Electric Propulsion Technology Status and Development Plans—European Programs

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Since 1960, nearly two dozen types of electric engines have been investigated and developed by 48 companies and institutes in Western Europe. At present, 220 scientists and engineers are working on 7 thruster types; about 78 test facilities and 4.6 million dollars per year are involved. The technology of the European ion engines has reached a state-of-the-art where the experimental phase could be finished and the actual use of the thrusters can be thought about. Of prime interest in this respect is the North-South stationkeeping for European communication satellites. Four industrial studies placed by ESRO indicated that the English mercury bombardment thruster T 4 and the German mercury rf-engine RIT 10 S are best suited. Moreover, two French, three German, and an ESRO microthruster are under development. Primary propulsion engines have also been studied by national and ELDO-contracts for spiralling-up of European commercial satellites. Four German units are under development. Unfortunately, the governmental interest decreased in the last years. European resistojet work is concentrated in England while plasma engine research and development is carried out in Germany and Italy.

Introduction

SINCE the benefit of electric propulsion (EP) for a great number of space applications was recognized, world-wide activity has started. At present, EP hardware is produced in the USA, the USSR, Japan, and Western Europe, namely in Great Britain, France, Germany, Italy, and at ESTEC. Table 1 gives an idea of European activities. Most of the work is concentrated about equally in the United Kingdom, the Federal Republic of Germany, and France. The European Organizations support mission studies and some hardware, too. Some plasma work is done also in Italy.

The total European manpower and funds are comparable to those of the United States. Unfortunately, the European activities are presently split into seven different EP types: Kaufman ion engines (UK, FRG, France); rf-ion engines (FRG); contact ion engine (France); Hall ion engine (FRG); field emission ion engine (ESRO, UK); resistojet engines (UK); and MPD-engines (FRG, Italy).

In 1973, two round table conferences of experts organized by ESRO considered the application of ion engines to the European Satellite program. It was agreed that electric North-South stationkeeping (NSSK) motors are both advantageous and desirable for geosynchronous communication satellites. The usefulness of EP for other secondary propulsion missions was acknowledged.

Contrary to this effort, European interest in primary electric propulsion has almost died out. However, the situation in Europe regarding EP in general took a turn for the better. Only a few years ago, there existed a vicious cycle: no electric propulsion missions were taken into consideration because no engines seemed suitable while, on the other hand, EP hardware was not supported sufficiently because no application came in sight. Now the urgent need for NSSK ion engines may overcome the confidence barrier. Primary propulsion engines may benefit from this, too.

European Mission Requirements

Secondary Propulsion

In Table 2, the secondary propulsion mission parameters are listed including velocity increment and thrust levels, the extent of European interest, and the anticipated year of European electric engines' readiness for operation. While the European interest in electrical attitude control, orbit adjustment, and East-West stationkeeping is relatively low, everything at this time points to the fact that European ion engines of 2.5–10 mN thrust will be first used at the end of this decade for North-South stationkeeping of European synchronous satellites.

As ESRO's activity is changing from scientific to commercial satellites, one expects the first application of NSSK thrusters on board the 400-kg European communication satellite ECS(O) to be operational late in 1979 and to be followed by a family of 8 to 10 ECS systems in the eighties. Moreover, 750-kg television and

Table 1 European manpower and funds related to electric propulsion

	UK	FRG	France	ESRO ELDO	Italy	total
Establishments (1960–1974)	16	14	13	3	2	48
Engineers (1973, estimated)	75	70	60	10	5	220
Facilities (1973, estimated)	25	31	19	1	2	78
Funds, million dollars (1974, estimated)	1.3	1.9	1.0	0.3	0.05	4.55
Engine types (1974)	3	4	2	1	1	7

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Table 2 European secondary propulsion requirements

Mission type	Mission	Velocity increment	Thrust, mN	European interest	European ESP available
Attitude	Attitude control	1–10 m/sec·yr	0.01–5	moderate	1978
Orbit	Orbit adjustment and positioning	30–100 m/sec	10–150	low	1976
	EW stationkeeping	1–5 m/sec·yr	0.1–0.5	low	1978
	NS stationkeeping	40–50 m/sec·yr	2.5–10	high	1976
	Drag compensation	10^3–10^4 m/sec·yr	30–300	no	1980

broadcasting satellites (TVBS) are scheduled to be launched in the middle eighties.

Therefore, in 1972, the European Space Research Organization (ESRO) placed four independent study contracts to investigate the feasibility of using EP with Messerschmitt-Boelkow-Blohm (MBB Munich), Hawker Siddeley Dynamics (HSD Stevenage), Société Européenne de Propulsion (SEP Puteaux), and Laboratoire d'Automatique et de ses Applications Spatiales (LAAS Toulouse).[1] All studies indicated that important mass savings of 10–15% of the satellite mass can be achieved by the use of EPS in place of hydrazine thrusters for NSSK even when charging the mass of any extra solar array, auxiliary systems, and redundant components against the EPS.[2,3]

In principle, East-West stationkeeping and attitude control can be done with electric microthrusters especially since the thrust demand is very low. However, no essential mass savings result. Concerning future missions with extremely high attitude accuracy requirements, EP may become more attractive if NSSK engines using thrust vectoring techniques will be used for the other orbit and attitude control purposes, too.

Primary Propulsion

Table 3 gives an idea of which primary propulsion missions are of interest in Europe. Both conventional and electrical interplanetary missions are of little interest in European intermediate term planning. Therefore, nearly all primary propulsion analysis work sponsored by the European Launcher Development Organization (ELDO) and by governments as well as most of the private mission studies dealt with geocentric applications.[5-7] Although a Van-Allen-Belt mapping mission would be of high scientific interest and is within the capabilities of European engines in the near future, there is little chance of such a plan being approved.

Among the different geocentric missions, orbit raising of commercial satellites into the stationary orbit by an electric upper stage is of prime interest. The reasons for this interest are the limited payload capacity of European launchers, cost savings calculated to be 20–30%, the fact that the satellite's power source could be used during the spiralling-up phase by EP, and the utilization of the electric engines for orbit adjustment, too. However, some restrictions like the degradation of the solar array, the reliability of the engines, additional costs, etc., must be taken into account.

The thrust requirements have been calculated for 100–500 mN. the optimum transfer times for 120–200 days, and the optimum exhaust velocities for 20–43 km/sec.[5,6] Clustering analysis resulted in different numbers of engines ranging from 4 to 8 thrusters of 2 kw each to 16–20 small motors (500 w power input).

In the last few years, the European interest in electric orbit raising decreased. The reasons are to be found in 1) the repeated failures of EUROPE launchers which resulted in the cancellation of the total ELDO booster program (1973), 2) NASA's willingness to launch European regional commercial satellites, and 3) the unavailability of large solar arrays as well as the cancellation of the German Incore Thermionic Reactor project ITR (1972). However, there is some hope now of overcoming these objections. For one thing, the European Secretary's Conference decided on the development of the L III S launcher, the payload of which could be increased by an electric upper stage. In addition, large solar panels are under development. Finally, the confidence barrier of EPS may be overcome by the successful operation of secondary propulsion ion engines.

European R & D Programs

Extensive EP programs exist in England, France, West Germany, and at the European Space Research and Technology Center (ESTEC Noordwijk). After a decade of basic research, in the course of which nearly a dozen types of electric propulsion devices were investigated by 48 companies and institutes, a phase of concentration on a few promising engines, of extended industrial development and of testing programs took place.

At present, the British, French, and German governments as well as the ESRO support only one electric engine each. Referring to the European mission requirements in intermediate term

Table 3 European primary propulsion requirements

Mission type	Mission	Velocity increment, km/sec	Thrust, N	European interest	European EPS available
Geocentric	Van-Allen-probe	4.5– 4.8	0.05–0.1	low	1976
	orbit transfer	1 – 4.5	0.1 –0.5	low	1980
	commercial satellite	3 – 4.5	0.1 –0.5	moderate	1980
Interplanetary	sun, planets	6 –40	0.1 –0.5	low	1980
	asteroids	6 –30	0.1 –0.5	low	1980
	comets	4 –15	0.1 –0.5	low	1980
	out-of-ecliptic	20 –60	0.1 –0.5	low	1980
Manned	lunar ferry	7 – 9	50–100	no	?
	Mars ship	15 –20	100–500	no	?

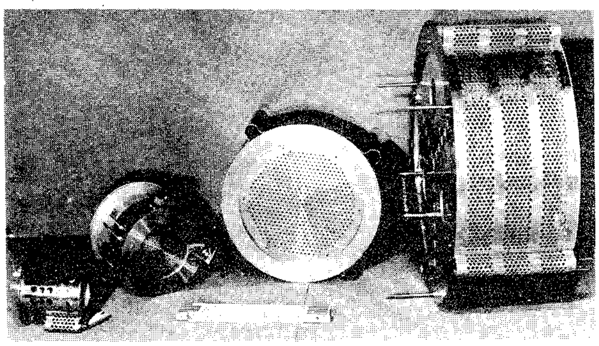

Fig. 1 The rf ion thruster-family of Giessen Univ. (from left: RIT 4, RIT 10 S, RIT 20, RIT 35; the numbers mean ionizer diam).

planning, all four engines are of the secondary propulsion class and all of them are of the electrostatic family, even if they are of different types (bombardment engine, contact motor, rf-thruster, field emission device). In addition, however, more NSSK thrusters, primary propulsion ion motors, and plasma engines are under development by companies and institutes under basic budget, mainly in Germany.

Contrary to the USA and the USSR, the European testing philosophy prefers ground facilities for performance mapping and endurance demonstration. ESTEC and all national governments believe that the space tests are only convenient if the engine's lifetime (given by the scheduled mission) has been proved by ground tests. Therefore, the planned English and German space tests X 5 and SELAM were cancelled in 1971.

Great Britain

In the sixties, the Elliot Brothers company investigated Kaufman ion engines as well as pulsed plasma microthrusters. Because of failure to receive governmental support, all in-house activities were cancelled. Since 1969, the Royal Aircraft Establishment (RAE Farnborough) developed 10-cm mercury bombardment engines T1 and T2.[8] In the same period, the United Kingdom Atomic Energy Authority Culham Laboratory carried out experimental work and theoretical studies with 15-cm SERT II-type thrusters C1 and C2, as well as with a 10-cm device C3.[9]

At present, the English R & D work is concentrated on a 10-cm mercury bombardment thruster for North-South stationkeeping. RAE and Culham Laboratories are jointly developing a T4 flight prototype using the experiences gained from the earlier T2 and C3 motors. The program includes the following steps[10]: 1) functional and beam investigation at Culham Laboratory; 2) integration tests at RAE on a new 1.5-m-diam facility; 3) long duration tests at Fulmer Research Institute, Stoke Poges; 4) initial studies of beam vectoring technique; 5) production of a complete electronics package by Marconi (major contractor); and 6) thermal, vibration, and durability tests of the total system by Marconi on a Culham facility. In total, five T4 engines, a peristaltic pump, and a propellant flowmeter have been constructed.

Moreover, the Mullard Mitcham Co. investigated hollow cathodes including lifetests and restart cycling. The British Aircraft Corp. worked on power supply systems. The Univ. of Liverpool carried out measurements on mercury breakdown problems and the City University of London investigated ion discharge physics including propellant research.

In the meantime, R & D work on a mercury rail accelerator (RAE) and on a 3-kw hydrogen resistojet (Rocket Propulsion Establishment)[11] was terminated because of low efficiencies and a lack of flight application, respectively. Nevertheless, some activity on small electrothermal thrusters for secondary propulsion purposes are pursued, namely by Hawker Siddeley Dynamics (hybrid hydrazine resistojet),[12] by the Univ. of Southampton (polyatomic propellants),[13] and by the Univ. of Reading (thermal insulation).

West Germany

German R & D programs on EPS started at the Deutsche Forschungs- und Versuchsanstalt fuer Luft- und Raumfahrt (DFVLR) and at the University of Giessen in 1960. At Giessen, a family of rf ion thrusters with ionizer diameters of 4, 10, 20, and 35 cm has been investigated, optimized, and tested.[14] Figure 1 shows the RIT family. Since 1971, the stationkeeping engine RIT 10 S is under industrial development at the MBB Co., Munich.[15] At present, the R & D program is sponsored by the German Space Project Agency GfW including the following steps[16]: 1) functional, integration, and cycling tests as well as plasma and beam diagnostics at Giessen; 2) lifetests of two neutralizers and the accelerator system at Giessen; 3) 1000-hr accumulative lifetest at MBB; 4) vibration tests, development of a space-qualified electronics, and a tank-feed-system, including a propellant flowmeter at MBB and Giessen; 5) clustering experiments on the large Giessen facility (2.6-m-diam); and 6) 10,000-hr duration and cycling tests of a cluster on a new large, 2.2-m-diam, automatic facility.[17] Besides the 10-cm NSSK rf engine, which can be also used as a small primary propulsion unit,[18] the microthruster RIT 4 as well as the main propulsion aggregates RIT 20 and RIT 35 are under functional tests and optimization at Giessen University.

After a 7-yr period of basic research on five different EP types, the DFVLR-Institute at Braunschweig started the development of a family of 3 mercury bombardment engines for primary and secondary propulsion purposes.[19] Figure 2 shows the ESKA 8, 18, and 28 thrusters. From 1971 to 1972, the ERNO Co. at Bremen industrialized the 18-cm beam diam motor under GfW-contract.[20] At present, final optimization, performance mapping, and initial lifetests of the ESKA 8 and ESKA 28 engine are running on a 2-m-diam family.[21]

At the DFVLR-Institute of Energy Conversion and Electric Propulsion at Stuttgart, efforts have been devoted to the development of Hall ion thrusters (HIT). After propellant investigations as well as ionizer and accelerator optimization,[22] performance mapping of the laboratory prototype HIT A 4 is running on an 1.2-m-diam facility.[23]

Since 1960, important work (optimizations, diagnostics, lifetests) on plasma propulsion has been carried out at the DFVLR-Institute of Plasma Dynamics at Stuttgart.[24] At present, three different types are under investigation, namely steady-state, high-power, self-magnetic MPD-thrusters;[25] steady-state, medium-power, applied-magnetic plasma engines of the X-family;[26] and pulsed, low-power, ablation thrusters.[27] A test assembly of seven large, 5-m-long vacuum tanks are at disposal. Further German EP activities on electromagnetic and electrothermal devices are being carried out at the Atomic Research Center (KFA) Juelich, and at the universities of Stuttgart and Aachen.[28]

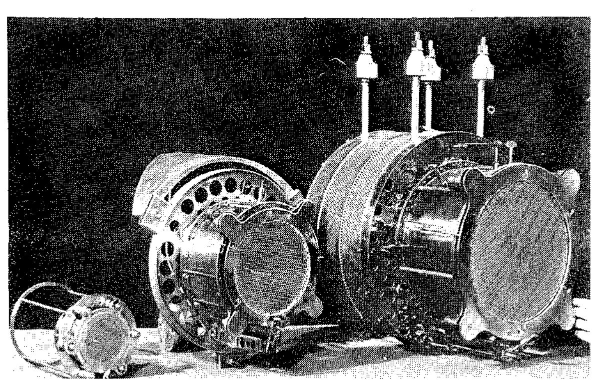

Fig. 2 The electrostatic Kaufman accelerator-family of the DFVLR Braunschweig (from left: ESKA 8, ESKA 18, ESKA 28; the numbers mean beam diam).

France

In 1960, R & D work on different EP types (mercury bombardment engines, hydrogen arcjets, ammonia resistojets, and traveling wave accelerators) was carried out at some French institutes.[29]

In 1968, the French governmental agency, named Centre Nationale d'Etudes Spatiales (CNES Bretigny), directed all of its resources to a small cesium contact engine for NSSK purposes.[30] The Office National d'Etudes et de Recherches Aérospatiales (ONERA Châtillon) is engaged in linear and button ionizers, accelerator optimization, analysis, and theoretical treatments, as well as in lifetime investigations.[31] The Laboratoire d'Electronique et de Physique Appliquée (LEP Limeil) carried out basic investigations, component lifetests, etc., and manufactured the linear slit prototype.[32] The Laboratoire d'Automatique et de ses Applications Spatiales (LAAS Toulouse) works on mission analysis, integration problems, and contact thruster electronics.[33]

At present, the ONERA, LEP, and LAAS labs and a company named Société Européenne de Propulsion (SEP Puteaux) are jointly developing the contact microengine CC 1.5 under CNES contract. The R & D program includes the following steps: 1) development of the prototype by LEP; 2) component development, functional and long duration tests of the total system on a new 0.9-m-diam facility by ONERA; and 3) industrialization by SEP with the aim of flight qualification till 1975.

Besides this national contact thruster, the SEP company (in cooperation with Lockheed) is developing a NSSK cesium bombardment engine CB 4 for INTELSAT V-class satellites. The present in-house program considers the reduction of the earlier thruster diameter from 10 to 7 cm, functional tests of the reduced model including storage-feed-system and breadboard electronics, and, finally, the manufacturing of the space qualified thruster till 1976.[34] Further French EP activities concern power conditioning units by Orion Electronic, Laboratoire Central de Telecommunications, and Laboratoire de Génie Electrique.

Italy

For some years now, plasma research has been conducted at the Instituto di Maccine e Tecnologie Meccaniche of the Univ. of Rome. Low voltage configurations for an MPD quasi-steady accelerator with an electrolytic capacitor bank have been tested and compared with theory. Performance data of the engine are mapped.[35] Further activities are carried out at the Univ. of Pisa and the Fiat Company.

European Organizations

As mentioned previously, both ELDO and ESRO have placed a great number of contracts for primary and secondary electric propulsion studies. They act as eventual customers. Besides this, the ESRO technology center (ESTEC Noordwijk) carried out R & D work on electrostatic spraying microthrusters. This activity started in 1968 with in-house basic research on colloid engines including thrust and mass flow measurements.[36] From 1971 to 1973, ESTEC placed two contracts with the Univ. of Southampton for investigation of the linear slit colloid type including propellant research.[37] In the same period, ESTEC left three contracts with the Culham Lab. for parametrical studies of the annular colloid type including preliminary lifetests.[38]

In order to concentrate ESRO's limited funds, all colloid activities were stopped in 1974 for the benefit of the development of a cesium field emission microthruster. In 1971, basic investigations on this electrostatic spraying device started at Culham Lab. under ESTEC contract. The 4-year R & D programs comprise: 1) performance mapping and 100-hr lifetest of a feasibility array; 2) system study of the total engine including all auxiliary components; 3) manufacturing, optimizations, and functional and duration tests of a predevelopment model; 4) production and design study of a demonstration thruster array; and 5) construction, performance and 2000-hr lifetests of the prototype.

European EPS Hardware

Secondary Propulsion Ion Engines

There are nine European secondary propulsion thrusters under development; most of them have been designed for NSSK of communication satellites. In some cases, thrust vectoring devices are scheduled for supplementary attitude control. Table 4 gives some important performance data.

The 10-cm-diam mercury bombardment thruster T4 of RAE, Culham, Marconi, and Fulmer, works with a dished double grid, a conical discharge chamber which approximates the shape of the contained plasma, a short conical discharge anode, solenoids positioned around the chamber, and a flat metallic bellows propellant tank. The engine produces a 10-mN thrust at 30 km/sec exhaust velocity, 230 w power input, and excellent efficiencies.[10]

The 8-cm-diam mercury bombardment thruster ESKA 8 of DFVLR Braunschweig is of a conventional design. It has been

Table 4 Comparison of European secondary propulsion ion engines

Thruster type	d.c. bombardment			rf bombardment		contact	Hall-accelerator	field emission	
Propellant	Hg		Cs	Hg		Cs	Hg	colloid	Cs
Thruster	T4	ESKA8	CB4	RIT 10S	RIT4	CC1.5	HIT A4	CTE 3/0	(FE 3)
Establishment	RAE, Culham, Fulmer, Marconi	DFVLR	SEP	Giessen, MBB	Giessen	ONERA, LEP LAAS, SEP	DFVLR	Culham	
Sponsor	RAE			GfW		CNES		ESRO	
State-of-the-art	industr.[b]	optim.[c]	funct.[d]	industr.[b]	optim.[c]	industr.[b]	optim.[c]	optim.[c]	feasib.[e]
Beam diam, cm	10	8	7	8.5	3.2	5 × 0.5	2	3	3 × 0.1
Ion current, ma	167	199	65.5	126	35	17	295	0.2	5.4
Exhaust velocity, km/sec	30	31	45	38	43	67	21	10	40
Thrust, mN	10	12.9	4	10	3.2	1.5	13	0.6	0.3
Thruster input, w	230	288	117.5	242	115	96	400	4.7[a]	7.5[a]
Thruster mass, kg	1.3	2.0	1.4	1.1	0.6	2.2	0.5	1.1	0.3
Ion gener. energy, ev/ion	240	367	220	240	571	2120	200	...	278
Over-all efficiency, %	59.0	57.6	67.3	70.6	24.3	51.7	23.7	...	75.5[a]

[a] Without neutralizer.
[b] Industrialization.
[c] Optimization.
[d] Functional tests.
[e] Feasibility demonstration.

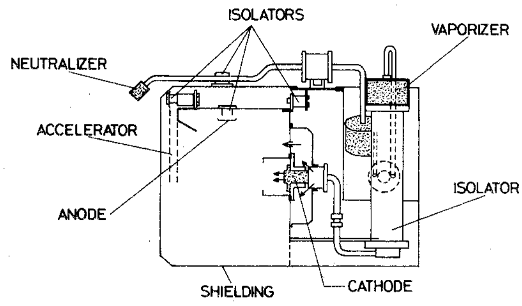

Fig 3 Cross section of the cesium bombardment thruster CB 6.7 of SEP Puteaux.

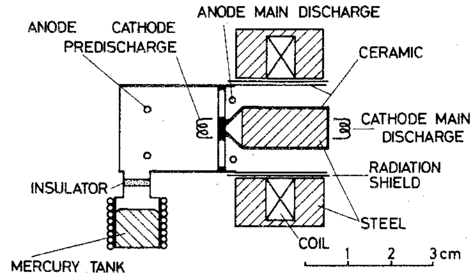

Fig. 5 Operation principle of the mercury Hall ion thruster HIT A 4 of the DFVLR Stuttgart.

improved remarkably by optimization of the flat double grid system during an 1000-hr experimental period in 1973. Optimization of the baffle geometry and thruster mass minimization are still pending. The ESKA 8 motor is running in the thrust range of 10–14 mN at 31 km/sec exhaust velocity and over-all efficiencies of 49–58%.

The 7-cm-diam cesium bombardment thruster CB 4 of SEP is derived from scaling-down of an earlier 10-cm experimental engine CB 6.7 (Fig. 3). The 4-mN engine is working with an autocathode, a 12-v arc discharge, a capillary feed system, a plane double grid system, and several plasma bridge neutralizers. The scheduled data comprise 45 km/sec exhaust velocity, 118 w power input, and 220 ev/Cs-ion generation energy (equivalent to 331 ev/Hg-ion).[34]

The 8.5-cm mercury rf-bombardment thruster RIT 10 S of the Univ. of Giessen and MBB (Fig. 1) works with an electrodeless, annular, self-sustaining rf-discharge eliminating discharge electrode problems and it uses an ion optical extraction system with a quartz plasma holder. The nominal thrust of 10 mN can be throttled to 5 mN corresponding to mission requirements. The ion production energy of 239 ev/ion and the total efficiency of 71% are excellent.[15,16]

The 3.2-cm RIT 4-thruster of the Univ. of Giessen is derived from scaling down of the 10-mN device. Mode of working and structural elements are similar to RIT 10 S. Due to scaling laws of the self-sustaining discharge, the specific data of RIT 4 are deteriorated in comparison to the 10-cm prototype.[16]

The 5-cm linear strip cesium contact microthruster CC 1.5 of LEP, ONERA, LAAS, and SEP (Fig. 4) has a rectangular shaped porous tungsten ionizer with a curved surface and two heaters (redundancy), a multiple foil thermal shield, an accel-decel system with a focusing electrode, and two neutralizer filaments (redundancy). The thruster is working on relatively low ion currents (17 ma) and high exhaust velocities (67 km/sec). It produces a 1.5-mN thrust at about 100 w power input. The ion generation energy of 2120 ev/Cs-ion is poor.[31,32]

The 2-cm mercury Hall-ion thruster HIT A 4 of DFVLR Stuttgart is considerably smaller than conventional ion engines (4 cm ionizer diam). Nevertheless, it produces an ion current of 295 ma at low exhaust velocities of 21 km/sec. This is done by space charge compensation in the accelerator region. Electrons are injected into the accelerator and they are trapped (Hall currents) by a perpendicular magnetic field (Fig. 5). Despite the excellent physical work on preionization and acceleration mechanism, some performance data (e.g., over-all efficiency of 24%) are still unsatisfactory.[22,23]

The 3-cm annular colloid thruster CTE 3/O of Culham Lab. (Fig. 6) seems to have reached the highest stage of development among the European electrostatic spraying devices. Liquid propellant (NaJ in glycerol) is fed by capillary forces to the narrow channel at the annular slit. An intense electrostatic field is established between the emitter tips (+9 to +15 kv) and the inner and outer extractor electrodes (−0.5 to −2 kv). The laboratory engine produces an 0.6 mN-thrust at 10 km/sec exhaust velocity.[38] The divergence of 30% and the homogeneity of 60% are rather unsatisfactory.

The 3-cm linear cesium field emission thruster at Culham Lab. seems to be a promising new electrostatic spraying concept because of physical simplicity and potentially high efficiencies. If cesium drops are subjected to sufficiently high electric fields, they distort into sharp peaked conical configurations and emit ions by field ionization. An emitter consists of a 3-cm linear array of 400 nickel or tungsten wires, precisely aligned and all electrolytically etched. The propellant is fed by capillary forces to the emitter-extracting system (+1.1 kv, −1.2 kv). Owing to the early development state, most of the performance data (Table 4) are estimated or calculated.[2]

In principle, most of these European secondary propulsion engines can be used for North-South stationkeeping of the operational European communication satellite ECS(O). In 1976, ESRO will make its own selection of the flight system. Already in the beginning of 1973, ESRO eliminated provisionally some candidate thrusters from contention because of poor performance data or an early development stage. The T 4, CB 4, RIT 10 S, and CC 1.5 engines are remaining in serious contention. The selection will be made based on the following aspects[1]:

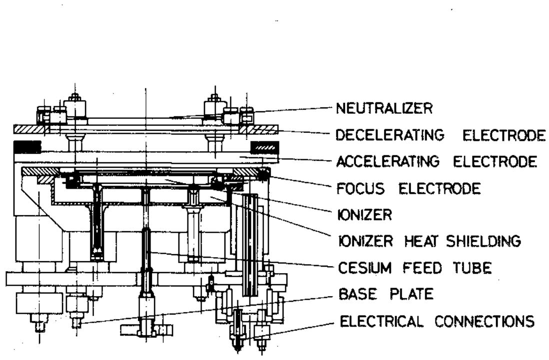

Fig. 4 Section of the cesium contact microthruster CC 1.5 of LEP Limeil.

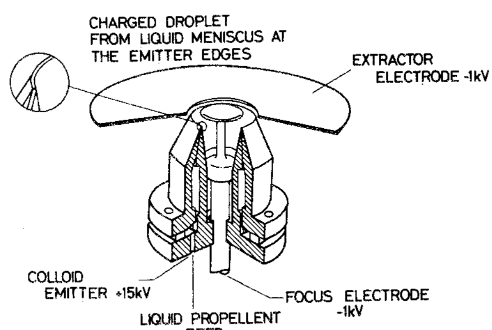

Fig. 6 Conceptual drawing of the 3-cm annular colloid thruster of Culham Lab.

Table 5 Comparison of candidate NSSK engines for ECS(O)

engine	thrust per unit, mN	resultant thrust per satellite face, mN	operating time per day, h	power draw per day per satellite face, wh	mass of 4 engines, kg	propellant mass +10%, kg	mass of 2 tanks, kg	mass of 4 PCU, kg	extra solar array mass, kg	mass of EPS and array, kg	mass savings, kg	required life time, h
T 4	10	16.16	0.57	289.9	5.2	7.7	2.0	15.8	3.5	34.2	45.8	1116
RIT 10 S	10	16.20	0.57	304.4	4.4	5.8	1.8	16.0	4.8	32.8	47.2	1113
CB 4	4	6.50	1.41	394.5	5.6	5.8	1.8	12.6	5.1	30.9	49.1	2774
CC 1.5	1.5	2.42	3.80	946.5	8.8	2.8	1.5	11.8	9.2	34.1	45.9	7464

1) Space qualification of the candidate system including all auxiliary components (power conditioning unit, storage-feed system, etc.).

2) Compatibility with the satellite power sources (640 w solar array, 250 wh/cycle for battery discharge) and with housekeeping (EP heat losses).

3) Acceptable impact of the ion engines on the satellite (propellant and sputtered material deposition on solar cells, sensors, etc.).

4) Remarkable mass savings over hydrazine engines (80 kg for ECS).

5) Within these limits, high thrust and short operating time (reliability, mean-time-to-failure qualification, ex-nodal losses).

It may be supposed that all four candidate systems will rise to the demand of items No. 1 and 2. The calculations of mass savings and operational time (Table 5) are based on the following assumptions[1,4,39]:

1) ECS(O)-data: 400-kg mass, 7-yr lifetime, 1967 thrust cycles, 66-Nsec daily impulse, 50-g/w specific mass of solar array, 250-wh/cycle battery capacity.

2) EP-data: 4 engines (effective thrust of two simultaneously working, 35° inclined motors including ex-nodal losses, beam divergence and homogeneity), 4 PCU (specific mass 664.2 $g/w \cdot P^{-0.6726}$), 2 propellant tanks (tank mass 0.6 kg + 5% m_p plus 10% expulsive losses). The mass savings of T 4, CB 4, RIT 10 S, and CC 1.5 are nearly equivalent (46–49 kg). For not too low exhaust velocities, the mass savings can be increased by engines' throttling (e.g., RIT 10 S: 10 mN, 47.2 kg; 6 mN, 49.4 kg; CB 4: 6.7 mN, 36.4 kg; 4 mN, 49.1 kg).[39]

Concerning lifetime requirements, T 4 and RIT 10 S (1116 and 1113 hr) are best suited for ECS(O) stationkeeping. CB 4 and CC 1.5 require enlarged lifetime (2774 and 7464 hr) resulting in longer test programs for mean-time-to-failure demonstration. In the case of thrust throttling, the operational time rises (e.g., RIT 10 S: 10 mN, 1113 hr; 6 mN, 1865 hr); however, it can be demonstrated that the erosion failure probability doesn't rise.[39]

Primary Propulsion Ion Engines

Because of the present lack of application, there are only in-house activities on primary ion propulsion and they are concentrated in West Germany. Both the DFVLR-Institute at Braunschweig and the Univ. of Giessen are developing a 20-cm class and a 30-cm class aggregate each. These 4 mercury motors are members of the ESKA and RIT families (Figs. 1 and 2).

Among the 20-cm, 800-w class, the ESKA 18-thruster represents the most advanced European primary propulsion device. This Kaufman-type engine produces a 34-mN thrust at 38 km/sec exhaust velocity and 62% over-all efficiency.[20]

By contrast, the rf-engine RIT 20 is also still under optimization.[16] The optimization experiments of the 122-mN aggregate ESKA 28 (3-kw class) have also not yet been completed resulting in some specific data (e.g., 451 ev/ion discharge energy) which need improvement.

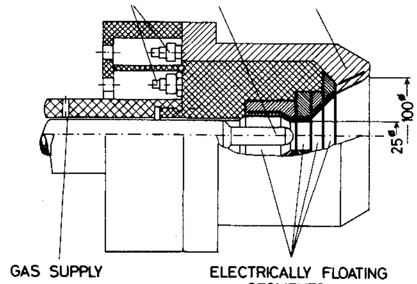

Fig. 7 Cross section of the steady-state self-magnetic MPD-engine EM 25/100 of DFVLR Stuttgart.

The 35-cm-diam ionizer experimental thruster RIT 35 is scheduled for the most powerful European primary propulsion engine (163 mN thrust, 2.5 amps ion current). The engine is derived from scaling-up of the RIT 20-type. At present, the RIT 35-aggregate is still in an early stage of diagnostics and optimization; however, the extrapolated experimental results as well as the scaling laws of a self-sustaining discharge indicate excellent performance data (e.g., 235 ev/ion total loss energy, 76% over-all efficiency, 19 w/mN power-to-thrust ratio, and 1.5 kg/kw mass-to-power ratio).[16]

Electrothermal and Electromagnetic Engines

The 3-kw hydrogen resistojet J 3 of Rocket Propulsion Establishment (RPE Westcott) represents the most advanced European primary propulsion electrothermal thruster.[40] It consists of a concentric tube heat exchanger (five propellant passes) and a conical nozzle (1.3-mm-diam throat), both manufactured of rhenium, and an outer insulation package. The scheduled performance data of 652 mN thrust, as well as of 8.1 km/sec exhaust velocity, and 79% over-all efficiency were verified approximately by tests (Table 6).

The applied-magnetic MPD-accelerator X 16 of the DFVLR-Institute at Stuttgart represents the most recent and advanced European stationary plasma engine in the medium-power range (6 kw). It consists of a center cathode, a coaxial, radiation-cooled anode, and a superimposed diverging magnetic nozzle (3.5 kgauss) produced by three different, water-cooled coils. The propellant (argon) is fed through the anode as well as along the cathode. By careful optimizations of geometry and working parameters, the recent X 16-model shows some promising

Table 6 Comparison of European electrothermal and MPD engines

Thruster type	Resistojet	Steady-state MPD Applied magnetic	Steady-state MPD Self magnetic	Pulsed MPD ablation
Thruster	J3	X16	EM 25/100	
Establishment	RPE/Oxford	DFVLR-Institute Stuttgart		
Propellant	Hydrogen	Argon	Argon	PbI_2, CsI
Thruster diam, cm	10	21	20.5	1.3[a]
Mass flow, mg/sec	80.6	10	1500	0.0067
Exhaust velocity, km/sec	7.6	20	11.5	4.2
Magnetic field, gauss	0	3500	(300)	270
Thrust, mN	610	200	17,300	0.028
Thruster input, w	3390	6000[+]	452,000	8.3
Over-all efficiency	68.1	33.3[+]	22	0.7

[a] Without magnet.

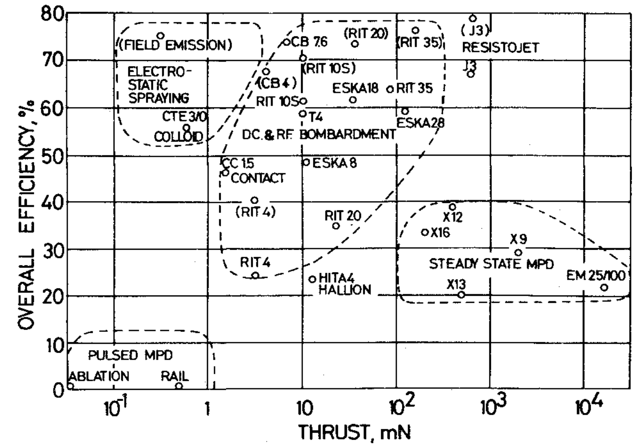

Fig. 8 Over-all efficiency vs thrust of European EPS hardware.

performance data such as an over-all efficiency of about 35% (Table 6).[26]

The self-magnetic MPD-accelerator EM 25/100 of the DFVLR at Stuttgart is a steady-state 17-N argon engine in the high power range (450 kw). Figure 7 shows a cross section true to scale demonstrating the thoriated tungsten cathode (1.6-cm-diam), the water-cooled copper anode, the segmented nozzle (10-cm-diam exit), and the electrically insulated outer surface layer. Because of the very high d.c.-arc currents (6000 amps) needed for the generation of the axial magnetic forces,[25] this thruster is mainly scheduled for plasma wind tunnel experiments rather than for space applications.

The 10-w ablation plasma thruster of DFVLR Stuttgart, too, represents a pulsed MPD-device for attitude control purposes (0.1-mNsec range). The solid propellant is supplied mechanically by a spring. A triggering element (center auxiliary anode and concentric cathode) ignites the main discharge which ablates, dissociates, ionizes, and accelerates the propellant ("electron pressure acceleration"). A perpendicular magnetic bias field constrains the ablation at the fuel surface. At a repetition rate of 0.5 Hz, the pulse bits last only 3 msec each. Exhaust velocity and over-all efficiency are low (Table 6).[27] The ablation engine demonstrated already 600,000 impulse bits.

Summary

Figure 8 shows a comparison of the European electric engines by means of an over-all efficiency-thrust-diagram. The thrust of European EP devices ranges over 6 orders of magnitude. The location of d.c. and rf bombardment aggregates, pulsed and steady-state MPD thrusters, and electrostatic spraying devices is signed by dashed lines.

To summarize the state-of-the-art of European electric propulsion:

1) As in the case of the United States, a concentration of European EP activities has taken place. However, this process has not yet reached the advanced stage of the Americans. In particular, at present there is no hardware cooperation among the European countries.

2) Referring to the performance data, European electric engines are comparable to the U.S. aggregates. However, the state-of-the-art of European motors is less advanced. Despite the comparable financial effort, this is caused by several parallel developments.

3) Contrary to the emphasis of mission in the United States, the European intermediate term planning considers the EP application mainly for orbit control of geosynchronous commercial satellites.

4) ESRO and the European governments prefer ground testing rather than space tests.

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