Emitter Depletion measurement and modeling in the T5&T6 Kaufman-type Ion Thrusters

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Abstract: This paper presents some of the aspects of a program undertaken by QinetiQ to characterize and determine the depletion rates and predict life time of its cathode technology. It reports on a long duration test performed on the T5 (15,000 hours) and a series of shorter tests on the T6 (800hours and 4000hours) including the results of destructive post test examinations and insert depletion measurements. The program also includes a modeling of insert depletion by Southampton University which has currently produced good agreement with measured depletion on the 15,000hour T5 insert. Two tests have also been carried out on the T6 cathode to determine an end of life condition. An accelerated lifetest where the insert temperature was increased by 120°C has to date accumulated 3790 hours of operation. This is equivalent to 30,320hours with an 8× acceleration factor or 60,640hours assuming a 16× acceleration factor. Another test was also undertaken with two grossly depleted T6 inserts (25% and 50% depleted). Both cathodes although grossly depleted still behaved nominally. All the results give a degree of confidence in the compatibility of the T6 thruster cathode with future high impulse mission lifetime requirements.

Nomenclature

A	=	Al_2O_3
B	=	BaO
C	=	CaO
D	=	Diffusion coefficient
E	=	Activation Energy
I_A	=	Discharge (Anode) current
I_k	=	Keeper current
I_m	=	Magnet (solenoid) current
k	=	Boltzman's constant
P	=	Pressure
P_{vac}	=	vacuum pressure
M_c	=	Cathode flow rate

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M_f = Main flow rate
T = Temperature
V_A = Discharge (Anode) voltage
V_k = Keeper voltage
V_m = Magnet voltage

I. Introduction

IN Gridded Electron Bombardment Ion Thrusters, hollow cathodes serve the dual purpose of providing primary electrons to ionize the propellant gas, and for neutralization of the ion beam space charge. They have been identified as one of the main lifelimiting factors for the operation of these thrusters. Thrusters developed by NASA have to date demonstrated a lifetime of 32,000 in ground testing and 16,000hours in orbit. However, there is currently demand for deep space missions requiring longer thrust duration. A large amount of effort has thus been expended in recent years in lifetesting, characterization, empirical measurement and modeling of the operating parameters of these devices to obtain a better degree of understanding of their operation, suitability, lifelimiting mechanisms and ultimately estimating their life time[3, 19-30].

Cathodes containing a porous tungsten matrix impregnated with barium calcium aluminate have been the subject of extensive study in vacuum applications such as CRT tubes and microwave tubes[31]. Cathode performance and behaviour were found to be completely dependant on two determinant parameters, namely, cathode temperature and operating time. Extensive investigations on hollow cathode dispensers have also concluded that the most critical cathode failure modes are driven by the temperature of the emitter[3, 26, 29, 30]. The lifetime of the cathode is dependent on the chemistry of the low work function material and its rate of loss via evaporation. With long operational lifetime, the reduced emission current will form the start of a positive feedback cycle; forcing the cathode to operate at higher temperatures to satisfy current requirement which will further accelerate the depletion. This will continue until a point is reached where the power supplies cannot provide enough power to either start the cathode or sustain the discharge.

To address concerns about cathode lifetime, and to demonstrate compatibility of the T6 thruster cathode with future high impulse mission requirements such as BepiColombo, QinetiQ undertook a program of work which includes representative cathode endurance tests and a family of shorter term tests and modeling in collaboration with Southampton University. The synergistic combination of empirical and modeling work will lead to an estimate of the hollow cathode end of life. This paper reports on the endurance tests carried out, the status of the Southampton modeling effort and some novel experiments carried out to determine an end of life condition for the T6 cathode by accelerated testing and by testing of intentionally depleted inserts.

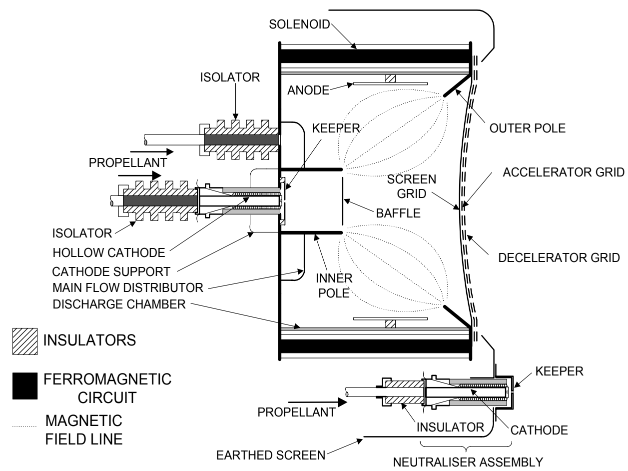


Figure 1. A modern Kaufman-type ion thruster.

The QinetiQ thruster family consists of two offerings:

1) The T5 thruster covering the low thrust range (1 to 25mN). The T5 is currently used on the Gravity Field and steady-state Ocean Circulation (GOCE) mission to be launched early in 2008 and whose cathode was previously employed on the UK10 (EITA) thrusters on the ESA Artemis spacecraft.
2) The T6 thruster covering the high thrust range (70 to 200mN). The T6 was selected for the Alphabus extended range application and is a candidate for the ESA BepiColombo Mercury mission.

Both the T6 and T5 engines employ a conventional Kaufman design (illustrated in Figure 1). Plasma is created by the interaction of electrons flowing between the cathode and anode and the neutral mass flow. The ionization of the discharge is greatly enhanced by an applied, azimuthally symmetric, divergent magnetic field. This field is generated by solenoids equispaced around the discharge chamber circumference.

The T6 cathode (rated to 20A discharge current) is a scaled up version of the T5 cathode (5A current rating). The T6 cathode orifice is larger by 1mm than that of the T5 with both employing the same materials and manufacturing processes. A typical hollow cathode (as originally manufactured by Philips UK and currently manufactured by for example by NASA, Laben-Proel, KeRC, Snecma, Mitsubishi, Lockheed Martin, Fakel etc.) is generally a tantalum, molybdenum or stainless steel tube (of less than 1cm diameter) with a tungsten tip, containing a small orifice (~1mm diameter), electron beam welded to the downstream end. The QinetiQ technology, specifically the T5 and T6 hollow cathodes, the cathode tube is entirely tantalum and is machined from solid, such that the tip and the tube are made of the same material and the tip weld is eliminated. This design obviates any risk associated with the differential thermal expansion of tip/tube and fracture/erosion of the tip weld. The cathode is surrounded by a resistance heater wire, which is wound around the cathode body. In many designs the heater wire is encapsulated in flame sprayed alumina. The QinetiQ technology however, employs machineable ceramics which eliminate all manufacturing process problems associated with flame spraying and allow the heater element to be fully inspected post manufacture.

The heater is used to raise the temperature of the cathode to thermionic emission temperatures (about 1000^{o}C for a standard oxide cathode) prior to starting the discharge. After discharge initiation has ensued, the heater can be switched off, as ion bombardment of the insert surface maintains the energy input required for electron emission. A multi-turn molybdenum heat shield surrounds the assembly in order to minimise radiative losses and therefore reduce the power requirement for heating. Neutral gas is fed from the other end of the cathode via a flange.

Lowering the work function of the hollow cathode surface would enhance the thermionic emission current dramatically. Thus, hollow cathodes usually contain a source of low work function material. Initial hollow cathode designs had the interior surfaces simply coated with a triple oxide mixture containing the substance. These designs suffered from rapid depletion of the internal coating, due to evaporation and/or ion sputtering. They were later modified to utilize rolled foil inserts coated with the same emissive mix, which provided a greater surface coverage of barium, but coating depletion persisted to be a problem. Porous tungsten dispensers were later developed. These are essentially hollow porous tungsten cylinders impregnated with a 4:1:1 mixture of BaO, CaO and Al_2O_3, which provide long operational lifetimes and robustness (which is a requirement due to the severe launch environment).

II. Depletion measurements on QinetiQ's T5 and T6 cathodes

Some endurance testing of hollow cathodes has been carried out on QinetiQ's T5 and T6 cathodes as part of a larger program to predict cathode life. The purpose of these tests was to complement other experiments such as dispenser temperature measurement and provide input and a validation technique to the cathode models being developed.

The results reported here are concerned with what is considered to be the main cathode life limiting process of barium loss via evaporation. Detailed analysis on the condition of other components, such as the keeper and cathode orifice has not been completed at the time of writing, but preliminary results will be reported

Any measurement of the barium depletion profile would require sectioning of the dispenser and measurement (qualitative or quantitative) of the amount and spatial distribution of impregnant. This is then compared to a standard unused control dispenser. At the beginning of the test program three candidate techniques were identified from the literature for measuring the depletion and its distribution in the insert:

1) <u>X-ray Fluorescence electron microprobe</u>: The surface of the sectioned insert can be scanned with an electron microprobe and the intensities of the characteristic Ba or Ca x-ray signals can be recorded. Figure 2[2] depicts such a measurement on a used cathode and the resulting x-ray profile for Ba and Ca concentration.

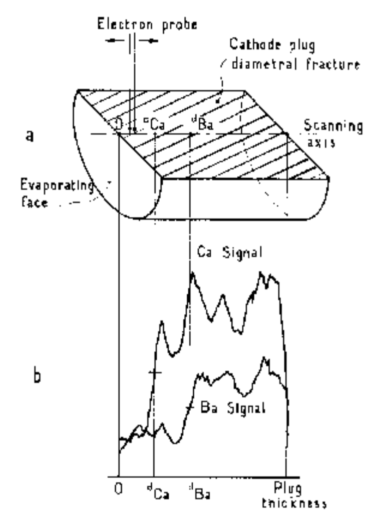


Figure 2. Method of Electron Microprobe Analysis applied on a used barium-calcium-aluminate cathode[2]

This method is however semi-quantitative due to the heavy presence of the tungsten matrix material. This causes the observed peaks and troughs in the spectra in figure 2, a smoothing or filtering profile will be necessary in data reduction.

2) Ba to W x-ray emission line ratio measurement: To overcome the problems of heavy presence of W emission lines obscuring those from the impregnate, it is possible to use a ratio of the tungsten to barium lines to integrated over a given area of the dispenser. The size of the area sampled by the electron beam (illustrated in Figure 3) must be carefully selected to include a consistent amount of tungsten matrix and pores to facilitate comparison. This assumes that the dispenser structure is uniform throughout.

This method suffers from a loss of resolution as the pixel size is increased to contain the same amount of pore and background tungsten material.

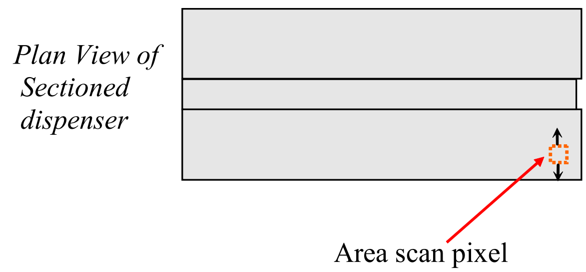


Figure 3. Illustration of Ba/W line ratio dispenser characterization method

3) EDX induced Ba emission mapping: In a scanning electron microscope an Energy Dispersive X-ray spectroscopy (EDX) mapping of the Ba Lα lines can be carried out [1].

The resulting image, see Figure 4, will create a visual record of the impregnate distribution from which both the axial and radial depletion profile can be deduced, which then can be compared to that found in the control. Roquais[1] compared this method with other standard methods for measuring depletion (such as barium evaporation rate) and found good correlation.

The last method was the one that gave the best and most consistent results. The insert samples were prepared by longitudinally fracturing them along a scribed mark. Figure 5 shows the resulting image for a unused T6 insert that will be used as control.

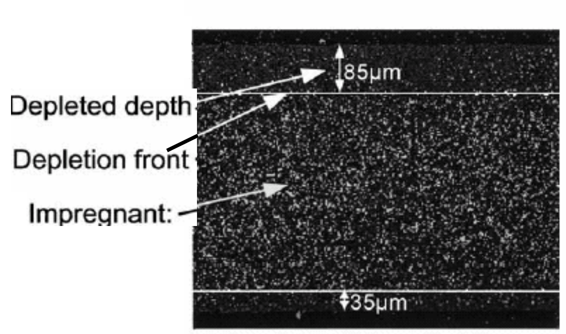


Figure 4. EDX mapping of Ba line on an M-type cathode[1]

Also included in the image is the EDX map of the Tungsten M α line. This was found useful as certain features such as the dark patch on the top right hand corner of Figure 5 (b) and (c) can be be seen as a product of fracture topology and not due to any barium depletion.

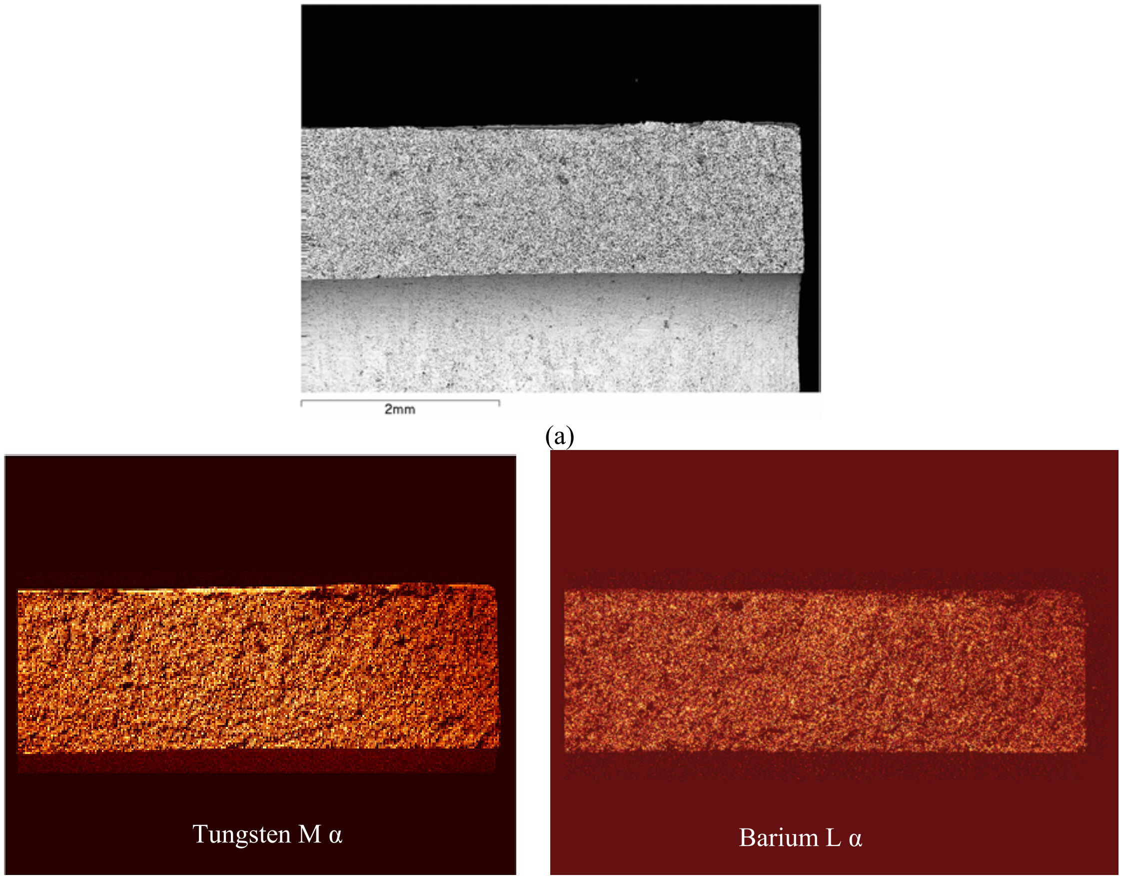


Figure 5. : EDX analysis of a fractured unused T6 control insert (a) **Backscattered electron image of downstream end** (b) **EDX mapping of Tungsten M α line** (c) **EDX mapping of Barium L α line.**

A. The Artemis T5 15,000hour lifetest

Four T5 cathodes have been life tested in support of the Artemis program. The four were mounted in fully representative discharge chambers and operated at the following set points:

Table 1. Set points for the four Artemis Life test cathodes

	Discharge Current (A)	Keeper Current (A)	Magnet Current (A)	Flow (mg/s)
C1	2.2	1	0.14	0.1
C2	2.2	1	0.14	0.1
C3	2.6	1	0.14	0.1
C4	2.6	1	0.14	0.1

Each of the four cathodes accumulated 15,000hours of operation and 5,000 of heater On/Off cycles. Figure 6 shows the trends in anode voltage observed during the test for cathode 2. No changes in parameters that would indicate the cathode was nearing its end of life (such as increase in anode voltage or marked increases in strike voltage) were observed during the test. In fact the anode voltage showed a trend of slow decrease as the cathode aged. The test was voluntarily terminated, and the cathodes remained inside the test chamber at roughing vacuum levels. Cathode C2 was actually restarted 4 years after the end of the Artemis lifetest and returned to the exact same operating condition, also illustrated in Figure 6.

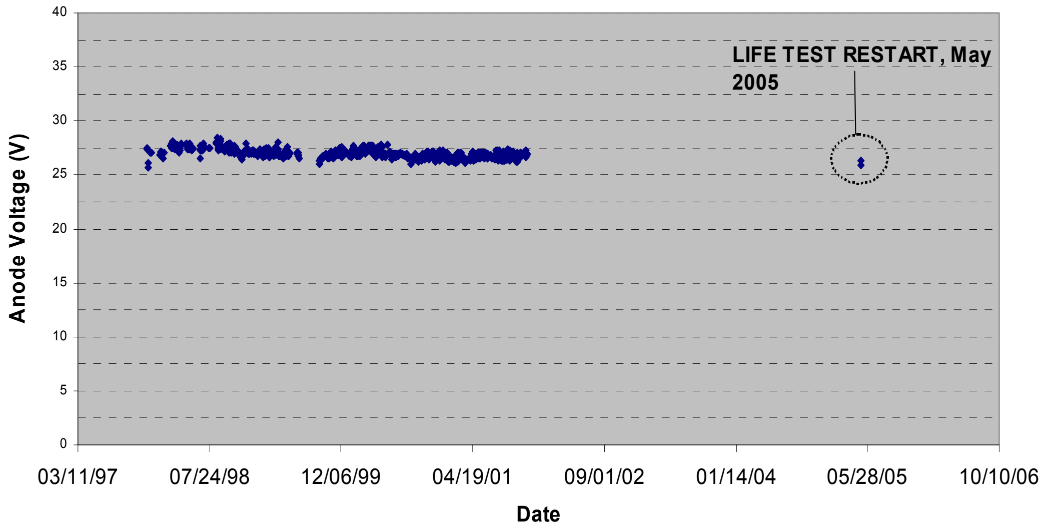
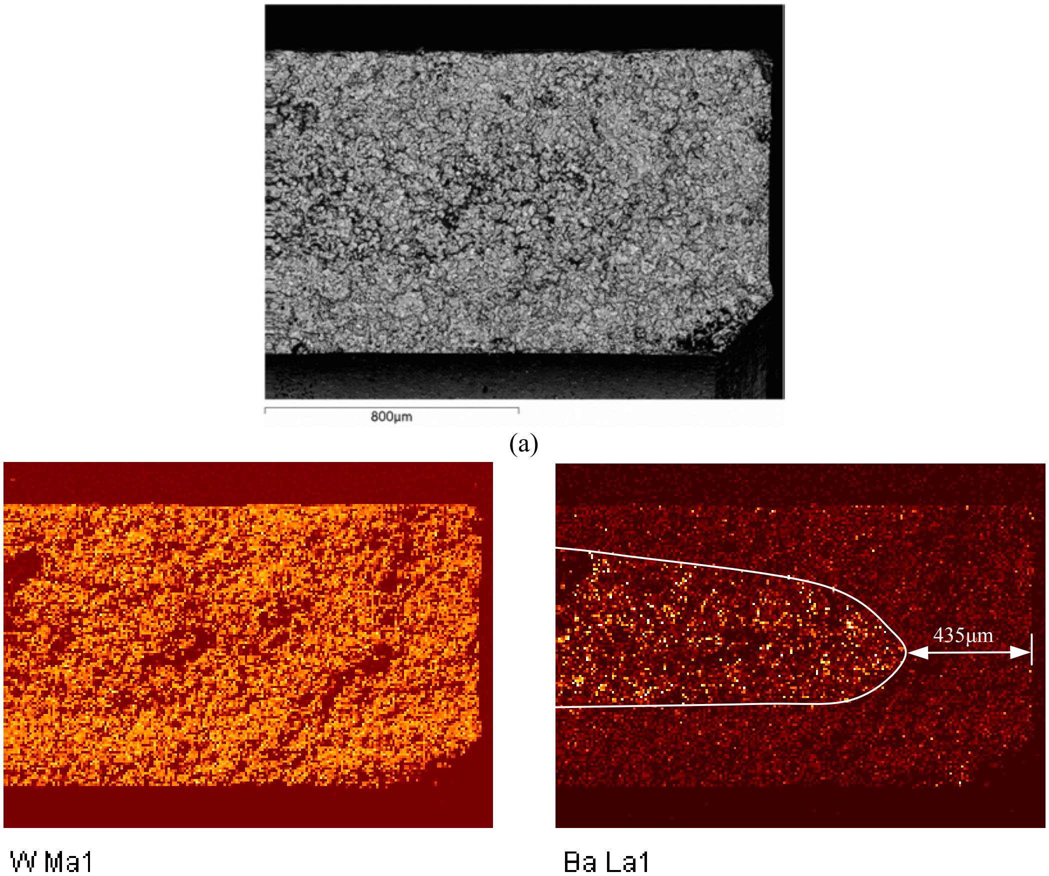


Figure 6. Artemis Lifetest cathode 2, Anode voltage over lifetest including restart

1. Depletion measurement

One of the Artemis cathodes C3 was removed and fractured. The resulting SEM/EDAX images for the first 1.6mm of the downstream end are shown in Figure 7. The barium was found to have depleted into a "tongue" shape, similar to that seen on the Life Demonstration Test (LDT) cathode that performed 8200 hours with an NSTAR cathode[4].The barium is expected to escape from the insert using all available open surfaces. Due to the temperature gradient along the dispenser length (decreasing with distance from the tip, see Figure 18) and physical considerations based on vacuum cathode experience[1] and modeling of hollow cathode inserts[5], it is expected that the depletion front will follow the tongue shape and retreat upstream through the dispenser as the dispenser ages. This makes the distance between the downstream edge of the dispenser and tip of the depletion "tongue" the most critical dimension, which can be termed the depletion depth. It was found that the Artemis cathode's depletion depth was only 0.435mm, which only constitutes 4% of the dispenser's total length. As mentioned previously this depletion level did not have any adverse effects on cathode operation and indicates that the T5 cathode depletion-limited lifetime is dramatically in excess of the 15,000hours demonstrated.



(b) (c)

Figure 7: EDX analysis of a fractured 15,000 Artemis T5 insert (a) Backscattered electron image of downstream end (b) EDX mapping of Tungsten M*α* line (c) EDX mapping of Barium L α line, showing 435µm of depletion from the downstream face after 15,000 hours of operation

The external surface of the Artemis cathode insert was coated in a greenish white crust which subsequent EDX analysis indicated was primarily barium impregnate. The T5 cathode tube was found to mirror this, containing a similar barium containing deposit covering its inner bore. These results are in agreement with previous life tests results with the NSTAR cathode showing a similar deposit on the cathode insert[3]. This indicates that the impregnate reaction products escape from all available free surfaces and not just the insert's inner bore and is in agreement with the shape of the depletion profile shown above.

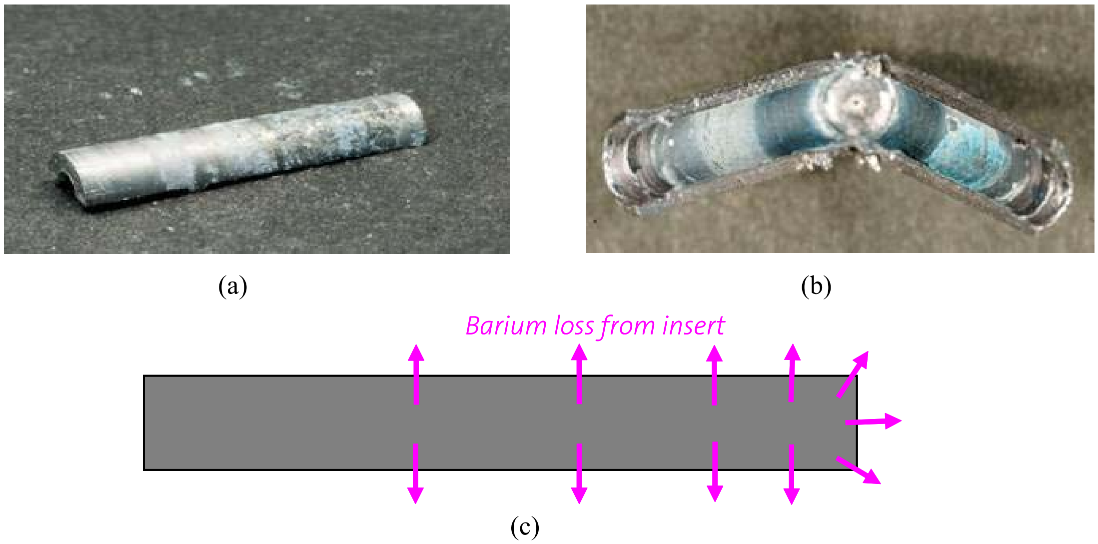


Figure 8. (a) Exterior surface of T5 cathode insert after 15,000hours showing barium containing crust (b) Interior surface of T5 cathode tube showing barium containing deposit. (c) Illustration of barium loss from all insert open surfaces

2. Condition of the keeper plate and cathode orifice plate

As mentioned previously at the time of writing the detailed investigations on the other parts of the cathode assembly have not been completed and only preliminary results are available which will be presented here. All the dimensional measurements were carried out using a Vision Engineering stereo dynascope.

The keeper plate in the T5 Artemis test, was made of Molybdenum, and is shown in Figure 9. Figure 10 shows the dynascope measurements of the keeper dimensions, with the red line defining the nominal shape of the keeper plate. The keeper plate thickness was measured at various points along its radius and its upstream and downstream orifice dimensions were measured. It was seen that the keeper thickness was nominal (1.04mm) at the outer edges. This seemed to increase as the orifice is approached until a maximum thickness of 1.12mm (+0.08mm from nominal) is reached, which indicates some deposition of material on the keeper plate probably ion bombardment products from the cathode tip. From there on, the thickness slowly decreases till it reaches a value of 0.99mm (-0.045mm from nominal) at the edge of the keeper orifice indicating a limited erosion mechanism acting at the keeper orifice. This is corroborated by measurements of the keeper orifice diameter. The nominal diameter of the keeper orifice is 3mm. The downstream face diameter of the keeper orifice is now 3.43mm after 15,000hours and at the upstream face it is 4.03mm. Although there is evidence of erosion, the damage is small when compared to keeper erosion on other tests such as the NSTAR life test over a comparable period of 15,000hours[3] and fully acceptable with respect to cathode operation. Furthermore, on the newer T5 and T6 cathode designs a carbon keeper replaced the molybdenum ones used in this test which will significantly reduce any erosion.

Figure 9: Photo showing condition of T5 Artemis moly keeper plate post 15,000 hour test

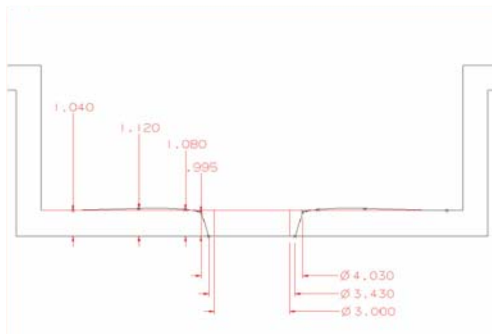


Figure 10. Illustration of measured T5 keeper plate condition post 15,000 hour test

Limited erosion damage observed on the cathode tip. Figure 11 illustrates the nominal (red) and the profile observed after 15,000 hours. The upstream end of the orifice plate still maintained its nominal diameter of 0.224mm. The downstream end 45^{o} chamfer on the orifice plate had disappeared. The orifice diameter at the downstream end is now 0.396mm. This erosion had no impact on the cathode functionality.

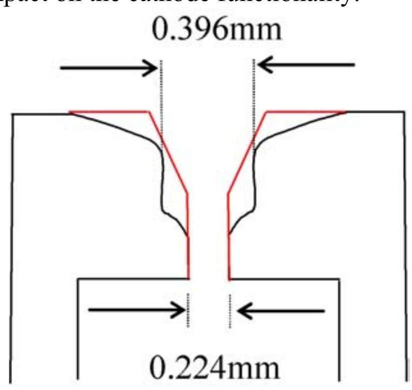


Figure 11 Illustration of measured T5 cathode orifice plate condition post 15,000 hour test

B. T6 800hours and 4000hours tests

Some short duration endurance tests were carried out on the T6 cathode to establish a depletion trend that can be later extrapolated. The T5 cathode although operating at a fraction of the T6 discharge currents actually operates hotter than the T6[6]. The T5 and T6 cathodes share the same dispenser technology and use exactly the same materials and processes. Hence, the Artemis test depletion data (scaled for the temperature difference) can be used in the extrapolation of the T6 data to an end of life condition. Due to programmatic constraints, the tests were only limited to 800 and 4000hours from which it was hoped a depletion trend will emerge.

Both cathodes were placed in representative T6 thruster discharge chambers and operated at 150mN thrust setting (the corresponding T6 discharge settings are I_A = 17.1A, M_c= 0.69mg/s, I_m=1A), the maximum expected throttle point for ESA's BepiColombo mission. At this set-point the performance and electrical parameters listed in Table 2 will be recorded. Data will be sampled at 1Hz.

Table 2: Parameters measured during the T6 800 hour and 4000hour tests

ID	Description	Unit
V_a	Anode voltage	V
I_a	Anode current	A
V_m	Solenoid voltage	V
I_m	Solenoid current	A
m_{total}	Flow rate	mg/s
P_{vac}	Chamber pressure	mbar

Figure 12 and Figure 13 plot the trends of the main discharge parameters over time for the T6 800 hour test and T6 4000hour test respectively. As would be expected for these short duration tests, no appreciable changes in test parameters occurred during the test and the thruster behaved nominally. The tests were terminated once their respective testing time has been accumulated and the cathode was inspected.

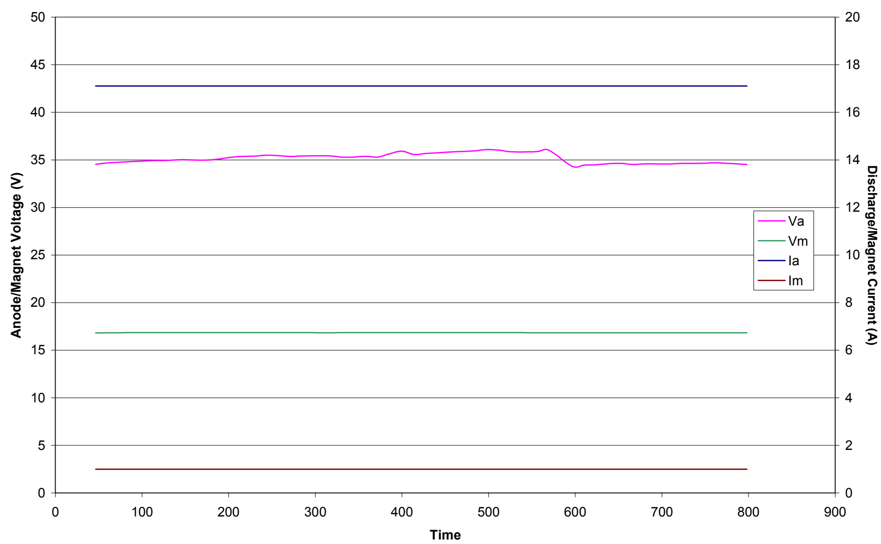


Figure 12. Observed trends in discharge parameters during the T6 800 hours test

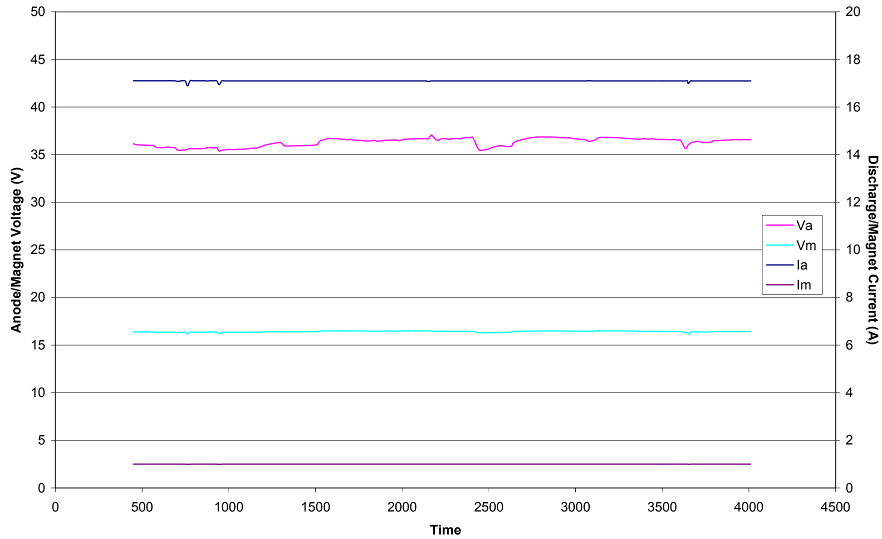
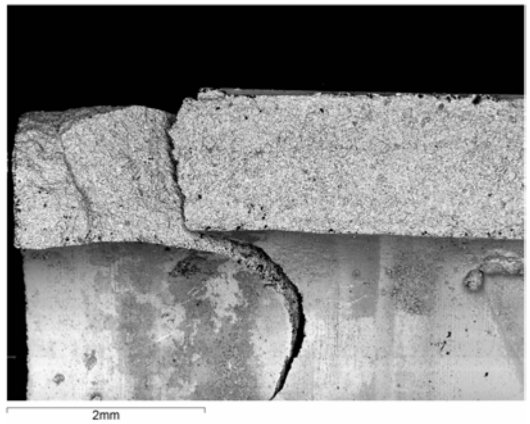


Figure 13. Observed trends in discharge parameters during the T6 4000 hours test

1. Depletion measurements

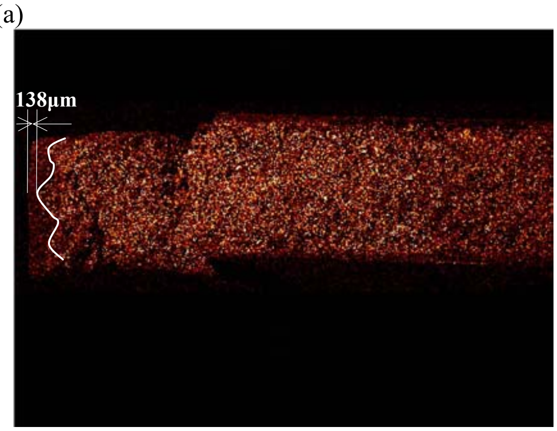
Visual examination of the T6 800 cathode when removed indicated it was in pristine condition. The insert was fractured and SEM/EDAX analysis was carried out. No measurable depletion was observed on the sample and the images resembled those shown in Figure 5 for the control sample.

The T6 4000hour cathode seemed to be in equally good visual condition. Unfortunately, during the insert removal from the cathode tube the insert downstream section snagged and fractured at approximately 1mm from the downstream end. Luckily, the break was clean, allowing the analysis to proceed and useful data to be obtained. The resulting SEM/EDAX images for the first 5.1mm of the downstream end are shown in Figure 14. The depletion depth was found to be only 0.138mm from the downstream end. It can also be observed that the characteristic "tongue" shape is beginning to develop. The depletion depth constitutes only 0.7% of the T6's total insert length. This, coupled with the low observed insert temperatures measured in the T6[6], gives a high degree of confidence in the T6's ability to achieve high impulse mission requirements and points to a lifetime in excess of 30,000hours.



(a)

(b)



(c)

Figure 14: EDX analysis of the fractured 4,000 hour T6 cathode insert (note accidental break to downstream end) (a) Backscattered electron image of downstream end (b) EDX mapping of Tungsten M*α* line (c) EDX mapping of Barium L α line, showing 138µm of depletion from the downstream face after 4,000 hours of operation

2. Condition of keeper plate and cathode orifice plate

In the case of the T6 800 hour cathode, visually the cathode seemed in pristine condition with machining marks still visible on the cathode orifice plate and the carbon keeper, so no measurements were taken. Preliminary measurements were made on the 4000hour cathode instead, using the Vision Engineering stereo dynascope.

The carbon keeper plate is shown Figure 15, it was in very good condition with machining marks still visible. There was evidence of trace amounts of deposit near the keeper orifice, this has not yet been subjected to SEM analysis but it could have possibly originated from ion bombardment of the cathode stainless steel casing. The keeper plate thickness was measured at several locations and found to be 0.7mm (the nominal value). The keeper orifice was measured from both the upstream and downstream directions and found to be nominal at 5.03mm.

(a) **(b)**

Figure 15. Photo showing condition of T6 keeper plate post 4000 hour test (a) downstream face (b) upstream face

Figure 16 shows the condition of the T6 4000hour cathode tip, note that the machining marks can still be seen and the very good condition of the orifice chamfer. There is visual evidence of light levels of erosion to the stainless steel cathode casing (seen as a halo around the Tantalum tip in the photo). The cathode orifice was measured from both the upstream and downstream directions and found to be nominal.

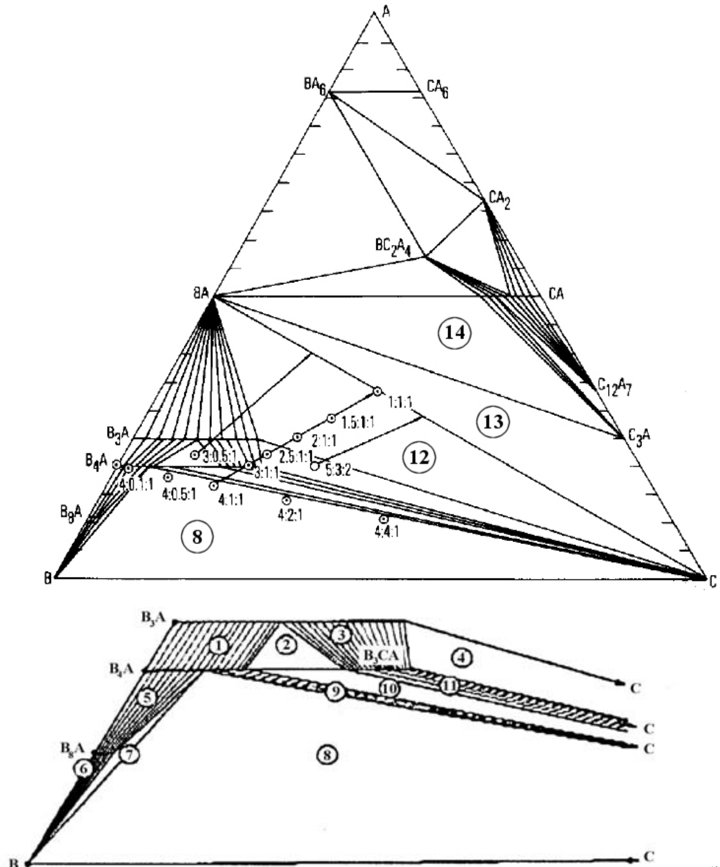
Figure 16. Photo showing condition of T6 cathode orifice post 4000 hour test

III. Depletion modeling

Data from the depletion studies reported above in addition to dispenser temperature measurements reported elsewhere[6], will be used as inputs to a depletion model currently under development at Southampton University. The data from the Artemis endurance test will be used as a validation technique prior to the model's application to the T6. This is made possible because the T5 and T6 cathodes, in spite of having different dimensions and operating conditions, share the same insert technology. A brief description of the model is presented here the reader is referred to reference [7] for more details.

A. BaO Depletion Model

Barium oxide diffusion and evaporation from an insert has been numerically modelled[7] starting from the knowledge of the behavior of the ternary system BaO – CaO – Al_2O_3 [15, 16,1 7].



(a)

(b)

Figure 17. **BaO-CaO-Al2O3 ternary diagram. (a) the whole diagram at 1250 °C, (b) particular of the diagram**

Each point of the diagram in Figure 17(a) represents a state of the system where the concentration of *A*, *B* and *C* are inversely proportional to the distance of the point from each corner. Each area in the diagram represents a different state of the state hence which compounds are presents.

The list of compounds present in each area is reported below[17, 18]

Table 3 Compounds present in each area of the ternary diagram. The up lined formulas refers to a well define composition of the corresponding solid solution			
Area N°	Compounds	Area N°	Compounds
1	B_3A s.s. and B_4A s.s.	8	B, C and $\overline{B_4A}$ s.s.
2	$\overline{B_3A}$ s.s., $\overline{B_4A}$ s.s. and $\overline{B_3CA}$	9	C and $\overline{B_4A}$ s.s.
3	B_3A s.s. and B_3CA s.s.	10	C, $\overline{B_4A}$ s.s. and $\overline{B_3CA}$ s.s.
4	C, $\overline{B_3A}$ s.s. and B_3CA s.s.	11	C and $\overline{B_3CA}$ s.s
5	B_4A s.s. and B_8A s.s.	12	C, B_3A and BA
6	B and B_8A s.s.	13	C, BA and C_3A
7	B, $\overline{B_4A}$ s.s. and $\overline{B_8A}$ s.s.	14	AB, C_3A and CA

From the knowledge of the compounds present it is possible to calculate the evaporation rate of barium oxide from the insert surface[3 17, 18]. This evaporation creates a barium oxide concentration gradient generating a BaO motion from the insert core to the insert surface.

The motion of barium oxide from the interior part of the insert to the surface is the result of various processes: Knudsen flow of gaseous Ba and BaO through the pores, solid diffusion of BaO inside the BaO-CaO-Al_2O_3 impregnate, solid diffusion of BaO inside tungsten and surface diffusion of BaO along the pores surfaces.

These processes, being too complicated to be modelled separately, were represented globally with a single diffusion coefficient reducing the BaO depletion problem to a diffusion problem where the evaporation rate represents one of the boundary conditions.

The diffusion coefficient trend with temperature and insert porosities has been derived by comparison with experimental data[1]. The diffusion coefficient formula is reported below

$$\begin{aligned} D_a &= (b\Pi + c)\, e^{-\frac{qE_{Da}}{kT}} \\ b &= 0.1165\, m^2/s \\ c &= -0.01653\, m^2/s \\ E_{Da} &= 3.5\, eV \end{aligned} \qquad (1)$$

B. Numerical analysis on the T5 Artemis Cathode

The T5 cathode insert chemistry has been simulated numerically assuming it to have an initial flat barium oxide content and using the measured values of the insert temperature relative to 2.6 A[6]. The temperature trend is shown in Figure 18

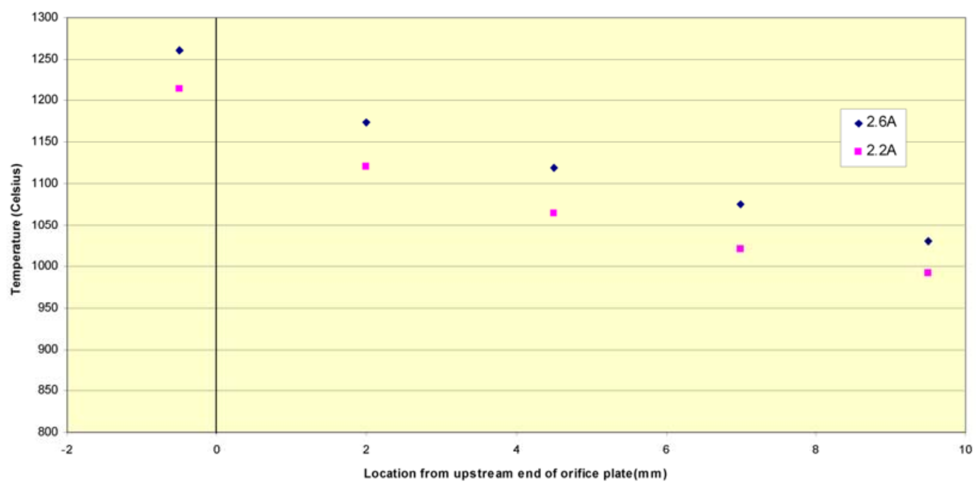


Figure 18 Instrumented T5 temperature profile and dependence on discharge current for 2.2A and 2.6A cases

As previously mentioned, the external surface of the Artemis cathode and the T5 cathode tube were found to be covered by barium deposits (Figure 8). This indicates that the barium oxide evaporates also from the external diameter surface and not just from the insert's inner and downstream surface.

With this evidences in mind the simulation has been run with two different set of boundary conditions. In the first case evaporation has been assumed to occur from all the surfaces whereas in the second it has been assumed to occur from the all the surfaces but the upstream one.

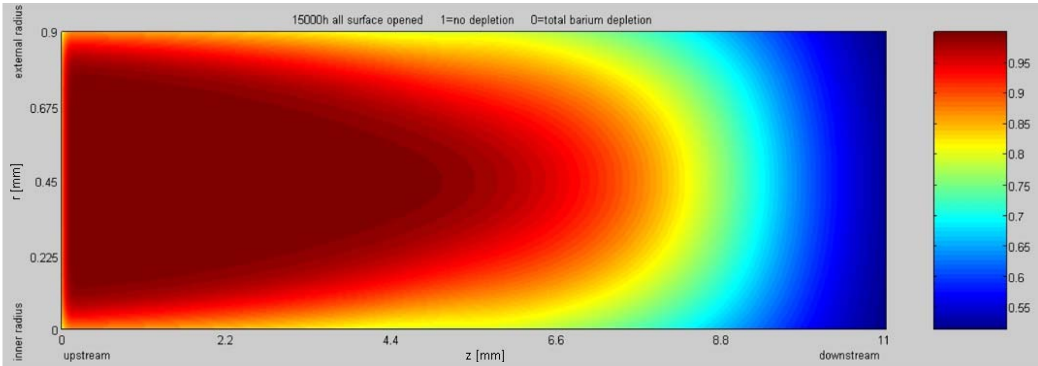


Figure 19. Modelled T5 insert barium oxide depletion profile after 15,000hours for the measured temperature profile at 2.6A – All surface opened

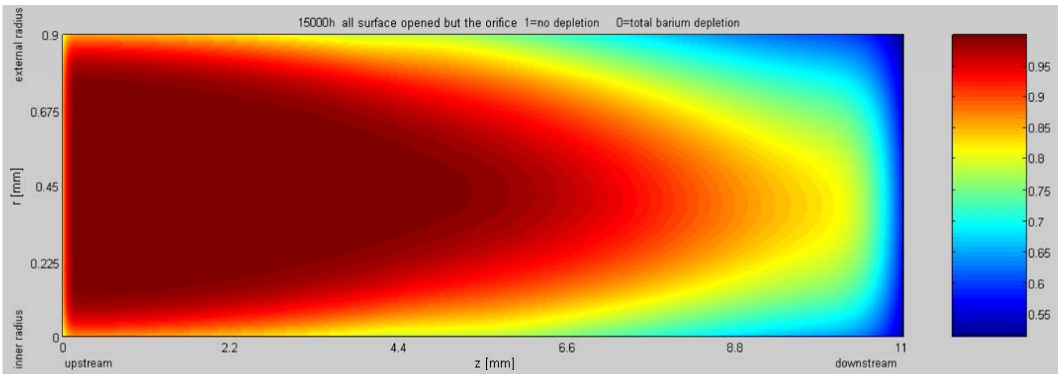


Figure 20. Modelled T5 insert barium oxide depletion profile after 15,000hours for the measured temperature profile at 2.6A – All surface opened but the orifice plate

The presence of evaporation from the orifice plate changes drastically the depletion profile. This can be justified noting that the orifice plate is the area with the highest temperature of the whole insert.

The profile obtained with the orifice plate surface closed are found to be in better agreement with the experimental results showing the characteristic “tongue” shape at the downstream end.

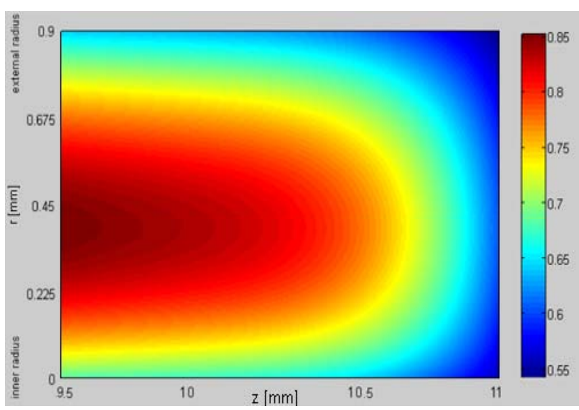


Figure 21. Computed barium depletion in the same region as that shown in Figure 7

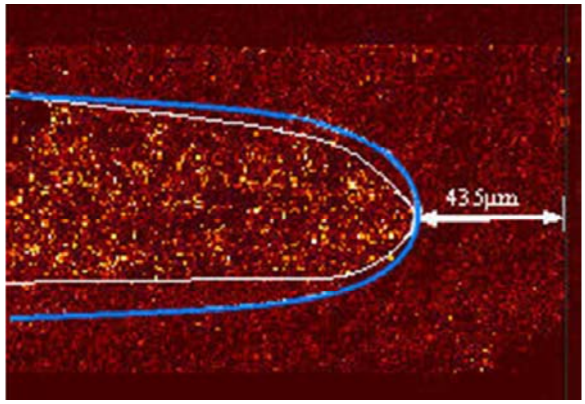


Figure 22. Direct comparison between experimental and numerical results

In Figure 21 the numerical depletion profile corresponding to the experimental one of Figure 7 is presented and a good qualitative agreement between them can be found.

In Figure 22 a closer comparison is presented showing together with the experimental depletion contour an iso-depletion line (blue line) relative to the numerical data that best fit the experimental contour.

The best agreement has been found using the line relative to a 25% depletion. At the current stage of model development, the model has demonstrated a good agreement (at least qualitatively) with experimental data. The next phase will involve application of the model to simulate T6 cathode depletion.

IV. Additional Hollow cathode lifetime projection studies

In recent years there has been a growing number of experimental evidence to suggest that the current state-of-the-art dispenser cathodes can last in excess of 50,000hours under current engine thrust demands. Specifically here we mention

1) The NSTAR long duration test which accumulated 30,372hours before voluntary shut down[3], where the subsequent dispenser analysis showed ample barium remaining in the matrix and was estimated to have another 25kHrs left (i.e. total life of 55,000 hours).

2) The small amount of depletion observed on other shorter lifetests such as the Life Demonstration Test (LDT) cathode (8,200 hours)[4] and Artemis T5 cathode Lifetest (15,000hours).

3) The small amount of depletion observed on the T6 cathode after 4000hours and the fact that the operating dispenser temperatures measured and reported elsewhere[6] were 35°C to 126°C lower than NSTAR.

Current life estimation is based on extrapolation of experimental results[3], modeling and comparison using the similarity with vacuum device cathodes[5, 8, 9, 10] (with a demonstrated 130,000hours)[11]. However, operators require verification of compatibility to lifetime requirement by test. To conduct a test of >30,000 requires a great expenditure of effort, man power and expense. A de-risking strategy prior to these lifetests is required and empirical studies need to form an integral part of these strategies to ensure accurate prediction. Hence, QinetiQ has undertaken a series of novel experimental studies to project hollow cathode lifetime and to determine a cathode ultimate life and end of life condition.

A. Accelerated T6 lifetest

Barium evaporation and loss from the emissive dispenser is considered to be the main life limiting mechanism in hollow cathodes. It has been shown by several authors that the rate of barium evaporation is solely dependant on the emitter's surface temperature[11, 12, 8]. This is exactly the situation found in similar dispenser cathodes used in vacuum tubes for applications ranging from traveling wave tubes, vacuum electronic devices, microwave tubes etc.. This enables direct comparison of ion thruster hollow cathodes with such devices which have been intensively investigated and have demonstrated lifetimes of 130,000 hours. It is possible to calculate the expected depletion-limited life time of hollow cathodes from available vacuum cathode data as long as the dispenser surface temperature is known[11].

The depletion life dependence on temperature comes about due to the fact that the processes involved all scale with temperature such as: chemical supply reactions, transport, diffusion, desorption and evaporation processes[13]. From the large volume of data, a simple "rule of thumb" has emerged; **that the dispenser life doubled for every**

30^o to 40^o reduction in temperature[8, 11]. The converse is also true, that increasing the emitter temperature by the same amount would half the lifetime. Accelerated testing of emitters at elevated surface temperatures allows for a substantial reduction in testing time and cost. It has been used for decades with vacuum dispenser cathodes and is known for giving a good estimate of expected cathode life[13,14]. To the author's knowledge this is the first time the accelerated testing methodology has been applied to ion thruster hollow cathodes.

The T6 thruster is currently proposed as a candidate for ESA's future mission to Mercury BepiColombo. The mission places a lifetime requirement of 14,000hours in space (21,000 hours for a lifetest including a 1.5 qualification margin). The maximum anticipated mission thrust level is 150mN, which corresponds to a discharge setting of 17.1A on the T6 thruster. Experiments have been carried out at QinetiQ to measure the dispenser temperature profile on an operating T6 cathode. The dispenser of a T6 cathode was drilled along its length to accommodate very fine high temperature D-type thermocouples. This instrumented cathode was mounted in a fully representative discharge chamber and was run through the range of throttle points available to the T6 thruster. The details of these series of tests are reported in more detail elsewhere[6], Figure 23 shows the results for the dispenser temperature profile for the 17.1A discharge condition.

The first task prior to starting the accelerated lifetest was to decide on an acceleration factor. It was decided to increase the temperature of the downstream segment of the insert (the thermocouple location 0.5mm downstream of the orifice plate) by 120^o. This would give an acceleration factor of 8 to 16 times (depending on whether every 30^o increase doubles the temperature or every 40^o). Upon completion of the T6 dispenser temperature measurement tests the selfsame instrumented cathode was used for the accelerated lifetest. The cathode was left in the same test arrangement, employing a fully representative discharge chamber. It was decided to effect the increase in dispenser temperature by increasing the discharge current (I_A) while leaving other parameters (flow rate, magnet current) the same. It was found that the discharge current value of 22.5A gave the required temperature increase (profile shown in Figure 23 along with that for 17.1A for comparison) and the instrumented cathode was left at that setting for the accelerated test duration.

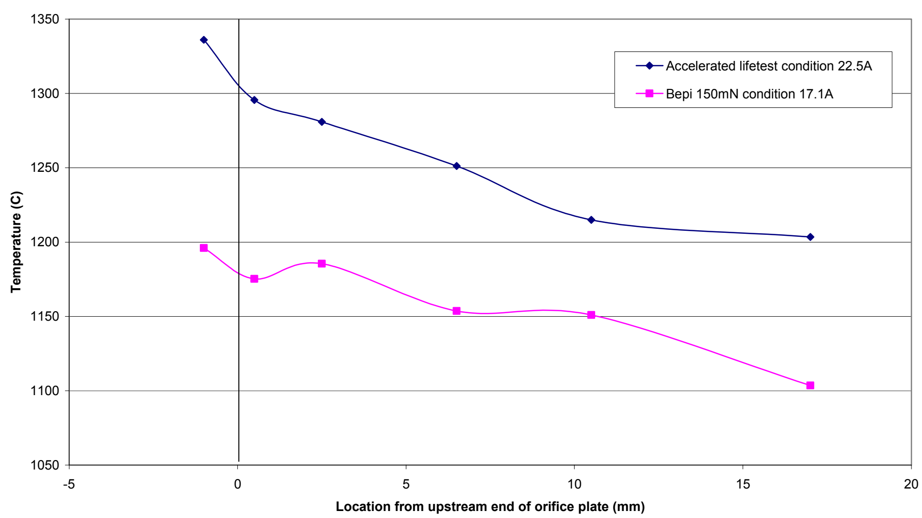


Figure 23. Comparison between the T6 cathode dispenser temperature profile at 17.1A and that used during the accelerated life test

A. Test Rationale

In the accelerated test the T6 cathode is operated at 22.5A discharge current to a point at which the barium content is depleted to the extent that the cathode will no longer start or operate within acceptable limits. The test sequence is presented in Figure 24.

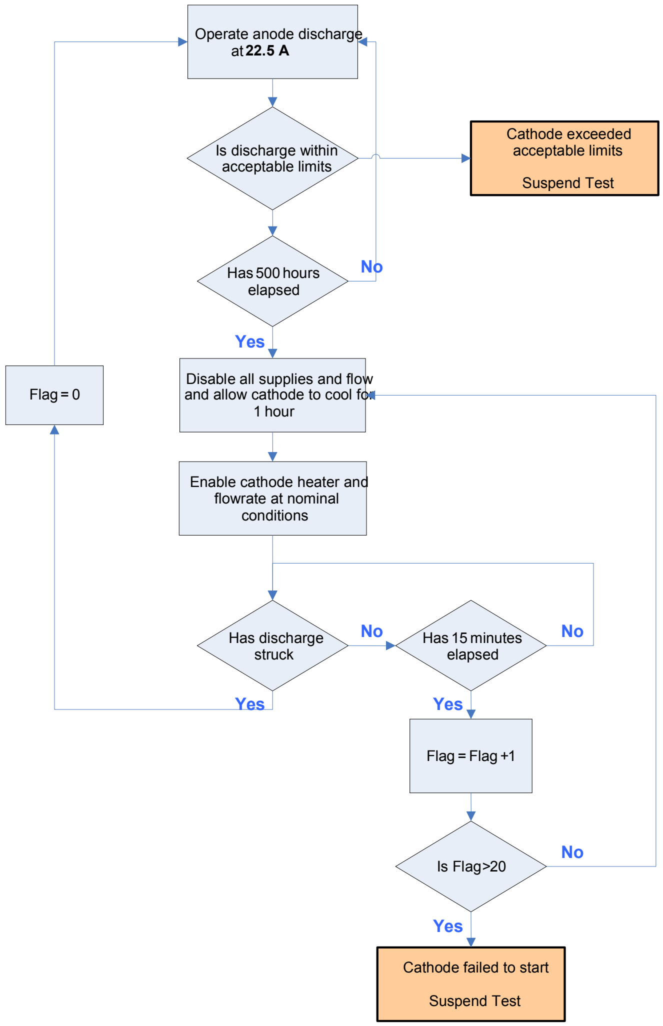


Figure 24. Accelerated T6 depletion test sequence

The T6 cathode is operated in the accelerated test condition in 500 hour segments, during which the discharge parameters are monitored to ensure that they are within acceptable limits. The test limits are listed in Table 4, they are there to ensure that the cathode still operates within the capabilities of the flight hardware supplies.

Table 4: Accelerated T6 lifetest test limits

ID	Description	Unit	Test Limits
I_h	Cathode heater current	Amps	Nominal T6 setting
V_h	Cathode heater voltage	Volts	< 23
t_H	Heater On time	mins	< 15
I_A	Anode current	Amps	Set-point ± 0.1
V_A	Anode voltage	Volts	< 42
R_t	Number of discharge initiation attempts	N/A	<21
V_A	Cathode strike voltage	Volts	<50V

The test is stopped every 500hours and the cryopumps are regenerated. After a suitable regeneration the heater current is applied for a maximum of 15minutes and attempts are made to restart the cathode. This is done to ensure that operation at elevated temperatures has not had a detrimental effect on the cathode's starting ability. If any of the test limits are exceeded or if more than 20 attempts have been made to restart the cathode. The test is stopped. The cathode is then removed and the dispenser analyzed. This will then constitute the cathode end of life condition (i.e. minimum barium content required to operate within power supply limitations). The cathode life capability is then determined by multiplying the actual run time by the appropriate acceleration factor.

The accelerated test is carried out under autonomous computer control using the test sequence described above. The electrical and performance parameters that were monitored are listed in Table 5 and were sampled at 1Hz

Table 5 Accelerated T6 lifetest measured parameters

ID	Description	Unit
I_h	Cathode heater current	Amps
V_h	Cathode heater voltage	Volts
I_A	Anode current	Amps
V_A	Anode voltage	Volts
I_m	Solenoid current	Amps
V_m	Solenoid voltage	Volts
M_c	Cathode mass flow rate	mgs^{-1}
Tx	Temperatures of cathode insert at a given location X	^oC
R_t	Number of discharge initiation attempts	N/A
P_{VAC}	Chamber pressure	mbar

B. Accelerated Test results

Figure 25 shows the trends in cathode tip temperature, peak insert temperature, cathode flange temperature, and anode voltage during the accelerated lifetest. Each point on the graph represents an average of 12hours.

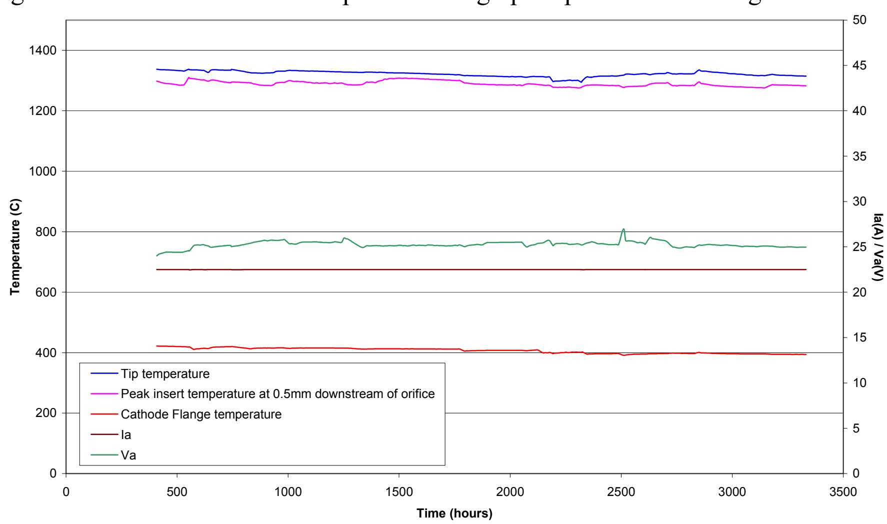


Figure 25: Observed trends in cathode temperature and discharge voltage in the accelerated T6 lifetest

At the time of writing, the accelerated test continues to operate nominally. It has currently accumulated a total of 3790 hours of operation. This is equivalent to 30,320hours with an 8× acceleration factor or 60,640hours assuming a 16× acceleration factor. Both figures well exceed the lifetime requirements for the BepiColombo mission. No more than 3 discharge initiation attempts were needed to start the discharge in any restart attempt after atmospheric exposure.

It can be seen that the test parameters have not experienced any significant permanent changes during the test. The average Discharge voltage remained nominal, with a standard deviation only 0.33V. There was a very slow decrease in the measured thermocouple temperatures, the peak insert temperature at 0.5mm downstream of the tip dropped by ~16^{o}C during the test.

Once any of the test limits are exceeded, specifically the anode voltage maximum and restart attempts, the test will be stopped the insert removed and fractured and EDAX analysis will be performed. The resulting defined insert state will constitute the cathode end of life condition

B. Experience with intentionally depleted inserts

An alternative approach was also adopted in our attempts to estimate the end of life condition for the T6 cathode. The question was asked: Assuming cathode life is determined purely by barium evaporation, how much depletion can a cathode experience before the performance is seen to degrade? To answer this question, two cathodes were manufactured with grossly depleted inserts. As shown by the section of the 15,000hrs Artemis cathode and 4000hour T6 tests, Barium is depleted more rapidly at the downstream end. This observation is also borne out by the results from temperature measurements on hollow cathodes where the downstream end of the dispenser generally operates at the highest temperature[6].

The approach adopted was to use an unfilled tungsten matrix (i.e. one that has not been filled with the barium-calcium-aluminate compound) to form the downstream end of a two part insert. The upstream part is made of a fully impregnated insert machined to make up the difference in length between the depleted downstream part and a standard T6 cathode dispenser (see Figure 26 and Figure 27). This two part insert is inserted into a standard cathode assembly and operated normally. Two cathodes were made in this way one with 5mm of its length devoid of barium (which constitutes 25% of the length of a T6 dispenser), and another with 10mm of its length devoid of barium (50% depleted), these are shown in Figure 26 and Figure 27).

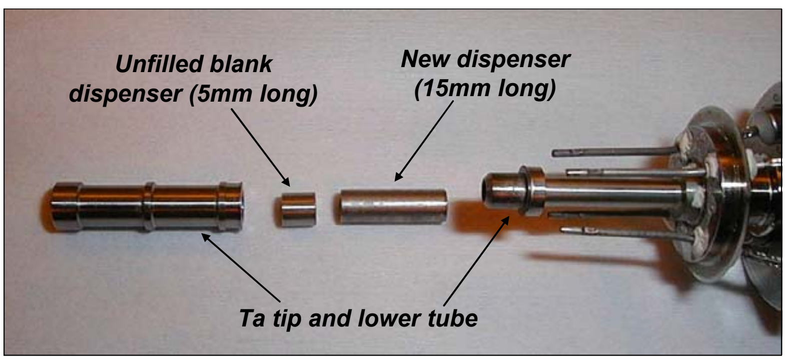
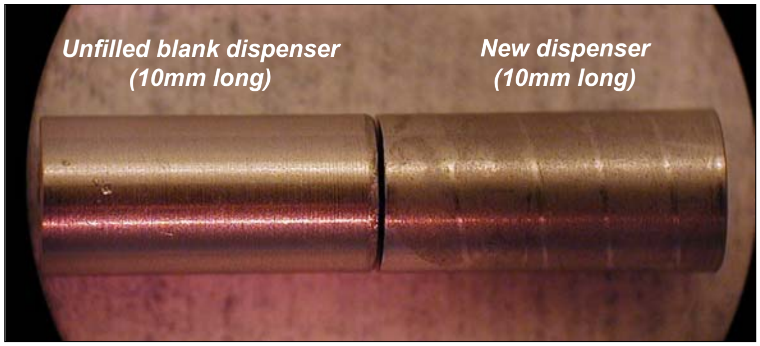
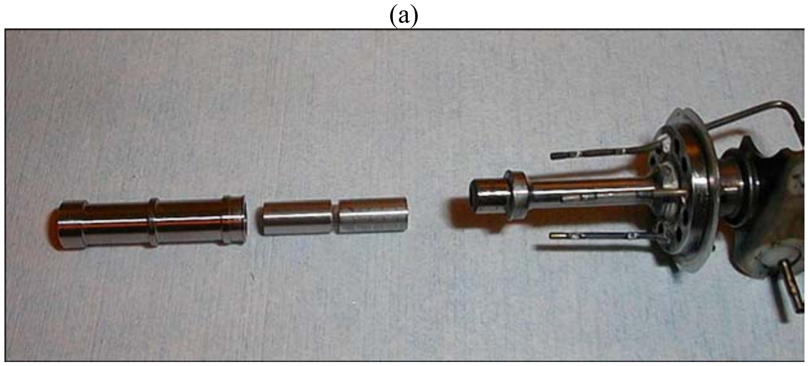


Figure 26. Photograph showing the 25% depleted cathode dispenser prior to welding into Ta cathode tube



(a)



(b)

Figure 27. (a) Photograph showing 50% depleted dispenser under the microscope (b) dispenser prior to welding into Ta cathode tube

It is realized that this approach oversimplifies the depletion process as it ignores its radial element. However it was felt that the lack of data from very long duration tests (>50,000 hours) and the considerable effort and costs that such an effort will entail would justify the value of this approach which is felt will give a feel and a "ball park" estimate for the cathode depletion limited end-of life. Preliminary rough estimates using the Southampton model initial results for the T6 puts the tip of the depletion tongue at the 5mm position after 63,000hours of operation for the 25% depleted (5mm position) and it estimates the tongue will be at the 50% depletion position after 110,000hours of operation.

1. Test procedure

The tests were carried out sequentially, with the 25% depleted cathode tested first. The cathodes were mounted in diode configuration. The test set up is shown in Figure 28. The anode was plate made of carbon 140mm in diameter and 12mm thick mounted 25mm from the cathode tip. The anode had 55, 5mm holes in a hexagonal pattern which enabled pyrometer measurements of the tip temperature to be taken via a window downstream in the test facility. This exact configuration (with the same anode plate and separation) was used previously with a fully filled T6 cathode[6] and will thus enable comparison of the depleted cathodes' performance. The fully filled cathode was the instrumented cathode discussed earlier which contained a thermocouple inserted into a the tip to measure its temperature.

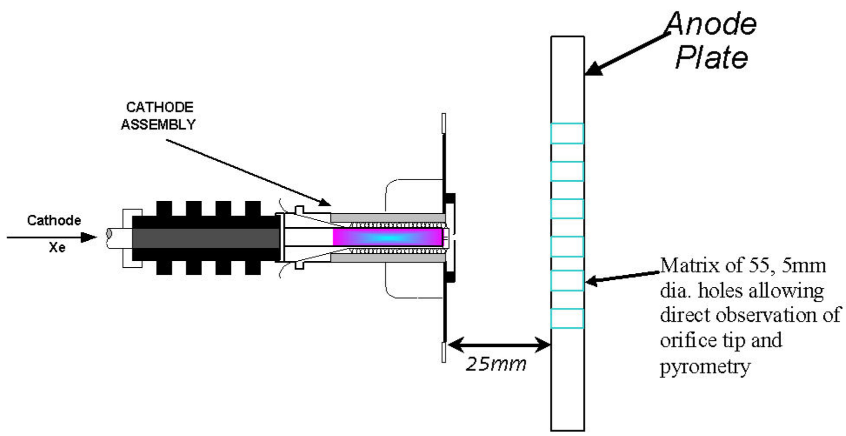


Figure 28. Diode configuration used in intentionally depleted cathode tests

The keeper was connected to the anode supply via a resistor and had a strike capability of 50V. The cathodes are installed in the test chamber and after a suitable outgassing period the tests were commenced. The cathodes are run at following discharge current settings: 11A, 15A, 17.1A and 19.5A which are the discharge settings for the BepiColombo thrust range. The flow rate was kept constant at 0.69mg/s. The heater was run and no more than 15minutes were allowed for heating. After the discharge is struck, the cathodes were taken to the first discharge setting and left for at least 30minutes to settle before measurements were taken, on completion, the cathode is then taken to the next setting. Following the steady state tests, the cathodes were subjected to starting tests. These involve heating the cathode and application of the strike voltage, if the discharge struck within the allotted 15minutes, the discharge is taken to the 17.1A condition and left for 30minutes. The discharge is then switched off and the cathode is allowed to cool for 15minutes before the sequence is repeated.

2. Test results

The 25% cathode discharge started on the first attempt after 13minutes of heating, it completed the test sequence described above and its performance is shown in Figure 29 and Figure 30 and will be discussed shortly. Subsequent starts required shorter heating times and took on average 5minutes to start. By the end of the test the 25% cathode had accumulated 52hours of operation and undergone 10 stop/start cycles with no changes in performance. After the 25% test was completed it was replaced by the 50% depleted cathode. The first start on that cathode occurred again on the first attempt and required 11minutes of heating. Subsequent starts were again shorter, averaging between 5 to 6minutes. By the end of the test the 50% depleted cathode completed 47hours of steady state operation and 5 start/stop cycles.

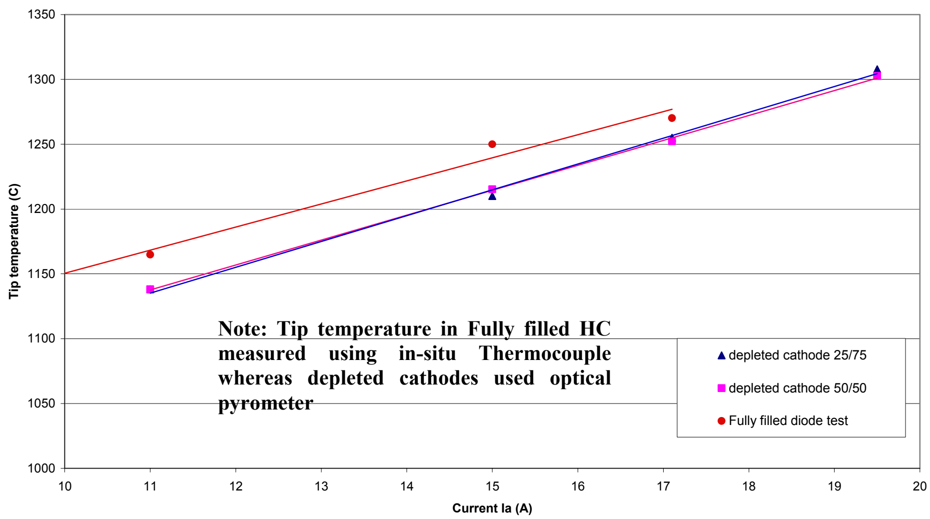


Figure 29. Comparison of Tip temperature dependence on discharge current in diode configuration between 25% depleted insert a 50% depleted insert and a fully filled one.

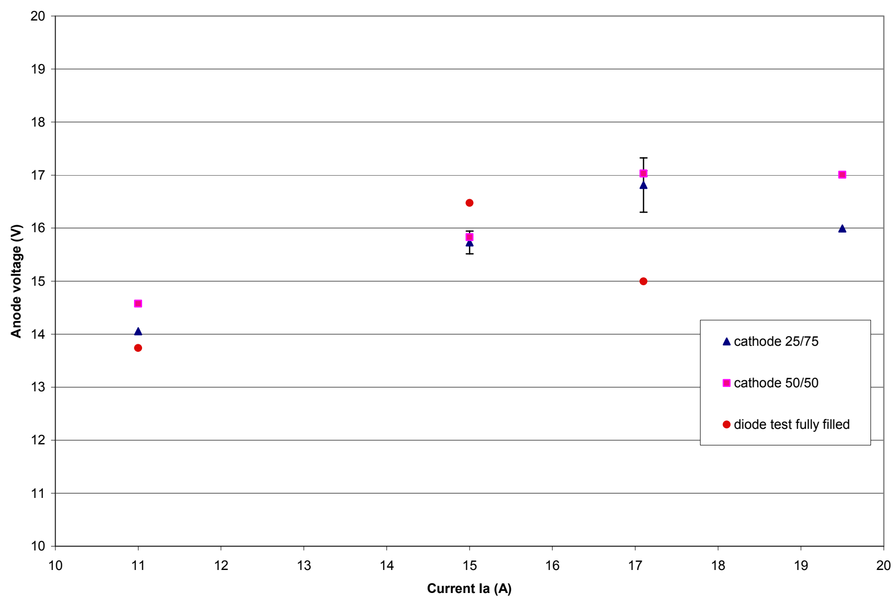


Figure 30 Comparison of discharge voltage dependence on discharge current in diode configuration between 25% depleted insert a 50% depleted insert and a fully filled one.

Figure 29 compares the tip temperature dependence on discharge current for the fully filled, 25% depleted and 50% depleted dispensers. The results show a linear increase with discharge current for all the cathodes. The graph shows an initially surprising result, that the temperatures for the depleted cathodes were actually ***lower*** than those for the fully filled dispenser (by an average of 27^{o}C), while the graphs for the two depleted cathodes were almost coincidental with a depletion factor of two between them. This can be explained by the fact that in the fully filled cathode case the temperature was measured by using a thermocouple embedded 1mm upstream of the orifice plate downstream end, while the temperature was measured using a pyrometer in the depleted cathode cases. It is thought that a temperature drop might exists over the final 1mm, furthermore pyrometer measurements taken with the fully filled dispenser were consistently 20 to 25^{o}C[6] lower than those measured with the tip thermocouple. Thus, it can be assumed that the depleted cathodes were operating at approximately nominal tip temperatures. Figure 30 compares the operating voltages for the three cathodes. No significant differences were observed between them, the maximum difference between the measured values V_a was found at the 15A discharge setting and was only 2V.

V. Conclusion

This paper presented some of the aspects of a program undertaken by QinetiQ to characterize and determine the depletion rates and predict life time of its cathode technology. The long duration test performed on the T5 (15,000 hours) showed some good results indicating that the dispenser at least was far from its end of life condition the same applies to the T6 4000hours test. The modeling program of insert depletion by Southampton University was also discussed and produced good agreement with measured depletion on the 15,000hour T5 insert. Two additional novel tests have also been carried out on the T6 cathode to determine an end of life condition. An accelerated lifetest where the insert temperature was increased by 120^{o}C has to date accumulated 3790 hours of operation. This is equivalent to 30,320hours with an 8× acceleration factor or 60,640hours assuming a 16× acceleration factor. Another test was also undertaken with two grossly depleted T6 inserts (25% and 50% depleted). The results were surprising in that both cathodes, although grossly depleted, still behaved nominally. All the results gave a degree of confidence in the compatibility of the T6 thruster cathode with future high impulse mission lifetime requirements.

References

[1] Roquais, J.M. et al. "Barium Depletion Study on Impregnated Cathodes and Lifetime Prediction". Applied Surface Science, 215, pg 5-17, 2003.

[2]Palluel, P. & Shroff, A.M. "Experimental Study of Impregnated-Cathode Behaviour, Emission and Life". J. Appl. Phys. Vol 51, (5), 1980.

[3]Sengputa, A. "Destructive Physical Analysis of Hollow Cathodes from the Deep Space 1 Flight Spare Ion Engine 30,000 Hr Life Test". 29th International Electric Propulsion Conference, IEPC-2005-026, 2005.

[4] Polk, J.E. "The Effect of Reactive gases on Hollow Cathode Operation". AIAA-2006-5153, 2006.

[5]Tighe, W.G., CHien, K.R., Goebel, D.M. & Longo R.T. "Hollow Cathode Ignition studies and Model Development". IEPC-2005-314, 2005.

[6] M. Ahmed Rudwan, I. F., Wallace, N.C. and Kelly, M. "Dispenser Temperature Profile Measurement in the T5 and T6 Kaufman-type Ion Thrusters". IEPC-2007-170.

[7] M. Coletti, S.B. Gabriel, "*A Chemical Model for Barium Oxide Depletion from Hollow Cathode's Insert*", AIAA-2007-5193, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, Cincinnati, Ohio, USA, July 2007.

[8]Katz, I. *et al.* "Model of Hollow Cathode Operation and Life Limiting Mechanisms". IEPC-2003-0243, 2003.

[9]Katz, I. *et al.* "Combined Plasma and Thermal Hollow Cathode Insert Model". IEPC-2005-228, 2005.

[10] Kovaleski, S.D. "Life Model of Hollow Cathodes Using a Barium Calcium Aluminated Impregnated Tungsten Emitter". IEPC-01-276, 2001

[11]Goebel, D.M. et al. "Extending Hollow Cathode Life for Electric Propulsion in Long Term Missions". AIAA-2004-5911, Space 2004 Conf. and Exhibit, 2004.

[12]Doerner, R. *et al.*"Plasma Surface Interaction Studies for Next Generation Ion thrusters". AIAA-2004-4104, 2004.

[13]Gartner, G., Barratt, D. "Life-limiting mechanisms in Ba-oxide, Ba-dispenser and Ba-Scandate cathodes". Applied Surface Science, v. 251, iss. 1-4 [SPECIAL ISSUE], p. 73-79, 2005.

[14]Williamson, M. "The Physics of Space Tubes". Phys. Technol., 17, 1986.

[15] Appendino P., *"Ricerche sul Sistema Ternario Calce-Ossido di Bario-Allumina"*, Ceramurgia, 1972, pp. 103-106.

[16] Lipeles R.A., Kan H.K.A, *"Chemical Stability of Barium Calcium Aluminate Dispenser Cathode Impregnants"*, Application of Surface Science 16, 1983, pp. 189-206

[17] Wolten G.M., *"An Appraisal of the Ternary System BaO-CaO-Al_2O_3"*, SD-TR-80-67, Space Division, Air Force System Command, Los Angeles, October 1980

[18] T.N. Resulhina, V.A. Levitskii, M.Ya. Frenkel, Izvestiya Akademii Nauk SSSR, Neorgan. Mater. 2, 1966, pp. 325-331.

[19]Malik, A.K. & Fearn, D.G. "The Study of the Physics of Hollow Cathode Discharges". IEPC-93-026, 1993.

[20]Malik, A.K., Monterde, P. & Haines, M.G. "Spectroscopic Measurements on Xenon Plasma in a Hollow Cathode". *Journal of Applied Physics*, Vol. 33, pgs. 2037-2048, 2000.

[21]Polk, J.E., Anderson, J.R., Brophy, J.R., Rawlin V.K., Patterson, M.J., Sovey, J. & Hamley, J. "An Overview of the Results from an 8200 Hour Wear Test of the NSTAR Ion Thruster". AIAA paper 99-2446, 1999

[22]M. Ahmed Rudwan, I.F. "Physics of Holow Cathode Breakdown and Steady-State Operation with Several Inert Gas Propellants" PhD Thesis, University of Southampton, 2003.

[23]Sengupta, A. *et al.* "Status of the Extended Life Test of the Deep Space 1 Flight Spare Engine after 30,352 Hours of Operation". AIAA-2003-4558, 2003.

[24]Sarver-Verhey, T.R. "Destructive Evaluation of a Xenon Hollow Cathode after a 28,000 hour Life Test". AIAA-98-3482, 34th Joint Propulsion Conference, 1998.

[25]Sarver-Verhey, T. R. “28,000 Hour Hollow Cathode Life Test Results”. NASA Contractor Report, Report No. NASA/CR-97-206231, 1997.

[26]Sarver-Verhey, T.R. “Scenario for Hollow Cathode End of Life”. NASA Contractor Report, Report No. NASA/CR-2000-209420, 2000.

[27]Goebel, D.M. *et al.* “Energetic Ion Production and Keeper Erosion in Hollow Cathode Discharges”. IEPC-2005-266, 2005.

[28]Jameson, K.K. *et al.* “Hollow Cathode and Thruster Discharge Chamber Plasma Measurements Using High-Speed Scanning Probes”. IEPC-2005-269. IEPC, 2005.

[29]Katz, I. *et al.* “Model of Hollow Cathode Operation and Life Limiting Mechanisms”. IEPC-2003-0243, 2003.

[30]Polk, J., Grubisic, A., Taheri, N. *et al.* “Emitter Temperature Distributions in the NSTAR Discharge Hollow Cathode”. AIAA-2005-4398, JPC. 2005.

[31]Palluel, P. & Shroff, A.M. “Experimental Study of Impregnated-Cathode Behaviour, Emission and Life”. J. Appl. Phys., Vol. 51, pgs. 2894-2902.