

ELECTRIC PROPULSION DEVELOPMENT AND APPLICATION IN THE UNITED STATES

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ABSTRACT

In the early 1960s, just as today, the community of electric propulsion technologists eagerly anticipated the near-term, wide-spread use of their technology in space. Between then and today a significant change has taken place. Today, many commercial firms are engaged in privately sponsored or co-sponsored programs to develop and demonstrate electric propulsion devices for specific applications. It is this commercial investment, coupled with government investment in some instances, that ensures the near-term application of electric propulsion to space missions. This process has already begun with the use of hydrazine arcjets by Lockheed-Martin on a communications satellite in 1994 and in the next few months Hughes will launch a spacecraft using gridded ion thrusters. More importantly, it is this commercial investment that allows us to foresee the revolution in on-board and deep-space propulsion that electric propulsion will provide.

INTRODUCTION

In the middle 1960s, relatively early in the history of electric propulsion, there was much discussion within the community of electric propulsion technologists about the soon to be realized advent of electric propulsion's use in space. In-space experiments had shown the performance and efficacy of small ion thrusters. A wide spectrum of arcjets was being vigorously developed. Nuclear reactors as power sources were being developed and assumed for a variety of Earth-orbiting and planetary missions. Enthusiasm and expectations within the community of electric propulsion technologists were high.

In the early 1990s the situation was generally much the same. Extensive ground testing of arcjets was preparing that technology for an in-space demonstration. Minor forms of electric propulsion (resistojets and pulsed plasma thrusters) were in regular, though infrequent, use on U. S. satellites. Ion propulsion devices continued to be developed in NASA laboratories. Russian satellites used Hall effect devices routinely. Enthusiasm and expectations within the community of electric propulsion technologists were high.

Today, in 1995, it appears as if this latter-day enthusiasm was well placed. Late in 1994 a hydrazine arcjet system was successfully used on Telstar 4, stimulating commercial interest in arcjets and, more generally, in electric propulsion for commercial satellites. At about the same time NASA's office responsible for planetary exploration became interested in ion propulsion as a means of reducing the size of launch vehicles and the transfer time required for planetary missions. Within the U. S. this commercial and government interest led to many programs to validate and demonstrate several of the more promising forms of electric propulsion.

This paper will briefly describe current work to validate, demonstrate, and commercialize electric propulsion in the U. S.

APPLICATIONS

The potential applications of electric propulsion encompass essentially all in-space satellite propulsion requirements including north-south and east-west station keeping of geostationary spacecraft, orbit insertion, drag makeup, orbit repositioning, attitude control, precise spacecraft positioning, and primary propulsion for interplanetary probes. To fulfill these applications no fewer than eight different electric propulsion systems are currently either in use or are in the process of flight qualification in the United States.

The major motivation behind the present flurry of activity in electric propulsion is the economic benefit provided by the use of electric propulsion for north-south station keeping (NSSK) of commercial communication satellites. The substantial mass savings enabled by electric propulsion for NSSK can be used to increase the payload, increase the spacecraft on-orbit life, reduce the launch cost, or provide some combination of these benefits. Five of the eight electric propulsion systems in use or in preparation for use (the electrothermal hydrazine thruster (ELIT); the hydrazine arcjet, the xenon-fueled, stationary plasma thruster (SPT), the xenon ion propulsion system (XIPS), and the xenon-fueled, thruster with anode layer (TAL)) are for NSSK.

The other three systems are the solid Teflon-fueled pulsed plasma thruster (PPT), the 2.5-kW NSTAR xenon ion engine, and the 26-kW ammonia arcjet. All eight systems and their potential applications are summarized in Table 1.

Table I Electric Propulsion Systems Under Development and Their Applications

	NSSK or EWSK	Orbit Insertion	Drag Make-up	Orbit Reposi- tioning	Attitude Control	Precise Space- craft Position -in	Primary Propul- sion for Plane- tary S/C
Hydra- zine Resist o- jets	√	√	√				
Hydra- zine Arcjets	√	√	√	√			
Xenon SPT	√	√	√	√			
XIPS Xenon Ion	√	√	√				√
Xenon TAL	√	√	√	√			
Teflon PPT	√	√	√		√	√	
NSTAR Xenon Ion	√	√	√	√			√
26-k W Ammonia Arc jets		√					

EARTH ORBIT

Electrothermal Hydrazine Thruster (EHT)

The EHT (Fig. EHT-1) built by Olin Aerospace Company (OAC) increases the specific impulse of monopropellant hydrazine thrusters by electrically heating the hydrazine decomposition products¹. The gas is heated by passing it by a resistive heater element to raise its enthalpy prior to expansion in the exhaust nozzle. This results in an increase in specific impulse from < 220s for a conventional monopropellant hydrazine thruster to 280s. There are currently 24 satellites flying with MR-501 model EHTs as indicated in Fig. EHT-2. These thrusters have a maximum input power of 510 W and produce a thrust of 0.33 N at a propellant flow rate of 0.12 g/s. The total impulse capability of the MR-501 is 310,000 N-s. An improved EHT from OAC (the MR-502A) has now been developed with a specific impulse of 299 s, an input power of 885 W, a thrust level of 0.80 N, and a total impulse capability of 525,000 N-s. This improved EHT is slated for use in the INMARSAT IV program. Olin resistojets have also been selected for use on the Iridium constellation of spacecraft (66 satellites and 11 spares) to be launched in 1998.

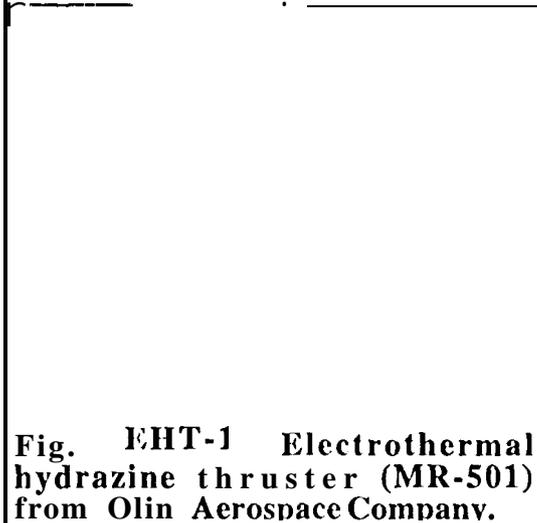


Fig. EHT-1 Electrothermal hydrazine thruster (MR-501) from Olin Aerospace Company.

Hydrazine Arcjet

Hydrazine arcjets provide a significant improvement in specific impulse by heating the hydrazine decomposition products to a higher temperature than can be obtained in a resistojet. This is accomplished by replacing the resistojet heater element with an electric arc discharge directly through the propellant gas. The arc discharge heats the propellant to a temperature much higher than the thermal limits of the resistojet heater element resulting in a substantial increase in specific impulse. A large temperature gradient from the centerline of the thruster, where the arc exists, to the thruster's refractory metal walls prevents melting.

The MR-508 hydrazine arcjet system from OAC (shown in Fig. HA- 1) has been flight qualified^{2,3,4} and is currently in use on the Telstar 401 spacecraft built by Martin Marietta for NSSK. This spacecraft was launched in December, 1994 and includes a total of 4 arcjets. Each arcjet has an input power of 1.8 kW and produces a maximum thrust of 0.250 N at a mission average specific impulse of 502s, and a total impulse capability of 870,000 N-s. Improved versions⁵ of the arcjet have been developed, designated the MR-509 and MR-510. The MR-510 has an average specific impulse of > 580s, an input power of 4.34 kW, a thrust level of 0.214 to 0.245 N and a total impulse capability of 812,000 N-s. The MR-509 and MR-510 are currently slated for use on 23 satellites as indicated in Table HA-I.

Fig. EHT-2 Satellites currently flying with electrothermal hydrazine thrusters.

Table HA-I Satellites slated to use hydrazine arcjets for NSSK

Satellite Name	Number of Satellites	Arcjet Type
Telstar 4	3	MR-508
Intelsat 8	6	MR-509
EHOSTAR	2	MR-509
EHOSTAR	2	MR-510
ASIASAT	2	MR-509
GE Americom	3	MR-510
ACES	2	MR-510
COSTAR	2	MR-510
“Whitetails”	2	MR-510

Xenon-Fueled Stationary Plasma Thruster (SPT)

The stationary plasma thruster (Fig. SPT- 1) was developed into a highly efficient propulsion device in Russia during the 1960s and 1970s ⁶. The thruster operates by ionizing xenon atoms through electron bombardment and accelerating the resulting positive ions electrostatically. The accelerating electric field is created by applying a voltage difference of typically 300 V between an external hollow cathode and the anode located at the upstream end of an annular discharge chamber. A radial magnetic field impressed on

the annular discharge chamber by electromagnets restricts the flow of the electrons emitted from the cathode to the anode. This establishes most of the applied voltage difference in a region at the downstream end of the discharge chamber where the magnetic flux density is a maximum producing the electric field which accelerates the ions from the thruster. Additional electrons emitted from the external hollow cathode provide current and spacecharge neutralization the positive ion beam.

The unique feature of the SPT is that the ion current density accelerated by the electric field is not subject to the Child-Langmuir spacecharge limitation. This is possible because the electric field is established in a quasi-neutral plasma in which the presence of electrons largely shields the ions from the spacecharge of the other ions. The result is that significantly higher ion current densities at lower voltages can be obtained relative to the more familiar (in the U. S.) gridded ion engine..

Space Systems/Loral is currently in the process of flight qualifying an electric propulsion system based on the 1.35-kW stationary plasma thruster (the SPT- 100) for use on commercial communication satellites built by Loral beginning in 1997 ⁷. The thrusters, built by the Russian Design Bureau Fakel in Kaliningrad (on the Baltic Sea), Russia, have a nominal input power of 1.35-kW (to the thruster) and produce a thrust of 80 mN at a specific impulse of 1500s, Russia has flown 72 of the smaller, lower power SPT-70 and SPT-50 model thrusters, Sixteen SPT- 100 thrusters are now providing north-south and east-west station keeping functions for two Russian GEO-spacecraft: GALS, a Ku-band, direct broadcast satellite launched in January 1994; and Express, a C-band FSS satellite launched in October 1994.

The SPT- 100 thruster has a total impulse capability of greater than 1,500,000 N-s as demonstrated in two recent tests, one at the Design Bureau Fakel and the other at the Jet Propulsion Laboratory in the U.S ⁸. In addition, almost 7,000 on/off cycles were demonstrated in the test at JPL. Performance, plume and EMI/EMC testing has been completed at the NASA Lewis Research Center and confirm compatibility of the SPT- 100 with planned communication satellites ^{9,10}.

Laboratory versions of the SPT have been built to operate at input powers up to 25 kW.

XIPS Ion Engine

The gridded ion engine has been under active research and development since the early 1960's. The Xenon Ion Propulsion System (XIPS) built by Hughes (shown in Fig. XIPS-1) is based directly on this extensive research and development experience. The use of the XIPS system is expected to save up to 400 kg of mass on a typical Hughes HS-601, body stabilized spacecraft,

The xenon ion engine operates by ionizing xenon atoms by electron bombardment in a DC discharge. The resulting positive ions are accelerated electrostatically between a set of three closely spaced, multi-aperture electrodes to an exhaust velocity of greater than 30,000 m/s. Electrons stripped from the xenon atoms in the ionization process are collected and injected into the accelerated ion beam to prevent the spacecraft from rapidly charging negative.

The Hughes XIPS thruster operates at an input power of 440 W and produces a thrust of 17.8 mN at a specific impulse of 2585s, The total impulse capability of the thruster is believed to be greater than 650,000 N-s. This thruster will be first flown on one of Hughes' own revenue bearing satellites, the Galaxy 111-R, which is scheduled to be

launched in December 1995. The ion propulsion system for this satellite includes four XIPS thrusters and is expected to provide 12 years of NSSK.

Hughes is currently conducting ground tests to flight qualify XIPS for service¹³. Vibration and thermal vacuum tests have been completed and a pair of prototype thrusters is now undergoing cyclic endurance testing with the objective of demonstrating 12,000 hours of operating time. A higher power (1.4-kW) XIPS system has also been developed and could be flight qualified¹³.

Xenon-Fueled Thruster with Anode Layer (TAL)

The thruster with anode layer technology^{14,15,16,17} was developed in the former Soviet Union beginning in the 1960's and is similar in both appearance and performance to the stationary plasma thruster (SPT). The TAL, however, uses metallic rather than dielectric discharge chamber walls and the accelerating electric field exists in a layer directly in front of the anode rather than several centimeters away from it as in the SPT. Modern versions of the TAL are designed such that much of the ionization and acceleration processes take place just outside of the thruster resulting in low thruster component erosion rates¹⁸.

As in the SPT the TAL discharge chamber is an annular channel with the anode placed at the upstream end. The channel, however, is much shorter than in the SPT, and in some cases the anode is almost flush with the downstream end of the thruster. A radial magnetic field is impressed across the annular channel by electromagnets and an external hollow cathode is used to supply electrons to the discharge and neutralize the ion beam.

No TALs have been flown in space, but a 1.35-kW thruster designated the D-55 (shown in Fig. 6) is currently in the process of being flight qualified by Olin and the Central Research Institute for Machine Building (TsNIIMASH in Kaliningrad, Russia) for a Ballistic Missile Defense Organization (BMDO)-sponsored flight experiment on NASA's Wakeshield Facility scheduled for launch in November 1996¹⁹.

The D-55 thruster, at an input power of 1.35-kW, produces a thrust of approximately 80 mN at a specific impulse of 1600s. The total impulse capability of the D-55 is projected to be > 1,400,000 N-s based on a 630-hr accelerated wear test performed at the Jet Propulsion Laboratory²⁰.

Teflon-Fueled Pulsed Plasma Thruster (PPT)

Development of pulsed plasma thrusters began in the early 1960's. A summary of the U.S. PPT history is shown in Fig. PPT-1²¹. The first flight of a PPT in the U.S. took place in 1970 on board the Lincoln Experimental Satellite (LES)-6 and successfully provided E-W station keeping for this spacecraft over its 5 year life²². Teflon PPTs were also used for final orbit insertion and drag make-up on the U.S. Navy's TIP/NOVA navigation satellites accumulating over 50 million pulses and 20 years of flight operation²³. A summary of the characteristics of PPTs developed for flight application is given in Table PPT-1.

Table PPT-I Summary of Flight or Flight Qualified PPTs

Parameter	LES-6	SMS	LES 8/9	TIP/NOVA
Thrust at 1 Hz (mN)	26.7	111	300	400
Specific Impulse (s)	312	505	1000	543
Thrust to Power (mN/W)	10.5	12.2	12	13.3
Capacitor Energy (J)	1.85	8.4	20	20
Total Impulse (N-s)	320	1779	5560	2450
Life (pulses)	12,000,000	13,000,000	18,500,000	10,000,000
Mission Application	E-W Station- keeping	Attitude Control	Attitude Control	Orbit Insertion Drag Make-up

The PPT operates by ablating, ionizing and accelerating the Teflon fuel. To accomplish this a capacitor connected across the electrodes of the thruster is charged to a voltage of several hundred volts. A spark plug is used to initiate the discharge by ablating and ionizing sufficient propellant to create a conducting path for the primary discharge. The primary discharge charge of order 100-kA ablates the Teflon propellant and ionizes it. The large current creates its own magnetic field. The current and magnetic field produce a Lorentz body force on the ionized propellant accelerating it out of the thruster. Ablated, but un-ionized propellant is expanded from the thruster due to joule heating from the arc discharge.

One significant advantage of PPTs comes from the use of solid Teflon propellant which eliminates the need for both expensive propellant feed system components (tanks, valves, regulators, etc.) and the safety requirements associated with liquid propellants. The other advantage is the ability to operate at very low power levels. Operational PPTs have ranged in power from 6 to 30 W. The average power and thrust level can be easily adjusted by varying the pulse rate.

Teflon PPTs are currently under development by Olin Aerospace Company for flight application to NASA's New Millennium spacecraft. The goals of this development program are given in Table PPT-II. A photograph of a prototype PPT is shown in Fig. PPT-2. A second PM is being developed for application to 100 kg and larger satellites. The performance of these larger PPTs is also given in Table PPT-II.

LEO-TO-GEO TRANSFER

In the interest of reducing the cost of placing satellites in GEO, the U. S. Air Force (USAF) is conducting a program called the Electric propulsion Space Experiment (ESEX) to demonstrate in space operation of a high-power (26 kW) arcjet. Arcjets, with their I_{sp} in the range of 500 to 1,000s, offer a unique combination of reduced propulsion system wet mass and reasonable LEO-to-GEO transfer times. This can be accomplished at power levels less than 50 kW and satisfy the dual needs of reducing launch vehicle requirements (and thus launch costs) while maintaining a reasonable time for the satellite to reach GEO. ESEX is an in-space experiment intended to provide data and operating experience with a high-power ammonia arcjet, thereby providing a significant impetus to the development of an electric propulsion Orbit Transfer Vehicle²⁴. With the advent of improved, lightweight thermal insulation for cryogenics, it is expected that the ammonia (NH₃) used in the ESEX

experiment would be replaced by liquid hydrogen (LH₂) so that the improved performance offered by LH₂, an I_{sp} of approximately 1,200s, can be realized,

ESEX (Figure ETO- 1) is a 26 kW NH₃ arcjet system composed of four subsystems: the propulsion subsystem, the diagnostics subsystem, the command and control subsystem, and the power subsystem. It is scheduled to be launched in February, 1997 on the ARGOS (Advanced Research and Global Observation Satellite). The arcjet will be operated ten times. Each operation will consist of a 15 min. thrusting period followed by 100 hours to thermally condition and recharge the batteries. The ESEX experiment has two objectives: "The first is to develop reliable flight hardware which will successfully complete a test firing in space. The second objective is to gather data on key spacecraft integration issues, verifying that a high power arc plasma source can operate without adversely affecting a spacecraft's nominal operations."²⁵

The ESEX experiment successfully completed its qualification tests. These tests consisted of 14 arcjet firings, called the Integrated Mission Simulation, for a total operating duration of 164 min. The first firing, of 10 min. duration, used facility power to determine EMI effects on the flight-design controller. The remaining 13 tests were conducted using batteries and the ESEX power conditioning unit. During these tests the arcjet demonstrated an I_{sp} of 800 (799 ± 17) s at an efficiency of 27.2 ± 1 %.²⁶

ESEX is a \$22 million effort that is funded by the USAF Phillips Laboratory. The prime contractor for the experiment is TRW. The propulsion subsystem was designed and fabricated by Olin Aerospace. CTA Space Systems is responsible for the design and fabrication of the other major systems. Integration of ESEX onto ARGOS is scheduled to begin in February, 1996²⁷

PLANETARY EXPLORATION

Missions beyond the region of the Earth and its moon require much more propulsive capability than that associated with spacecraft that remain within the gravitational influence of the Earth. In addition to the energy required to inject the spacecraft onto an interplanetary trajectory, energy is often added to shorten trip time. Additional propulsion is needed to match spacecraft velocity to that of a target asteroid or comet in the case of small body rendezvous missions. Missions to orbit a spacecraft about a planet or extraterrestrial moon require additional propulsive capability. Generally, the more impulse a planetary mission requires, the more it will benefit from the advantages provided by the high I_{sp} offered by electric propulsion. These considerations lead to the conclusion that planetary missions benefit most from the forms of electric propulsion that offer the highest efficiency and I_{sp}²⁸. Of the forms of electric propulsion offering high efficiency and I_{sp}, ion propulsion is closest to application. With the advent of advanced, lightweight solar arrays, of efficient, low-mass circuits for power processing, and lightweight flow control components, it became apparent that ion propulsion offered planetary missions the opportunity to use smaller (hence less expensive) launch vehicles, to complete their missions in less time, and still deploy the same functional capability at the target body as their chemically propelled counterparts^{29,30,31}.

With this stimulus, NASA decided to make ion propulsion available for planetary exploration and initiated the NSTAR (NASA SEP Technology Application Readiness) program. NSTAR will use ground tests to demonstrate the life and performance of an ion propulsion system based on a 30-cm diameter, 2.3 kW gridded, ring-cusp ion thruster. A photo of the Engineering Model Thruster just prior to the start of the 8,000-hour, full-power Life Demonstration Test is shown in Figure PE- 1. An in-space determination of the

interactions of the ion propulsion system with its host spacecraft will be made on one of the NASA New Millennium Program's technology demonstration missions, currently planned for early 1998³². The thruster and power processor for this in-space demonstration are being provided by Hughes Electron Dynamics Division and the Xenon propellant storage, and control system by Moog, Inc. Space Products Division. At the completion of the NSTAR Program, it is expected that this equipment will form the basis for a commercially available ion propulsion system. NSTAR is managed by JPL and jointly conducted by LcRC and JPL.

CONCLUSIONS

A significant step in the evolution of space propulsion seems near at hand. The commercial advantages of electric propulsion for Earth-orbiting satellites is apparent. Arcjets supplied by Olin Aerospace for communications satellites produced by Lockheed-Martin have significantly improved the payload and lifetime of those satellites. Significant efforts have already been undertaken to improve the performance and increase the power handling ability of those hydrazine arcjets. At the same time Hughes is working to field 13-cm Xenon ion thrusters as part of their XIPS system for GEO communications satellites. The first in-flight use of such a system is planned for the end of 1995. The importance of ion propulsion for these applications is pointed up by Japan's demonstration of an ion propulsion system in 1995 and by the United Kingdom's plan to demonstrate such a system in 1996. Further, NASA is working to validate a 2.5 kW Xenon ion propulsion system for planetary exploration, a program which will demonstrate such a system in 1998 as part of the NASA New Millennium Program. As these programs proceed, the U. S. Ballistic Missile Defense Office (BMDO) is conducting with Loral an evaluation of Russian-built Hall-effect thrusters, which offer promise for LEO-to GEO orbit transfer and for station keeping for GEO satellites. In all these cases, significant amounts of commercial and government resources are being expended to develop and demonstrate the capability offered by electric propulsion,

It is this commercial involvement that represents a significant change from the 1960's and even the early 1990s. While building on the base provided by government investment in advanced electric propulsion technology, these commercial interests are focusing on the specific needs of their firms for applications in Earth orbit. It is this private investment that provides the real reason to expect growth in the application of electric propulsion in the near-term. This is at some variance with earlier expectations that government spacecraft would be the first to accept the risks associated with the use of electric propulsion. It has turned out that the pressures of competition have induced private satellite manufacturers to incorporate electric propulsion in their designs so that the improved payload, functional capability, and lifetime that electric propulsion permits can be used for competitive advantage. Electric propulsion will be applied to government spacecraft after it has been used on commercial satellites. For planetary exploration, the unique, demanding requirements imposed on electric propulsion are being addressed by a government-sponsored technology validation program with industry involvement, leading to its application to future planetary missions.

Today electric propulsion is poised to revolutionize spacecraft propulsion for a great many missions. The number and variety of commercially funded and co-funded demonstration programs allows us easily to foresee the time when the overwhelming majority of earth-orbiting spacecraft use electric propulsion to meet on-board propulsion requirements. The same revolution will lead directly to the use of electric propulsion for primary propulsion for planetary missions.

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