THE DEVELOPMENT OF ION PROPULSION IN THE UK: A HISTORICAL PERSPECTIVE

David G Fearn
EP Solutions,
23 Bowenhurst Road,
Church Crookham,
Fleet, Hants, GU52 6HS, UK
dg.fearn@virgin.net

INTRODUCTION

With the current flight of the UK-10 ion propulsion system[1] (IPS) on the Artemis communications satellite[2] and the selection of the same Kaufman-type ion thruster for the Gravity and Ocean Circulation Explorer (GOCE) mission[3], this would appear to be a suitable time for an assessment of the way in which this form of electric propulsion (EP) has developed in the UK. This paper traces the progress of this development over the 4 decades since the original suggestion[4,5] to work in the EP field was made by Bryan Day of the Royal Aircraft Establishment (RAE) in 1962, with the support of his Division Head, Allan Earl, and the Head of Space Department, George Burt.

Although this original suggestion favoured cesium bombardment[4] and plasma thrusters[5], it led to an experimental programme to study a 10 cm diameter laboratory electron bombardment gridded ion thruster[5], the T1, with tests commencing in early 1968. Mercury was selected as the propellant, to take advantage of its high atomic mass and ease of storage. The T1 thruster was followed by a much improved device, the T2[7], which incorporated hollow cathode electron sources[8] for both the main discharge and the neutraliser[9]. The next step was to design a space-compatible thruster, the T4[10], then the improved T4A[11], with the subsequent T5[12] being accepted for flight in the north-south station-keeping (NSSK) role on ESA's L-Sat communications satellite[13]. However, financial problems caused the thruster work to be cancelled in 1978.

When development restarted on the T5 thruster in 1985, xenon was selected as the propellant to avoid possible chemical reactions with spacecraft materials. Initial tests[14] were very successful, so an experimental flight of the thruster on ESA's Sat-2, later Artemis, spacecraft in the NSSK role was proposed[15] and accepted; this role later became operational. In parallel, the UK-25 300 mN thruster[16] was designed in the late 1980s for interplanetary missions, and this was later followed in the mid-1990s by the T6[17], which is also suitable for such applications as well as for NSSK. The various hollow cathodes designed for these ion engines are now also being used in Hall-effect thrusters (HETs)[18].

After describing the development of these thrusters in more detail, together with some of the supporting technologies, the paper concludes with an acknowledgement of the efforts of the organisations and personnel responsible for implementation of this very successful programme. It is also worth noting that the philosophy adopted throughout has been to investigate as fully as possible the physical principles underlying the operation of the thrusters and associated components in order to establish firm design principles. This approach has led to the formulation of reasonably accurate scaling relationships[19,20] which now permit the design of new thrusters with reasonable precision[21].

THE EARLY PROGRAMME USING MERCURY PROPELLANT

The T1 and Elliott Brothers' Thrusters

Bryan Day's successful suggestion[4,5], in 1962/3, that RAE should commence a programme to develop an EP system was initially based on the perceived need at that time to provide an attitude control[4] and station-keeping capability[5]. However, a later priority became the requirement for a high energy upper stage[22] for the Black Arrow launcher[23], utilising the spiral orbit-raising principle[24] from an initial low altitude parking orbit. Interestingly, at that time the European Launcher Development Organisation (ELDO) was also considering the augmentation of the payload capability of its launch vehicle by the same means[25].

This first design, the T1[6], was influenced by US studies by Kaufman[26] and by the work on gridded ion accelerators performed at Fort Halstead by Clayden and Hurdle[27]. A diagram of their ion source is shown in Fig 1 and a section through the T1 in Fig 2. Fig 3 is a photograph of T1. As a result of this earlier experience, a filament electron source was initially employed, together with an axial magnetic field, and the importance of adequate beam neutralisation was recognised[4,27]. A porous tungsten vaporiser produced and controlled the flow of mercury vapour propellant, but the single accelerator (accel) grid was replaced by a twin grid system soon after testing began in early 1968. An ion accelerating potential of about 1.5 kV was chosen, giving a specific impulse (SI) of close to 3000 s, the benefits of which were clearly understood.

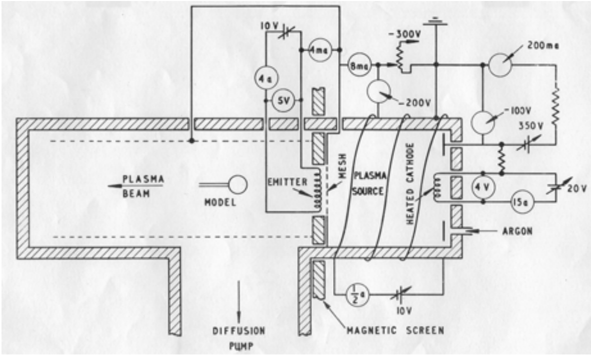

Figure 1. *Ion source designed by at Fort Halstead.*

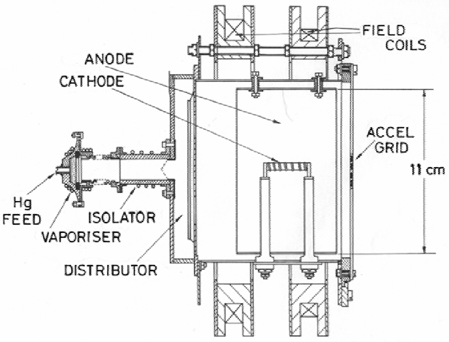

Figure 2. *The initial configuration of T1 thruster.*

Somewhat earlier and independently, work commenced[28] in the same field at Elliott Brothers (London) Ltd (later to become part of Marconi Space and Defence Systems (MSDS)) at Frimley, near Farnborough. Their programme was eventually aimed at orbit transfer applications, following the initial operation of a small laboratory thruster as early as 1963, using mercury propellant. A diagram of one of their earlier designs, using a twin grid ion extraction system, is reproduced in Fig 4. However, this independent programme was discontinued in about 1970, owing to lack of funding, but only after successfully demonstrating a 500 W thruster using a hollow cathode electron source and a 1.6 kV beam accelerating potential[29].

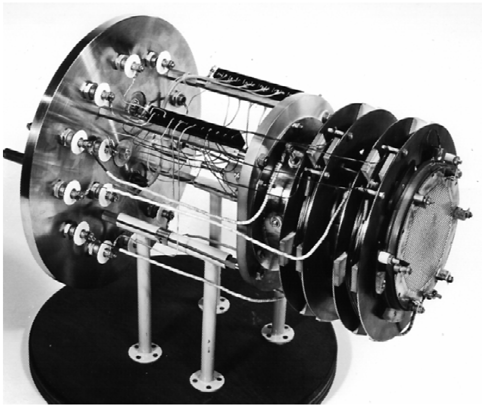

Figure 3. *A photograph of the T1 thruster.*

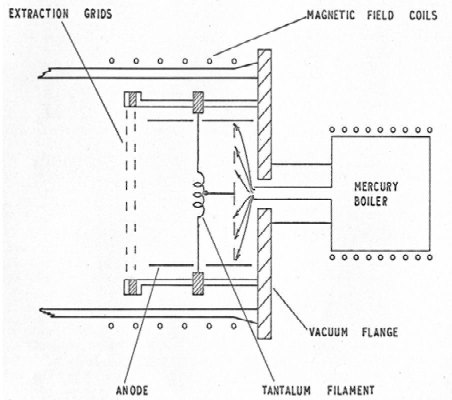

Figure 4. *An early Elliott Brothers thruster.*

The T2 and T3 Thrusters

At the RAE, the success of the initial tests with the T1 thruster resulted in the design of a new device[7], the T2, for which a 10 cm beam diameter was selected to provide a thrust of 10 mN with a beam accelerating potential of 2 kV. The design incorporated a hollow cathode electron source[8] and employed the primary electron accelerating principle established by Harold Kaufman[30] at the NASA Lewis Research Center. In this, as indicated in Fig 5, the centrally mounted cathode emits electrons into a coupling plasma contained within a cylindrical inner magnetic polepiece. The opening from this polepiece is partly blanked off by a circular disc, the baffle. The electrons, in emerging through the annular gap between these components, have to cross a magnetic field with a strong radial component. This impedes their motion and causes them to gain energy. This geometrical design, coupled with the use of the correct value of the magnetic field, allows the energy to be adjusted to maximise the rate of ionisation within the main discharge chamber[20].

As it is necessary to change the magnetic field to suit performance requirements, such as thrust and efficiency, the decision was made in designing the T2 thruster to employ solenoids rather than permanent magnets, and this policy has been retained to the present day. It has, amongst other advantages, permitted extremely wide throttling ranges to be achieved with all the thrusters.

The hollow cathodes fitted to this thruster were based initially on those designed in the USA for ion beam neutralisation[31] purposes and for the discharge chamber of the SERT II thruster[32]. The first versions were

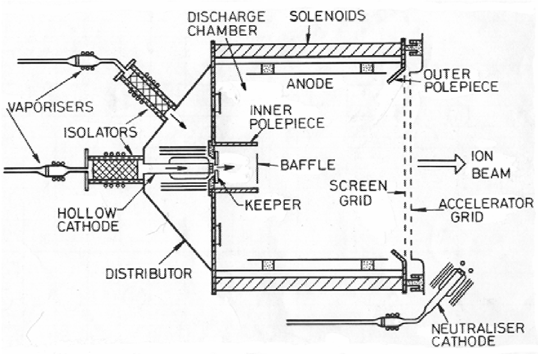

Figure 5. *Sectional diagram of the T2 thruster.*

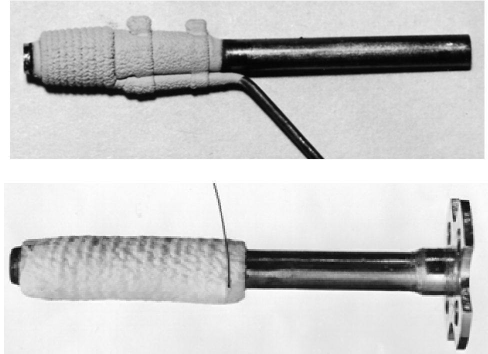

Figure 6. *Hollow cathodes for the T2 thruster. Top: made by GEC. Bottom: made by RAE.*

made by GEC (Fig 6, top), but the RAE soon set up its own manufacturing and test facilities in 1968. An example of an RAE cathode is shown at the bottom of Fig 6. This has a single-ended heater winding, with the return current passing through the cathode body, but all later versions, to the present day, have employed bifilar windings insulated from the body. In parallel with the cathode work at RAE[8], in 1968 Mullard Ltd at Mitcham commenced a major programme of research and development in this field[33], which culminated in cathodes and neutralisers designed for the thrusters to be flown on the L-Sat mission.

The T2 thruster exhibited a much increased performance[7], with a notable early achievement being the realisation that the open area ratio of the grid system has a marked effect on efficiency. It was shown that, at a propellant utilisation efficiency of 80%, the discharge losses were reduced from 540 W/A to 260 W/A by increasing the open area ratio from 50% to 75%. An electrical efficiency of 80.7% was achieved with an input power of 433 W and thrust of 10 mN. One of three T2 thrusters was subjected to life-tests[34] in the early 1970s, achieving about 2000 h, and hollow cathodes and vaporisers were tested for longer times.

While this work was underway, fundamental discharge chamber and ion beam investigations were being undertaken at the UKAEA's Culham Laboratory, using a diagnostic version[35] of the SERT II thruster design[32], shown in Fig 7 These studies benefited from the wide plasma physics diagnostics expertise at Culham, together with a vacuum facility modified specifically for this purpose. Initially, the particle fluxes

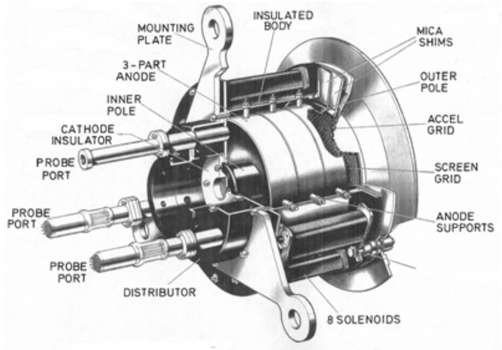

Figure 7. *Sectional diagram of the Culham 15 cm thruster.*

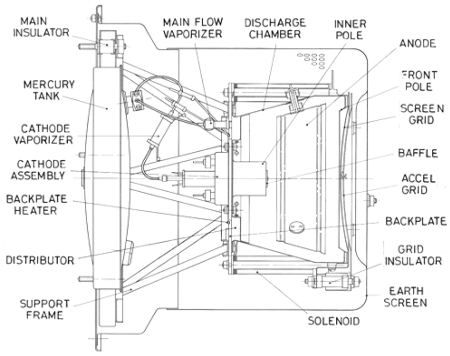

Figure 8. *Sectional diagram of the T4 thruster.*

to all parts of the thruster were measured under widely varying conditions[35], which aided considerably the future design process. Later work, on a special diagnostic version of the T4A thruster, extended the investigations to cover virtually all physical processes[19], including the acceleration of primary electrons[20], the production of doubly charged ions, the ion extraction and acceleration processes, ion beamlet vectoring and ion beam neutralisation[36]. The accumulated expertise allowed Culham to bid successfully for a major Intelsat contract for thruster testing in 1976, but this was withdrawn at the last moment.

Work was also progressing in parallel at the City University in London, where the physical processes in a simple laboratory ion engine were being studied with a variety of diagnostics[37]. Argon was used as the propellant, and much valuable information was gleaned from this programme, which eventually influenced subsequent work at Culham. Another significant contribution was made at this time by the University of Liverpool, where the electrical breakdown of mercury vapour was investigated in detail[38], to aid in the design of electrical isolators.

The T3, T4, T4A and T5 Thrusters

Using the experience gained from the T1 and T2 programmes, coupled with the plasma and ion beam diagnostics carried out at Culham, RAE then designed the T3 thruster, which was constructed in Industry in 1971, but was replaced a year later by the T4[10], prior to the commencement of any testing. A sectional view of the T4 is shown in Fig 8 above and features a conical discharge chamber and an integrated propellant tank; the neutraliser is excluded from this view. The small size of the tank is interesting, since the equivalent xenon tank would have 10 to 15 times the volume, depending upon the storage pressure. Cathodes and neutralisers were procured from Mullard[33]. Unfortunately, the conical discharge chamber caused primary electrons to reach the anode too easily and the utilisation efficiency was low as a result.

As a consequence of this problem, the T4A[11] variant reverted to a cylindrical discharge chamber. The design much more closely resembled flightworthy hardware, and initial performance assessments were very encouraging. These were conducted in three laboratories, the RAE, Culham and the Fulmer Research Institute (FRI), with essentially identical results. Photographs of the two types are shown in Figs 9 and 10.

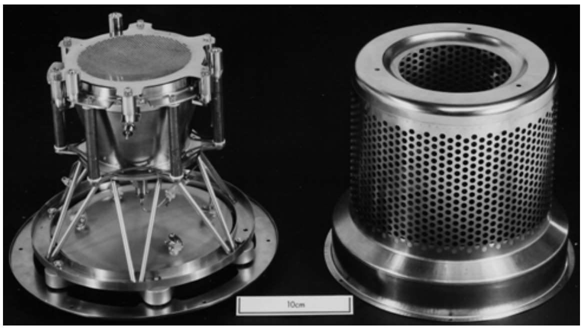

Figure 9. *Photo of T4 thruster.*

Figure 10. *Photo of T4A thruster.*

Life testing of the T4A thruster[39] at the Fulmer Research Institute (FRI) compared two grid sets, with 0.5% and 1% compensation, at 10 mN thrust. With each operated for 1000 h, it was found that the latter, although giving a beam divergence of below 8°, was subjected to some direct ion beam impingement on the accel grid. Thus the former value of compensation was selected for all future work, with a divergence normally in the range 10 to 12°, depending upon operating conditions. Grid lifetimes were predicted to be at least 30,000 h under these 10 mN conditions.

The success of this work led to the plan to fly both UK and German gridded thrusters on ESA's L-Sat spacecraft[13] in the NSSK role. The contractors selected to produce the flight hardware were MSDS and MBB, respectively, and the thrusters were designated T5[12] and RIT-10[40]. This communications satellite eventually flew as Olympus[41], but without an IPS, the EP project having been cancelled for financial and administrative reasons in 1978. An artists impression of the T5 Mk 1 thruster is given in Fig 11 and it is shown mounted in the load-lock of RAE's large test facility in Fig 12. A major feature of this programme was the successful design of a modular power conditioning and control equipment[42] (PCCE) with a mass of 10 kg, which operated the thruster entirely automatically under microprocessor control.

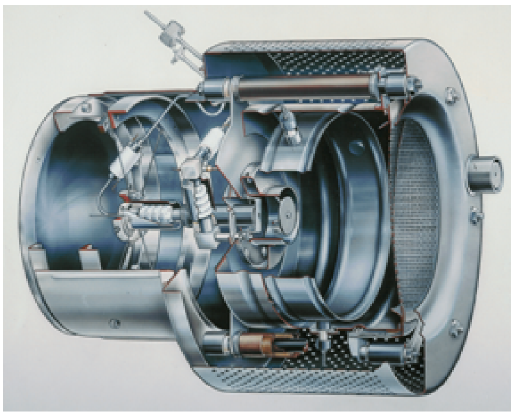

Figure 11. *Artist's impression of a sectional view of the T5 Mk 1 thruster.*

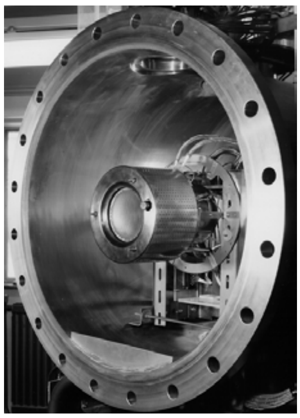

Figure 12. *T5 Mk 1 thruster in load-lock of RAE's test facility.*

Components, Ancillary Equipment and Thruster Test Facilities

An essential part of this programme was the development of cathodes[8,9], vaporisers[10] and isolators[10], together with the PCCE[42], the tank, and a thruster simulator[43] to act as a representative load for the PCCE. This work included a considerable amount of life-testing[12] to more than 10,000 h.

Thruster test facilities were provided at RAE, Culham and FRI. The small RAE facility was modified from an earlier use and was of 3 feet (0.91 m) internal diameter and 6 feet (1.82 m) long. It was later fitted with a load-lock chamber and gate valve to permit work to be conducted on the thruster while the main chamber was under vacuum[7]. This was necessary because the internal surfaces of the latter were covered with liquid nitrogen-cooled shrouds to condense the mercury propellant. Later, a larger, 5 feet diameter custom-designed facility was constructed with the same configuration. An overall view is shown in Fig 13; the rack to the right contains the breadboard PCCE produced by MSDS.

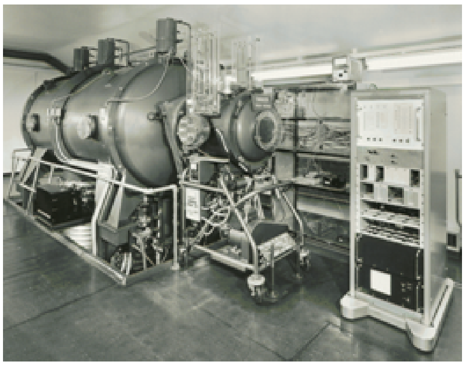

Figure 13. *Larger of the two RAE test facilities.*

The facility at Culham was notable for the diagnostic equipment provided. This included a time-of-flight mass spectrometer, which was used to determine the ratio of doubly- to singly-charged ions in the beam. It also had a segmented target, which allowed the radial distribution of the beam current to be measured.

The FRI facility[39] was custom-built for life-testing and was therefore vertical to permit a solid mercury target to be employed. Diagnostics included several different ion beam probes, and collectors to obtain samples of the material sputtered from the grids at different angles to the beam axis. The mercury sputtered from the target towards the thruster was also carefully investigated in some detail.

This and the other facilities were pumped by oil or mercury diffusion pumps, which gave an ultimate vacuum in the region of 5×10^{-7} Torr. While appearing to be satisfactory at the time, it was later found that the degree of contamination by atmospheric gases under these conditions is too great for realistic life-testing. Thus the more modern facilities now use cryo- or turbo-pumps, which enable pressures in the 10^{-8} Torr range to be reached prior to thruster operation.

THRUSTERS USING XENON PROPELLANT

From 1978, there was a long gap in the UK's work in this field until the Department of Industry (DoI) decided, in 1985, that there was merit in restarting the programme, due to a wider acceptance of the advantages of using EP. Initial work was based on the T5 thruster, but was soon extended to larger devices.

The T5 Thruster

An old T4A thruster was retrieved from the University of Bristol, where it had been operated using argon, and a new series of tests commenced at the Culham Laboratory, this time with xenon propellant. These were very successful[14] and a second UK team was formed, led as before by the RAE, to further develop this technology. No changes were necessary to the thruster, apart from a modification to the inner polepiece-baffle disc assembly to optimise performance. A 1 m diameter facility was modified at RAE to accommodate part of the testing programme.

While very few changes to the thruster were found to be necessary, the performance envelope was extended to more than 70 mN thrust and 2 kW input power (Fig 14). The other work concentrated on the achievement of qualified status, and the development of the propellant supply and monitoring equipment[44] (PSME) and of the PCCE[45]. This was mainly undertaken by Marconi Space Systems (MSS) Ltd, which eventually became Matra Marconi Space (MMS) Ltd. Simultaneously, the RAE became the Defence Research Agency (DRA), then the Defence Evaluation and Research Agency (DERA) and, most recently, QinetiQ.

A joint bid was made by RAE, MSS and Culham in late 1989 for an Intelsat programme of testing. This was successful and one of the most significant achievements of this contract was the confirmation that a decel grid adds considerably to the durability of a grid system[46]. As a consequence, all subsequent T5 thrusters have been fitted with a triple-grid system, as indicated in Fig 15. Also as part of this contract, thruster-spacecraft interactions were studied in great detail, covering sputter deposition, electromagnetic interference (EMI), the emission of infra-red radiation from the ion beam, and spacecraft charging phenomena[46].

In support of the T5 programme and the Artemis mission[2], cathode life-testing has reached in excess of 15,000 h at QinetiQ and limited thruster testing at MMS, designed to validate models of life-limiting factors, reached 2000 h. The cathodes were initially provided by Philips Components, once Mullard Ltd, but they discontinued work in this field in the early 1990s and QinetiQ now manufacture all these devices.

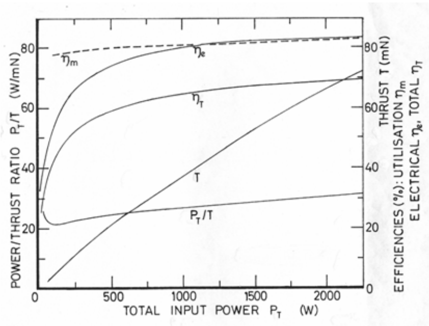

Figure 14. *Summary of the performance of the T5 thruster.*

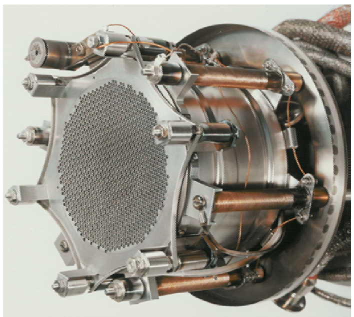

Figure 15. *T5 Mk 4 thruster without earth screen.*

An even more extensive set of diagnostic tests became possible in the early 1990s, owing to the implementation of a Foreign Comparative Test Program[23] at Aerospace Corporation, funded by the USAF. This work commenced in 1993 following a year of planning and setting up equipment, and involved a wide variety of ion beam probes, sputter deposition detectors, mass spectrometers, a thrust balance, EMI measurements, laser-induced fluorescence and microwave measurements of plasma parameters, and thermal and optical measurements of the grids during thruster operation. At the end of the programme in 1995, no thruster was probably better characterised. Later work accomplished the full characterisation of the thruster over the throttling range 0.3 to 30 mN[48], and aided in winning the contract for the GOCE mission[3].

In 1993 an opportunity arose for DRA and Culham to bid to supply one of the ion thrusters to be tested in an orbit-raising mode on the Nuclear Electric Propulsion Space Test Program (NEPSTP) [49], in which a Russian Topaz 2 nuclear reactor was to be operated in orbit. Although this bid resulted in a contract to supply a complete IPS, the project was cancelled before much progress was made.

The UK-25 and T6 Thrusters

While the development of the T5 IPS was continuing, the need for a much larger thruster for high energy interplanetary missions[50] became apparent in 1987. It was thus decided to design a 200 mN-class device, based on the scaling relationships developed during the 10 cm thruster programme[19,20]. This resulted in the 25 cm beam diameter UK-25 thruster[16], which exceeded all expectations, reaching a maximum SI of nearly 5000 s and a thrust limited by the capabilities of the Culham test facility to 320 mN. This is shown in Fig 16 with its earth screen detached. Additional work, particularly on the plasma region outside the cathode, was undertaken by Southampton University[51] and PCCE studies were performed by Birmingham University[52].

Figure 16. *UK-25 25 cm beam diameter thruster.*

Figure 17. *The T6 22 cm beam diameter thruster.*

Unfortunately, appropriate missions were not funded for the UK-25 thruster, so the decision was made to develop a device of intermediate size, specifically for NSSK. This, the T6[17] (Fig 17) has a beam diameter of 22 cm and a nominal thrust of 150 mN, although 200 mN is readily achieved, with a wide throttling range.

It is currently a contender for NSSK on the AlphaBus communications platform and for primary propulsion on the BepiColombo Mercury orbiter mission[53].

Components and Test Facilities

Figure 18. *T6 neutraliser.*

As before, the development of thruster components and ancillary equipments has been a major feature of the recent programme. A primary need was for a cathode for the relatively high discharge currents of the UK-25 and T6 thrusters, which reach approximately 30 A and 20 A, respectively, at the highest thrust levels. In addition, neutralisers of comparably enhanced capabilities were required. The programme to develop these devices was undertaken by DRA/DERA/QinetiQ, with the assistance of the Plasma Physics Group at Imperial College[54]. The T6 neutraliser cathode is shown in Fig 18 as an example of this collaboration.

Other component work has included the development of a new compact and low mass analogue propellant feed system, based on the use of the variation of the viscosity of xenon with temperature to control flow rate[55]. Associated with this has been the development of an effective thermal flowmeter. The power conditioning studies by the University of Birmingham were the precursor to more detailed work by MMS, although flight systems are likely to require the participation of contractors from other countries.

Figure 19. *T6 thruster mounted on thrust balance.*

A custom-designed cryo-pumped test facility is available at Astrium UK's site at Portsmouth. This has been utilised to validate the theoretical models derived by Culham[56] for predicting grid life, and is equipped with an ion beam probe system. The 1 m facility at QinetiQ has been replaced by a much superior custom-designed 2.2 m diameter chamber with a pumping speed of 400,000 l/s in order to cope with the high mass flow rates from the larger thrusters. More recently, the solar simulation facility at QinetiQ has been converted[57] for testing both gridded ion engines and Hall-effect thrusters with input power levels of at least 10 kW. This is of 3.8 m diameter, with a length of 5.2 m, although the pumping units occupy half of this length; they are situated behind the thruster under test, with the ion beam pointing away from the pumps. As in the 2.2 m facility, a graphite water-cooled target is used to minimise sputtering. An array of 15 ion probes is provided which can be swept through the exhaust of the thruster and a thrust balance is also available. This is suspended from the roof of the chamber and a T6 thruster can been seen mounted on this in Fig 19.

MISSION ANALYSES

As well as thruster design, construction and test, the programme has included a considerable amount of mission analysis. This commenced with some of the first definitive work on spiral orbit-raising, published in the 1960s[24]. Later studies included detailed analyses of NSSK, of both solar and nuclear powered interplanetary missions, and of low altitude remote sensing spacecraft with drag compensation provided by ion thrusters. Most recently, the possibility of extending the capabilities of these thrusters to meet the needs of precursor interstellar mission shave been considered. Unfortunately, there is insufficient space in this paper to give even a summary of this extensive work.

FUTURE PROSPECTS

The programme is now much more diversified than in the past, with work on hollow cathodes for HETs and also HET testing, as well as on gridded thrusters. In addition, the future of EP for commercial spacecraft, although not completely secure, looks much more healthy than in the past, due partly to the realisation throughout the space community that this technology is essential for most missions.

With the T5 thruster fully qualified to the Artemis specification and, in the near future, for GOCE, and the T6 approaching this standard, the thrust ranges 1 to 20 mN and 50 to 200 mN are covered, as is the extended range up to beyond 300 mN if a market for the UK-25 develops. Whether it is worth designing a very small thruster optimised for below 5 mN and one specifically to cover the intermediate range 20 to 50 mN has not been decided; it will depend on funding and demand. The most important technical challenge is to enhance lifetime, and this work is concentrating on carbon grids and on raising the propellant utilisation efficiency. Another likely future demand is for much greater values of SI, which will perhaps necessitate re-designed grids and the use of propellants with lower atomic masses.

ORGANISATIONS AND PERSONNEL

A historical account of a challenging scientific and engineering topic such as ion propulsion cannot be concluded without some reference to the many people who often overcame severe technical, financial and administrative difficulties to achieve great success. It is clearly not possible to list all those who have participated, but mention should be made of the key personnel.

It is clear that no programme would have started without the enthusiastic initial efforts of Bryan Day at RAE, who convinced his Division Head, Allan Earl, of the viability of his proposal. With the support of the Head of Space Department, George Burt, funding was obtained and work commenced under Day's leadership. Without the joint determination of Day, Earl and Burt, nothing would have been done. Another major influence was plasma physicist Alan Wells, who contributed much to the theory of thrusters and went on to commence a programme on hollow cathode research, before moving to the Culham Laboratory to head their programme. Wells' position was then occupied by David Fearn, who later led the whole UK programme. In those early years, major technical contributions were made at RAE by George Burton, Bob Hastings, Ray Hughes, Colin Philip, John Pye and Noel Williams, and by Tony Martin at City University. Arthur Parker and Peter Johnson provided expertise on the electrical breakdown of mercury vapour.

Very soon, many other organisations became involved, notably the Culham Laboratory under the leadership of Alan Wells, who was replaced later by Peter Harbour, with overall direction being provided by Mike Harrison. The excellent life test programme at the FRI was headed by Duncan Stewart, and hollow cathode development at Mullard Ltd benefited greatly from the expertise of George Charlton, George Davis and Doug Newson. As the H-Sat programme began to dominate in the mid-1970s, Peter Openshaw at MSDS took charge of the development of the flight hardware, aided by John Williams. Openshaw and Ray Dunster had previously been responsible for the Elliott Brothers' research.

When the programme recommenced in 1985, the initial technical work was undertaken by the Culham Laboratory, under the leadership of Tony Martin, but with a major scientific contribution from Paul Latham. Others involved included Alan Bond, Rob Bond, Mark Harvey, Bill Moulford, Herb Watson and Stuart Watson. At RAE/DRA/DERA, David Fearn again headed the programme, ably assisted by Neil Wallace, Manoj Mohan and Keith Ryden. Later, Angela Brown, Clive Edwards, Mike Kelly, Dave Mundy, Paul Roe, Huw Simpson and others joined the team, which is now headed by Neil Wallace.

Other organisations contributing to this phase of the programme have included ERA, MSS/MMS, Mullard (which became Philips Components), Imperial College, and Aerospace Corporation. During this period, the determination of successive Heads of Space Department to continue with the work should not be overlooked, together with the support from various Heads of Division (and equivalent); the former are Roy Bain, Brian Atkinson, Grant Dawson and Graham Davison, and the latter include Roger Jude, Chris Morton, Mike Gage, Richard Bavin and Richard Blott.

The MSS/MMS contribution to PCCE and PSME development and to the Artemis programme was led initially by Peter Smith and later by Howard Gray, with the notable participation of Ray Dunster, Mick Lovell and Clive Edwards (now at QinetiQ), amongst others. At Philips Components, mention must be made of Ron Copleston, George Charlton, Salem Gair, Doug Newson and Peter Harris. The Imperial College team, which concentrated on basic plasma processes, was directed by Prof Malcolm Haines and led by Khaliq Malik, with extensive participation by Pilar Monterde and Steve Patterson. At Birmingham, Prof Peter Evans and Andy Forsyth provided the leadership, and Sahana Chanda conducted EMI work at ERA.

The very talented Aerospace Corporation team was headed by Ron Cohen, with Mark Crofton, Siegfried Janson and Jim Pollard providing major contributions. More recently, a very active ion propulsion group has been formed at Southampton University, under the leadership of Steve Gabriel.

Finally it should be mentioned that, including the collaboration with Aerospace Corporation, international ties have always been very strong, with good and productive relationships with a wide variety of commercial companies, government laboratories and universities. These have included MBB/Astrium Germany, Proel/Laben, SEP/Snecma, Alcatel, NASA Lewis/Glenn, JPL, Keldysh Research Center, Moscow Aviation

Institute, Colorado State University, Michigan State University, and many others.

CONCLUSIONS

Thanks to the determination and scientific and technical expertise of the people involved, the UK ion propulsion programme has, after many difficulties, culminated in the availability of three thrusters of different sizes, covering most of the thrust range 1 to 300 mN. The smallest, the T5, is qualified at 18 mN thrust, and the GOCE programme will see this extended to cover the range 1 to 20 mN. The T6 thruster will be qualified for the range 50 to 190 or 200 mN, and the UK-25 has to potential to exceed 300 mN. These thrusters have all been designed using basic scaling relationships based on a good understanding of the physical principles underlying thruster operation. In addition, the associated hollow cathode and propellant feed technologies are becoming well-established in other EP programmes, including a variety of HETs.

It can thus be concluded that the initial choice of thruster type, together with the selection of the auxiliary technologies, were soundly based, and that the philosophy of gaining a good, although not complete, understanding of the basic physics of these devices was correct. This has resulted in a design capability which can respond reasonably quickly to a new set of requirements.

REFERENCES

Notes:

AIAA is American Institute of Aeronautics and Astronautics

IEPC is International Electric Propulsion Conference

IAF is International Astronautical Federation

1. Gray, H L, “Development of ion propulsion systems”, GEC Rev, 12, 3, 154-168, (1997).
2. Renault, H, Silvi, M, Bohnhoff, K and Gray, H, “Electric propulsion on ARTEMIS: a development status”, Proc *Second European Spacecraft Propulsion Conf*, Noordwijk, Holland, 27-29 May 1997. ESA SP-398.
3. Bassner, H, Killinger, R, Marx, M, Kukies, R, Aguirre, M, Edwards, C and Harman, H-P, “Ion propulsion for drag compensation of GOCE”, AIAA Paper 2000-3417, (July 2000).
4. Day, B P, “The principles of ion jets and a comparison with gas jets for satellite control”, RAE Farnborough Tech. Note Space 3, (March 1962)
5. Day, B P, “The use of electric propulsion in Earth satellites and a suggested research programme”, RAE Farnborough Tech. Note Space 41, (July 1963).
6. Day, B P and Hastings, R, “Experiments with the first RAE electron bombardment ion engine”, RAE Tech Report TR71023, (1971).
7. Day, B P and Hastings, R, “The RAE 10 cm hollow cathode mercury thruster”, Proc DGLR Symp on *“Electric Space Propulsion Systems”,* Braunschweig, Germany, 22-23 June 1971.
8. Philip, C M, “A study of hollow cathode discharge characteristics”, AIAA Paper 70-1087, (Aug 1970).
9. Fearn, D G, "The operation of hollow cathodes under conditions suitable for ion beam neutralisation", Proc Conf on *Electric Propulsion of Space Vehicles*, Culham Laboratory, UK, (April 1973). Inst of Electrical Engineers Conference Publication 100, pp 146-150, (1973).
10. Fearn, D G, Hastings, R, Philip, C M, Harbour, P J and Watson, H H H, "The RAE/Culham T4 10 cm electron-bombardment mercury ion thruster", AIAA Paper 73-1130, (1973)
11. Fearn, D G, Stewart, D, Harbour, P J, Davis, G L and Williams, J, "The UK 10 cm mercury ion thruster development program", AIAA Paper 75-389, (1975)
12. Fearn, D G, "A review of the UK T5 electron-bombardment mercury ion thruster", Proc ESTEC Conf on *Attitude and Orbit Control Systems*, Noordwijk, Holland, (Oct 1977); ESA SP-128, pp 491-510, (Nov 1977)
13. Anon, “Definition of electric propulsion experiments for the large platform satellite (Ariane LO4)”, ESA Document TCA/WB/76.724/CL”, (Oct 1976).
14. Fearn, D G, Martin, A R and Bond, A, "The UK ion propulsion programme: past status and new results", *Acta Astronautica*, **15**, 617, 353-365, (1987).
15. Fearn, D G, "The proposed demonstration of the UK-10 ion propulsion system on ESA's SAT-2 spacecraft", IEPC Paper 88-031, (Oct 1988).
16. Latham, P M, Martin, A R and Bond, A, “Design, manufacture and performance of the UK-25 engineering model thruster”, AIAA Paper 90-2541, (1990).
17. Wallace, N C, Mundy, D H, Fearn, D G and Edwards, C H, “Evaluation of the performance of the T6 ion thruster”, AIAA Paper 99-2442, (June 1999).
18. Simpson, H B, Wallace, N C, Fearn, D G and Kelly, M K, “A summary of the QinetiQ hollow cathode development programme in support of European high power Hall-effect and gridded thrusters”, IEPC Paper 2003-0214, (March 2003).
19. Harbour, P J, Wells, A A, Harrison, M F A and White, B M, “Physical processes affecting the design and performance of ion thrusters with particular reference to the RAE/Culham T4 thruster”, AIAA Paper 73-1112, (1973).

20. Wells, A A, “Current flow across a plasma “double layer” in a hollow cathode ion thruster”, AIAA Paper 72-418, (April 1972).
21. Fearn, D G, “The design of a versatile ion thruster for large communications spacecraft”, IAF Paper IAF-97-S.3.01, (Oct 1997).
22. Day, B P and Treble, F C, “The ion engine and large solar array for the X-5 spacecraft”, RAE Tech Report TR 68191, (Aug 1968).
23. Staff of Space Dept, RAE, “A proposal for the X4 and X5 spacecraft in the Black Arrow programme”, RAE Tech Report TR 68144, (June 1968).
24. King-Hele, D G, “The enlargement of elliptical satellite orbits by continuous micro-thrust”, RAE Tech Note Space 38, (July 1963).
25. Godwin, R C and Rees, T, “Electric propulsion for ELDO vehicles”, *ELDO/CECLES Tech Rev*, **3**, 2, 127-148, (1968).
26. Kaufman, H R and Reader, P D, “Experimental performance of ion rockets employing electron-bombardment ion sources”, American Rocket Soc Paper 1374-60, (Nov 1960).
27. Clayden, W A and Hurdle, C V, “Diagnosis of a plasma beam extracted from an electron-bombardment ion source”, Proc AGARD Propulsion and Energetics Panel meeting on “Plasmas and Interactions of Electromagnetic Radiation with Plasmas and Flames”, Pisa, 6-10 Sept 1965.
28. Anon, “Ion thruster development”, Elliott Brothers (London) Ltd Report SWRL 225/1, (Dec 1968).
29. Openshaw, P R, “Electric propulsion systems for European use”, AIAA Paper 69-274, (March 1969).
30. Kaufman, H R, “An ion rocket with an electron bombardment ion source”, NASA TN-585, (1961).
31. Rawlin, V K and Pawlik, E V, “A mercury plasma-bridge neutraliser”, AIAA Paper 67-670, (Sept 1967).
32. Byers, D C and Staggs, J F, “SERT II flight-type thruster system performance”, AIAA Paper 69-235, (March 1969).
33. Davis, G L, Charlton, M G and Newson, D, “Starting behaviour of hollow cathodes including multiple starts”, Proc 3rd European Electric Propulsion Conf, Hinterzarten, Germany, (Oct 1974). DGLR Fachbuchreihe Band 5, pp 227-232.
34. Fearn. D G and Williams, T N, "The behaviour of hollow cathodes during long-term testing in a 10 cm ion thruster and in a diode discharge system", Proc Conf on Electric Propulsion of Space Vehicles, Culham Laboratory, UK, (April 1973); Inst of Electrical Engineers Conference Publication 100, pp 131-135, (1973).
35. Wells, A A, Eden, M J and Harrison, M F A, “Experimental studies of ion loss, energy balance and ion extraction in a SERT II type ion thruster”, AIAA Paper 70-1091, (1970).
36. Harbour, P J, “Charge exchange and beam bending at extraction electrodes”, Proc 3rd European Electric Propulsion Conf, Hinterzarten, Germany, (Oct 1974). DGLR Fachbuchreihe Band 5, pp 270-275.
37. Martin, A R, “Scaling laws in electron-bombardment ion engines”, *J Brit Interplan Soc*, **25**, 19-29, (1972).
38. Johnson, P C and Parker, A B, “The dielectric breakdown of low density gases. II. Experiments on mercury vapour”, *Proc Roy Soc A*, **325**, 529-541, (1971).
39. Stewart, D, “Life-testing of the UK T4A thruster”, AIAA Paper 76-1023, (1976).
40. Bassner, H, Birner, W, Mueller, H and Klein, W U, “Development status of the RF-ion thruster RIT 10”, AIAA Paper 76-1035, (Nov 1976).
41. Conchie, P J, “The Olympus satellite”, *J Brit Interplan Soc*, **38**, 397-400, (1985).
42. Fearn, D G and Hughes, R C, "The T5 10 cm mercury ion thruster system", AIAA Paper 78-650, (1978).
43. Pye, J W, “The design and performance of a versatile ion thruster simulator”, AIAA Paper 75-383, (1975).
44. Smith, P, "Current status of the UK-10 ion propulsion system propellant supply and monitoring equipment", AIAA Paper 90-2590, (1990).
45. Lovell, M, "The UK-10 power conditioning and control equipment", AIAA Paper 90-2631, (1990).
46. Fearn, D G, "Intelsat contract 1NTEL-920. Evaluation and test of spacecraft/xenon ion thruster interfaces. Final report", DRA Working Paper DRA/CIS/CSC3/WP/94/04 ,(Jan 1994).
47. Crofton, M W, “Evaluation of the T5 (UK-10) ion thruster: summary of principle results”, IEPC Paper 95-91, (Sept 1995).
48. Mundy, D H and Fearn, D G, “Throttling the T5 ion engine over a wide thrust range”, AIAA Paper 97-3196, (July 1997).
49. Bythrow, P F, Mauk, B H and Gatsonis, N A, “Operational experiments and thruster performance plan for the Nuclear Electric propulsion Space test program (NEPSTP)”, AIAA Paper 93-1896, (June 1993).
50. Melita, O (Ed), “The comet nucleus sample return mission”, ESA SP-249, (1986).
51. Milligan, D J and Gabriel, S B, “Plasma properties around the baffle aperture region of the UK-25 ion thruster”, IEPC Paper 99-157, (Oct 1999).
52. Forsyth, A J, Evans, P D and Al-Mothafar, M R D, “A comparison of dc to dc converter topologies for high power ion engine control”, AIAA Paper 89-2270, (July 1989).
53. Novara, M, “the BepiColombo ESA Cornerstone mission to Mercury”, IAF Paper IAF-01-Q.2.02, (Oct 2001).
54. Fearn, D G and Patterson, S W, “The compatibility of hollow cathode characteristics with a variety of ion thruster designs”, IEPC Paper 99-133, (Oct 1999).
55. Edwards, C H, Mundy, D H and Clark, S D, “The development of gas flow control equipment at DERA”, IAF Paper IAF-99-S.4.09, (Oct 1999).
56. Bond, R A, Fearn, D G, Wallace, N C and Mundy, D H, “The optimisation of the UK-10 ion thruster extraction grid system”, IEPC Paper 97-138, (August 1997).
57. Simpson, H B, Wallace, N C, Clark, S D and Mundy, D H, “A description of the new 3.8 m diameter high power electric propulsion test facility at QinetiQ Farnborough, UK”, IEPC Paper 2003-0213, (March 2003).