Dispenser Temperature Profile measurement and Discharge Current Division in the T5& T6 Kaufman-type Ion Thrusters

IEPC-2007-170

Presented at the 30th International Electric Propulsion Conference, Florence, Italy
September 17-20, 2007

Ismat M. Ahmed Rudwan*, N.C. Wallace† and Mike Kelly**
Space Division, QinetiQ Plc Ltd, Farnborough, Hampshire, GU14 0LX, UK

Abstract: The most significant life-limiting process in hollow cathodes is the temperature of the tungsten matrix. To support development of cathode life models and a cathode life time estimation program, experiments were carried out to measure the emission current and cathode temperature profile for QinetiQ's T5 and T6 ion engine cathodes. It has been shown that a current balance operates in Kaufman type ion thrusters which results in a reduction of cathode emission currents (by 23-25% in the case of the T6) due the additional contribution of an ion current to the cathodic surfaces describing the discharge chamber volume. The result causes a significant reduction in the operating temperature of the cathode and is significant for the suitability of Kaufman-type ion engines for long duration missions. Insert temperatures were measured using high temperature thermocouples at conditions corresponding to the range of throttle points achievable with both engines. The temperatures observed on the T6 insert at 150mN thrust setting (the maximum expected for BepiColombo) were 35^o to 126^{o}C lower than those experienced on the NSTAR cathode which demonstrated 32,000hours of life. This gives a high degree of confidence in the T6 satisfying future high impulse mission requirements such as BepiColombo.

Nomenclature

I_A	=	Discharge (Anode) current
I_b	=	Baffle return current
I_c	=	Cathode emission current (cathode discharge return current)
I_{dc}	=	Discharge chamber return current
I_k	=	Keeper current
I_m	=	Magnet (solenoid) current
P_{vac}	=	vacuum pressure
M_c	=	Cathode flow rate
M_f	=	Main flow rate
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

*Propulsion Scientist, Space Department, S&DU, EMEA, imrudwan@qinetiq.com.
† Electric Propulsion Chief Engineer, Space Department, S&DU, EMEA, ncwallace@qinetiq.com

identified as one of the main lifelimiting factors for the operation of these thrusters. The thrusters 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[1-13].

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[14]. 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[5, 9, 12, 13]. 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 focuses on one aspect of that program concerning the determination of the dispenser temperature profile, which forms a critical input to the dispenser modeling and can be used independently to reach an estimate of cathode life by comparison with other lifetested cathodes

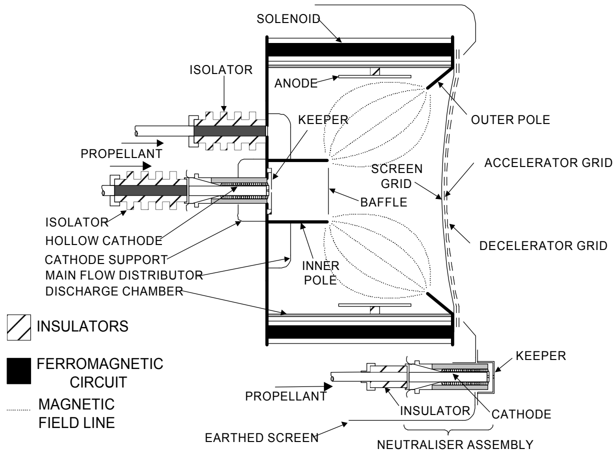

Figure 1. A modern Kaufman-type ion thruster.

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°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. Discharge current division in a Kaufman-type thruster

Prior to the start of the cathode's insert temperature profile measurements, it was important to identify the total cathode emission current. The cathode emission current is not the same as the total discharge or anode current. The reason is that in Kaufman engine the discharge chamber, baffle, backplate and screen grid are all cathodic surfaces at cathode potential. These surfaces receive a proportion of the discharge current due to ion recombination on the walls which results in an electron current to the discharge. At the anode the current is purely electronic but the return current is caused by a combination of cathode return current (from electron emission at the cathode and ion recombination at the cathode) plus discharge chamber return current (from the recombination of ions produced by volume ionization in the discharge chamber on the discharge chamber and screen grid surfaces). This is illustrated in Figure 2.

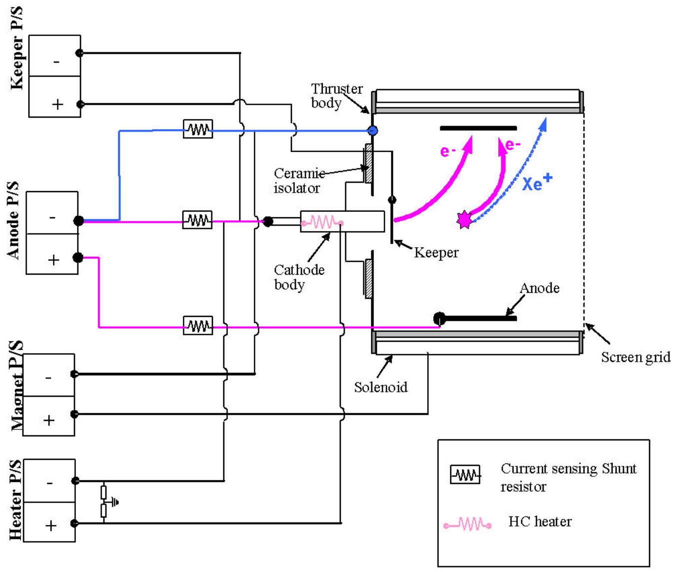

Figure 2. A hollow cathode mounted in a full Kaufman-type thruster geometry, figure shows arrangement used to measure cathode emission current percentage of total current.

This effect was previously observed in the late 1970's by Brophy[15] during experiments to increase the thrust density from ion engines by using multiple cathodes. In these tests it was initially found difficult to initiate the cathode/keeper discharge in both cathodes, due to the coupling that takes place between the plasma of the first cathode to be initiated and the keeper plate of the second yet non-emitting cathode. To overcome this problem the two cathodes had to be physically isolated from the thruster chamber and from each other to prevent this coupling. On measuring the return current from each cathode, Brophy found that the total cathode current only accounted for just under 70% of the total discharge current. The remaining 30% of discharge current was attributed to ions recombining on the discharge chamber walls.

This will be a significant effect for the Kaufman type engine with its large effective cathodic surface. It is generally agreed in the HC modeling literature and CRT tube experience that as a rule of thumb a 30° to 40° reduction in operating temperature will double the insert expected life[12]. Consequently, the reduction of cathode emission in the Kaufman discharge chamber will have important implications for the expected cathode lifetime as the discharge current drives the cathode operating temperature which in turn is the main variable in determining cathode life.

A. Experiments and range of operating parameters

Figure 2 also shows the general set-up used to determine the cathode emission current for the QinetiQ T5 and T6 thruster cathodes. A ceramic flange was used to isolate the cathode from the discharge chamber which allows the return current to each to be monitored independently.

The tests on the T5 cathode were carried out in a fully representative discharge chamber. The main flow rate (M_f) was varied in the range 0 to 0.3mg/s in 0.1mg/s steps. The magnet current (I_m) was only operated at two settings namely 0.14A or 0.4A. The discharge current (I_A) was varied in the range of 2.1A to 4.7A. The cathode flow rate (M_c) and keeper current (I_k) were kept constant at 0.1mg/s and 1A respectively. Figure 3 shows the results for the dependence of the cathode percentage of total current on M_f for various values of total discharge and magnet current.

The percentage of cathode contribution to total current was found to depend on flow rate and magnet current each of which determines the efficiency of the volume ionization in the discharge chamber and it was possible to reduce the cathode current percentage to as low as 59.5% of total current. In general, the Cathode current (I_c) percentage of total current I_A seems to be increasing with increasing M_f for a given I_m. With the increased neutral density (which is a product of increasing flow rate) the mean free path decreases, increasing the collision frequency. The electron thus gains less energy between collisions in the discharge chamber and the discharge chamber current proportion decreases. Another probable contributing factor is the reduction in the arrival rate of the ions to recombine at the wall due to collisions with neutrals. The magnetic field strength was found to have the biggest positive effect, increasing it enhances the electron path length thus effectively increasing the probability of it achieving an ionizing collision in the discharge chamber. As a consequence, this will increase the volume ionization and hence decrease the current requirement from the hollow cathode. An increase in the magnet current from 0.14A to 0.4A has reduced the cathode current by an average of 17.1% and as much as 19.3%.

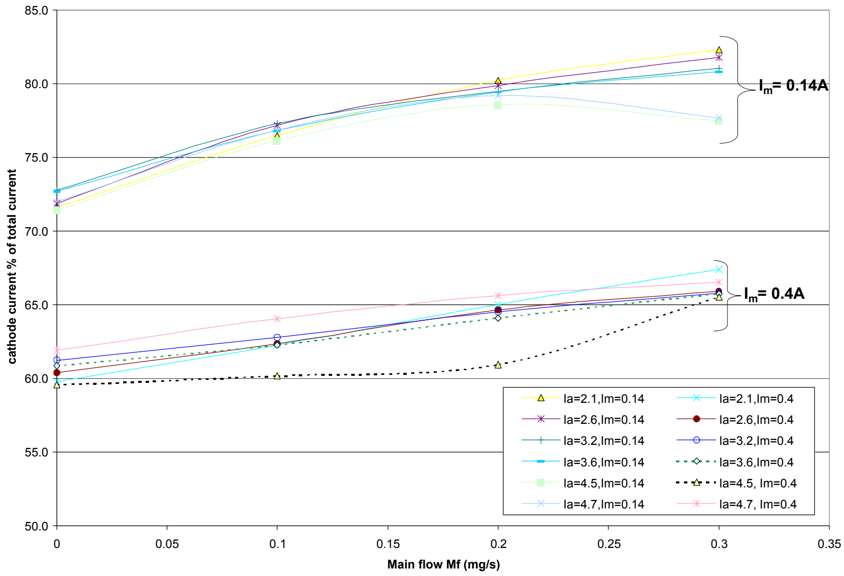

Figure 3. T5 Cathode emission current percentage of total current as a function of main flow rate for various values of discharge and magnet currents

A slightly different philosophy was employed in the T6 tests. Firstly, the baffle disc was also isolated to determine its current collection independent of the cathode and discharge chamber. The current division was determined at various thrust points, Table 1 summarizes the discharge set-points for the thrust conditions covering the range of 70mN to 175mN, the initially proposed throttle range for the BepiColombo mission.

Table 1. T6 ion thruster throttle points and corresponding discharge set-points used in this work

Corrected Thrust (mN)	Cathode flow rate (mg/s)	Main flow rate (mg/s)	Discharge (anode) Current (A)	Magnet Current (A)
68.54	0.69	0.798	9.5	0.966
100.56	0.69	1.433	13.3	0.925
133.19	0.69	2.138	15.17	1.044
150*	0.69	2.481	17.1	1.031
164.80	0.69	2.834	18.5	1.04
166.15	0.69	2.870	20	0.972
174.89	0.69	3.058	19.5	1

*150mN set point not used in the current division test but employed later in dispenser temperature measurements

The results shown in Figure 4 are for the T6 using the discharge settings for six of the engine throttle points detailed above. It shows for the T6 discharge chamber that 75-77% of anode current is emitted by the cathode, 19.2 to 20.7% is due to the discharge chamber return current (I_{dc}), and only 3 to 5% coming from the baffle disc return current (I_b). The results are in broad agreement with those previously encountered with the T5.

A further set of experiments was also conducted to determine the sensitivity of the T6 cathode emission current to the magnetic field strength in the discharge chamber. The magnet current was varied, within the discharge stability limits, by ~ ±20% from the nominal settings, keeping all other parameters constant. The results are illustrated in Figure 5. They again show the expected reduction in I_c with increasing magnet current. In the case of the 15.17A discharge setting, an increase of 0.2A in I_m reduced the cathode emission by 7.5%.

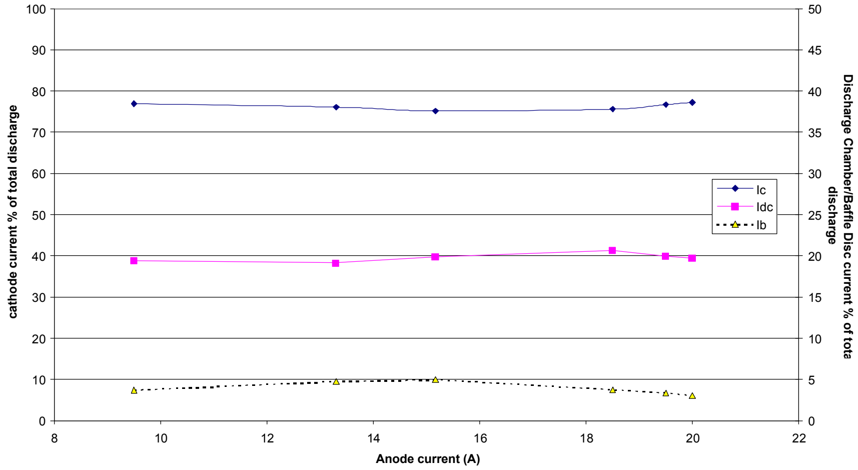

Figure 4. T6 cathode emission current percentage of total current at various engine throttle points, also shown is the relative current balance between the baffle disc and the discharge chamber.

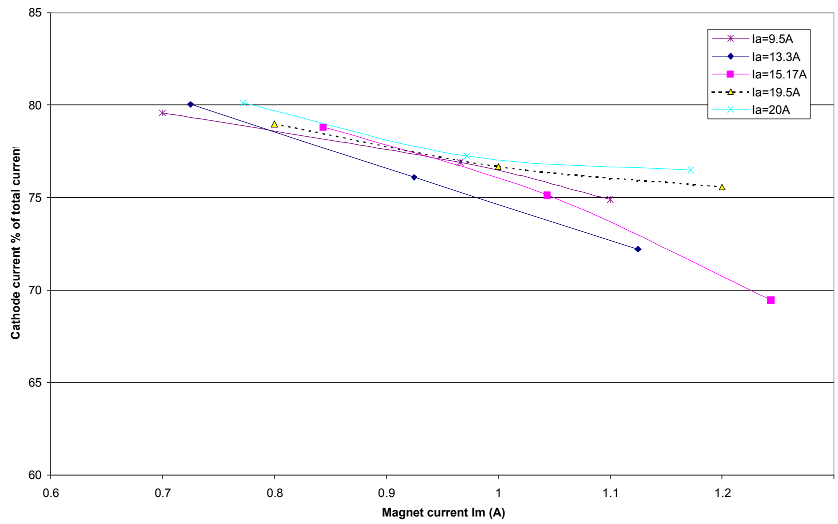

Figure 5. Effect of magnet current on the T6 hollow cathode emission current fraction at various throttle points.

It is also interesting to plot the dependence of the cathode discharge current percentage on the anode voltage. The anode voltage, although a dependant variable set by the discharge conditions, shows a direct inverse proportionality with the cathode emission current as illustrated in Figure 6 for the T5 and Figure 7 for the T6.

The anode voltage usually increases with increasing magnet current due to the magnetic field restricting the direct arrival of primary electrons to the anode before undergoing ionizing collisions. The results in Figure 6 and Figure 7 are for a range of magnet currents, flow rates and discharge currents and point to a direct relationship between the anode voltage and the volume ionization process in the discharge chamber.

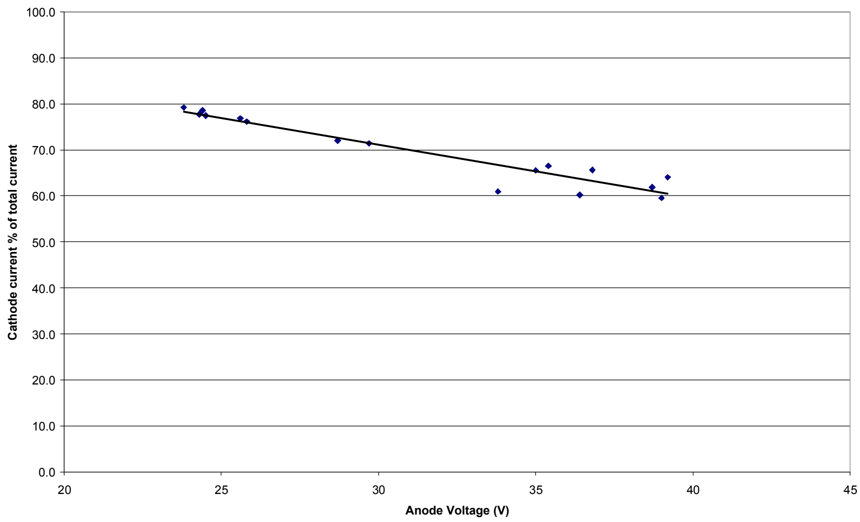

Figure 6. T5 hollow cathode emission current fraction as a function of discharge (anode) voltage.

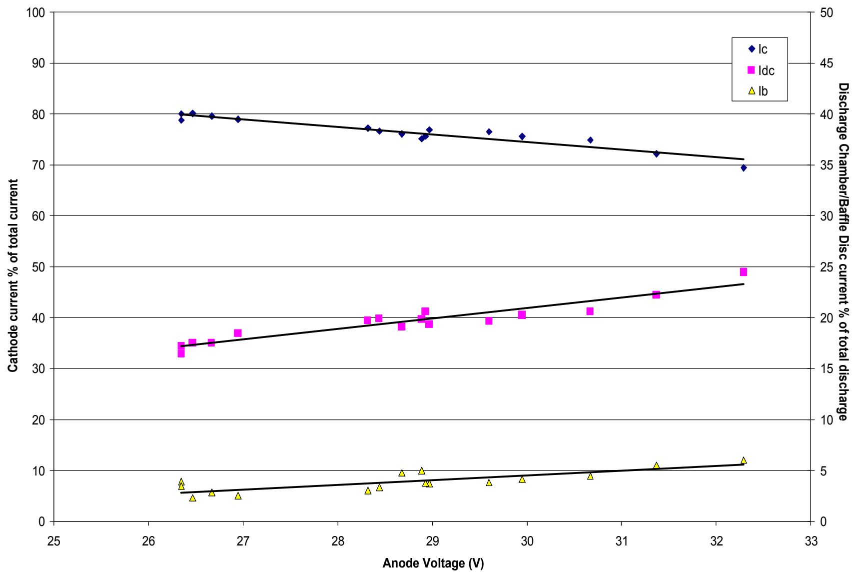

Figure 7. T6 hollow cathode emission current fraction as a function of discharge (anode) voltage.

III. Hollow cathode Dispenser temperature profile measurements

As mentioned previously a critical input to any dispenser modeling or estimation of cathode life is to determine the operating temperature of the bulk of the dispenser body during cathode operation. This has been done in the past with the NSTAR cathode but the temperature measurements were limited to dispenser surface measurements and cathode tip temperatures[13]. To allow these measurements, two instrumented cathodes a T5 and a T6 have been manufactured.

Two methods were envisaged for in-situ insert temperature profile measurement. a) A non contact method using sapphire high temperature optical fiber probes: The fibers formed a very suitable method for non-intrusive high temperature measurement. However, various factors have been found which discouraged from their eventual use. The bare fibers are brittle in nature which poses handling problems and consequently have a large bend radius. The radiative power loss from the drilled holes will result in changing the Hollow Cathode thermal equilibrium. And, contamination of the fibre surface caused by barium effusion from the insert will require constant calibration of the thermometry system, complicating our set-up. b) Thermocouples: There are various types of thermocouples capable of fulfilling the high temperature requirement of hollow cathode operation. D-type thermocouples (W-3%Re and W-25%Re) were selected because of their high temperature capability (up to 2500°C), material compatibility with the tungsten matrix insert and relatively high EMF output.

A test rig was constructed to calibrate the D-type thermocouple in a vacuum furnace with an R-type thermocouple of known response up to a temperature of 1300°C. The calibration results are shown in Figure 8, and indicate a maximum error of 1.5% from tabulated D-type response curves.

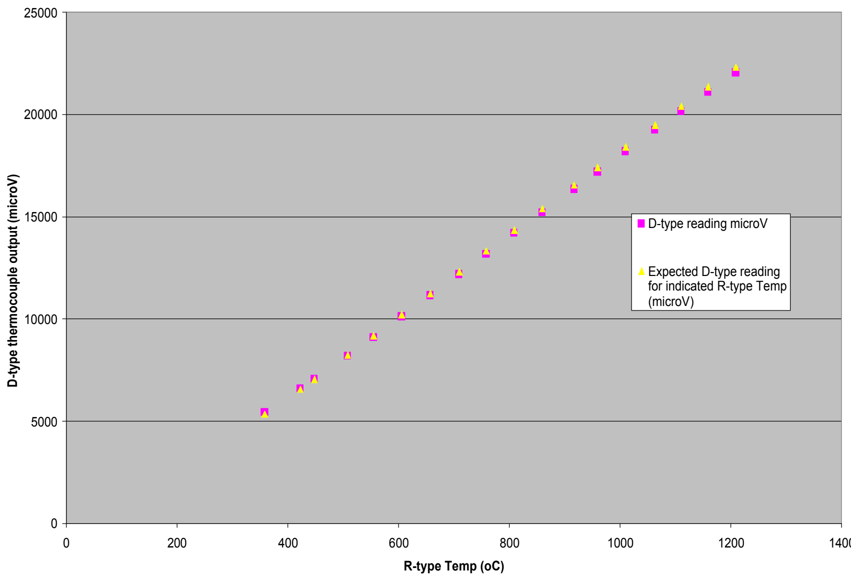

Figure 8. Calibration curve for D-type thermocouple

B. Design and construction of instrumented T5 and T6 cathodes

It was originally proposed to drill radially through the complete cathode assembly to a depth as close as possible to the insert inner surface. However, it was realized that such an arrangement will result in increased radiative losses from the cathode, changing the thermal equilibrium in the system and resulting, under the same discharge conditions, in higher observed temperatures in the instrumented cathodes than in a standard one. The alternative arrangement shown in Figure 9 has been adopted.

The insert and tantalum cathode body was drilled to a depth of approximately 100micron from the insert's inner surface. The Shapal-M heater support is segmented into two components. An outer segment, having the same outer diameter as a standard T5 or T6 cathode and containing the cathode heater wire. It, however, has a larger internal diameter to sandwich a heater inner sleeve between itself and the tantalum cathode body. The inner sleeve, made of the same material (Shapal-M), has grooves cut along its length to guide the thermocouples to the back of the cathode assembly via the cathode isolator flange. This design will leave the insulating heater holder, molybdenum heat shields an cathode casing intact and hence minimize radiative losses from the instrumented cathode.

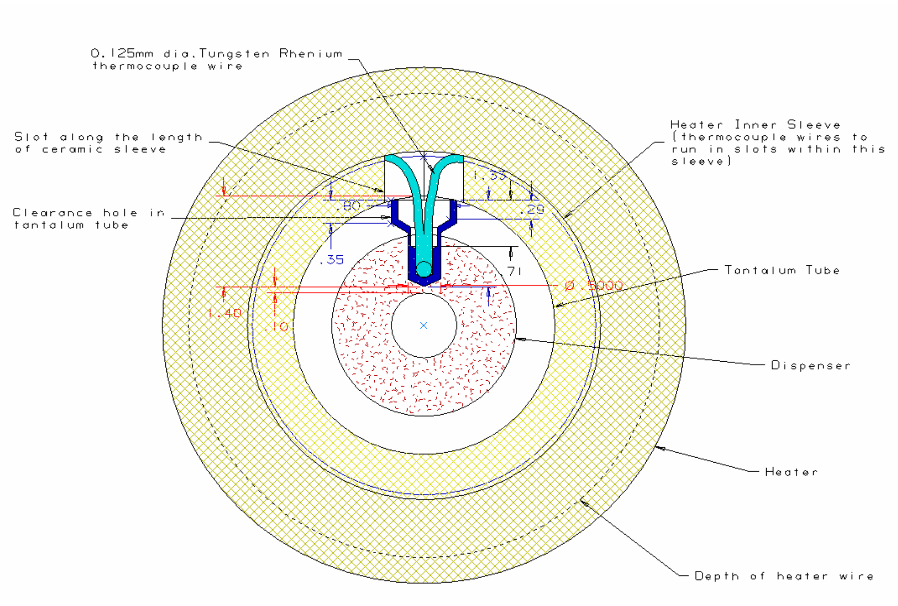

Figure 9. Cross-section of an instrumented cathode showing cathode construction with thermocouple inserted

The above figure shows how the thermocouples (shown as light blue) are inserted into the dispenser. The thermocouple leads were kept as thin as possible to minimize conductive losses along their lengths. The thermocouple leads are 0.125mm thick and are sheathed in a small tantalum sleeve to prevent the junction of the thermocouple from being contaminated and potentially damaged by oxides produced inside the dispenser, see Figure 10.

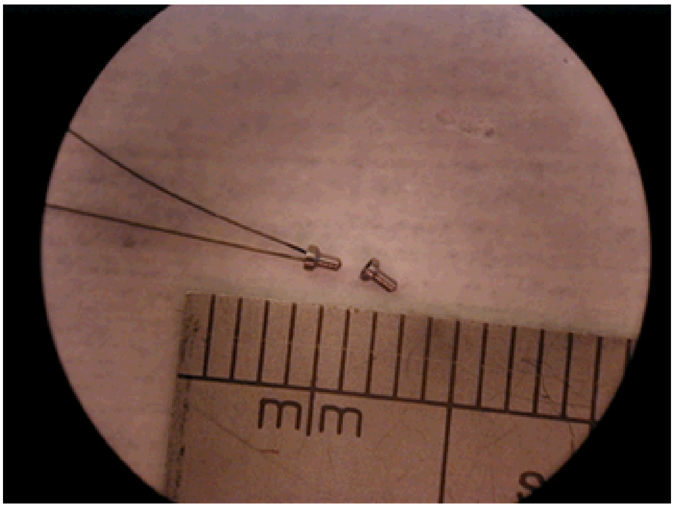

Figure 10. Type-D thermocouple inserted in Ta sheath prior to insertion in dispenser.

Each of the T5 and T6 instrumented cathodes has 5 thermocouples inserted along the length of the insert to produce an axial profile of the insert temperature. In addition, each cathode has a D-type thermocouple inserted in the cathode tantalum tip to monitor the tip temperature.

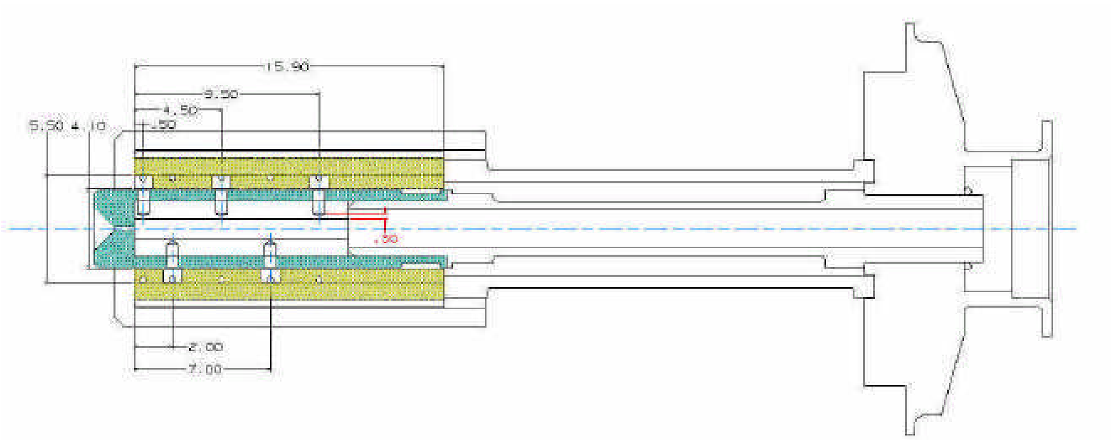

Figure 11. Cross-section of T5 cathode showing thermocouple locations in dispenser, one thermocouple inserted into the cathode tip and five into the dispenser at 0.5, 2, 4.5, 7 and 9.5mm

The instrumented T6 follows the same design as that shown in the previous figures of the T5, with the only difference being the location of the thermocouple probe holes. The 5 holes along the insert are drilled at 0.5, 2. 5, 6.5, 10.5 and 17mm from the upstream face of the tip. In addition an extra K-type thermocouple was attached to the cathode flange on the T6 to monitor its temperature.

The thermocouple leads are insulated along the length of the cathode structure in channels machined into the inner heater support ceramic, see Figure 12, Figure 13 and Figure 14.

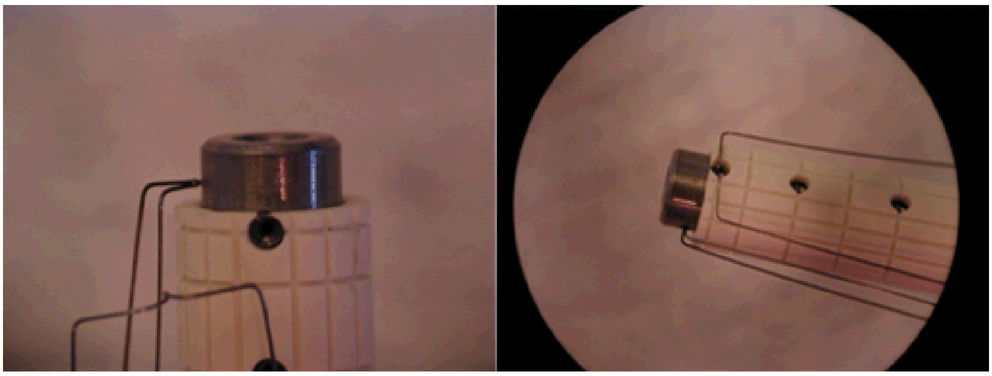

Figure 12. Thermocouples being installed into cathode structure

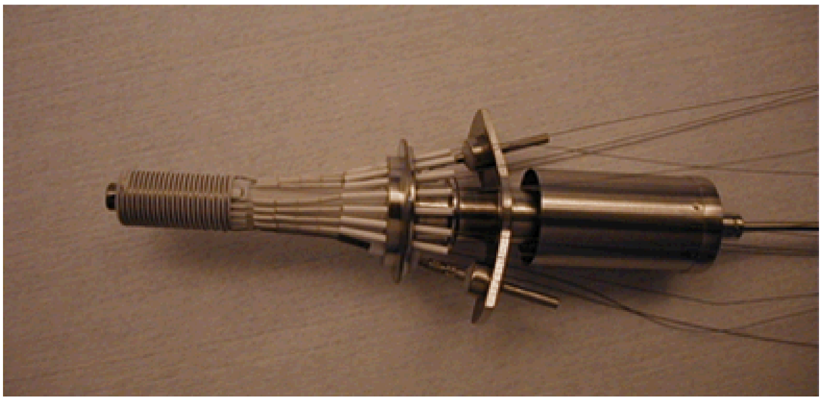

Figure 13. Completed instrumented T5 thermocouple with 6 D-type thermocouples

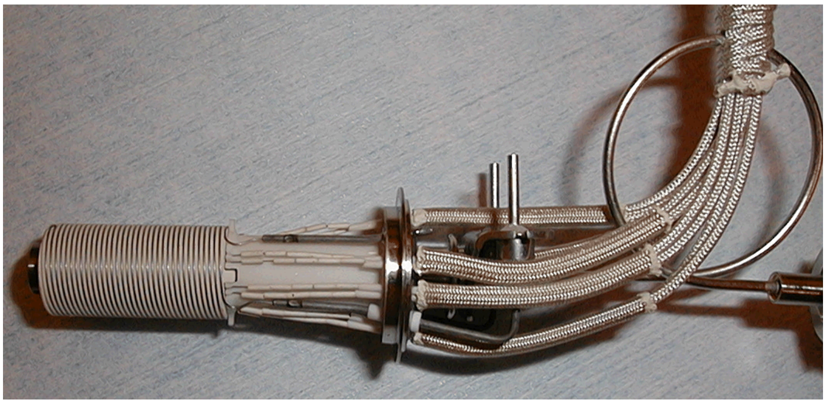

Figure 14. Completed instrumented T6 thermocouple with 6 D-type thermocouples

As illustrated by the previous discussion on current division in Kaufman thrusters, it was important to match the test conditions expected during thruster operations in the temperature profile measurements. Testing the cathodes in diode configuration for example would have led to an overestimation of the cathode temperature. The cathodes were mounted in fully representative discharge chambers with an arrangement similar to that shown in Figure 1 being used to conduct the temperature measurements. The instrumented cathodes were isolated from the thruster discharge chamber and its return current was monitored to ensure the correct level was being achieved.

The T5 cathode was run at test conditions representative the two set conditions used in the 15,000hours Artemis life test (the instrumented T5 cathode tests were actually carried out using an Artemis discharge chamber). The discharge settings are summarized in Table 2.

Following the completion of the T5 test , the cathode was replaced with the instrumented T6 cathode. The cathode was operated at discharge conditions corresponding to a number of thrust levels spanning the BepiColombo thrust range summarized earlier in Table 1.

At each set-point the performance and electrical parameters listed in Table 3 were recorded for the T5 and T6 cathodes. Once the discharge has stabilized, data was sampled at 1Hz. An Agilent Switch Unit digital scanner with a data acquisition PC were used to acquire and log the data from the thermocouples. After the cathode has reached thermal equilibrium (< 2 deg/hour on the cathode thermocouples), it was then operated for a minimum of 12 hours at the stabilised thermal equilibrium condition. The dispenser temperature profile was obtained from the results averaged over 12hours of operation at the given discharge conditions. The cathode under test is then moved to the next set point.

Table 2: T5 cathode set conditions

Description	**Setting**
Set-point 1	
Anode current	2.6 A
Cathode keeper current	1 A
Solenoid current	0.14A
Cathode flow rate	0.1mg/s
Set-point 2	
Anode current	2.2 A
Cathode keeper current	1 A
Solenoid current	0.14A
Cathode flow rate	0.1mg/s

Table 3. Monitored parameters during the instrumented cathode tests (Note: no Keeper supply exists for the T6 thruster as the keeper is run off the anode supply using a resistor)

ID	**Description**	**Unit**	**Comments**
V_a	Anode voltage	V	
I_a	Anode current	A	
V_k	Cathode keeper voltage (T5 only)	V	
I_k	Cathode keeper current (T5 only)	A	
V_m	Solenoid voltage	V	
I_m	Solenoid current	A	
m_{total}	Flow rate	mg/s	
T_x	Temperatures of cathode insert at a given location X	^{o}C	via thermocouples
P_{vac}	Chamber pressure	mbar	

C. Test results

At the beginning of the test campaign during the first heating cycle with the T5 cathode the thermocouple at 0.5mm downstream of the orifice plate went open circuit. This was attributed to recrystallisation of the thermocouple wires, causing it to undergo a ductile to brittle transition. The wire would have snapped under the applied thermal expansion loads. To prevent this from reoccurring, the thermocouple wires were heated to above 200^{o}C and left for at least two hours, this would anneal the tungsten alloy relieving any stresses caused by cold working. No further problems were encountered during the test campaign.

Temperature profiles for the T5 two Artemis lifetest thruster set points are shown in Figure 15. The profiles show a monotonic temperature increase as the orifice plate is approached. The T5 temperature profile is qualitatively similar to that obtained previously by Polk for the International Space Station (ISS) plasma contactor[13]. The peak temperatures were found at the orifice plate and were 1260^{o}C for I_A = 2.6A and 1215^{o}C for I_A = 2.2A. The estimated error in the thermocouple measurements is approximately ±15^{o}C.

To test the effects of the discharge current division in the T5 on cathode temperature, the magnet current was varied by ±0.06A (increased to 0.2A and reduced to 0.08A) at the 2.2A setting. As seen in Figure 16, it was observed that the tip temperature decreases with increasing I_m, commensurate with the expected reduction in I_c with increasing magnet current illustrated previously in Figure 5. The dispenser temperature reduced by 45-50^{o}C across the board throughout the range of magnet current variation. Also illustrated in Figure 16, is the expected rise in discharge voltage with increasing magnet current.

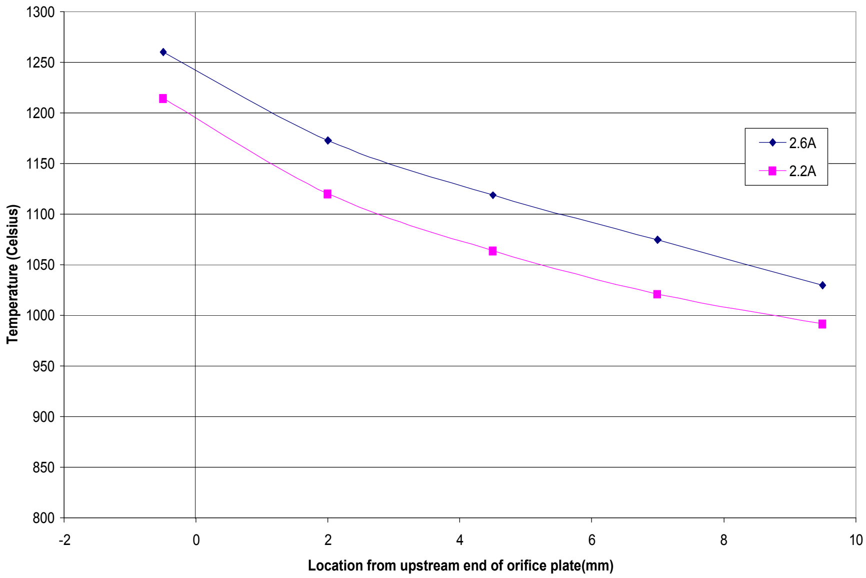

Figure 15. T5 hollow cathode temperature profile at two discharge current settings

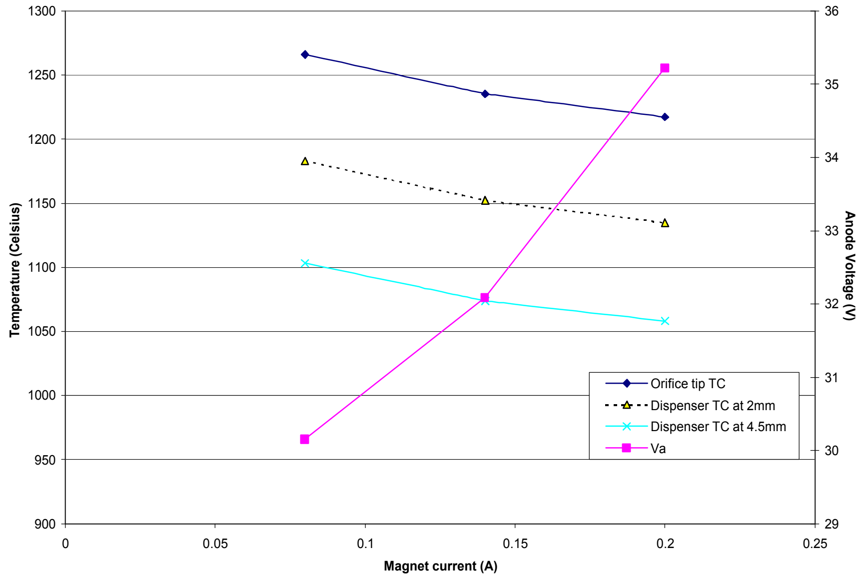

Figure 16. Influence of magnetic field strength on measured T5 thermocouple measurements

On the completion of the instrumented T5 tests, the cathode was removed and placed in a furnace. The D-type thermocouples were then post-calibrated by heating the furnace in 50^o steps, up to a temperature of 500^{o}C. A calibrated R-type thermocouple was attached to the cathode flange and used as a comparator. The results for all the thermocouples were within 2% of the R-type reading indicating no damage was inflicted on the thermocouples due to running for extended periods in a hollow cathode insert.

Following the removal of the T5 thruster from the vacuum chamber it was replaced with the instrumented T6 cathode in diode configuration to determine the effect of discharge configuration on the cathode temperature and profile. The test set up is shown in Figure 17. 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 quartz window mounted downstream in the test facility.

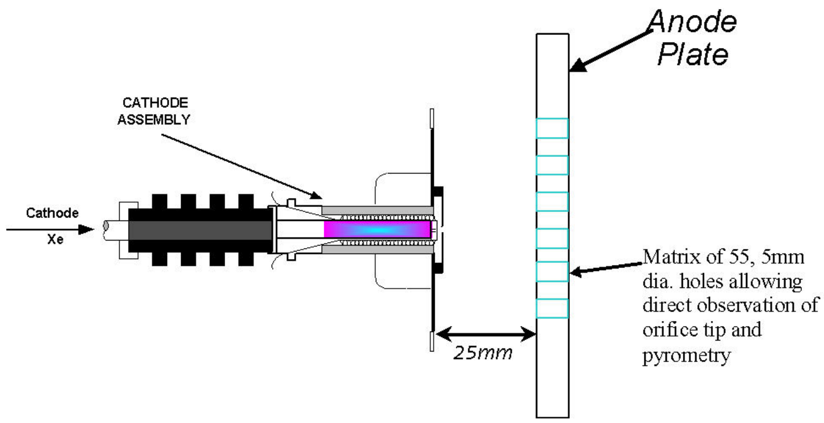

Figure 17. Schematic of the instrumented T6 cathode in diode configuration

Spot mode operation was achieved in this configuration at the 19.5A current setting. The corresponding thermocouple temperature profile is shown in Figure 18 and will be discussed later. A disappearing filament pyrometer was used for tip temperature measurements. It was noted that the pyrometer reading was consistently 20-25° lower than that obtained by the tip thermocouple. This indicates good agreement as the difference is within the pyrometer measurement error. However, the fact that the pyrometer reading was consistently lower might hint at the existence of a thermal gradient between the thermocouple location and the downstream face of the orifice plate.

The cathode was then removed from the vacuum chamber and installed in a fully representative discharge chamber in the configuration illustrated previously in Figure 2 and tested to the full range of discharge set points. The results in Figure 18 and Figure 19 represent the averages from a 12 hour run. Figure 18 shows the dispenser temperature profile while Figure 19 recasts the data by plotting temperature as a function of discharge current.

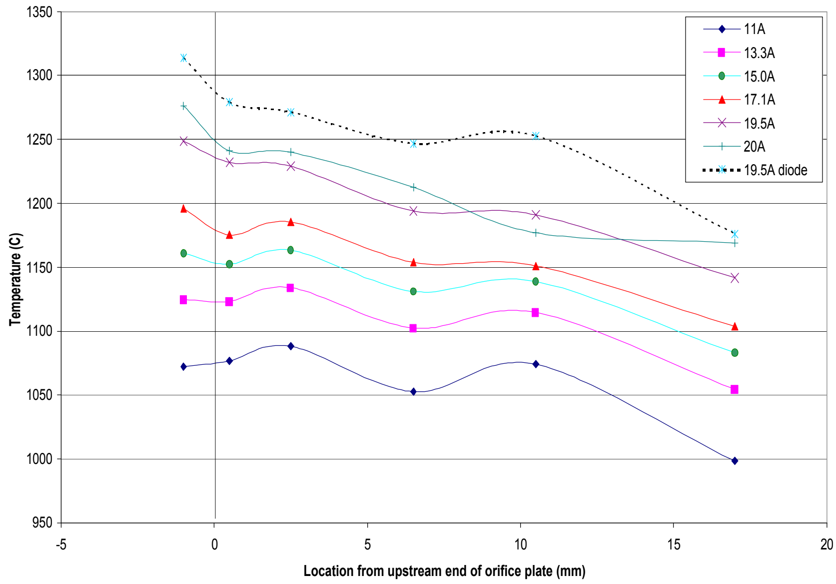

Figure 18 T6 hollow cathode temperature profile at several engine throttle points, included for comparison is results for the diode configuration test at 19.5A.

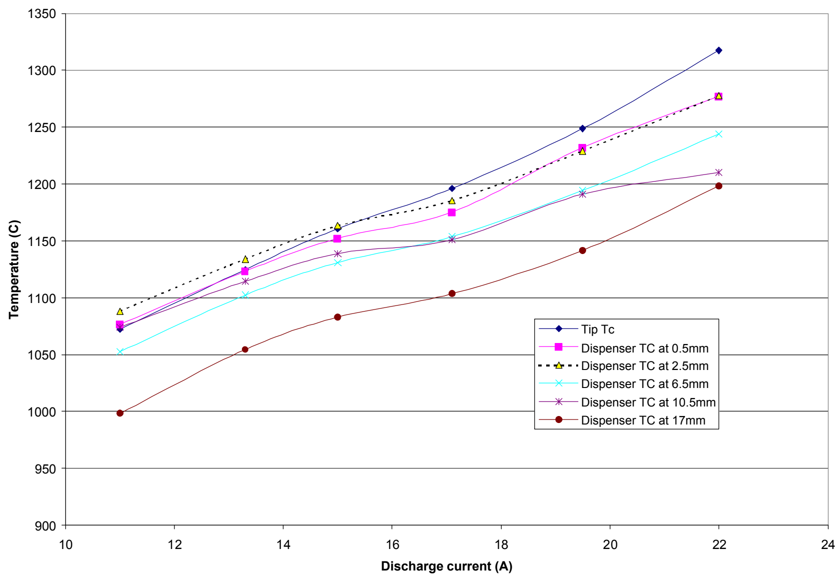

Figure 19. T6 dispenser temperature dependence on discharge current plotted for various points along the dispenser length

Some general characteristics can be inferred from the thermal profiles obtained for the T6 cathode. Starting from the most upstream location, the insert temperature rises very rapidly over the next 7mm. From then on it remains almost essentially flat over the rest of the dispenser surface for the lower discharge currents. As the discharge current increases an appreciable gradient develops giving the highest temperatures at the orifice plate (the gradient is as much as 100°C between the orifice plate and the 10.5mm dispenser location). Figure 19 shows the temperature dependence on discharge current for each thermocouple location. It shows a monotonic increase with I_A which is to be expected, it also shows that the peak cathode temperature occurs inside the cathode dispenser at the lower current settings. As the thermal gradient gets steeper in Figure 18, with increasing current, the orifice plate becomes the hottest part of the T6 cathode at current settings >15A. It maybe inferred that increasing the throttle demand causes the peak of the plasma density profile in the T6 to move further downstream towards the orifice plate and causes it to have a steeper gradient, which is in agreement with results from Langmuir probe studies of hollow cathode interior plasma[11].

Of particular interest is to compare the results for the 19.5A case in full thruster and diode configurations. Both produce the same total discharge current but the cathode in diode mode runs at the full discharge current while in the thruster configuration it only needs to emit 75% of the total current. This has caused a reduction of the dispenser operating temperatures of as much as 65°C, which translates to a lifetime extension by a factor of 3 to 4.5 (assuming every 30° to 40° reduction doubles the dispenser lifetime).

IV. Implications for T6 cathode lifetime and conclusions

It has been shown that a current balance operates in Kaufman type ion thrusters which results in a reduction of cathode emission currents by 23-25% due the additional contribution of an ion current to the cathodic surfaces describing the discharge chamber volume. The results are significant for the suitability of Kaufman-type ion engines for long duration missions. This current reduction was conclusively shown to reduce the operating temperature of the cathode resulting in a significant lifetime enhancement for the low work function insert.

To gauge the T6 cathode's potential lifetime and to determine its suitability for long duration missions, the dispenser temperature measurements will enable a comparison to be made with other hollow cathodes that have undergone lifetesting and where temperature data is available. The T6 thruster is currently proposed as a candidate for ESA's future mission to mercury BepiColombo. The mission calls for a lifetime of 14,000 hours in space (21,000hours for the lifetest including a 1.5 qualification margin).

The T5 hollow cathode has undergone a lifetest under the Artemis program. Four cathodes accumulated 15,000hours (including 5,000 On/Off cycles) with a pair operating at 2.2A discharge current and the second pair operating at 2.6A discharge current (test conditions summarized in Table 2). The tests were voluntarily terminated. It has to be noted that no changes in operating parameters were observed during the test indicating that at 15,000hours the cathode was far from the end of life condition. In fact one of the T5 cathodes was removed from storage and restarted 4 years after the end of the lifetest and it returned to the same operating voltages.

In the United States, the Deep Space 1 flight spare engine underwent a lifetesting program and has demonstrated a life of 30,352hrs before voluntary test shut down[6].The temperature distribution at the insert surface was measured using a non-contact fiber optic probe system for an identical cathode at various throttle points[13].

At the T6 17.1A discharge current setting (corresponding to the 150mN thrust setting currently the maximum thrust envisaged for the BepiColombo mission) the T6 operated at a temperature 35°C to 126°C lower than the NSTAR cathode at its maximum throttle point of 15A. This gives the T6 a potential lifetime of double to 6 times that of the NSTAR (with a demonstrated 30,352hours and a projected ultimate lifetime of 57,000hours[6]). This coupled with the fact that the downstream temperatures of the T6 insert is lower than the T5, results in a high degree of confidence in its ability to satisfy the requirements of the Mercury mission.

References

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

[2]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.

[3]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

[4]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.

[5]Sengupta, A. "Destructive Physical Analysis of Hollow Cathodes from the Deep Space 1 Flight Spare Ion Engine 30,000 Hr Life Test". IEPC-2005-026, IEPC, 2005.

[6]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.

[7]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.

[8]Sarver-Verhey, T. R. “28,000 Hour Hollow Cathode Life Test Results”. NASA Contractor Report, Report No. NASA/CR-97-206231, 1997.
[9]Sarver-Verhey, T.R. “Scenario for Hollow Cathode End of Life”. NASA Contractor Report, Report No. NASA/CR-2000-209420, 2000.
[10]Goebel, D.M. *et al.* “Energetic Ion Production and Keeper Erosion in Hollow Cathode Discharges”. IEPC-2005-266, 2005.
[11]Jameson, K.K. *et al.* “Hollow Cathode and Thruster Discharge Chamber Plasma Measurements Using High-Speed Scanning Probes”. IEPC-2005-269. IEPC, 2005.
[12]Katz, I. *et al.* “Model of Hollow Cathode Operation and Life Limiting Mechanisms”. IEPC-2003-0243, 2003.
[13]Polk, J., Grubisic, A., Taheri, N. *et al.* “Emitter Temperature Distributions in the NSTAR Discharge Hollow Cathode”. AIAA-2005-4398, JPC. 2005.
[14]Palluel, P. & Shroff, A.M. “Experimental Study of Impregnated-Cathode Behaviour, Emission and Life”. J. Appl. Phys., Vol. 51, pgs. 2894-2902.
[15]Brophy, J.R. “Multiple Cathode Study”, NASA/CR-165253, 1980.