[3], T5[4,5], UK-10[6,7], UK-25[8,9,10] and most recently the T6[11,12] gridded ion thrusters. From 1990 QinetiQ developed the T5 ion engine that has recently been selected for ESA's GOCE mission[13] and the 3.6A hollow cathodes have completed a qualification programme that includes lifetest. The T6 cathodes were scaled from these T5 devices and configured for both Gridded Ion Engines (GIE) and Hall Effect Thrusters (HET). Over the last three years the same cathode design has also been used for the ROS2000 programme. QinetiQ have recently delivered six 20A cathodes to Astrium (UK) for use on the Engineering Model (EM) and Engineering Qualification Model (EQM) ROS2000 engines.

This paper describes in general terms the recent work that has been completed by QinetiQ in the design, development and qualification of hollow cathodes, particularly in relation to the cathodes qualified for the ROS2000 programme. To this end, QinetiQ would like to acknowledge the support of Astrium (UK) who have assisted QinetiQ in achieving the qualification of a robust and reliable hollow cathode that is of benefit both to the ROS2000 programme and to QinetiQ's own gridded ion engine activities.

3.6A CATHODE

The cathodes planned for Artemis[14] were originally manufactured by Philips Components[15] before a rationalisation of their business resulted in the closure of their facilities in Mitcham, UK. As a result, QinetiQ developed and set-up a manufacturing capability for the discharge cathodes used on the Artemis UK-10 ion thrusters. This work had three main objectives. The first was to provide a source of cathodes for in-house research and development. The second was to simplify the design to improve the manufacturing repeatability and reduce costs. The third was to provide a source of devices in the event of problems with the existing Artemis cathodes which had already been procured by Astrium before the Philips facility was closed.

This development work became very important in late 1995 when a number of problems were experienced with the Philips cathodes that were being life tested. Although some of these problems have subsequently been attributed to facility effects [16], one of the failures was shown to be an unpredicted and slowly-occurring chemical reaction that was common to all of the Artemis flight units already procured by Astrium. Fortunately in parallel with the identification of these problems, the development work at QinetiQ on the 3.6A cathode design had been very successful. The problems associated with the Philips cathodes had been eliminated and development was advanced enough for the 3.6A design to be adopted.

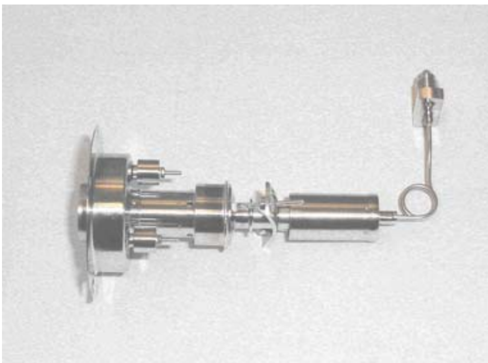


Figure 1 3.6A Discharge Cathode for Artemis

It should be noted in passing that 3.6A is the nominal emission current. In fact, these cathodes have operated successfully at much higher currents and were used in the initial development of the UK-25 thruster. In addition, the same basic design is used for the neutraliser on the T5 thruster, but at much lower current levels.

The new 3.6A design has been life-tested at QinetiQ. The numbers of cycles and hours achieved are shown in Table 1. The lifetest was stopped after each device had exceeded 15000 hours, representing the full lifetime of the cathodes (with qualification margin) on Artemis. All cathodes operated within specification throughout the lifetest.

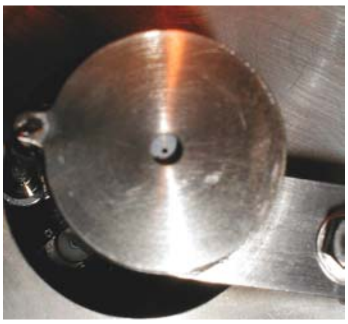
Device	Hours	Starts
DERA / CATH1	15059	5502
DERA / CATH2	15035	5482
DERA / CATH3	15003	5499
DERA / CATH4	15143	5483

Table 1 Cathode lifetest summary

In parallel with this lifetest a cyclic test of the heater design was also performed on four cathodes. At first the cathodes were allowed to cool to -40^{o}C before the heater power was enabled. The cathode tips were then heated to 1200^{o}C. This cycle was performed fifteen times. After these cold start cycles the cathodes were allowed to cool to +70^{o}C before the heaters were enabled. A total of 228 cycles were performed under these conditions until it was decided to increase the minimum temperature to +130^{o}C. This reduced the cycle time from 90 minutes to 45 minutes allowing 32 cycles to be achieved every day. The test continued in this manner until 5000 heater cycles had been accumulated on each cathode. During every cycle the current in the heaters was a constant 3.3A which would heat the cathode tip from 130^{o}C to 1200^{o}C in approximately 7.5 minutes.

As part of the qualification of the T5 thruster for the GOCE mission[13] it was necessary to demonstrate that a cathode could operate for the required mission duration in the relatively poor vacuum conditions that would exist at the low orbital altitude of the mission. To address this, QinetiQ performed a test in which a T5 neutraliser was operated in a deliberately poor vacuum. Air was continuously bled in to the test chamber via a needle valve to maintain the vacuum level at 4.2 x 10^{-3} Pa. At this pressure the number density of O_2 molecules (at room temperature) is 1.7 x 10^{17} m^{-3}. The neutraliser was operated at 20mN thrust levels, i.e. 1.0 Amp keeper current and 0.5 Amp emission current to an external anode, for a period of 1,000 hours. This test simulated a total equivalent exposure time of 70,000 hours in a circular 200 km altitude orbit.

Photographs of the neutraliser before and after the 1,000 hour test can be seen in Figure 2. The effects of operation in the poor environment have caused surface oxidation of the keeper plate.



Before

After

Figure 2 Downstream view of neutraliser before and after 1000 hours operation in poor vacuum

Despite this degradation to the cathode structure, performance was nominal and unchanged throughout the duration of the test, indicating that there was no degradation of the electron emission mechanisms.

T6 HOLLOW CATHODE

In late 1997 development work on the T6 22 cm diameter ion thruster[11,12] began at QinetiQ in conjunction with Astrium. As part of this development two cathodes were required; a 20 Ampere hollow cathode for the production of the primary discharge electrons and a 7 Ampere cathode for the neutraliser (to enable one neutraliser to neutralise the space charge of two adjacent ion beams). These cathodes were based on the T5 devices, employing all of the same processes and materials. A concurrent engineering approach was adopted in which the manufacturing processes, cathode design and testing were all performed in parallel. By adopting this approach engineering qualification model (EQM) cathodes were produced within 12 months of the start of the programme. The two cathodes are shown in Figure 3.

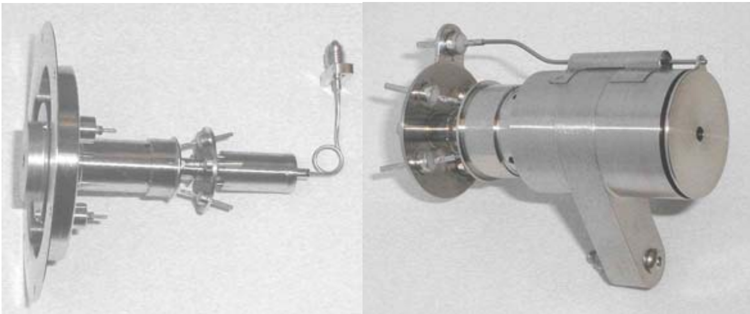


Figure 3 Discharge Cathode and Neutraliser for T6 Thruster

ROS2000 HOLLOW CATHODE

In support of the ROS2000 programme Astrium (UK) invited QinetiQ to provide cathodes for both the EM and the EQM thrusters, the former of which at the time of writing is under test at Alta, Italy. Two cathodes are installed on each thruster. The cathodes were subjected to a formal qualification programme, with the exception of a lifetest which will be performed in conjunction with the EQM thruster lifetest at Alta. The major elements of the development and qualification programme are described in this section. Two of the prototype cathodes are shown in Figure 4.

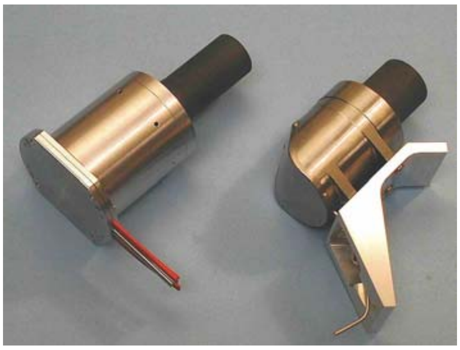


Figure 4 ROS2000 Prototype Cathodes

Coupling Tests with T-140 Thruster

The main objective of this test programme was to demonstrate that the cathode prototype would operate an appropriate HET with success, and with no signs of any adverse interactions. The latter could include excessively high coupling potentials, which might cause sputtering damage, and elevated temperatures which could also lead to lifetime limitations. The T-140 thruster was selected by KeRC to satisfy the test requirements. To ensure that operating parameters would not be unduly restrictive, and that there would be significant growth potential, it was also recognised that the tests would need to encompass wide ranges of all relevant variables. These were primarily discharge current, I_d, and propellant flow rate, $\dot{m}$.

The current was changed during testing by varying the thruster input power from 1.3 to 3.6 kW, which was the greatest range that could be accommodated at the time. The flow rate was varied independently at each power setting; the nominal range selected was 0.1 to 0.7 mg/s. However, it was found, after the tests had been concluded, that a large calibration error had occurred, causing the actual flows to be approximately double those required. An additional objective was to measure the potential in the plasma adjacent to the cathode tip, so that assessments could be made of the efficiency of the electron extraction process. This was accomplished by the use of a Langmuir probe, which enabled electron temperature, T_e, and floating potential, V_f, to be measured. Plasma potential, V_p, was then derived from these parameters. A final objective was to gain, from the state of the cathode at the conclusion of the tests, whether any serious erosion had occurred which might have lifetime implications. This was to be accomplished by a simple visual examination of all surfaces subjected to sputtering.

This short experimental programme showed that the cathode will operate entirely satisfactorily with a T-140 thruster. The thruster continued to operate well as the cathode flow rate was reduced to 0.2 mg/s. Although this was double the intended minimum value, owing to a feed system calibration error, it was clear that this provided an appreciable performance advantage, giving a 5% improvement to the specific impulse. Figure 5 illustrates the results of thrust against varying flow rate.

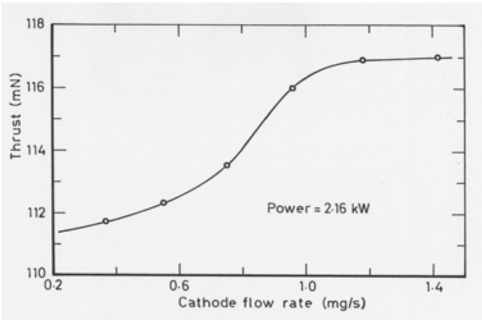


Figure 5 Performance of thruster using cathode prototype 1

As the HET cathode is derived from the T6 thruster main cathode, which routinely operates at 18 A and has been tested extensively to 30 A, it can be deduced that it will satisfy the requirements of thrusters of much higher power than the T-140 and ROS2000.

Heater Cyclic Test

QinetiQ manufactured four cathodes which were installed in a vacuum chamber and cycled for up to 5000 times. The four cathodes before installation into the chamber are shown in Figure 6. Cycling consisted of running the heater at 3A to heat the tantalum tip to the temperature required for electron emission. This occurred within ten minutes and required less than 60W. Tip temperature was measured using an optical pyrometer.

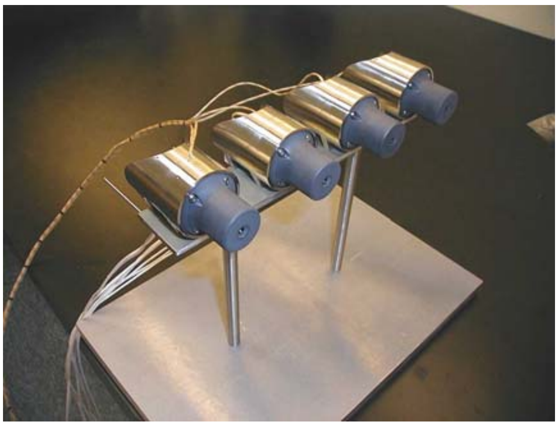


Figure 6 Heater Cyclic Test Cathodes

As an example of the results obtained, the 5000th cycle of HET003, indicated the parameters listed in Table 2. The actual data from this cycle are plotted in Figure 7.

Parameter	Value	Parameter	Value
Highest voltage	19.13 V	Highest body temperature	439 ^{o}C
Highest current	3.00 A	Lowest body temperature	238 ^{o}C
Highest power	57.39 W	Heater on time	460 s
Highest impedance	6.38 Ω	Heater off time	2280 s

Table 2 HET003 Parameters

The tip temperature measurements remained the same throughout the test, at 1100^{o}C. However it was noted that the time taken to heat the tip to this temperature decreased during the test, from an initial 580s down to 460s after 5000 cycles, even with the same 57 W of heater power applied. The cathode body was cooler at the end of the test by approximately 40^{o}C. This suggests that the cathode heater becomes more efficient over time and is probably a result of contraction of the heater coil onto the ceramic holder which would therefore provide greater thermal contact between the holder and the tantalum tube.

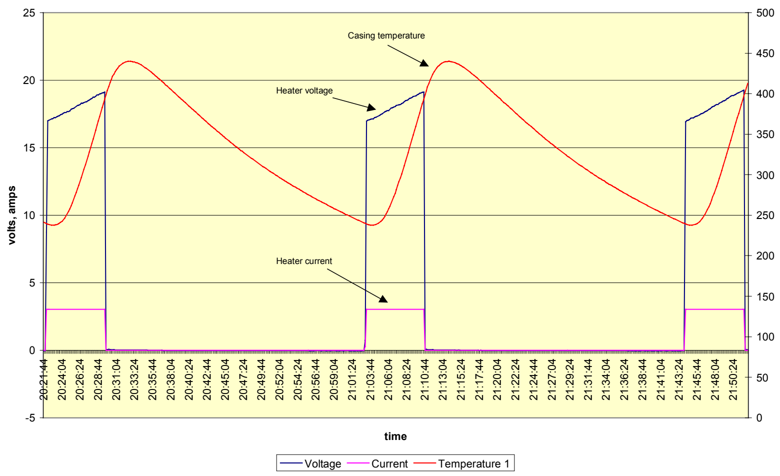


Figure 7 5000th HET003 cycle test

The cathode was removed from the vacuum chamber and inspected for damage, wear and discolourisation. A helium leak check and electrical inspection was also carried out. These results indicated no signs of damage to the cathode. The cathode was disassembled to allow inspection of the heater ceramics which were in good condition. This was confirmed through detailed inspection under a scanning electron microscope (SEM), as shown in Figure 8. Of particular importance to the design of the cathode is the reverse bend at the tip of the heater and it is clear that there is no damage to the wire in this region.

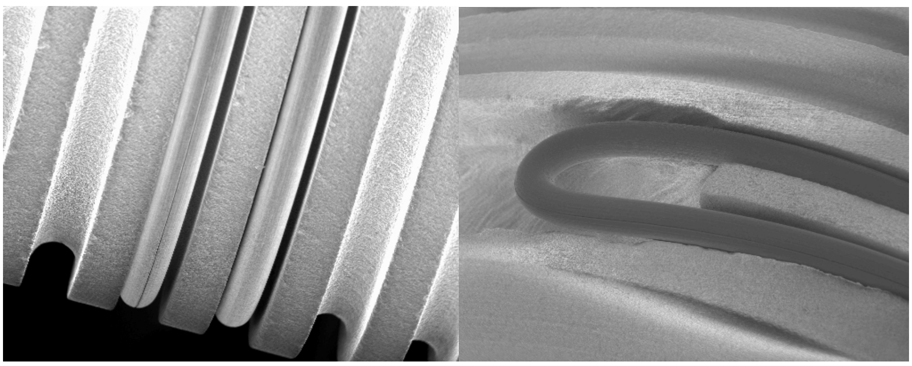


Figure 8 HET003 coil under SEM analysis

Accelerated Contamination Testing

Two accelerated contamination tests have been performed on the cathodes at different emission currents and impurity levels. The first test was directly in support of theROS2000 programme and the second was to explore the limits of the cathode.

Accelerated Contamination Test 1

The objective of this test campaign was to pass the total mass of impurities through an operating cathode that it would experience in the operational lifetime of the device. Obviously the most representative method of performing this test is to complete a full lifetest on the ROS2000 EQM thruster. However, to gain confidence in a shorter period an accelerated test was devised in which xenon was procured with a factor of ten higher impurity levels than normal, as indicated in Table 3. Hence by operating the cathode for a tenth of the operational lifetime (approximately 10000 hours) the cathode would be exposed to the lifetime mass of impurities.

Constituents	Impurity level in xenon
Hydrogen	20 ppm
Nitrogen	20 ppm
Oxygen	10 ppm
Water	non-measured
Carbon Dioxide	10 ppm
Freon 14	non-controllable (< 5 ppm)
CnHm	non-controllable (< 10 ppm)

Table 3 Parts per million (PPM) impurity constituents of xenon gas mixture

To examine the effects of operation with these higher levels of impurities, the operational characteristics of the cathode were examined at regular intervals during the test. After the test the cathode was also disassembled and analysed, with particular emphasis on identifying any adverse effects on the active elements of the device. The cathode was operated at the levels presented in Table 4. By passing the xenon flow through a heated getter pure xenon was produced. The cathode was cycled on/off on nine occasions using this pure xenon and once stable operation was achieved the contaminated xenon was introduced. Pure xenon was also used throughout the first and last cycles of the test for comparative purposes. This test campaign was performed in a diode configuration presented in Figure 9.

Parameter	Value
Heater current	3A +/- 0.2A
Heater power	less than 60W
Emission current	6.7A+/- 0.1A
Flow rate	0.3 mg/s

Table 4 Operating parameters employed in 1st contamination test

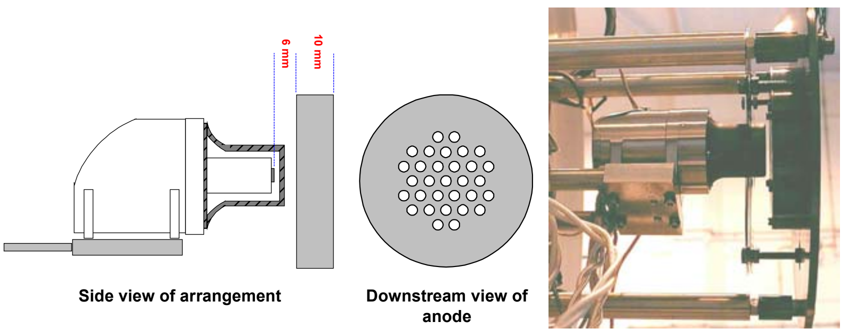


Figure 9 Cathode in Diode Mode

The evolution of the key operating parameters is shown in Figure 10. As can be seen the overall trend in anode voltage and tip temperature was a reduction punctuated by increases at each cycle when the contaminated xenon was introduced. It is noteworthy that the cathode was operated for 144 hours at the end of the test using pure xenon. During this period the anode voltage did not increase, suggesting that operation on the pure xenon was not degrading the emitting surface conditions and hence a constant operating condition was maintained. The reason for the increase followed by a decrease in anode potential during cycle 2 (the first in which contaminated xenon was used) is currently unexplained.

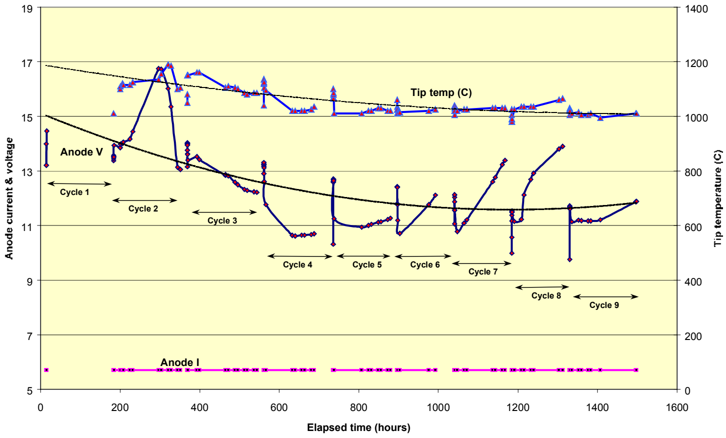


Figure 10 Evolution of operating parameters (contaminated cycles only)

Following removal from the vacuum chamber the cathode was helium leak-tested, electrically checked and visually inspected. All observations indicated no damage to the cathode. The cathode was then disassembled and the outer casing removed to allow the heater assembly to be inspected. No damage was observed. Of particular note was the condition of the tantalum tip. This was found to be in excellent condition, as shown in Figure 11, with no evidence of erosion or oxidation of the surface.

The cathode tantalum tube was sectioned to allow the internal surface and the dispenser/emitter to be examined using an SEM. Analysis was conducted at the upstream end of the tube, the centre section of the tube, and the downstream end of the tube, in the dispenser region. Evidence of oxygen was readily observed at the upstream end of the tube but this diminished the further downstream the tube was inspected until at the dispenser region there was virtually no indication of oxygen or tantalum oxide. The dispenser/emitter was examined at many points. Oxygen was present in the dispenser, which is to be expected since it is manufactured with a compound of barium oxide and there was also obvious indications of barium, indicating that the cathode was far from an end of life condition. Finally the tip was examined for tantalum oxide deposits or erosion. As can be seen in Figure 11, no oxide, deposits or damage was identified.

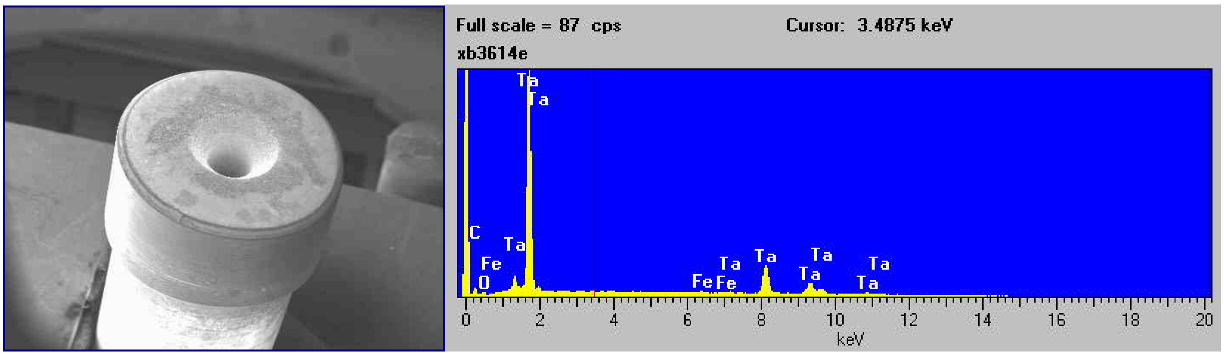


Figure 11 SEM image of the tip and orifice region.

The conclusion from this test was that the introduction of contaminated xenon did have an observable effect on the performance of the cathode, although it continued to operate within specification. This effect was reversible by the use of pure xenon. It should also be noted that the rate at which impurities were introduced was a factor of ten higher than normal and it was therefore unsurprising that these effects were observed. Even with this level and rate of impurity the cathode is extremely robust. The signs of tantalum oxide on the surface of the upstream region of the cathode tube also suggests that the cathode construction acts as an inherent getter, removing the bulk of the impurities before they reach the dispenser. The efficiency of this process would obviously be dependent on the temperature of the tantalum tube and the rate at which impurities are introduced.

Accelerated contamination test 2

The objective of this second test campaign (which was not a part of the ROS2000 programme) was to pass the total mass of impurities through a cathode operating at a higher emission level and with a different xenon purity. As before a xenon gas mixture was purchased containing the impurity levels shown in Table 5, which represents a much more severe environment than was experienced in the initial test.

Constituents	Impurity level in xenon
N_2	121 ppm ± 6.1 ppm
O_2	22.4 ppm ± 1.1 ppm
H_2O	71 ppm ± 7.1 ppm
CO_2	14.3 ppm ± 0.7 ppm
CH_4	12.8 ppm ± 0.6 ppm
Kr	31.9 ppm ± 1.6 ppm

Table 5 Parts per million (PPM) impurity constituents of xenon gas mixture

The cathode was operated at an emission current of 18A and a flow rate of 0.3 mg/s. During operation with the contaminated xenon the cathode was also cycled on/off on 9 occasions. In terms of oxygen content this test was equivalent to 16,600 hours of cathode operation.

The evolution of the key operating parameters is shown in Figure 12. As can be seen, the effects of the xenon impurities appeared to have virtually no effect on the cathode performance when operated at the higher emission current. The reason for this is that the tantalum tube stabilises at a higher temperature and therefore acts as a more efficient getter, reducing the impurities reaching the dispenser and tip. To verify this the cathode was operated at the end of the test for a period of 194 hours at the original emission current level of 6.7 A. During this period the anode voltage exhibited the same increase as seen previously. The anode potential also exhibited a similar initial drop in potential during the first few hundred hours of operation.

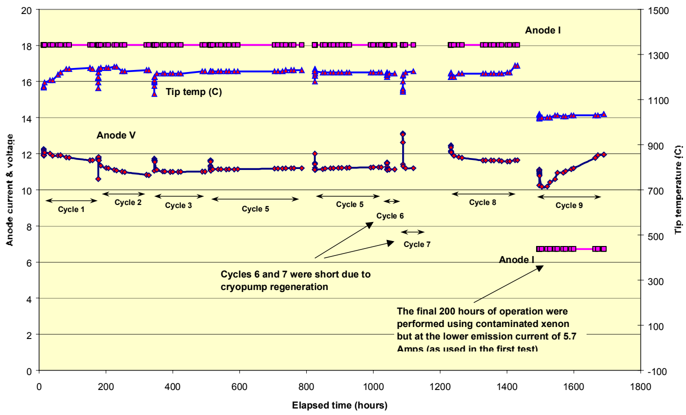


Figure 12 Evolution of anode and temperature operating parameters

Following removal from the vacuum chamber the cathode was helium leak-tested, electrically checked and visually inspected. All observations indicated no damage to the cathode which was in excellent condition and showed no evidence of erosion or oxidation of the outer surface.

Qualification Vibration Test at 19.7g_{rms} and 45g_{rms}

Qualification vibration testing of HET001 was carried out at QinetiQ in September 2000. Testing was performed to the ROS2000 requirements as known at that time and equated to approximately 19.7g_{rms}. Following vibration testing, the cathode was helium leak-tested to confirm the integrity of the joints. No leaks were observed. Cathode electrical isolation was also tested and there was no electrical breakdown between the keeper and cathode body at a potential of up to 400V. The cathode was then carefully taken apart to inspect the components, in particular the ceramic items. It was immediately noted that all the ceramics were in good condition. The cathode was reassembled and installed in a vacuum chamber for functional testing. At a nominal flow rate of 0.5 mg/s a discharge was readily initiated. QinetiQ subsequently operated this cathode for 1657 hours with no adverse effect.

HET010 was subjected to acceptance vibration test at approximately $45g_{rms}$ in each axis after installation on the EQM ROS2000. A comparison between pre and post resonance sweeps indicated a 7% shift in frequency and the cathode outer casing material may have yielded during the first vibration test in the X-axis at the third mode of 1443Hz. The outer casing is used to retain the heater assembly and tantalum tube; in the event of some movement of the outer casing, the cathode performance will not be impaired since the outer casing has no effect on discharge characteristics. Other cathode modes were unaffected. HET010 was therefore installed on the EM thruster, with HET012, and both cathodes have been successfully operated as part of the EM thruster characterisation and optimisation tests. However as a result of this marginal movement some minor modifications can be made to strengthen the outer casing and QinetiQ are currently in the process of implementing these changes for future devices.

Operation on EM ROS2000

HET010 and HET012 were installed on the EM thruster and HET012 was fired at Alta on 1st July 2002 (see Figure 13). To date the cathode has been operated for approximately 50 minutes and 66 starts in a number of tests of the EM engine. HET010 was first fired at Alta on 17th July 2002. The cathode has been operated for approximately 114 minutes and 70 starts. No anomalous behaviour on either cathode has been observed.

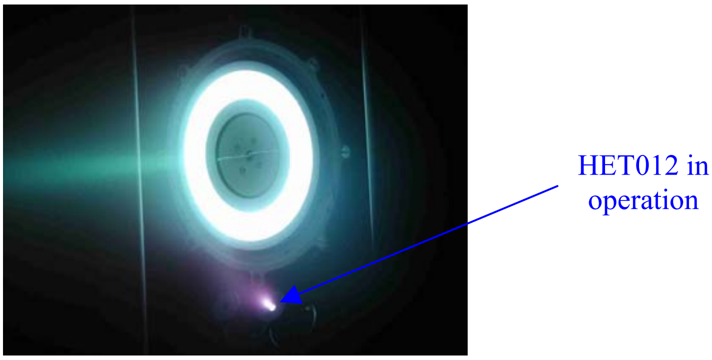


Figure 13 First firing of HET012 (photograph courtesy of Astrium Ltd)

HET012 is shown at the bottom of the picture. HET010 is off at this time but may just be observed to the left of HET012.

Results from characterisation testing of the cathode are shown in Figure 14 and Figure 15 Cathode flow rate for this test was 0.6mg/s.The cathode has consistently started each time the ignition voltage has been applied after approximately 8 to 9 minutes of heating. The temperature of the cathode enclosure is 245°C in steady-state condition, lower than the predicted 283°C. However the interface temperature is only 170°C and lower than the 210°C measured during validation of QinetiQ's thermal model. Furthermore, the temperature of the interface is clearly rising when it is switched off. These results are therefore not steady-state and to date there has been no long duration operation of this cathode which identifies the final enclosure temperature. Keeper ignition voltage is low, at 15V, demonstrating the good starting characteristics of this device and the cathode reference potential is maintained at around -15V with excursions down to -17V. Throughout testing, the cathode has performed excellently and within specification at a range of emission currents.

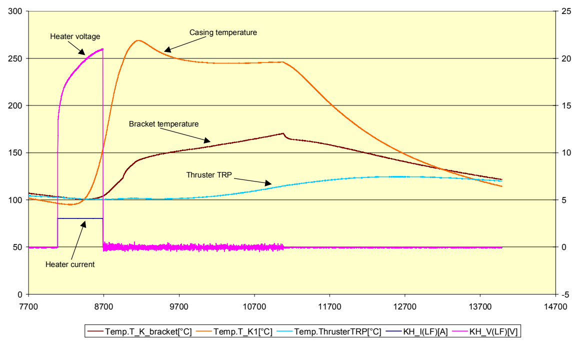


Figure 14 HET010 Characterisation Test (4th July 2002)

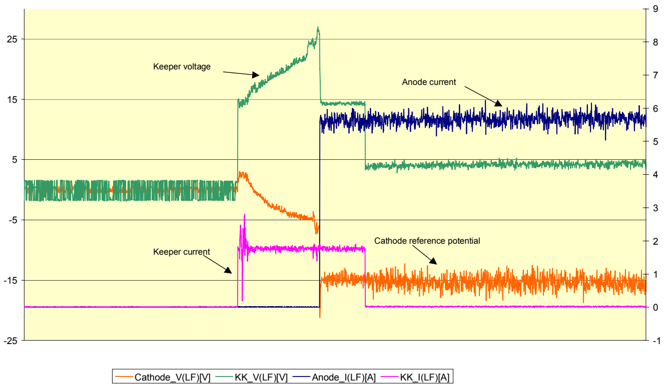


Figure 15 HET010 Characterisation Test (4th July 2002)

CONCLUSIONS

QinetiQ's range of hollow cathodes represent a mature, commercially-off-the-shelf technology that can be adapted to meet specific customer requirements. Devices have already been qualified for the ROS2000 programme and there is currently a design improvement programme to provide mechanically more robust devices for possible future markets. These include both HET and gridded ion thrusters, with qualified devices being available to suit T5, T6 and UK-25 and similar requirements.

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