A REVIEW OF THE CATHODE CONSTRUCTION FOR THE RAE 10/25mN THRUSTER

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ABSTRACT

This paper describes the constructional steady state operation of the cathode and some of the exploratory work which led to the choice of materials and methods. The joining methods are described and examples given to illustrate the criteria for judgement of the adequacy of these methods. The operation for long times at high temperatures requires protection of surfaces from interaction with each other and some of the work performed to understand these interactions is mentioned. The electrical isolation of the cathode is achieved by the use of ceramic components which have to be ruggedly incorporated into the structure. The thermal insulation is provided by wrapped molybdenum foil which minimizes the power requirements for starting and stabilizes the operation.

1.0 INTRODUCTION

Recent studies (1, 2) on ion thruster systems provide comprehensive performance data of such systems using hollow cathodes. This paper highlights some of the techniques used in the manufacture of cathodes for the UK10 Ion Thruster. It is based mainly on the work done by Charlton, Davis and Newson of the Central Materials Laboratory of Mullard Ltd. who made, tested and analysed the behaviour of cathodes using mercury as the propellant. The same laboratory is now part of Philips Components and we are working with the Royal Aircraft Establishment to make cathodes for use with Xenon. This programme is based on the philosophy, considerations and techniques of our retired colleagues.

There are two cathode components in an ion thruster. One is used to support the plasma from which the ions are extracted to provide the thrust, and the other to provide electrons to neutralise the positive charge created by the ion beam. The construction illustrated in this paper refers generally to the main cathode. A similar construction is used in the neutraliser.

2. THE HOLLOW CATHODE

A great deal of attention has been devoted to the need for a sound thermal and mechanical design, aimed at minimising the total power input for starting and for steady state operation. At the cathode, the requirement is to attain the operating tip temperature rapidly and then to maintain it after discharge initiation. With sufficiently low heat loss from the cathode, the energy dissipated in the cathode discharge is sufficient to maintain the tip temperature, and hence the discharge, without operation of the heater. It is important to ensure that the tip temperature by ion bombardment is not excessive (~1100°C), minimising loss of barium from the dispenser and erosion of the tip.

The main assembly is made up of a cathode assembly and an isolator assembly electron beam welded together (Figs. 1, 2 & 3).

The cathode consists of a tantalum tube 3.5 mm O.D. x 0.35 wall thickness joined at the downstream end to a tungsten disc 3.0 mm O.D. x 1 mm thick, with a 0.3 mm dia parallel sided central aperture. A barrier layer of tungsten is sintered on the tantalum tube followed by a flame sprayed layer of alumina. A bifilar heater, made from split free tungsten is wound on grooves machined in the alumina. Another coating of flame sprayed alumina ensures effective encapsulation of the heater around the tube, with just sufficient heater lead available for joining to specially made heater connecting leads. The tantalum tube is welded and then vacuum brazed to a Nilo K base, with the heater connecting leads anchored through alumina tubes to the base. The assembly is located in an outer stainless steel case and is thermally insulated from it using several turns of dimpled molybdenum as a radiation screen. The tip of the cathode protrudes through a central hole in a stainless steel disc welded at its periphery to the end of the outer tube (Fig. 4).

An impregnated dispenser is fitted into the tantalum and held against the tungsten tip. The Nilo K base of the assembly is electron beam welded to an isolator assembly which terminates in a suitable gas feed pipe.

It is now proposed to describe some of the features of the design in greater detail.

3. MATERIALS AND PROCESSES

The choice of materials and processes for the manufacture is set out in Tables 1 & 2.
Both materials and processes are well known: the combination of these to produce the cathode component has involved their careful application to ensure reliability in the space environment.

Table 1. Choice of Materials

<table>
<thead>
<tr>
<th>Component Detail</th>
<th>Material Choice Alternatives</th>
<th>Criteria</th>
<th>Indications/Possibilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode tip with orifice</td>
<td>Tungsten, Thoriated Tungsten</td>
<td>Ability to withstand high temperature. Erosion resistance.</td>
<td>No observed performance difference between alternatives</td>
</tr>
<tr>
<td>Cathode Tube</td>
<td>Tantalum, Molybdenum</td>
<td>Ability to join tantalum without loss of material integrity</td>
<td>Tantalum currently preferred</td>
</tr>
<tr>
<td>Cathode tube barrier</td>
<td>Tungsten, Molybdenum, Ruthenium</td>
<td>Barrier to prevent reaction between tantalum and alumina</td>
<td>Sintered tungsten</td>
</tr>
<tr>
<td>Heater insulation</td>
<td>Flame sprayed Alumina, Zirconia</td>
<td>Machinable robust encapsulation of heater</td>
<td>Alumina</td>
</tr>
<tr>
<td>Heater</td>
<td>Tungsten/Rhenium, Tungsten: Winding configuration</td>
<td>20w rating, long life characteristics with thermal cycling</td>
<td>Split free tungsten, bifilar form</td>
</tr>
<tr>
<td>Heater lead-outs</td>
<td>Tantalum, Molybdenum, Nickel, Stainless Steel</td>
<td>To provide a low resistance, reliable lead</td>
<td>Composite lead of Tantalum and Molybdenum</td>
</tr>
<tr>
<td>Dispenser</td>
<td>Tungsten, Various porosities. Impregnated with Barium Calcium Aluminate. 4:1:1 mix or above with added Scandate</td>
<td>Ability to maintain discharge characteristics during cathode life</td>
<td>Possible that &quot;Scandate&quot; dispensers will offer advantages</td>
</tr>
<tr>
<td>Thermal insulation</td>
<td>Rolled Molybdenum foil</td>
<td>To provide good thermal insulation</td>
<td>&quot;Dimpled&quot; rolled foil</td>
</tr>
</tbody>
</table>

3.1 Electron Beam Welding: Cathode tip to cathode tube

The tungsten tip, bought in as a finished part 3 mm dia x 1 mm thick, is drilled by the method used for drilling wire - drawing dies to produce a 0.3 mm diameter central hole, parallel sided to within a few microns. Approximately one half of the tip is rebated to a precisely controlled diameter using spark erosion. The close control of this diameter ensures a good push fit into the tantalum tube. An electron beam weld is made with all the welding parameters. (beam power, rate of rise/fall of power, beam position, target rotation, weld time) closely controlled to ensure not only reproducible welds, but also minimum alteration of materials in and beyond the heat affected zones. It is important to preserve the integrity of the tantalum tube in the weld region and avoid the risk of failure due to detached tips.

A section of the welded tip is shown in Fig. 5.

We have found that electron beam welding is both a reliable and versatile process for a number of the sub-assemblies made. For instance, we have been able to weld a 0.5 mm thick molybdenum disc to a more substantial Vacon 70 tube. We have made up a composite lead structure involving welding thin walled tantalum and molybdenum tubes together.

3.2 Tungsten Barrier Layer

Early work by Charlton, Davis and Newson indicated that above about 1200°C there is
a reaction between tantalum and alumina. To avoid this reaction at high temperature, a layer of tungsten a few microns thick is sintered on the tantalum. The work involved the following experiments designed to ascertain whether the tantalum-alumina reaction was of significant importance at cathode working temperature:

(i) tantalum ribbons, coated with alumina were mounted in sealed evacuated bulbs, and the ribbons run at a temperature of about 1200°C for 1500 hours. No trace of evaporated reaction products, aluminium or its sub-oxide was seen in the glass envelope wall.

(ii) further experiments were carried out in which the formation of deposits on the glass walls were monitored by measurement of the optical transmission with tantalum filaments run at temperatures from 1300°C - 1400°C.

The results are shown in Fig. 6.

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics of Process</th>
<th>Where Applied</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron-beam welding</td>
<td>Precise, reproducible, clean. Joining with minimum heat affected zone</td>
<td>Tantalum-Tungsten, Tantalum-Molybdenum, Tantalum-Nilo K, Molybdenum-St.Steel, St.Steel-Nilo K, etc.</td>
</tr>
<tr>
<td>Vacuum brazing</td>
<td>Reproducible, clean</td>
<td>Tantalum-Nilo K</td>
</tr>
<tr>
<td>Inert gas, furnace brazing</td>
<td>Reproducible, well established production process</td>
<td>Nilo K parts to metallised ceramic</td>
</tr>
<tr>
<td>Alumina flame spraying</td>
<td>Established method for coating metal parts with refractory oxides</td>
<td>Heater insulation and encapsulation</td>
</tr>
<tr>
<td>Dimpling molybdenum foil</td>
<td>Simple, controlled method for preparing molybdenum radiation shield of high efficiency</td>
<td>Thermal insulation between cathode tube and cathode cylinder</td>
</tr>
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</table>

It is evident that the rate of reduction of alumina by tantalum increases quite rapidly from 1200°C - 1300°C and dramatically over the range 1300°C - 1400°C. There was no evidence, however, at least in the form of an evaporated film, of any reaction with zirconia at 1400°C, at which temperature a rapid reaction was occurring with alumina. It would need to be established though, whether there is, to any significant extent, a solid phase reaction which could degrade the tantalum. Also the possible disadvantages of the higher electrical conductivity at high temperatures and lower thermal conductivity compared with alumina led to the choice of alumina and the need for a barrier layer.

Application and Sintering of Tungsten Barrier Layer

A number of methods of applying a tungsten layer were investigated. The most successful was to make a paint using tungsten powder with a small addition of nickel (care being taken to ensure a homogeneous mix) and an appropriate binder. The nickel depresses the solubility temperature from 3400°C to about 1550°C, facilitating sintering. The tantalum tube is painted and sintered in vacuum at a high temperature.

The resulting sintered layer is a firmly adherent, grey coating with some roughness. This makes it a suitable substrate to achieve good adhesion of the spray coated alumina.

Examination of cathodes after extensive life tests has shown that the barrier layer prevents chemical reaction between the tantalum tube and alumina.

3.3. Flame sprayed Heater Insulation

The insulating material for the cathode heater consists of flame sprayed alumina. An underlayer is applied first, this is then ground to size and grooved to locate the heater wire turns.

After assembly of the heater, another layer of alumina is applied over the heater and ground to size. The insulation is applied using a gun which accepts the alumina in the form of a powder. The exact spraying procedure needed considerable investigation in order to establish the optimum conditions for achieving satisfactory coatings, particularly over the irregular shape produced by the heater.

The operating variables for the spray gun are the oxygen and acetylene flow rates, the powder flow rate, the gun/workpiece distance, and, for intermittent spraying as used in this work the spraying frequency. In addition, nitrogen is fed around the workpiece to control the temperature.

The gas flow rates used and found satisfactory were manufacturer’s recommendations. However, careful control of the oxygen/
The mandrel made of molybdenum and grooved to winding tungsten wire in bifilar form on a with the tungsten heater in position, some The type of structure that does fulfill At the second stage of the coating process, diamond impregnated wheels, needs to be mechanically robust and re- garded using different wires, a composite shows that the heat loss at 1000°C until the samples just glowed visibly red shield surface area of 793 capacity terminal posts and current passed 348 clamped between comparatively high thermal turn of the coil) has been measured as data, particularly emissivity, practical temperature on the outside of the heat Because of the uncertainty about known With the tip temperature at short lead wires depends on the thermal purposes of comparisons with other forms of insulation. it is useful to have the loss expressed as a thermal conductivity. With the tip temperature at 1000°C, the temperature on the outside of the heat shield system (thermocouple under the last turn of the coil) has been measured as 348°C. Assuming an emissivity of 0.05, shield surface area of 793 mm² and inner foil temperature of 1000°C, calculation shows that the heat loss at 1000°C corresponds to a thermal flux of 60uW/cm²°C.

3.6 Cathode Radiation Shields

The commonly used radiation shield struct- ure, consisting of a series of concentric cylinders, with negligible conduction between adjacent shields, present serious difficulties in applications where the space available for insulation is very re- restricted, and where also the structure needs to be mechanically robust and reproducible in thermal behaviour.

The type of structure that does fulfill these requirements, however, is the so-called multifoil type of insulation, which consists essentially of a continuous length of metal foil, wrapped in cylindrical form, but with restricted contact between the layers. With this configuration, the lower efficiency caused by the conducting paths between layers is more than offset by the ability to accommodate a large number of closely packed layers.

One type of multifoil insulation that has been investigated in the U.S.A. (3,4,5) employs a metal foil, sparsely coated with very fine refractory oxide particles on one side, to prevent good thermal contact of adjacent layers. Alternative types of multifoil shields have been used (6,7), but for simplicity and reproducibility of fabrication, the dimpled foil construction used by R.A.E. Farnborough is chosen for use on the integrated assembly. This consists of a continuously rolled foil into which dimples have been pressed to prevent intimate contacts being made with adjacent layers. Good reproducibility of the dimple geometry is essential in order to minimise the variation in thermal characteristics of the multifoil heat shield, and to achieve this a simple hand operated machine is used for the dimpling operation (Fig. 7). The lower roller, produces the dimples by means of an array of tungsten carbide balls, cemented into conical depressions distributed over the roller surface in a quasi-random manner.

The machine described above is also used to dimple the small washer shaped heat shields used at the cathode tip. For the purposes of comparisons with other forms of insulation, it is useful to have the loss expressed as a thermal conductivity. With the tip temperature at 1000°C, the temperature on the outside of the heat shield system (thermocouple under the last turn of the coil) has been measured as 348°C. Assuming an emissivity of 0.05, shield surface area of 793 mm² and inner foil temperature of 1000°C, calculation shows that the heat loss at 1000°C corresponds to a thermal flux of 60uW/cm²°C.
which for a total heat shield thickness of 1.6 mm is equivalent to a thermal conductivity of $2.5 \times 10^{-5}$ cal/sec/cm/°C.

### 3.7 The Porous Tungsten Dispenser

This is in the form of a porous tungsten cylinder accurately machined to fit precisely into the cathode tube. The porosity of the tungsten is initially about 20%. This is impregnated with barium calcium aluminate ($4BaO.CaO.A1_2O_3$) The amount of barium present is 20-30 mg and about half of this is available to contribute to the emission process.

Porous tungsten dispensers are routinely made by Philips Eindhoven for other applications. Recent developments using impregnated cathodes have in addition scandium compounds in the impregnant. These offer the possibility for supporting higher emission at lower temperature. $^8$

### 4.0 FAILURE MECHANISMS

Extensive life testing over thousands of hours $^9$ have indicated that the processes and materials used in the construction of hollow cathodes have met their design specifications. Several failure mechanisms have been identified.

#### 4.1 Tip Weld Failure

In previous work $^10$, this has been identified as being caused mainly by operation in a poor vacuum and this can be a very significant problem. By rebating the tungsten tip to fit precisely into the tantalum tube, the integrity of the tantalum tube wall during electron beam welding has been preserved. (Fig. 5)

#### 4.2 Tip Erosion

Severe erosion has been noticed when operating cathodes with orifice diameters of less than 0.2 mm $^9$.

#### 4.3 Barium Supply

In the early work $^9$, uneven distribution of porosity and impregnant caused some problems limiting life and affecting starting time. More recent observations on end of life barium content have given results which show that barium loss is not life limiting.

#### 4.4 Flame Spraying Technique

Oxidation of the barrier layer, tantalum body and tungsten heater can occur if the flame spraying technique is incorrect. An oxidized barrier layer affects the integrity of the flame sprayed alumina. Oxide deposits on the interior of the cathode wall react with dispenser material, trapping some of the free barium. Oxide deposits from the heater can diffuse into the alumina, thereby degrading insulation.

### 5.0 DEVELOPMENT PLANS

In summary, the current development plan is:

1) to further characterise the behaviour of the current device in thrusters for use at 25 mN.

2) to study the effect on performance of cathode geometry.

3) to design a cathode with current capable of supporting up to 200mN thrust.

Extensive life testing is planned as part of this programme.

### 6.0 CONCLUSIONS

This paper has described the details of some of the processes involved in the manufacture of hollow cathodes. The process of industrialisation continues.

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### References


Fig. 6. Reaction between Tantalum and Alumina and Zirconia

Fig. 7. Dimpling Machine