30 Years of Electric Propulsion Flight Experience at Aerojet Rocketdyne

IEPC-2013-439

Presented at the 33rd International Electric Propulsion Conference,
The George Washington University • Washington, D.C. • USA
October 6 – 10, 2013

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Abstract: **Flight experience for Electric Propulsion (EP) supplied by Aerojet since the first launch of Aerojet's Electrothermal Hydrazine Thruster in 1983 is reviewed. In total, over 210 spacecraft have flown one of four different EP technologies provided by Aerojet: resistojets, arcjet systems, a pulsed plasma thruster system, and Hall thruster systems. The flight systems include over 100 power processing units of seven different designs and over 500 individual thrusters, as well as propellant management hardware. The development history and basic characteristics of each flight system are reviewed. This survey discusses the application of Aerojet's flight systems in the context of the historical use of electric propulsion flight programs worldwide. Roughly two-thirds of all currently operational spacecraft with EP are flying Aerojet electric propulsion. The usage of total spacecraft flying EP and user type by year is traced. Additionally, trends in the major characteristics of EP bearing spacecraft, such as orbit, mass and power, are discussed. Finally, future developments in electric propulsion at Aerojet and trends in electric propulsion in general are discussed.**

I. Introduction

ELECTRIC Propulsion (EP) for spacecraft was first proposed as long ago as the early 20th century by rocketry pioneers such as Robert Goddard and Konstantin Tsiolkovskiy, although broad and systematic research in the area did not begin until the 1950s with Ernst Stuhlinger.[1] The rapid pace of spacecraft technology development in the 1960s engendered an over-extrapolation of many capabilities, including that of available spacecraft power, for which 100s of kilowatts to multiple megawatts of power were envisioned within a few short years, especially for human exploration. These expectations led to significant amounts of early research on very high power electric propulsion. However, by 1965, much of the research into high power thrusters began to wane as it became clear that space nuclear power sources were going to be heavier and take longer to develop than had been assumed.

The first application of electric propulsion beyond suborbital tests occurred on December 14, 1964 with the firing of an ablative Pulsed Plasma Thruster (PPT) on the Soviet Zond-2 mission to Mars.[2] The thrusters were used

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for attitude control but at a very modest power consumption of less than 100W. In the 16 years up through 1980, electric propulsion was flown only on three dozen missions, not counting sub-orbital tests, a third of which were for short experimental missions and the rest were for early military applications, such as weather, navigation and early warning. Of these early EP missions, two-thirds were resistojets, i.e. electrothermally augmented with resistive heaters. In keeping with power levels available on early spacecraft, these electric propulsion systems were of very low power, with most under 100 W and almost all no more than a few hundred Watts.[3]

Meanwhile, by the late 1960s, monopropellant hydrazine thrusters were becoming more widely used due to their simplicity compared to hypergolic bipropellant engines. However, monopropellant thrusters suffered from a somewhat lower performance than bipropellants. In a 1967 study, Yvonne Brill of RCA (now part of Lockheed Martin) proposed using electrothermally augmented (resistojet) hydrazine thrusters for geosynchronous communications spacecraft. This would boost the performance of the monopropellant thruster to over 300s specific impulse, a level competitive with bipropellant thrusters. Her study also showed the electrothermally augmented hydrazine thruster system to be mass competitive with a combined unaugmented hydrazine thruster / mercury ion engine system.[4]

In 1981, TRW-designed electrothermally augmented hydrazine thrusters were first operated on the Intelsat 502 geosynchronous communications spacecraft for North-South StationKeeping (NSSK). Although they were the first use of electric propulsion in a commercial application, the thrusters suffered from significant life limitations inherent in their design and were not flown again after the Intelsat V series.

In April, 1983, an Aerojet Rocketdyne (AR) Electrothermal Hydrazine Thruster (EHT) of a fundamentally different design was fired for the first time on board the SatCom1R (G) spacecraft, also for NSSK. This represented the first use of Aerojet Rocketdyne electric propulsion. It also coincided with the beginning of widespread use of electric propulsion.

II. Electric Propulsion Technologies at Aerojet Rocketdyne

In the past 30 years, Aerojet Rocketdyne has done significant work in five electric propulsion technologies: electrothermal thrusters (resistojets), arcjets, ablative pulsed plasma thrusters, gridded ion engines, and Hall thrusters. To date, AR has provided flight systems for each of these types of EP except for gridded ion engines. In total, over 210 spacecraft have flown over 550 AR thrusters with over 100 AR designed and built PPUs of seven designs.

A. Electrothermal Thrusters (Resistojets)

Resistojets using electric heaters to augment the specific impulse of nitrogen or ammonia propellant were used on a handful of satellites, starting in 1965 with the Vela-1 satellite.[5] After being first proposed in 1967, work on hydrazine resistojets was conducted throughout the 1970s by TRW[6] and AVCO.[7] In the early 1980s Aerojet Rocketdyne (then Rocket Research Company) was selected by RCA to provide resistojets for North-South Station Keeping (NSSK) for their new geosynchronous (GEO) communication satellite series. In only 18 months, AR developed, qualified and delivered its first such electric propulsion thrusters. The MR-501 Electrothermal Hydrazine Thrusters (EHTs) were fired for the first time in orbit in April, 1983 on Satcom 1R.[8]

The design of the MR-501 provides reliable operation for lifetimes required for GEO satellites by successfully addressing the shortcomings of earlier designs that significantly limited their life and throughput. In 1987, AR qualified an uprated design, the MR-502 (Figure 1). This thruster provides up to 0.8N thrust with up to 885 W at 303 s specific impulse for 525 kN-s total impulse.[9] After the TRW thrusters on Intelsat V, the AR thrusters are the only other electrothermally augmented hydrazine thrusters ever flown. MR-502s are still being used on GEO spacecraft, and either the MR-501 or MR-502 have been in continuous production for the past 30 years. Over 150 spacecraft, including all 95 Iridium, have been launched with AR electrothermal hydrazine thrusters, making them the most prolific form of EP to date.

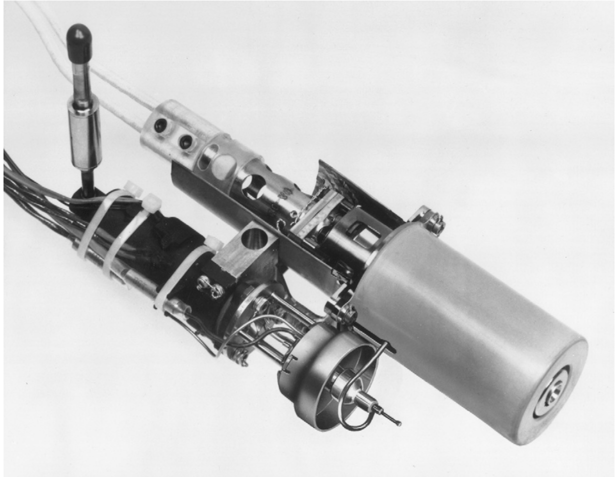


Figure 1. MR-502 Improved Performance Electrothermal Hydrazine Thruster (IMPEHT).

B. Arcjet Systems

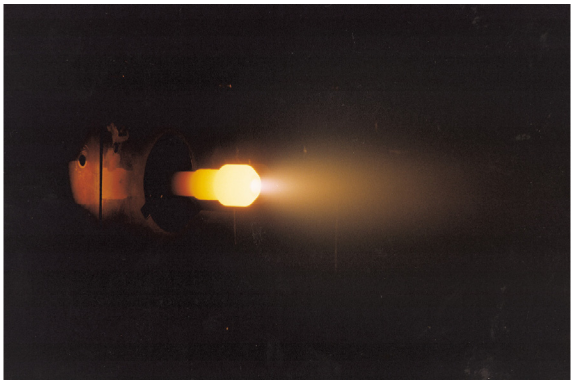


Figure 2. MR-510 2kW Hydrazine Arcjet.

As EHTs gained acceptance and as spacecraft mass and power levels increased through the 1980s, the need grew for better performance than the EHT could deliver. Hydrazine arcjets had been proposed as early as 1962.[10] However, little work was done until the late 1980s when development began at NASA Glenn Research Center and Rocket Research Company (now AR).[11]

Development of the first flight design was conducted in the early 1990s under AR, NASA, and Lockheed Martin funding. The first ever hydrazine arcjet was launched in 1993, providing over 500s mission average specific impulse at 1.6 kW per thruster for NSSK of the Telstar 401 spacecraft. The flight arcjet system included four thrusters and their four dedicated power conditioning units (PCUs) per shipset. Both the thrusters and the PCUs were qualified and built at AR.

A subsequent upgrade to the arcjet system, the MR-510 (Figure 2), now flies on the Lockheed Martin A2100 spacecraft, providing over 585 s mission average specific impulse at 2 kW into each thruster for a life time of 1730 hours and a total impulse of 1.45 MN-s per thruster.[12,13] In the MR-510 configuration, a single PCU per spacecraft, also built by AR, powers any two of four to eight arcjets. All told, AR hydrazine arcjets have been fired for over 60,000 hours in orbit.

In 1992, under funding from the Air Force and TRW, AR began work on a high power ammonia arcjet system called the Electric propulsion Space EXperiment (ESEX). The purpose of the program was to collect on orbit data to address questions associated with operation of arcjets in space, especially at high powers. AR designed, built and qualified the thruster, PCU and propellant feed system. ESEX flew in 1999 with a suite of diagnostics, logging just under an hour of firing time. The system provided just under 2N thrust at approximately 800s specific impulse at 26 kW, making it the most powerful electrical system of any type ever operated steady state in space at that time and the most powerful EP system to the present.[14]

C. Pulsed Plasma Thruster

The attraction of ablative Pulsed Plasma Thrusters (PPT) is their ability to provide small, controlled impulse bits in a self-contained package with indefinitely storable solid propellant and a simple spacecraft interface. With these attributes, PPTs have been used for attitude control, constellation maintenance, and precision station keeping. Starting with the 1964 Zond-2 flight there have been at least nine orbital or deep space flights with PPTs prior to 2000, most of which were experimental applications. However, the three NOVA spacecraft in the 1980s were operational Navy navigation spacecraft that were the precursor to today's Global Positioning System. The PPTs were highly successful in providing drag compensation by maintaining the spacecraft's position with millimeter precision relative to free-flying test masses enclosed inside the spacecraft.

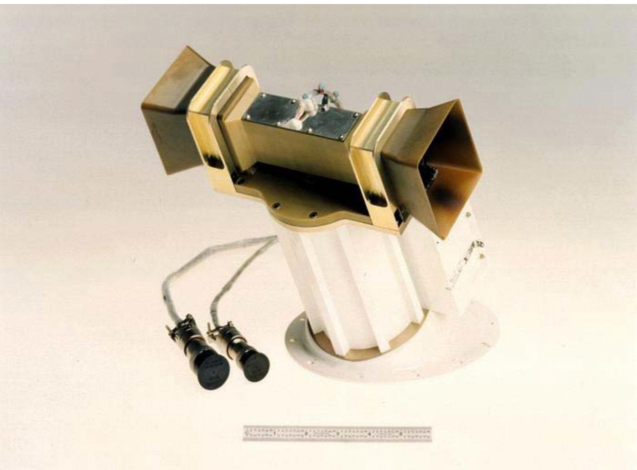


Figure 3. Earth Observing-1 Pulsed Plasma Thruster.

In the 1990s, the growing use of smaller spacecraft with a need for simple, and in some cases precise, station-keeping and attitude control led to a resurgence of interest in PPTs. Under contract to NASA Glenn Research Center within NASA's New Millennium technology development and demonstration program, AR developed a PPT (Figure 3) for the first all-propulsive precision attitude control demonstration, flown on the Earth Observing-1 (EO-1) test bed spacecraft. In the first on orbit demonstrations in early 2002, the EO-1 PPT controlled the attitude in the pitch axis with the pitch momentum wheel disabled for as long as 9 hours at a time. Telemetry showed pitch control comparable to or better than that of the momentum wheel. Images of the ground taken with the Advanced Land Imager have shown equal clarity to those take during wheel operation and no detectable interference with the instruments.[15]

Although widespread application of the PPT has yet to materialize, their simplicity, safety, and ability to be miniaturized make them increasingly attractive for small spacecraft, especially those built by universities. Additionally, notable wheel failures on such high profile spacecraft as Hayabusa and Kepler sustain interest in PPTs as a wheel replacement.

D. Gridded Ion Engines

Extensive research and development of gridded ion engines has been conducted since the early 1960s, including work at AR (then Rocketdyne) for NASA with mercury ion engines. However, only half a dozen experimental flights were made through 1980 and these all used mercury or cesium as propellants. None of these used AR hardware. In the 1980s, the propellant of choice became xenon due to the environmental and handling difficulties of mercury and cesium. However, the first commercial use of gridded ion engines did not occur until 1997 with an L-3 Communications (then Hughes) XIPS-13 ion engine system. Then, in 1998, the NASA Solar electric propulsion Technology Applications Readiness (NSTAR) ion propulsion system was flown quite successfully on NASA's Deep Space One mission, demonstrating the great potential for xenon gridded ion engines to enable ambitious science missions.[16]

In 1995, Aerojet Rocketdyne began work to develop, qualify and fly the Plasma Contactor Unit for the Space Station (ISS). Although not a propulsive application, the NASA GRC-built Hollow Cathode Assembly (HCA) is identical to the design of the neutralizer cathode used on the NSTAR engine. AR built the power electronics and xenon feed system and integrated them with the HCA into the entire flight PCU system that is installed and continues to be operated on ISS.[17]

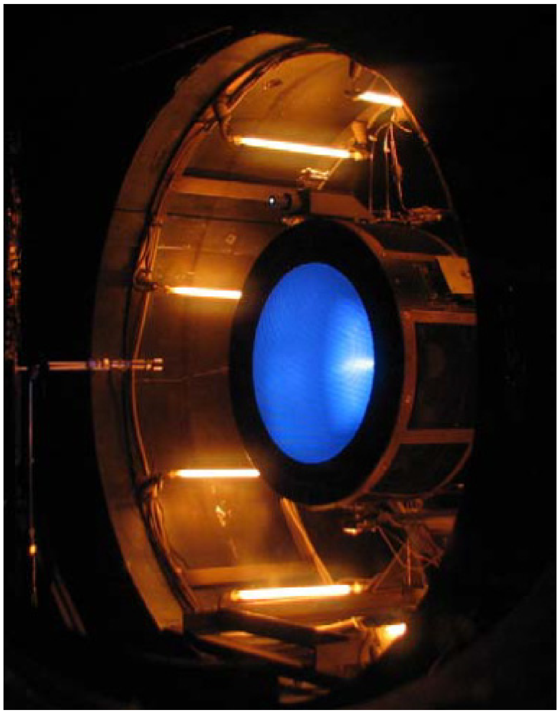


Figure 4. The Aerojet Rocketdyne-produced NEXT Ion Engine Successfully Completing Thermal Vacuum Tests at JPL.

In 2002, Aerojet Rocketdyne was selected as a co-investigator on a NASA Glenn Research Center (GRC)-led team, also including the Jet Propulsion Laboratory (JPL) and L-3 Communications Electron Technology Inc. (L-3ETI), to develop the NASA Evolved Xenon Thruster (NEXT) ion propulsion system (IPS). The project was sponsored by the NASA Science Mission Directorate and conducted under the In-Space Propulsion Technology Program. The 7 kW NEXT system built on the success of 2.5 kW NSTAR system, while addressing its limitations and extending its capability. NEXT technology is applicable to a wide range of NASA solar system exploration missions, as well as earth-space missions of national interest. The performance of the NEXT system affords larger delivered payloads and smaller launch vehicle size, and is even enabling for some particularly ambitious missions.[18]

The five elements of the IPS developed under the NEXT project were the thruster, xenon Propellant Management System (PMS), Power Processing Unit (PPU), Digital Control Interface Unit (DCIU), and gimbal. The objectives of the project were to develop the thruster, PMS and PPU to a Technology Readiness Level 6 (TRL6) and to transfer the NASA technology to industry partners, AR and L-3ETI, in order to facilitate the manufacturing of future flight systems. AR had primary responsibility for the thruster, PMS and DCIU, while L-3ETI had primary responsibility for the PPU. However, the project was structured so that each teammate was involved in the development of each element, making each teammate independently capable of producing every element of the NEXT system.

The AR thruster and PMS designs addressed several limitations of the NSTAR design, particularly the ion optics aperture uniformity, alignment and grid gap stability. After delivery of the AR built engineering model thruster and PMS hardware, each component was tested in relevant qualification level environments (Figure 4). The successful completion of this testing advanced the thruster and PMS to TRL 6 at the subsystem level. Other than a single rework of the discharge cathode to bring ignition times within family, all thruster performance parameters duplicated the GRC thruster baseline performance in the "as received" condition in the first performance test block. The AR-built thruster was subsequently operated for a 2000 hour endurance test, demonstrating stable performance in all critical parameters. This significant achievement demonstrated the effectiveness of the transfer of critical thruster technology from NASA to AR.[19,20]

Additionally, an AR-built optics assembly attached to a GRC-built discharge chamber recently completed a record breaking 48,000 hour endurance test in excellent working condition, exceeding the life and throughput requirements of any mission contemplated for the NEXT system. The successful demonstration of such extreme life capability was enabled in part due to the AR design improvements to critical optics assembly parameters.[21]

While the PPU has had failures of capacitors in its beam supply control circuit, preventing it from completing TRL 6 environmental testing to date, the root cause has been identified, thoroughly investigated and resolved. AR is confident that an engineering model PPU of the present design will pass qualification level environments and attain a TRL 6 rating, should funding for the effort become available.

AR has yet to fly gridded ion engine technology. However, based on the success of the AR thruster and PMS design, the access to the complete set of PPU development data, and AR's unmatched experience with electric propulsion power processing, AR looks forward to producing entire NEXT systems, including PPUs, for future NASA missions. Additionally, Aerojet has entered into agreements with NEC of Japan to provide the Hayabusa-based MIU-10 and with QinetiQ of the UK to provide the T6 based XENITH™ ion engine systems.

E. Hall Thruster Systems

Various schemes for utilizing the Hall Effect to accelerate heavy ions, such as those of xenon, were first investigated in the 1960s in both the US and the Soviet Union. Research into Hall Effect thrusters was effectively abandoned in the US in the early 1970s in favor of gridded ion engines. However, robust development of Hall thrusters in the Soviet Union continued, with the development of two main types of such thrusters, Stationary Plasma Thrusters (SPT) and Thrusters with Anode Layer (TAL). The first firing of a Hall thruster in space was a test flight of SPT-60 thrusters, built by the Experimental Design Bureau "Fakel", on the Meteor-10 spacecraft in 1972.[2, 22] Hall thrusters of the Fakel Stationary Plasma Thruster family flew on a total of at least seventeen more Soviet spacecraft prior to 1994.

In the early 1990s, as the Soviet Union disbanded, Russian agencies such as Fakel, Tsniimash, and Keldysh began to market their Hall thruster technology, essentially unknown in the West, outside of Russia. Several US and European entities began working with different Russian organizations to develop, qualify and fly Russian Hall thruster technology.

For nearly twenty years, since 1994, AR has been developing Hall thruster systems targeted at the LEO and GEO marketplace. These efforts began with the development, qualification, and integration of a Hall thruster system for NASA GRC using a 1.5 kW D-55 Hall thruster of the TAL family, built by Tsniimash. In addition to providing integration and testing of the system, AR designed, built and qualified the PPU, one of AR's seven flight-proven PPU designs. In 1998, the system was flow by the National Reconnaissance Office (NRO) on the Space Technology EXperiment (STEX), becoming the first flight of a Hall thruster on a Western spacecraft.[23] Work with Tsniimash continued for some time after that, within the then Rocketdyne portion of AR.

Starting in 1997, AR (then Primex), in partnership with the Busek Company, began development of the BPT family of thrusters of a "clean sheet" design wholly indigenous to the US and targeted for use on US military spacecraft, as well as commercial spacecraft. Laboratory designs of the 2 kW BPT-2000 and 4 kW BPT-4000 were manufactured and extensively tested at JPL and AR test facilities, including three successful accelerated life tests that indicated life capabilities in excess of 6000 hrs.[24] Aerojet Rocketdyne patented design improvements[25] on a scaled up 4.5 kW BPT-4000 further increased life capability and were ultimately proven to reduce the erosion rate to zero after a certain amount of wear but before reaching the magnetic pole, effectively eliminating ring erosion as a life limiting factor.[26]

Simultaneously to the thruster development effort, AR also developed, as part of an internal technology development program, a low-cost hollow cathode based on the NASA Space Station Plasma Contactor, a

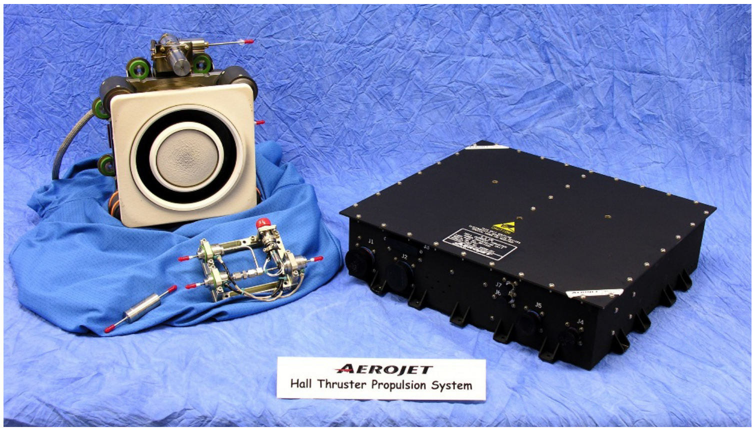
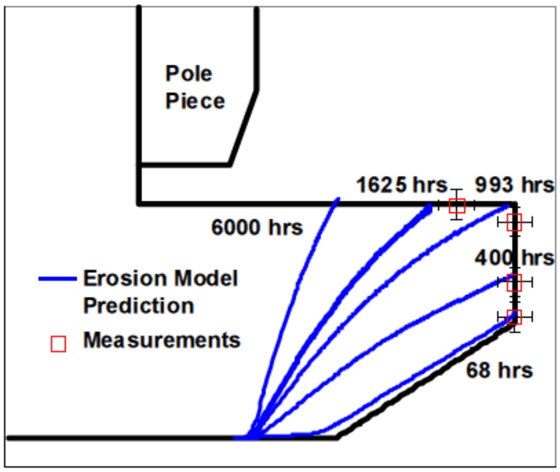


Figure 5--A Single String of the 5 kW Class BPT-4000 (XR-5).

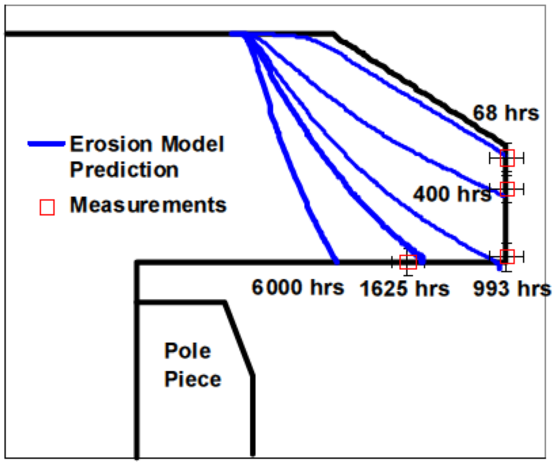
Xenon Flow Controller (XFC), and a breadboard Power Processing Unit (PPU). The PPU drew heavily from the AR Hall thruster PPU successfully flown on STEX. In late 1998, these components were tested together, along with a laboratory model BPT-4000, as part of an integrated Hall thruster system.[27]

In 2000, these efforts led to a long term agreement between AR and Lockheed Martin Space Systems Company (LMSSC) to develop jointly a 4.5 kW flight Hall Thruster Propulsion System (HTPS) for next generation LMSSC geosynchronous spacecraft. For HTPS, AR has been responsible for the development and qualification of the thruster, PPU, XFC, and all associated integration tasks between these components. LMSSC has had responsibility for the xenon tanks, the Xenon Feed System (XFS) and all spacecraft level integration tasks.

The multi-mode, flight weight BPT-4000 (now designated the XR-5) Hall thruster is based on the successful 4.5 kW BPT-4000 lab thruster and also leverages other work done under funding from NASA GRC on the development of multi-mode Hall thrusters to provide improved performance over a wide range of voltages.[28] Unlike previous Hall thrusters, which were qualified for a single design point, the BPT-4000 (XR-5) was qualified to operate at power levels from 3.0 to 4.5 kW and at both 300 and 400 V discharge voltages. This multi-mode capability provides flexibility to optimize mass and cost savings by allowing low voltage, high thrust operation for reduced trip times during orbit raising and high voltage, high Isp operation for station-keeping. AR has successfully completed design, fabrication, and qualification of the PPU, XFC, and thruster, as shown in Figure 5, including extensive testing on the integrated system to demonstrate start-up, flow control loop stability, and EMI/EMC compliance.



Outer Ring



Inner Ring

Figure 6. Comparison of in Situ Optical Measurements and Model Predictions for Erosion of the Insulator Rings of the BPT-4000 (XR-5) thruster

In 2001, Lockheed Martin was awarded a development contract from the Air Force for the Advanced Extremely High Frequency (Advanced EHF) satellites as the successor to the Milstar system. After HTPS was selected as part of the propulsion system, built, tested and delivered the first three shipsets between 2007 and 2009.[26] Except for the brief experimental flight of AR's ESEX arcjet system, the BPT-4000 (XR-5) system joins the XIPS-25 ion engine system as the highest power electric propulsion systems ever flown.

On October 24, 2011, following initial perigee raising maneuvers by AR's 22N hydrazine thrusters, the BPT-4000 (XR-5) system completed unplanned maneuvers to perform nearly all of the orbit acquisition of AEHF Space Vehicle-1 (SV-1) from Geosynchronous Transfer Orbit.[29] AR has recently been put under contract by LMSSC to provide BPT-4000 (XR-5) system components for AEHF SV-4 through 6.

Subsequent to the baseline qualification of the BPT-4000 (XR-5) system at 3.0 and 4.5 kW, performance map extensions have been completed that demonstrated stable operation and good performance as low as 1 kW and as high as 2700s specific impulse at 5.5 kW.[30] Additionally, two life test extensions have been conducted, demonstrating a total of 10,400 hours of firing time, 7316 starts, 452 kg of xenon throughput and 8.7 MN-s of total impulse. The tests were voluntarily terminated with the thruster in excellent working condition. The thrust and specific impulse performance stayed within a range no greater than 5% over the entire test and significantly less than that after the first 2000 hours. The erosion profiles closely followed predictions of AR's widely validated erosion model (Figure 6). And most importantly, no measurable erosion occurred between 6700 hours and 10,400 hours (Figure 7) while the erosion surface was well short of the magnetic pole piece.

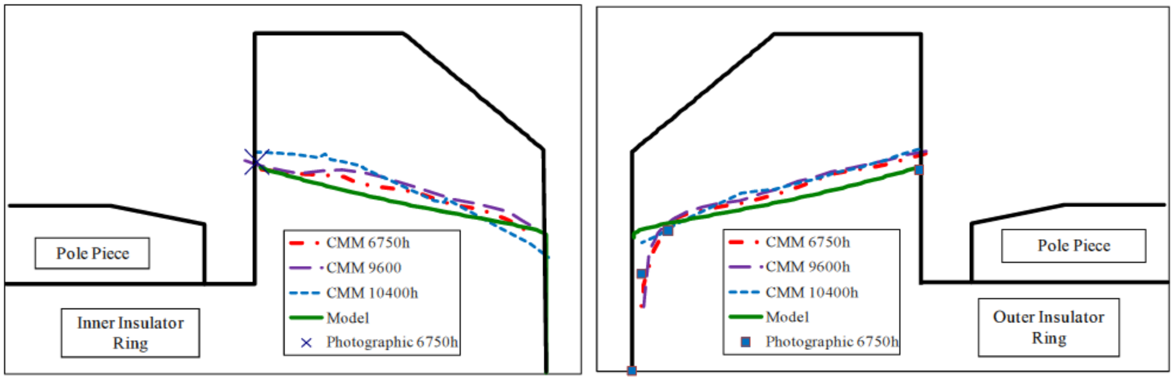


Figure 7. Comparison of Insulator Erosion Profile Measurements and Model Predictions for the Insulator Rings of the BPT-4000 (XR-5) thruster after 6750 Hours of Operation

Beyond the application of the BPT-4000 (XR-5) to AEHF, AR continues to work toward providing that system for other commercial and military Earth-space missions, as well as selected NASA science missions. First, AR is now licensed to provide the flight proven Russian SPT family of Hall thrusters with power levels of 1350W and below. Additionally, since 2007, Aerojet Rocketdyne has been working with NASA GRC on the HiVHAC program to develop a 4 kW class, low cost, high specific impulse, extremely long life Hall thruster system for NASA science missions. These thrusters have a life extending innovation that has already demonstrated >5000 hours operation and is projected to provide a xenon throughput of at least 300 kg, which corresponds to a life time of at least 15,000 hours at full power. [31] AR has developed the engineering model thruster design and delivered two thrusters. Tests at NASA GRC have demonstrated up to 2700 s specific impulse at an efficiency of 58%.[32]

Aerojet Rocketdyne has established the design principles to create "Zero Erosion™ Hall thrusters" that scale up from the XR-5. In 2009, AR successfully completed an extensive demonstration of a 10 kW-class XR-12 Hall thruster system, developed by AR and Lockheed Martin as part of the Transformational Satellite Communications System (TSAT) space segment team. The system, including thruster, PPU and xenon flow control, was developed for both orbit transfer and on-orbit station keeping of large communications satellites and is now at TRL 4-5. 400 hours of endurance testing showed erosion rates consistent with modeled lifetime total impulse of 20 MN-s and 1100 kg xenon throughput. Performance testing demonstrated up to 800 mN thrust at 12 kW thruster input, 2000 s specific impulse, and a corresponding total efficiency of 65%, significantly better than the performance even of the BPT-4000 (XR-5). The system also demonstrated 2200 seconds at 4.5 kW for use in station keeping. Since then, Aerojet Rocketdyne and NASA Glenn Research Center have explored the use of the XR-12 for NASA exploration missions.[33]

AR has also been investigating scaling the proven performance and life capabilities of the XR-5 up to a 20 kW class Hall thruster under Air Force funding. In conjunction with this effort, AR has demonstrated modular power processing modules that have flexible input voltages from 70 to140 V and 170 to 220V in order to be compatible with a range of commercial spacecraft as well as future, high power NASA and military missions. The modules have an output voltage from 150 to 400 V and can be configured in parallel or series to cover a wide range of power and specific impulse for Hall thrusters and gridded ion engines, including the XR-5, XR-12 and XR-20, HiVHAC, and NEXT. Such flexibility will greatly reduce the NRE cost and schedule by applying the identical module design to a large number of future missions, greatly reducing their recurring cost as well.[34]

III. Global Trends in the Application of Electric Propulsion

After the period of infrequent experimental and operational military flights throughout the 1960's and 1970's, the "Era of Application" for EP began in the early 1980's. Starting with the first flight in 1983, Aerojet Rocketdyne Electrothermal Hydrazine Thruster (EHT) resistojets became the standard North-South station-keeping (NSSK) propulsion for the RCA (now part of Lockheed Martin) Series 3000 and Series 5000 spacecraft buses, as well as some Series 4000 GEO buses. This led to a steady increase in the number of spacecraft flying with EP throughout the 1980's and into the early 1990's. Also at this time, Russian communications and data-relay spacecraft were beginning to fly EP operationally. Both the Luch (Altair) and the Luch (Gelios) flew Fakel SPT-70 Hall effect thrusters in the mid-1980's to early 1990's.

The steady growth in cumulative numbers of satellites with EP through-out the late 1980's and into the early 1990's is evident in Figure 8. In 1993, the first hydrazine arcjet flew on the Telstar 4 spacecraft (a Lockheed-Martin Series 7000 bus), which led to a whole new series of spacecraft using EP. Meanwhile Hughes (later Boeing, now L3-ETI) had been developing an ion engine system for over a decade. The increasing use of arcjets for advanced NSSK performance on Lockheed spacecraft prompted Hughes (Boeing) to design their BSS-601HP bus with the first generation Xenon Ion Propulsion System, the XIPS-13. The first XIPS system flew on PanAmSat 5 (later renamed Badr C) in 1997. At the same time, Orbital

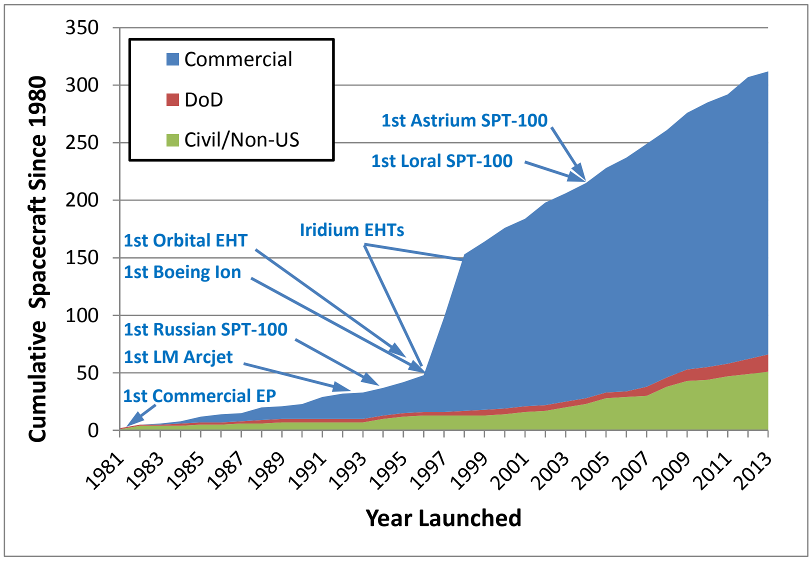


Figure 8. Cumulative Number of Spacecraft Using EP.

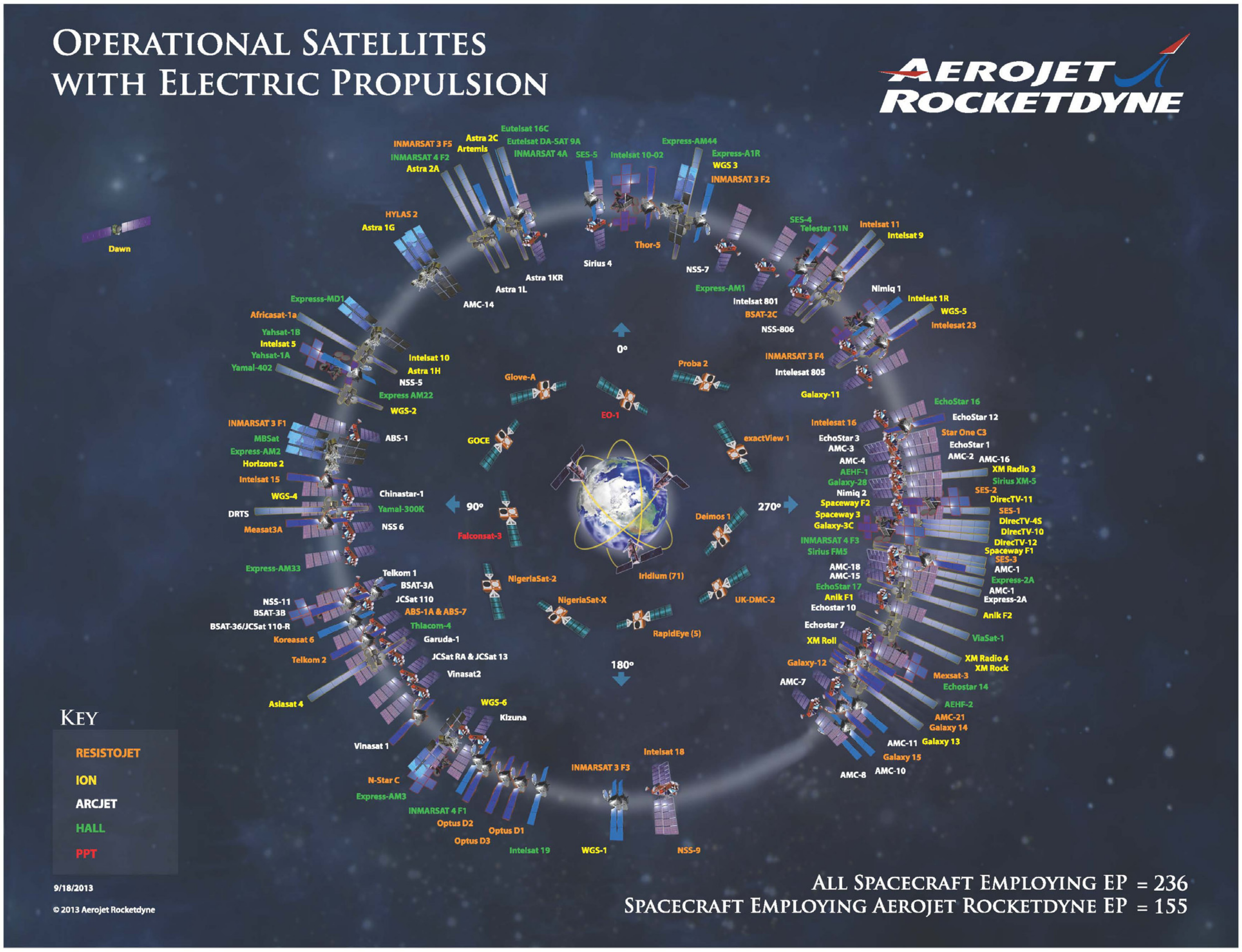


Figure 9. Operational Spacecraft with Electric Propulsion

entered the GEO communications satellite market with their Star bus using AR MR-502B IMPEHT resistojets for station-keeping. This marked a milestone as three Western satellite primes were then flying EP on their communications satellite buses.

The major discontinuity in Figure 8 at about that time results from the 86 LM-700 spacecraft launched in the 2 years from 1997 to 1998 for the Iridium Low Earth Orbit (LEO) satellite constellation. In all, 95 spacecraft were launched by 2002. Each spacecraft flew a single EHT resistojet for orbit trim and deorbit maneuvers.

After the step in cumulative spacecraft due to Iridium, resistojets, arcjets, and ion engines continued to be launched on an increasingly frequent basis on Orbital Star 2, LM A2100™, and BSS-702 spacecraft, corresponding to a clear increase in the slope of Figure 8.

In Russia, 1994 marked the advent of the use of the Fakel SPT-100 Hall effect thrusters on the GALS-1 spacecraft. This was significant not only because of the use of the higher power thrusters (1350W vs. 650W for the SPT-70) on a Russian spacecraft, but also because it was used as a part of an evaluation program with France's SEP and the US satellite builder Space Systems/Loral (SS/L). Eventually this evaluation led to the use of the SPT-100, or its derivative PPS-1350, on European satellites, starting with Intelsat 10-02 in 2004. The same year, SS/L launched MBSat1, their first LS-1300 with SPT-100s, bringing to five the number of Western primes, in addition to Russia, that regularly flew EP on their GEO satellites.

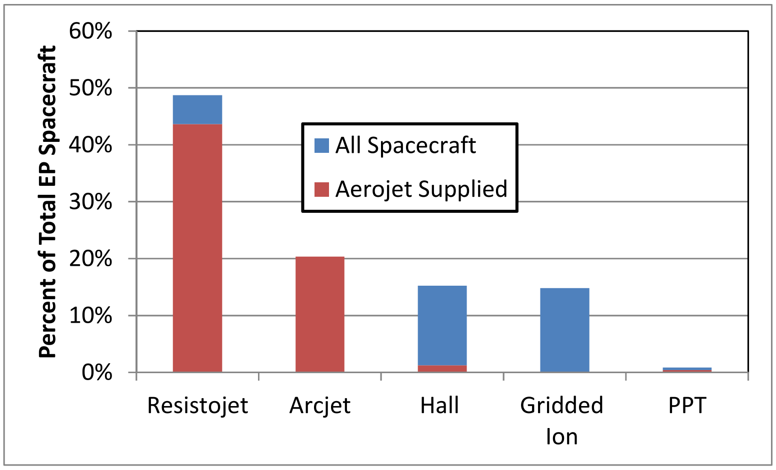


Figure 10. Breakdown by Type of EP on Operational Spacecraft.

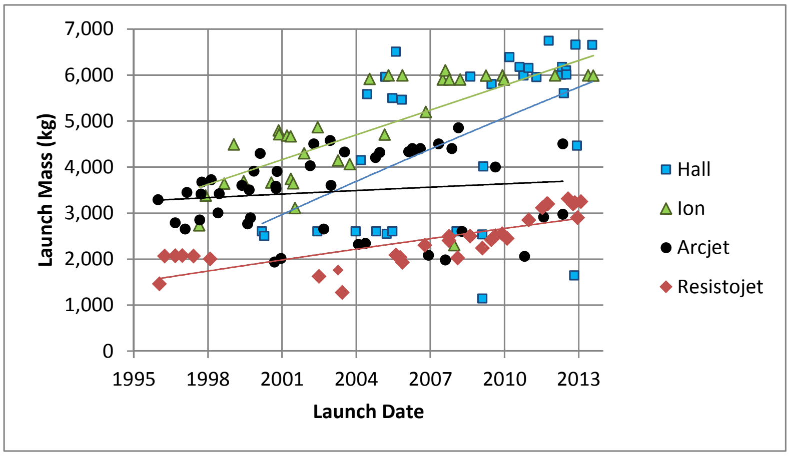


Figure 11. Launch Mass of Operational GEO Spacecraft with EP.

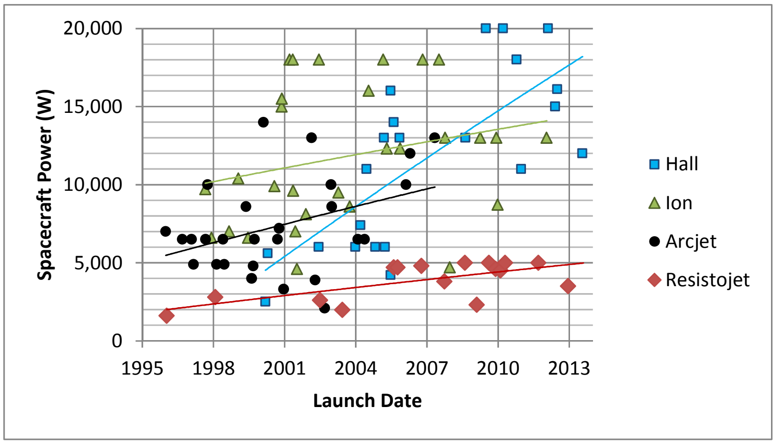


Figure 12. Total Power of Operational GEO Spacecraft with EP.

After the NASA technology demonstration of the NSTAR gridded ion engine system on Deep Space One in 1998, other notable firsts include the rescue of the European Artemis spacecraft with its ion engine system in 2001. In 2002, AR PPTs demonstrated all-thruster precision attitude control on EO-1, and EP was first used on a Japanese GEO satellite with AR arcjets on Kodama. 2003 saw the launch of the European SMART-1 probe that used a PPS-1350 to spiral all the way to the moon, where it entered lunar orbit and completed a science mission before being intentionally crashed into the lunar surface. 2003 also saw the beginning of the epic journey of the Japanese Hayabusa probe, in which another rescue of a mission by EP was accomplished as ion engines enabled the probe to gather the first ever sample from the surface of an asteroid and return to Earth in a fiery reentry in June, 2010. The first dual asteroid mission, enabled by ion engines on the Dawn spacecraft was launched in 2007. And yet another large, unplanned maneuver enabled by EP was completed by AEHF in 2011, Finally, the very recently launched Inmarsat-4A F4 with PPS-1350 Hall thrusters is the first of the AlphaBus spacecraft jointly developed by ESA and European spacecraft primes that has baselined Hall thruster propulsion.

Although these and other government sponsored firsts continue to demonstrate expanded capabilities for EP systems, pushing its use into new applications, Figure 8 makes it clear that the driver for the widespread use of EP is commercial communications satellites, especially for orbit raising and station-keeping of GEO satellites. As of September 18, 2013, a total of approximately 350 spacecraft have flown EP, including those before 1981. Of this total, roughly 70% have been commercial and every one of them has occurred since 1980. Only 10% have been US military and the majority of those flew before 1981. Approximately 20% of all spacecraft with EP have been civil or non-US of all categories.

There are currently 236 *operational* spacecraft with EP onboard, of which 155 are using Aerojet Rocketdyne EP systems(Figure 9). Figure 10 shows the breakdown in percent of operational spacecraft between type of EP and the proportion of each with AR supplied EP systems. To date most of the EP systems have been resistojet and arcjet systems, and Aerojet Rocketdyne has provided the majority of those. Hall thruster systems are a growing fraction of EP –bearing spacecraft, and AR will provide an increasing fraction those Hall thruster systems.

To look at trends for the application of EP in the future, Figures 11 and 12 plot available data[35] launch mass and total spacecraft power. In order to eliminate variation due to the wide range of spacecraft missions in other trajectories such as LEO or interplanetary, these only plot GEO spacecraft. Note that an estimate of launch mass is available for almost all GEO spacecraft with EP. However, an estimate of spacecraft power is not available for about a third of GEO spacecraft with EP.

Generally, launch mass has increased over time, especially before 2008, for arcjets, Hall thruster, and ion engines. As might be expected for the modest potential benefit from saving mass on station-keeping for smaller spacecraft, the simpler and less expensive resistojets are used only spacecraft approximately 3200 kg or less. Note also that even resistojets are rarely used below the 2 MT class of spacecraft. At the same time, approximately 40 GEO spacecraft under 2 MT for the period shown do not carry any EP, suggesting that the savings from EP for small GEO spacecraft are not generally cost effective. .

For larger spacecraft, the much greater potential savings make the higher performance for the more expensive arcjets, Hall thrusters and ion engines cost effective. Interestingly, there are a few spacecraft below 3.2 MT that still carry arcjets and Hall thrusters. The arcjets are all Lockheed Martin satellites for Asian customers. The Hall thruster systems are all Russian spacecraft, which tend to be much smaller than Western spacecraft. After 2008, almost all Western spacecraft carrying xenon systems are of the 6 MT class, again reflecting the higher payoff and higher cost of such systems. Future market assessments for the application of xenon systems would suggest that they would be an option for few spacecraft below the 6 MT class. The exception would be the advent of all-electric spacecraft with low launch mass but similar dry mass to the larger spacecraft.

The power trends are less clear, in large part due to larger fraction of missing data. However, an increase is unmistakable. in typical power levels from 5-10 kW in the mid-1990s to the large, 10-20 kW, xenon system-bearing spacecraft especially after approximately 2004. It is interesting to note that, despite requiring under 3 kW total for a pair of thrusters for most Hall thruster systems, they are almost exclusively used on spacecraft over 10 kW, with many in the range of 20 kW. This represents significant excess power capacity that can power higher power Hall systems for orbit raising on future spacecraft. Again, resistojets remain in use, but only on relatively small GEOs of 5 kW or less.

These observations suggest a rough bifurcation in future GEO spacecraft between small 3 MT/5 kW class spacecraft and 6 MT/10-20 kW and larger spacecraft. For some smaller spacecraft, resistojets will continue to be cost effective into the indefinite future. Arcjets will continue to trade well for some spacecraft over a range as low as the 3 MT class, up to some limit, possibly in the neighborhood of 5 MT, above which xenon is more cost effective. The larger spacecraft will continue to increase in power to 20-25 kW, over the next few years, although launch mass will continue to be limited by launch vehicles. The higher available power will drive an increasing use of Hall and ion systems and at higher power than SPT-100s. These higher thrust systems will allow more EP orbit raising, although with only partial adoption as new GEO operators will continue to be sensitive to time to orbit. All electric GEOs represent a possible third category of high power, medium mass but highly capable spacecraft. The degree to which these are adopted is again dependent on the mix of operators with time sensitivity.

IV. Conclusion

Electric Propulsion has begun to realize its great promise first envisioned by pioneers of rocketry such as Goddard, Tsiolkovsky, and Stuhlinger. Largely, this was made possible by hard work over many years by dozens of researchers and engineers in laboratories around the world. However, widespread application also required the driving force of a clear economic advantage to the commercial industry, which began 30 years ago with the use of EP for station-keeping on GEO spacecraft. As the Roman philosopher Seneca said in the first century A.D. “luck is what happens when preparation meets opportunity.”

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