Chapter 9
Flight Ion and Hall Thrusters

9.1 Introduction

Ion and Hall thruster technology development programs continue to improve the performance of these engines. However, it is worthwhile to survey the state-of-the-art thrusters that have been flown to date. In this brief look, we are covering modern thrusters that have flown in the last ten to fifteen years in satellite station-keeping and spacecraft prime-propulsion applications. These thrusters are ion thruster and Hall thruster systems that use xenon as the propellant. The parameters given for the thrusters include the neutralizer or external cathode flow rates, since that is required for flight operation on satellites and spacecraft.

9.2 Ion Thrusters

The first of the modern ion thrusters flown were intended for station-keeping applications on geosynchronous satellites and developed by Mitsubishi Electric Corporation (MELCO) for use on the Japanese "Engineering Test Satellite (ETS-6)" in 1994 [1,2]. These 13-cm Kaufman thrusters produced nominally 20 mN of thrust at an Isp of about 2400 s. Despite launch vehicle problems that caused the satellite to fail to reach its planned orbit, the thrusters were successfully operated in orbit. The same electric propulsion subsystem was launched on the COMETS satellite in 1996, which also failed to reach its planned orbit. Development of Kaufman ion thrusters for communications satellite station-keeping applications is continuing at MELCO.

The first successful use of ion thrusters in commercial station keeping applications was the Hughes 13-cm Xenon Ion Propulsion System (XIPS) [3,4], which was launched into orbit in 1997 on the Hughes PAS-5 satellite. The XIPS system utilizes two fully redundant subsystems, each consisting of two thrusters, a power supply, and a xenon gas supply. The performance parameters for the 13-cm XIPS thruster are shown in Table 9-1. The thrusters produce nominally 18 mN of thrust at an Isp of 2500 s and a total efficiency of about 50%. A schematic of the 13-cm XIPS thruster is shown in Fig. 9-1, and a photograph of the thruster, which is manufactured by L-3 Communications, Electron Technologies, Inc., is shown in Fig. 9-2. Over 60 of these thrusters were launched into orbit and successfully used for North-South station keeping on Hughes and Boeing satellites.

The next ion thruster to fly was NASA's NSTAR ion engine [5,6], which is a ring-cusp, DC electron-bombardment discharge thruster with an active grid

Table 9-1. 13-cm XIPS performance.

Parameter	Station Keeping
Active grid diameter (cm)	13
Thruster input power (W)	421
Average Isp (s)	2507
Thrust (mN)	17.2
Total efficiency (%)	50.0
Mass utilization efficiency (%)	77.7
Electrical efficiency (%)	71.3
Beam voltage (V)	750
Beam current (A)	0.4

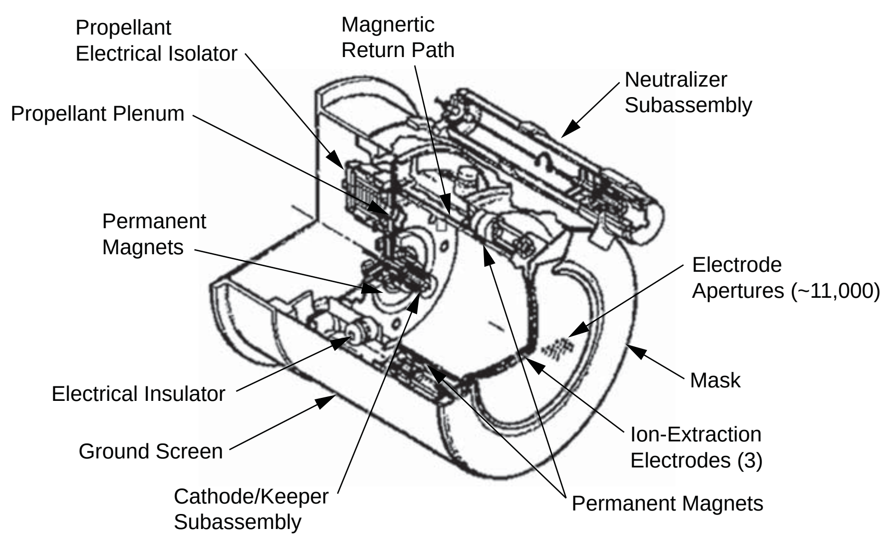

Fig. 9-1. Schematic of the 13-cm XIPS thruster (from [4,10]).

Fig. 9-2. Photograph of the 13-cm XIPS ion thruster (photo courtesy of L-3 Communications, Electron Technologies, Inc.).

diameter of 28.6 cm. NSTAR was developed and manufactured by a team of NASA GRC, JPL and Hughes/Boeing and launched in 1998 on the Deep Space 1 spacecraft. This ion engine has arguably been the most analyzed and tested ion thruster in history, with over 16,000 hours of operation in space, over 40,000 hours of life testing, and hundreds of papers published on its design and performance. NSTAR was operated over a wide throttle range in the DS1 application from a minimum input power to the power processing unit (PPU) of 580 W to a maximum power of over 2550 W. The Extended Life Test of this thruster at JPL demonstrated 30,252 hours of operation distributed across several of the throttle levels and was terminated with the engine still running in order to provide life status and data for the subsequent DAWN mission [7]. The throttle table used on DS1 with parameters for the NSTAR thruster from a review by Brophy [6] is shown in Table 9-2. A photograph of the NSTAR engine manufactured by L-3 Communications, Electron Technologies, Inc. is shown in Fig. 9-3.

The next ion thruster technology launched was designed for both orbit raising and station keeping applications on a commercial communications satellite. The 25-cm XIPS thruster was first launched in 1999 on a Hughes/Boeing 702 satellite. Although the 25-cm XIPS ion thruster was developed [9] at Hughes Research Laboratories in the same time frame as the NSTAR engine and has a similar basic design as the 13-cm XIPS shown in Fig. 9-1, the 25-cm thruster entered production after the 13-cm version and incorporated sufficient

Table 9-2. NSTAR throttle table.

NSTAR Throttle Level	PPU Input Power (W)	Engine Input Power (W)	Calculated Thrust (mN)	Specific Impulse (s)	Total Efficiency (%)
15	2567	2325	92.7	3127	61.8
14	2416	2200	87.9	3164	62.4
13	2272	2077	83.1	3192	63.0
12	2137	1960	78.4	3181	62.8
11	2006	1845	73.6	3196	63.1
10	1842	1717	68.4	3184	62.6
9	1712	1579	63.2	3142	61.8
8	1579	1456	57.9	3115	61.1
7	1458	1344	52.7	3074	59.6
6	1345	1238	47.9	3065	59.0
5	1222	1123	42.6	3009	57.4
4	1111	1018	37.4	2942	55.4
3	994	908	32.1	2843	52.7
2	825	749	27.5	2678	48.7
1	729	659	24.6	2382	47.2
0	577	518	20.7	1979	42.0

improvements to be considered a second-generation device. A photograph of the 25-cm XIPS thruster, which is also manufactured by L-3 Communications, Electron Technologies, Inc., is shown in Fig. 9-4. To date, fourteen of the Boeing 702 communications satellites with a total of 56 XIPS thrusters have been successfully launched and are in operation.

The initial operation of the 25-cm thrusters in space on the 702 satellites was described in 2002 [10]. After launch, these thrusters are first used for orbit raising and then provide all of the propulsion requirements for orbit control including north-south and east-west station keeping, attitude control, and momentum dumping. The ion thrusters are also used for any optional station change strategies and will ultimately be used for de-orbit at the end of the satellite’s lifetime. The “high power” orbit insertion mode requires nearly continuous operation by two of the thrusters for times of 500 to 1000 hours, depending on the launch vehicle and satellite weight. This mode utilizes about 4.5 kW of bus power to generate a 1.2-kV, 3-A ion beam, which produces 165-mN thrust at a specific impulse of about 3500 seconds. Once orbit insertion

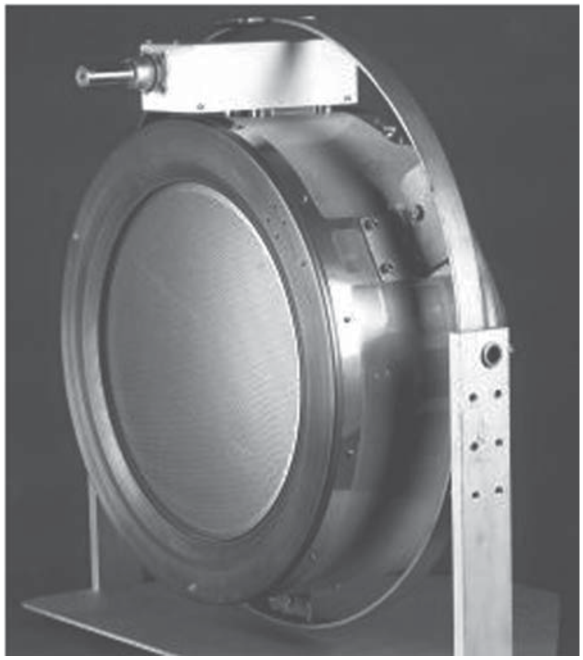

Fig. 9-3. Photograph of the NASA NSTAR ion thruster (photo courtesy of L-3 Communications, Electron Technologies, Inc.).

Fig. 9-4. Photograph of the 25-cm XIPS ion thruster (photo courtesy of L-3 Communications, Electron Technologies, Inc.).

is completed, each of the four thrusters is fired once daily for an average of about 45 minutes in a “low power,” 2.3-kW mode for station keeping. In this mode, the beam voltage is kept the same, and the discharge current and gas flow are reduced to generate a 1.2-kV, 1.5-A beam that produces nominally 79 mN of thrust at an Isp of 3400 s. The thruster performance parameters are shown in Table 9-3. Recently, tests by the manufacturer L-3 Communications Electron Technologies Inc. have demonstrated that the XIPS engine and PPU can be throttled from a PPU input power level of 400 W to over 5 kW. Over this range, the performance significantly exceeds the NSTAR thruster performance [11].

The next flight of ion thrusters was on the European Space Agency Artemis spacecraft launched in 2001. Artemis carried four ion thruster assemblies, two EITA (Electron-bombardment Ion Thruster Assembly) systems manufactured by Astrium UK, and two RITA (Radio-frequency Ion Thruster Assembly) systems developed by Astrium Germany. The EITA system, also called the UK-10 system, used copies of the T5 thruster [12,13], and the RITA system used RIT-10 ion thrusters [14,15]. Artemis was intended to be launched into a geosynchronous orbit, but a malfunction of the launcher’s upper stage placed the satellite into a lower orbit. The ion thrusters were used in an unplanned orbit-raising role to rescue the spacecraft from the lower 31,000-km parking orbit and raise the spacecraft to the proper geosynchronous orbit. The thrusters then successfully performed standard EP station keeping activities.

The EITA/UK-10/T5 thruster is a 10-cm Kaufman thruster [13] presently manufactured by Qinetiq in England. The performance of the T5 Kaufman

Table 9-3. 25-cm XIPS performance parameters.

Parameter	Low-Power Station Keeping	High-Power Orbit Raising
Active grid diameter (cm)	25	25
Thruster input power (kW)	2	4.3
Average Isp (s)	3420	3550
Thrust (mN)	80	166
Total efficiency (%)	67	68.8
Mass utilization efficiency (%)	80	82.5
Electrical efficiency (%)	87	87.5
Beam voltage (V)	1215	1215
Beam current (A)	1.45	3.05

thruster in station keeping applications [13] is shown in Table 9-4. A schematic of a generic Kaufman thruster was shown in Chapter 4, and a photograph of the T5 thruster is shown in Fig. 9-5. The T5 thruster generates an 1100-V, 0.329-A xenon ion beam that produces about 18 mN of thrust at a nominal Isp of 3200 s with a total efficiency of about 55%.

The RITA system uses a RIT-10 rf ion thruster originally developed [14] at the University of Giessen in Germany and manufactured [15] for Artemis by Astrium in Germany. The performance of the RIT-10 thruster in the station keeping application [15] is shown in Table 9-5. A schematic of a generic rf thruster was shown in Chapter 4, and a photograph of the RIT-10 rf ion thruster from [16] is shown in Fig. 9-6. The RIT-10 thruster generates a 1500-V, 0.234-A xenon ion beam that produces 15 mN of thrust at an Isp of 3400 s and a total efficiency in excess of 51%.

The Institute of Space and Astronautical Science of the Japan Aerospace Exploration Agency (JAXA) launched four of the µ10 ECR ion thrusters on the Hayabusa (formerly Muses-C) spacecraft [17] in 2003. These 10-cm grid-diameter thrusters are successfully providing primary propulsion for an asteroid sample return mission that will return to Earth in 2010. The thruster [18,19] uses 4.2-GHz microwaves to produce the main plasma in the thruster and drive the electron neutralizer. A schematic drawing of the thruster was shown in Chapter 4. The performance of the 10-cm ECR thruster is shown in Table 9-6, and a photograph of the thruster from Ref. 20 is shown in Fig. 9-7. The 10-cm ECR ion thruster generates a 1500-V, 0.136-A xenon ion beam that produces 8.1 mN of thrust at an Isp of 3090 s and a total efficiency of 36%.

The most recent launch of a new ion thruster was by the Japan Aerospace Exploration Agency (JAXA), who launched four 20mN-class Kaufman ion thrusters developed by Mitsubishi Electric Corporation on the Engineering Test Satellite VIII (ETS-VIII) [21] in 2006. The 12-cm grid-diameter Kaufman thrusters provide north-south station keeping for this large geosynchronous communications satellite. The performance of the 12-cm Kaufman thruster [22] is shown in Table 9-7, and a photograph of the thruster from [23] is shown in Figure 9-8. At its nominal operating condition, the thruster generates a 996-V, 0.432 to 0.480-A xenon ion beam that produces 20.9 to 23.2 mN of thrust at an Isp of 2402 to 2665 sec and a total efficiency of about 46 to 50%.

There are a significant number of new ion thrusters in development world-wide for prime propulsion and satellite station keeping applications. Since these thrusters have not flown as of this date, they will not be covered in detail and only mentioned here. NASA Glenn Research Center (GRC) is leading the

Table 9-4. T5 Kaufman thruster performance parameters.

Parameter	Station Keeping
Active grid diameter (cm)	10
Thruster input power (W)	476
Nominal Isp (s)	3200
Thrust (mN)	18
Total efficiency (%)	55
Mass utilization efficiency (%)	76.5
Electrical efficiency (%)	76.6
Beam voltage (V)	1100
Beam current (A)	0.329

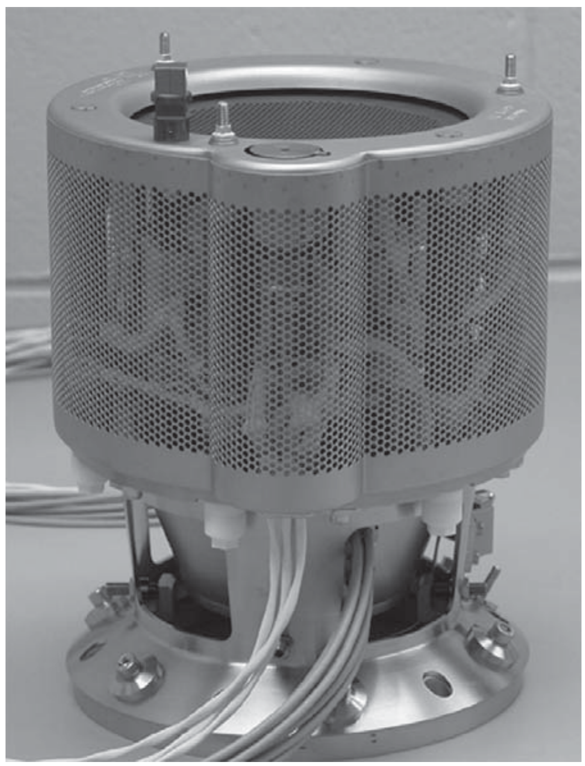

Fig. 9-5. Photograph of the T5 Kaufman ion thruster (photo courtesy of Qinetiq, Limited).

Table 9-5. RIT-10 rf thruster performance parameters.

Parameter	Station Keeping
Active grid diameter (cm)	10
Thruster input power (W)	459
Nominal Isp (s)	3400
Thrust (mN)	15
Total efficiency (%)	52
Mass utilization efficiency (%)	69.3
Electrical efficiency (%)	76.5
Beam voltage (V)	1500
Beam current (A)	0.234

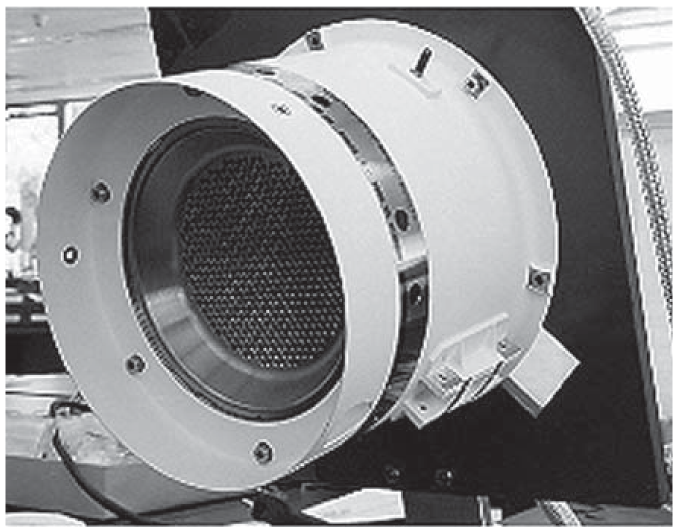

Fig. 9-6. Photograph of the RIT-10 rf ion thruster (from [16]).

development of the 7-kW NASA Evolutionary Xenon Thruster (NEXT) [24]. NASA's Jet Propulsion Laboratory (JPL) led the development of the 25-kW Nuclear Electric Xenon Ion thruster System (NEXIS) [25], which produced the highest efficiency (>81%) xenon ion thruster developed to date. NASA's GRC also led the development of the 30-kW High Power Electric Propulsion (HiPEP) thruster [26], which featured a rectangular geometry with both rf and DC hollow cathode plasma production versions. In England, Qineteq is developing the T-6 20-cm Kaufman thruster [27], which is capable of

Table 9-6. µ10 ECR microwave ion thruster performance.

Parameter	Primary Propulsion
Active grid diameter (cm)	10
Thruster input power (W)	340
Average Isp (s)	3090
Thrust (mN)	8.1
Total efficiency (%)	36
Mass utilization efficiency (%)	70
Electrical efficiency (%)	60
Beam voltage (V)	1500
Beam current (A)	0.136

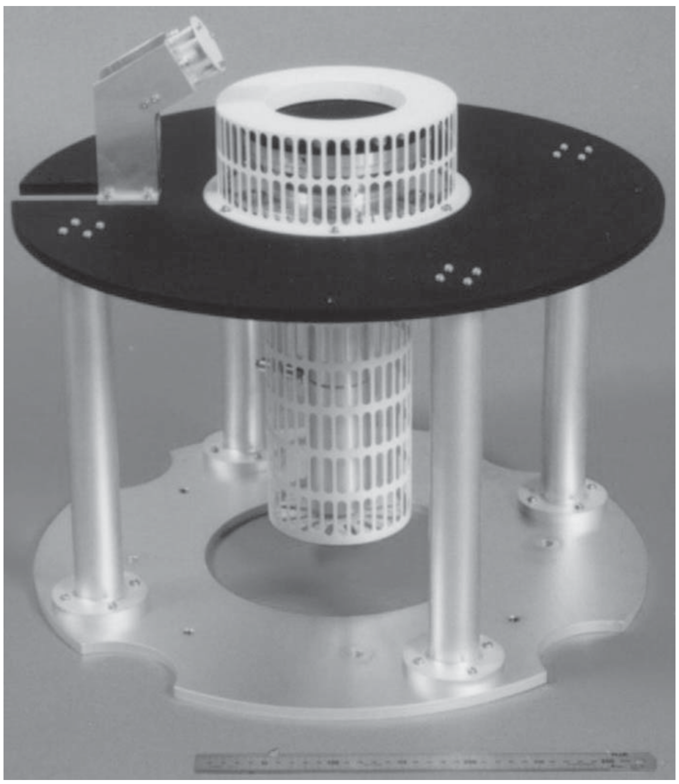

Fig. 9-7. Photograph of the µ10-ECR microwave discharge ion thruster (10-cm grid diameter) and microwave neutralizer [20].

Table 9-7. ETS-8 Kaufman thruster performance parameters.

Parameter	NS-Station Keeping
Active grid diameter (cm)	12
Thruster input power (W)	541–611
Nominal Isp (s)	2402–2665
Thrust (mN)	20.9–23.2
Total efficiency (%)	45.6–49.7
Mass utilization efficiency (%)	66.2–73.5
Electrical efficiency (%)	78.2–79.5
Beam voltage (V)	996
Beam current (A)	0.43–0.48

Figure 9-8. Photograph of the ETS-8 Kaufman ion thruster (from [23]).

producing up to 200-mN thrust for European communications satellite station keeping applications. In Japan, the Institute of Space and Astronautical Science is developing a 20-cm-diameter, 30-mN-class microwave ion thruster [28]. In Germany, Astrium is developing a 200-mN-class rf ion thruster (RIT-22) for station keeping applications [29]. Finally, ring-cusp and rf ion thrusters are being miniaturized for applications that require thrust levels of the order of 1 mN or less. The 3-cm Miniature Xenon Ion thruster (MiXI) [30] uses a DC discharge, ring-cusp geometry with closely spaced ion optics to produce up to

3 mN of thrust at beam voltages of up to 1200 V. The micro-Newton Rf Ion Thruster (µN-RIT) [31] use a low frequency (≈1 MHz) rf discharge scaled down to 2 to 4 cm in diameter to produce precision thrust levels as low as 20 µN at beam voltages in excess of 1 kV. There are many additional small research and development programs at universities and in small businesses, but these are too numerous to be covered here.

9.3 Hall Thrusters

The most successful and extensive electric propulsion development and application has been by the Russians flying Hall thrusters for station keeping on satellites [32]. Over 140 Hall thrusters have been operated in space since 1971 when the Soviets first flew a pair of Hall thrusters called Stationary Plasma Thrusters (SPT) on the Meteor satellite [32]. This name is translated from the Russian literature, but refers to the continuous operation ("stationary") of the Hall thruster in comparison to the Pulsed-Plasma Thrusters (PPT) that the Russians had previously tested and flown in the 1960s [32]. SPT thrusters for satellite applications have been developed with different sizes characterized by the outside diameter of the plasma discharge slot of 50 to over 140 mm [32].

The performance of four sizes of the SPT thruster manufactured by Fakel in Russia is shown in Table 9-8. The SPT-100 operates nominally at a discharge voltage of 300 V and current of 4.5 A to produce 82 mN of thrust at an Isp of 1600 s and a total efficiency of 50% averaged over the life of the thruster. The different SPT thrusters shown have been tested at discharge voltages of 200 to 500 V and power levels of a few hundred watts up to 5 kW. These Hall thrusters have also been tested on a variety of gases such as argon and krypton, but xenon is the present standard for space applications. A schematic of the Hall thruster was shown in Chapter 7, and a photograph of a Fakel SPT-100 thruster from [33] is shown in Fig. 9-9.

The first flight of a Hall thruster on a U.S. spacecraft was the 1998 launch of a D-55 TAL (Thruster with Anode Layer) Hall thruster [34,35] manufactured by TsNIIMASH in Russia on the National Reconnaissance Office's Space Technology Experiment Satellite (STEX). The STEX mission was intended to develop and demonstrate advanced spacecraft technologies in space, including Hall thrusters. The xenon D-55 TAL thruster nominally operates at 1.4 kW with an Isp of about 1500 s, but due to power limitations on the spacecraft was required to run at a discharge of 300 V and 2.2 A (660 W).

The European Space Agency (ESA) has demonstrated the use of commercial Hall thruster technology on the SMART-1 (Small Mission for Advanced Research in Technology) spacecraft in a lunar orbiting mission [36]. A

Table 9-8. STP Hall thruster performance.

Parameter	SPT-50	SPT-70	SPT-100	SPT-140
Slot diameter (cm)	5	7	10	14
Thruster input power (W)	350	700	1350	5000
Average Isp (s)	1100	1500	1600	1750
Thrust (mN)	20	40	80	300
Total efficiency (%)	35	45	50	>55
Status	Flight	Flight	Flight	Qualified

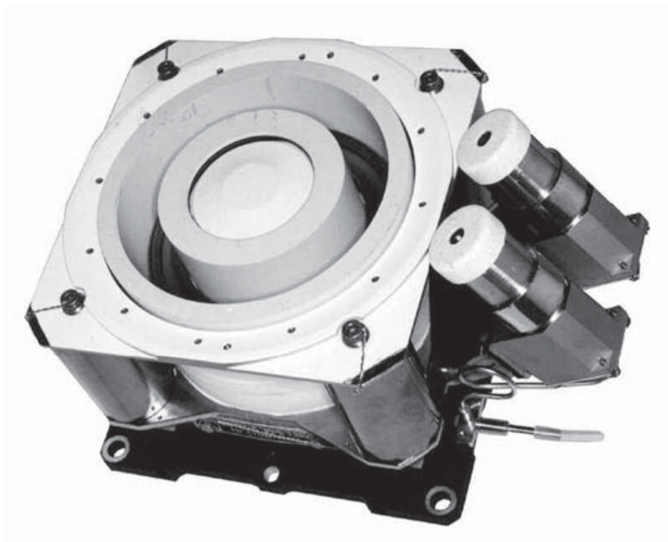

Fig. 9-9. Photograph of an SPT-100 Hall thruster (from [33]).

PPS-1350-G Hall thruster [37,38] manufactured by SNECMA Moteurs in France [39] was launched on SMART-1 in 2003 and provided primary propulsion for this mission. This thruster is based on the SPT-100 and is similar in size and power level. The thruster was operated over a throttleable power range of 462 to 1190 W for this lunar mission, producing a maximum thrust of 70 mN at an Isp of 1600 s. The finite efficiency of the power processing system required that the spacecraft supply 650 to 1420 W to the electric propulsion system. The PPS-1350 Hall thruster accumulated about 5000 hours of operation in space, and processed 82 kg of xenon in a very successful mission that featured several extensions of the mission life due to the thruster capabilities. The nominal performance of this thruster at 1.35 kW is shown in Table 9-9. The thruster schematic was shown in Chapter 7, and a photograph of the PPS-1350 Hall thruster is shown in Fig. 9-10.

The first commercial use of Hall thrusters by a U.S. spacecraft manufacturer was in 2004 by Space Systems Loral on the MBSAT satellite [33], which used Fakel SPT-100s provided by International Space Technologies Incorporated (ISTI). Loral has launched three communications satellites to date that use two pairs of SPT-100 Hall thrusters on each satellite, and plans to continue launching these systems in the future. Busek, Inc. was the first U.S. company to provide flight Hall thruster technology for a spacecraft when the 200-W BHT-200 flew on board the Air Force TacSat-2 spacecraft that was launched in late 2006 [40,41]. Beginning in 2008, Lockheed Martin Space Systems plans to begin flying BPT-4000 Hall thrusters (also developed in the U.S. by Aerojet) on the Air Force Advanced-EHF defense communications satellite [42]. Aerojet

Table 9-9. PPS-1350 Hall thruster performance.

Parameter	Primary Propulsion
Slot diameter (cm)	10
Thruster input power (W)	1500
Average Isp (s)	1650
Thrust (mN)	88
Total efficiency (%)	55
Discharge voltage (V)	350
Discharge current (A)	4.28

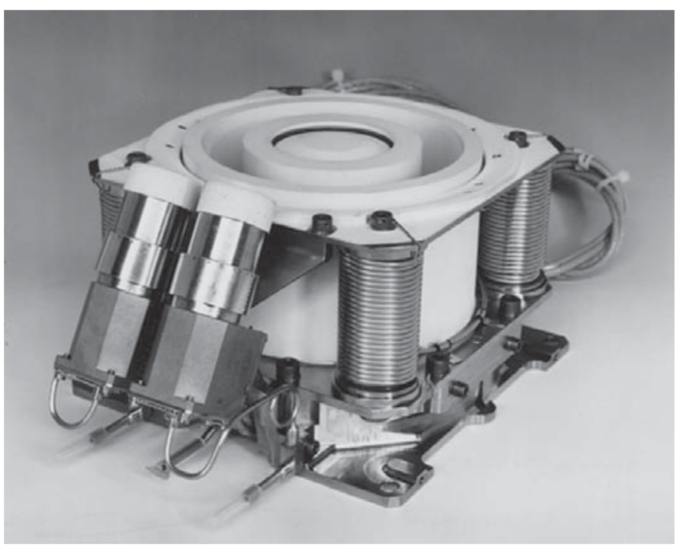

Fig. 9-10. Photograph of the PPS-1350 Hall thruster (photo courtesy of Snecma-Eric Drouin).

and JPL have jointly investigated the applicability of the BPT-4000 to NASA deep-space missions [43] where throttle range and efficiency are important. The throttleability of the BPT-4000 engine [44] from power levels 1 kW to 4.5 kW was demonstrated with very high efficiency observed at low power levels for this size thruster. Hall thruster technology will continue to be developed and used in commercial and scientific missions due to their high performance and relatively simple construction and operation.

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