

Electric Propulsion Systems Development & Integration Activity at Orbital ATK

IEPC-2017-293

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017*

Michael J. Glogowski¹, Jason W. Pilchuk², Andrea D. Kodys³, Jason M. Molinsky⁴, and Gregory E. Rahal⁵
Orbital ATK, Space Systems Group, Dulles, Virginia, 20166, USA

Mike I. Eskenazi⁶
Orbital ATK, Space Systems Group, Goleta, California, 93117, USA

and

Walter H. Tam⁷
Orbital ATK, Space Systems Group, Commerce, California, 90040, USA

Abstract: Orbital ATK has been actively involved in the development and integration of spacecraft systems and hardware that support the use of electric propulsion over a range of missions for both government and commercial customers. Starting in 1997, Orbital ATK, in collaboration with the Jet Propulsion Laboratory, designed and built the Deep Space 1 spacecraft and, subsequently, the Dawn spacecraft, each of which carried the NSTAR ion thruster for its primary propulsion system. Within commercial satellites, Orbital ATK deployed resistojets on over thirty GEOStar satellites since 1997. The latest upgrade to the GEOStar product line introduces Hall thrusters for orbit raising and in-orbit control. The first two satellites with this ion propulsion system will be launched in 2018 and then followed by the Mission Extension Vehicle (MEV). MEV is the first step at Orbital ATK in the development of space logistics services that will ultimately include higher power SEP systems for cargo transport beyond Earth orbit. This paper provides an overview of the past, present, and future spacecraft systems using electric propulsion at Orbital ATK and discusses the hardware technology under development to enable these systems.

I. Introduction

SINCE its first commercial introduction in 1980 on the Intelsat 502 satellite built by Space Systems/Loral (then Ford Aerospace), electric propulsion has gone from a system used primarily for North South station keeping to one used for all propulsive maneuvering of geostationary satellites as represented by the all-electric 702SP bus from Boeing. Within the space science arena, it has evolved from a system used primarily for technology demonstration

¹ Senior Director, Advanced Product Development, Satellite Systems Division, michael.glogowski@orbitalatk.com

² Principal Mechanical Engineer, Propulsion Engineering Department, jason.pilchuk@orbitalatk.com

³ Principal Mechanical Engineer, Propulsion Engineering Department, andrea.kodys@orbitalatk.com

⁴ Staff Mechanical Engineer, Propulsion Engineering Department, jason.molinsky@orbitalatk.com

⁵ Staff Mechanical Engineer, Mechanisms Department, gregory.rahall@orbitalatk.com

⁶ Chief Engineer, Solar Arrays, Space Components Division, michael.eskenazi@orbitalatk.com

⁷ Senior Director, Business Development, Space Components Division, walter.tam@orbitalatk.com

to the primary propulsion system for government-funded exploration missions as represented by the Dawn spacecraft. Owing to this growing technological maturity, electric propulsion usage has become more ubiquitous within the commercial satellite industry, and is now directed toward newer systems for both government and commercial customers with larger total delta-V and propellant throughput requirements^{1,2}.

The early electric propulsion systems, such as the resistojet³ on the Intelsat 502 satellite and the arcjet thruster⁴ on the Telstar 401 satellite, were closely compatible with the host spacecraft since they integrated more directly into the pre-existing hydrazine propulsion system. However, they required steady state operation with much longer burn durations leading to changes in the attitude control logic. They also drew more power, and in the case of the arcjet thruster system, which operated at total power levels as high as 4.4 kW⁵, they required the satellite system engineer to rethink how the electrical power system had to operate in the presence of these loads. The increased power levels combined with the longer burn durations brought on new challenges in battery capacity management and introduced new requirements for bus operation, stability and protection against start-up and burn terminations. In terms of their plumes, the resistojet and arcjet yielded very low levels of ionized species and, as a result, interacted in a similar manner as their chemical counterparts with the external spacecraft systems. Because of this performance and commonality with existing systems, the resistojet and arcjet thrusters continue to be used on communications satellites including the Orbital ATK GEOStar and Boeing 702MP satellites, respectively.

Ion propulsion systems, which offer even higher performance capability, began to show their potential within the United States for station keeping of geostationary satellites with the introduction of the XIPS-13 gridded ion thruster⁶ on the PAS V satellite from Boeing (then Hughes). In Russia, another form of ion propulsion known as the Stationary Plasma Thruster (SPT)⁷ had been routinely used for satellite orbit control since 1971. This success led to the adoption of the SPT-100 thruster on US and European satellites starting in the early 1990's and leading to the launch of the Intelsat 10 satellite from Airbus (then Astrium) in 2004⁸. The use of ion propulsion technology for orbit raising of geostationary comsats became a possibility with the introduction of the high power XIPS-25 gridded ion thruster⁹ on the Boeing 702HP bus. It was realized, albeit unintentionally due to a launch vehicle upper stage anomaly, in 2001 when the Artemis satellite completed the final ascent to geostationary orbit using its RIT ion thrusters¹⁰. Roughly, in the same time frame, ion propulsion became the primary system for interplanetary transfer with the launch of Deep Space 1 in 1999 using the NSTAR thruster¹¹ and subsequently, the Hayabusa¹² probe in 2003 using a microwave ion thruster and the SMART-1¹³ probe in 2003 using the PPS-1350 Hall thruster.

While resistojet and arcjet systems integrated relatively seamlessly with the majority of spacecraft systems, ion propulsion systems did not. These systems required fundamentally different algorithms for attitude control and steering of the spacecraft, new methods for station keeping with large cross-track delta V components in the case of geostationary satellites, and new tools for optimizing long duration, low thrust maneuvers with considerations for collision avoidance and longitudinal targeting. Ion propulsion systems also introduced new environmental effects associated with the quasi-neutral plasma plume, which have to be factored early into the spacecraft design. They also introduced new manufacturing techniques to achieve higher cleanliness levels and new loading equipment to maintain these cleanliness levels while accounting for the compressibility effects of xenon.

Over the past 20 years, Orbital ATK has developed the skills and know-how required to design, integrate, test and operate an array of spacecraft that use ion electric propulsion systems. As shown in Fig. 1, this experience covers both interplanetary and geostationary satellites and extends into future systems for in orbit servicing and cargo transportation missions, such as the Mission Extension Vehicle (MEV) and the Mission Transport Vehicle (MTV). Orbital ATK's involvement also includes the development of the hardware technology that enables these systems. The following sections provide an overview of the past, present, and future EP-enabled spacecraft systems at Orbital ATK and a discussion of the key products under development.

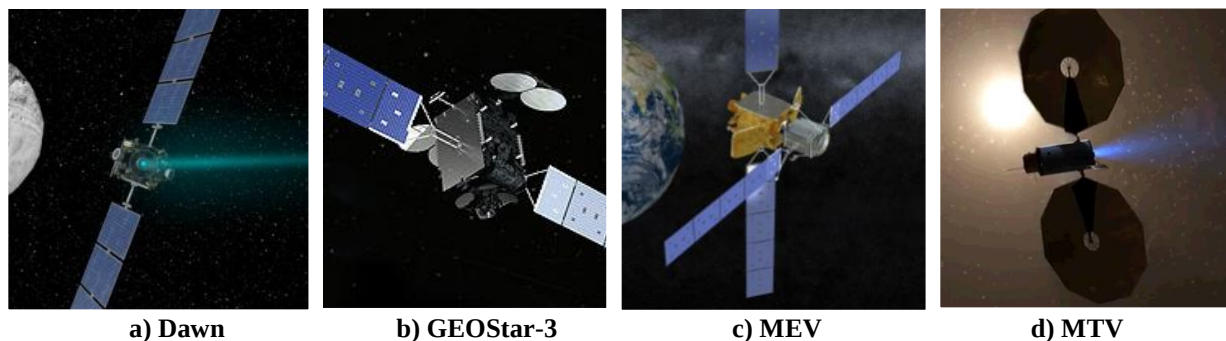


Figure 1. Orbital ATK ion electric propulsion systems.

II. Spacecraft Systems

A. Deep Space 1

The Deep Space 1 spacecraft was the first of NASA's New Millennium series of low-cost, high return technology demonstration spacecraft and was the first interplanetary spacecraft to utilize a solar electric (ion) propulsion system as its primary means of propulsion. The xenon ion propulsion system was provided by JPL and provided about 10 times the specific impulse of chemical propulsion. Deep Space 1 was launched on October 24, 1998 and traveled to the asteroid Braille to collect visual and spectroscopic images of the object. In July 1999 it came within 16 miles of Braille's surface during a fly-by maneuver and continued on to the comet Borrelly in September 1999 as part of a mission extension to conduct comet science. After traveling nearly 1.5 billion miles, Deep Space 1 reached the comet in September 2001 and came within 1,400 miles of the comet itself. The mission was again extended for a few more months of technology testing, devoting some time to all of the hardware that comprised the technology demonstration spacecraft. Deep Space 1 was finally retired on December 18, 2001 after 1,151 days (3.2 years) of operation in space with its supply of xenon exhausted. The NSTAR ion engine had operated for 16,246 hours and had consumed about 72 kilograms of xenon propellant. Pictured in Fig. 2, the Deep Space 1 spacecraft was designed and developed in a cooperative effort between NASA's Jet Propulsion Laboratory and Orbital ATK's Gilbert facility (formerly Spectrum Astro).

B. Dawn

The Dawn spacecraft¹⁴, shown in Fig. 3, was launched on September 27, 2007, and traveled to the main asteroid belt between Mars and Jupiter to study the proto-planet Vesta and the dwarf planet Ceres for clues of the origin and evolution of the solar system. Dawn arrived at Vesta in July 2011 and spent 14 months orbiting the asteroid and performing remote sensing observations. The spacecraft departed Vesta in September 2012 and arrived at Ceres in March 2015 where it has been performing remote sensing observations at different orbital altitudes. The Dawn spacecraft is powered by a solar electric propulsion system based on the technology successfully demonstrated on Deep Space 1. As reported in Ref. 15, the ion propulsion system operated nearly continuously in the cruise phase, applying very low thrust over many thousands of hours. The ion propulsion system was also used during operations at the two proto-planets to raise and lower the orbit altitude. Orbital ATK was responsible for the spacecraft design, flight software, integration and test, launch operations, and flight operations support of the DAWN spacecraft. JPL furnished the integrated ion propulsion system composed of three NSTAR ion thrusters with integral gimbal assemblies, two power processing units, one 450 kg capacity xenon tank, two plenum tanks, and one xenon flow control assembly.



Figure 2. Deep Space 1 spacecraft.



Figure 3. Dawn spacecraft.

C. GEOSTar

The GEOSTar platform was the first use of electric propulsion on a geostationary communications satellite at Orbital ATK. Shown in Fig. 4, the spacecraft employ four resistojet thrusters in total and operate two simultaneously in balanced pairs for North South station keeping only. To date, over 30 GEOSTar satellites have been flown successfully without incident with this technology.

The resistojets are the MR-502 Improved Electro-thermal Hydrazine thrusters (ImpEHTs)¹⁶ from Aerojet Rocketdyne. The power electronics are built by Orbital ATK and deliver approximately 800W of power directly from the solar arrays circuits to the ImpEHT augmentation heaters using voltage regulation logic that resides within spacecraft flight software.

The four thrusters are arranged in redundant half systems and fed hydrazine propellant directly from the dual-mode propulsion subsystem. On orbit they operate in pressure blow-down mode following completion of orbit raising maneuvers with the liquid apogee engine and isolation of the hydrazine tank from the helium pressurant tank.

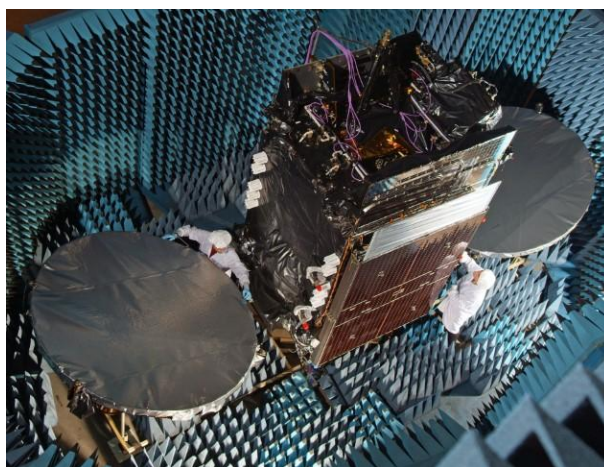
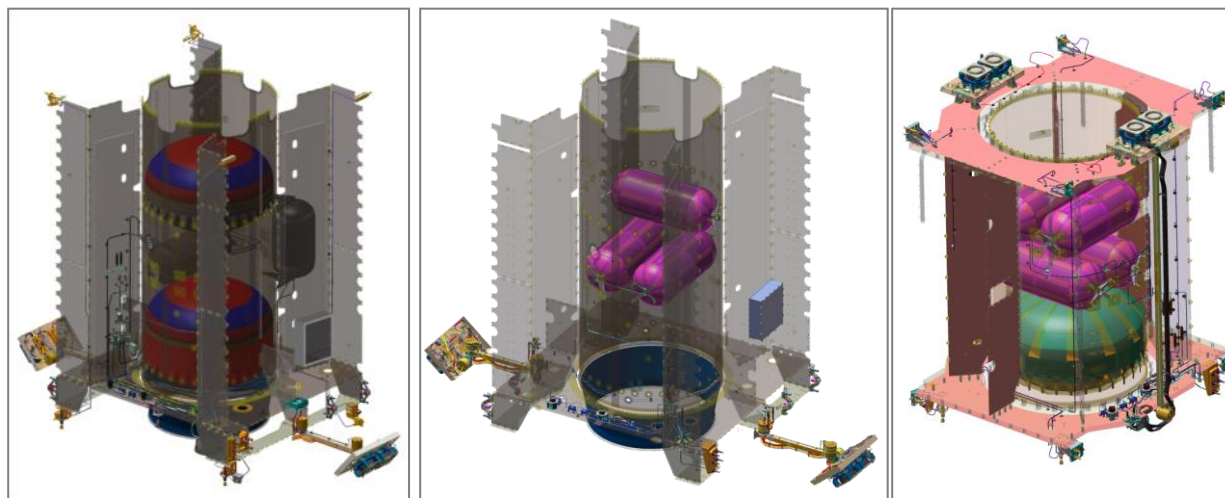


Figure 4. GEOSTar spacecraft with ImpEHTs.

D. GEOSTar Evolution

The GEOSTar spacecraft has been further developed to support a wide range of mission applications with a single platform in a dedicated launch or stacked launch configuration. It can be built in an all-chemical configuration with a dual-mode propulsion system plus ImpEHTs, in hybrid ion electric/chemical configurations with either a dual mode or monopropellant chemical propulsion system, and in an all-electric configuration with the ion propulsion system performing all orbit raising, station keeping, and momentum management functions. For orbit raising, the system can deliver 6 kW of thruster power with scalability to lower or higher power levels if required. For station keeping, the system operates a single thruster at 3 kW using a proprietary station keeping and momentum management algorithm in combination with a multi-axis gimbal. This system can achieve different eccentricity targeting modes while providing inclination and longitude control and three-axis momentum. Fig. 5 provides an illustration of the core structure and propulsion module for the three configurations using the ion propulsion system. Fig. 5a is the hybrid configuration with a dual-mode chemical propulsion system, for which there are two satellites in production. Fig. 5b is the all-electric configuration, and Fig. 5c is the hybrid electric configuration with a monopropellant hydrazine system.

The core ion propulsion system consists of two Hall thruster strings, each having one Power Processing Unit,



a) GEOSTar Hybrid/Biprop

b) GEOSTar All Electric

c) GEOSTar Hybrid/Monoprop

Figure 5. Orbital ATK ion propulsion systems for geostationary satellites.

two XR-5 Hall thrusters, and two xenon flow controllers. The string is provided by Aerojet Rocketdyne and has been adapted from its heritage configuration¹⁷ for use on the GEOStar bus. Each string is fed by an independent xenon feed system, while the xenon gas is sourced from one or more composite overwrapped tanks depending on the mission requirements. One pair of thrusters from separate strings is mounted onto the multi-axis gimbal mechanism known as the Thruster Pointing Assembly (TPA). The TPA supports operation of one thruster at a time and deploys a short distance from the spacecraft for greater maneuverability and improved plume separation distance from critical spacecraft systems.

The GEOStar ion propulsion system development program covered a broad range of activity required for the implementation of a xenon ion propulsion system on geostationary satellites. The program began in 2013 and completed qualification of all new hardware and software algorithms by early 2017. In the area of system design and integration, the program established the spacecraft bus accommodations and system technical budgets for operating the Hall thruster over the different mission phases, including orbit raising with and without thruster operation through eclipse passage. The effort also produced the algorithms for controlling the thruster gimbal in accordance with the system momentum unloading requirements, for propagating the orbit ephemerides during thruster firings, and for steering the spacecraft for optimal power generation during orbit transfer maneuvers. These algorithms have been validated against a high-fidelity dynamic spacecraft simulator and tested successfully on the first two GEOStar satellites with ion propulsion during integrated systems testing. The system integration effort also included the development of the software tools, experimental techniques, and technical databases for plasma plume effects analyses, which is the subject of a companion paper¹⁸.

In the area of mission design, the program focused on the development of the methods and algorithms for the optimization, planning, and execution of low thrust transfer orbits while accounting for mission operational requirements such as periods of autonomous operation, longitudinal targeting, collision avoidance, and radio frequency interference. The mission design effort also established the method and algorithm for station keeping of geostationary satellites. Both algorithms have been converted to executable code and validated successfully against a series of test cases on the Orbital ATK Flight Dynamics System software platform.

The new hardware developed and qualified under this program were primarily the 36V Power Processing Unit and Thruster Pointing Assembly, but also included other delta-qualification efforts within the xenon feed system, Hall thruster, and xenon flow controller. The hardware development effort culminated in a successful, integrated system test at the University of Michigan using all elements in the flight system chain to fire an XR-5 Hall thruster on the Thruster Pointing Assembly as shown in Fig. 6. The elements included the power processing unit, actuator control electronics, and flight software. The test ran the thruster over its full operational temperature range by means of a specially designed thermal shroud and concurrently with the articulation of the TPA over its on-station operational range of travel.

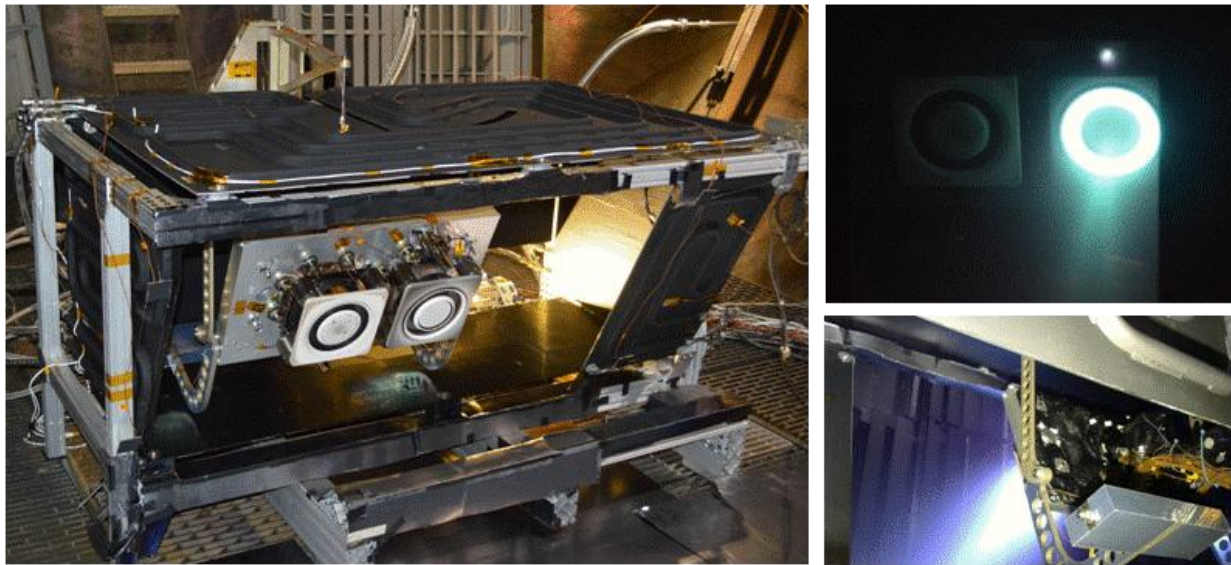


Figure 6. Integrated ion propulsion system hot fire test.

All hardware for the GEOSTar ion propulsion system have been delivered and integrated onto two GEOSTar spacecraft, one of which is shown in Fig. 7. Both spacecraft have completed all environmental testing and will reach on-ground delivery in the 4th quarter of 2017. Loading operations will be performed by Orbital ATK using a xenon loading cart designed and built by Linde. The loading cart has the functionality to perform self leak check, pull vacuum, load xenon to the desired pressure, and verify xenon purity using internal moisture and oxygen sensors and a mass spectrometer. If necessary, the cart can offload xenon back into the supply cylinders. Additional cart features include heaters and coolers to speed xenon loading, line heaters to bake out the system to desired cleanliness levels, and automated procedures to simplify setup and loading process.

E. Mission Extension Vehicle

The Mission Extension Vehicle is a revolutionary spacecraft system that attaches to the aft end of a geostationary satellite using its proprietary rendezvous proximity operation & docking sensor suit. Once attached, MEV is able to adjust the inclination of the client vehicle and perform all station keeping and attitude control functions within its nominal orbit control box. Through these services, MEV can extend by several years the orbital maneuver life of a client vehicle that is at or near the end of its fuel supply.

Shown in Fig. 8, MEV is based on the GEOSTar platform and uses the hybrid ion electric/chemical configuration with a monopropellant propulsion system. In addition to the on-station maneuvering requirements with a client vehicle attached to MEV, the ion propulsion system is also capable of performing all or part of the orbit raising maneuvers from a standard geostationary transfer orbit provided by the launch vehicle.

Given the large delta V requirements, the MEV service can only be accomplished through the use of ion propulsion technology. The first MEV spacecraft is in production and is expected to launch in 2018.

F. Future Architectures

Orbital ATK continues to evaluate and develop new electric propulsion system architectures in response to customer needs and market trends. Orbital ATK recently completed a design study of a high power Solar Electric Propulsion-enabled spacecraft for the Asteroid Redirect Robotic Mission (ARRM). As shown in Fig. 9, the spacecraft uses four HERMeS thrusters operating at a total power level of approximately 40 kW and leverages key technologies developed at Orbital ATK in xenon storage, thruster steering, thermal management, and solar power generation in order to provide a low risk approach.

The ARRM mission aligns with Orbital ATK's long term plan to provide mission transportation services to an array of customers as part of its push into the space logistics business. The Mission Extension Vehicle represents the first phase of this infrastructure build-out. The next phase will include robotic servicing and higher power, cargo transportation services. Missions that



Figure 7. GEOSTar with ion propulsion.

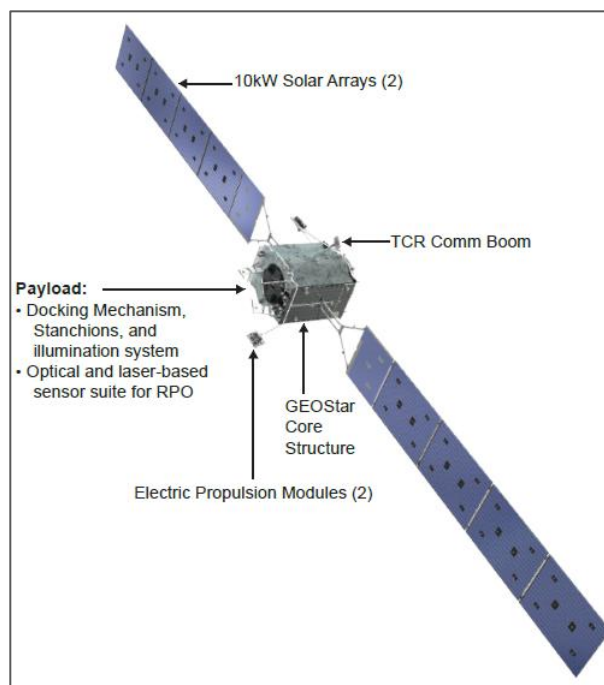


Figure 8. Mission Extension Vehicle.

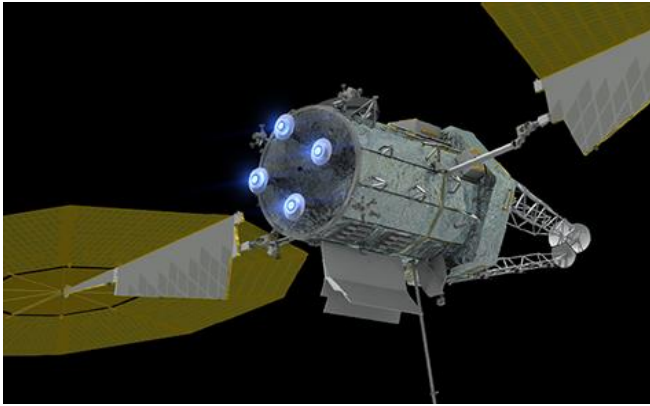


Figure 9. 40 kW class MTV.

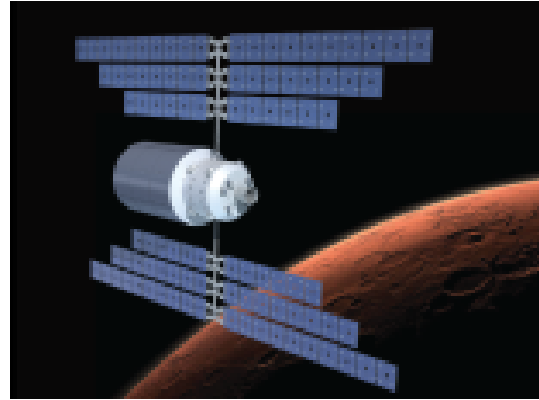


Figure 10. 350 kW class MTV.

would benefit from this capability include LEO-to-GEO tugs for commercial or government customers, cargo transportation missions to the Moon in support of NASA's plans to develop a Deep Space Gateway, and even higher power cargo missions to Mars. An early concept of a 350 kW Mars Transport Vehicle is shown in Fig. 10.

In the area of commercial space, Orbital ATK continues to see a strong interest in electric propulsion as a means of achieving low total system cost for GEO, MEO, and LEO spacecraft. In this vein, Orbital ATK continues to evolve its ion/electric propulsion systems to meet the needs of the marketplace.

III. Hardware Development

Solar electric propulsion systems require investment and development in a multitude of technologies. While the core technology lies with the electric propulsion string composed of the electric thruster, flow controller, and power processing electronics, the full potential of solar electric propulsion can only be realized with complementary development in other supporting areas. One critical area is the spacecraft power generation, storage, and distribution system, where a significant amount of work has been done by Orbital ATK and other suppliers to produce high-power solar arrays with high specific powers and very low packaging volumes. Another area is the storage of xenon propellant where Orbital ATK has had a long presence in providing Composite Overwrapped Pressure Vessels (COPV) to multiple prime contractors. The thruster steering mechanism, which is essential for optimizing electric thruster maneuver efficiency and expanding its usage into other mission maneuvering modes, represents another key area of development that has been actively pursued by Orbital ATK for its GEOSTar and MEV programs. The following sections provide a summary of this hardware development activity at Orbital ATK and its suppliers in support of the Orbital ATK electric propulsion programs.

A. Electric Propulsion Strings

Over the last several years, Orbital ATK has participated in the development of different forms of electric propulsion, from basic research and development to flight system qualification. In the area of ion propulsion systems, Orbital ATK has partnered with the Busek Company to develop a 2 kW class Hall thruster system based on the existing Busek BHT-1500 thruster with center-mounted cathode. One area of interest in this effort was demonstration of stability and efficiency of the main discharge supply. To that end, a breadboard model of the main discharge supply and auxiliary circuits were built and tested over the different operating conditions of the thruster. Another area was the lifetime capability of the thruster, for which an endurance test was performed on engineering models of the BHT-1500 thruster and BHC-2500 center-mounted cathode. The thruster and cathode completed 1000 hrs of cumulative testing and provided the necessary data for better estimation of the thruster propellant throughput capability and mission lifetime performance. The program met its objectives, and the center mounted cathode design showed very strong potential¹⁹ in terms of performance, stability and lifetime capability. Fig. 11 provides pictures of the breadboard PPU and the BHT-1500 thruster in endurance testing.

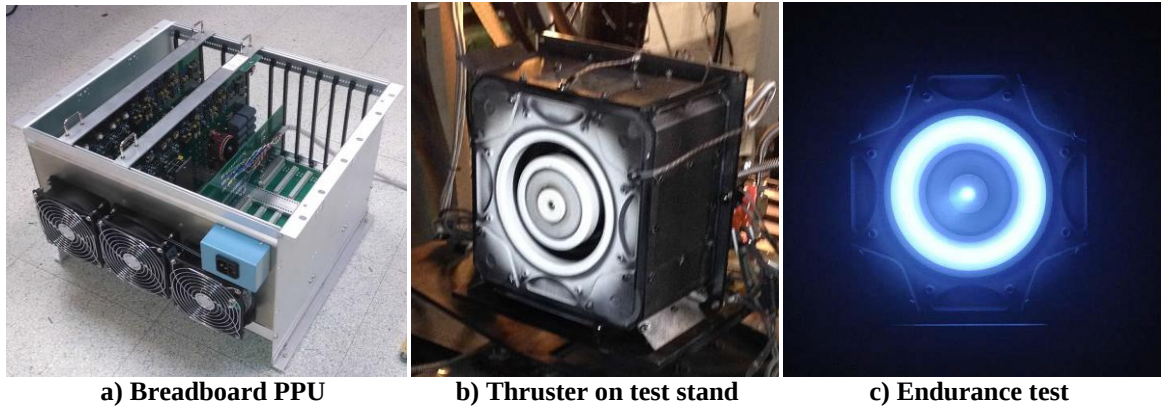


Figure 11. BHT-1500 Hall thruster system.

Orbital ATK has also partnered with the Aerojet Rocketdyne Corporation to adapt its flight proven XR-5 Hall thruster system for the GEOStar platform. This system has flown on three AEHF satellites, achieved extensive amount of life testing²⁰, and provides a high power operating point suitable for hybrid and all-electric satellites. Starting in July 2014, Aerojet Rocketdyne and Orbital ATK pursued a joint development program to produce a 36V version of the legacy 70V PPU with internal output switching capability and to repackage the xenon flow controller for installation near the thruster on the deployable gimbal platform.

The development of the 36V PPU included initially an exhaustive test phase with an engineering model PPU, which allowed for identification of mechanical and electrical design improvements prior to the fabrication of the qualification and flight units. The qualification model (QM) PPU was built at the same time as the flight units using the same parts, materials, and processes as the flight units. It completed all qualification testing in early 2017 after undergoing full environmental testing and comprehensive EMI/EMC/ESD testing. In addition, the complete XR-5 Hall thruster system went through a series of tests to verify the 36V PPU performance and stability against different Hall thruster transient modes using the new xenon flow controller configuration. The integrated system test also included measurement of the radiated emissions from the Hall thruster when powered by the PPU, the radiated emissions from the PPU and harnessing when powering the Hall thruster, and cold start-ups when integrated onto the thruster pointing platform.

Fig. 12 depicts the 36V PPU, the XR-5 Hall thruster, and the integral xenon flow controller. Two ship-sets of Hall thruster strings have been built, tested, and integrated onto two GEOStar spacecraft. The PPUs have completed the full complement of spacecraft systems testing including simulations of electric orbit raising with two PPUs operating into load simulators and station keeping with a single PPU. The flight HCT/XFCs have been integrated onto their flight Thruster Pointing Assemblies and have completed all spacecraft-level dynamics testing including the TPA deployment tests.

Beyond these two programs, Orbital ATK continues to evaluate other systems for different mission applications, such as the NEXT-C gridded ion thruster for interplanetary missions, the HERMeS thruster for precursor missions to Mars, and electro-spray thrusters for fine station positioning applications. These thrusters have been integrated into the Orbital ATK plume properties database for plasma plume effects evaluation²¹ in support of spacecraft design.

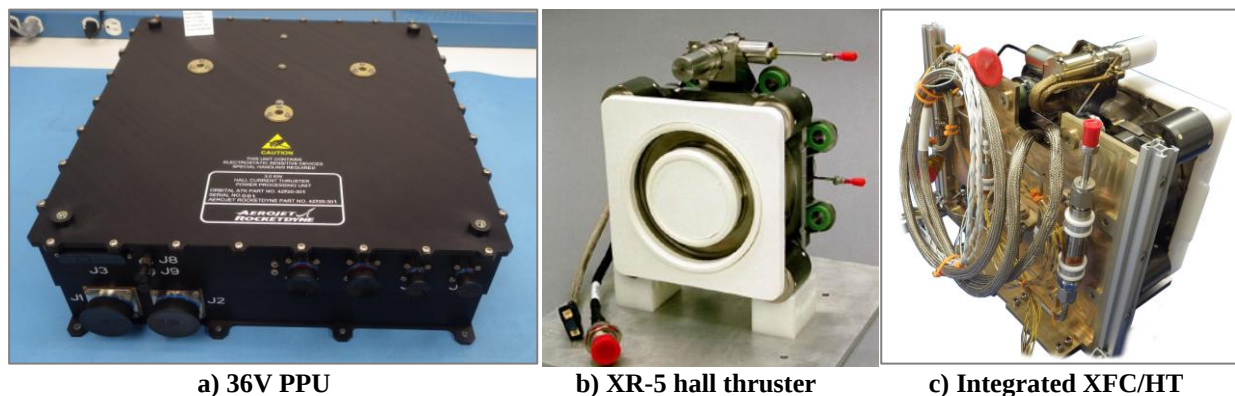


Figure 12. XR-5 Hall thruster system.

B. Mechanisms

Under internal R&D funding, Orbital ATK has developed a multi-axis thruster pointing mechanism for use in the steering of hybrid and all-electric commercial satellites and the MEV in-orbit servicing satellite. The mechanism, known as the Thruster Pointing Assembly (TPA), employs three rotary actuators. One is mounted to the spacecraft body for deployment and delta-V steering of the HCT pallet and two are mounted onto the pallet for two-axis thrust vector control. In between the spacecraft-mounted actuator and thruster pallet is a single boom. The thruster pallet provides a mounting interface for two Hall thrusters and their xenon flow controllers and can support the operation of one XR-5 Hall thruster at a power level of up to 4.5 kW. For launch the pallet stows with a low profile on the spacecraft radiator panel.

The TPA development program began in 2014 and followed a systematic approach whereby major subassemblies underwent early risk mitigation activity before design finalization and qualification. This activity included establishment of a low-shock launch lock configuration, a nested coil assembly that provides a very wide range of travel while accommodating primary and redundant feed lines, and a harness routing configuration that minimizes both resistive torque and packaging volume. Qualification was performed at the unit level, including the launch lock and rotary actuator, and then at the assembly level. The qualification model TPA shown in Fig. 13 underwent full environmental testing, launch lock release and full range of motion testing at hot and cold operational temperatures, extensive life cycle testing over temperature, and an integrated hot fire test with a flight representative Hall thruster as mentioned in Section IID of this paper. Qualification testing was completed in early 2017.

A variant of the TPA is under development for the Mission Extension Vehicle and accommodates a much longer boom and fourth actuator at the spacecraft interface using the building blocks of the original design. In this configuration, the TPA can redirect the thruster pointing for the inertial properties of the stand-alone MEV and of the composite spacecraft with the MEV attached to a client vehicle with a wide range of masses.



Figure 13. GEOStar Thruster Pointing Assembly.

C. Propellant Storage Tanks

Orbital ATK has been a leading supplier of light weight pressure vessels for both chemical and electric propulsion systems. The Orbital ATK facility in Commerce, CA, has delivered over 6,400 tanks to date with 611 tank designs with zero failures. The tanks have supported hundreds of space programs covering commercial, earth observation, interplanetary, and defense spacecraft across multiple prime contractors.

For liquid propellant storage, Orbital ATK products include tanks with passive surface tension devices, elastomeric diaphragms, and other internal devices, such as vortex suppressors and baffles, for high rotational rate environments. Tank shells are all-metal with and without a composite-overwrapped section for increased stiffness and lower mass for larger tank volumes. Orbital ATK has also produced propellant tanks that are completely integrated with the composite structure for load bearing purposes.

For xenon propellant storage, Orbital ATK has produced numerous COPV tanks beginning with early versions used on HS-601²² and ETS VIII²³ and leading to higher capacity versions currently in production for GEOStar, MEV, A2100TR, and NEOSAT. These tanks are shown in Fig. 14 and use a commercially pure titanium liner constructed of a center cylinder welded to end domes and overwrapped with carbon fiber. The tanks in production provide a minimum internal volume of 7300 in³ at a maximum expected operating pressure of 2700 psig.

In view of the growing demand for higher capacity xenon tanks, Orbital ATK continues to invest in the design and development of future COPV tanks with storage capacities on the order of 1,000 kg. At these capacities, the boss mounts shown in Fig. 14 are no longer enough, and a circumferential tab mount becomes necessary. Orbital ATK has the technology for bonding a mounting tab ring to the composite shell through its work on solid motor casings. Potential mission applications for these larger capacity tanks include the former Asteroid Redirect Robotic Mission, Deep Space Gateway, SEP LEO-to-GEO Tugs and future missions to Mars.

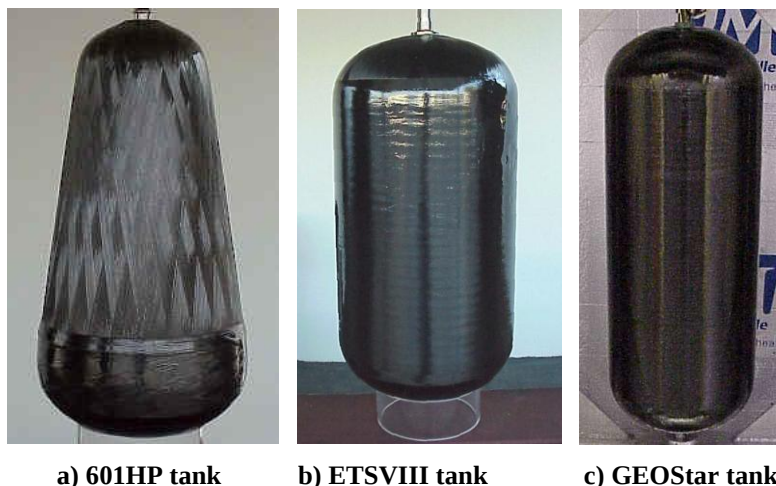


Figure 14. Xenon storage tanks.

D. High Specific Power Solar Arrays

Under contract to NASA, Orbital ATK has developed the UltraFlex and MegaFlex solar arrays²⁴ to address NASA's needs for power sources that can drive solar electric propulsion (SEP) systems requiring 5 to 30 kW in the near term and 300 kW or more in the long term. The UltraFlex array technology supports the initial range of power levels, while the MegaFlex array supports the higher power needs, achieving power levels up to 175 kW per wing.

The UltraFlex and MegaFlex are round flex blanket arrays that provide the desirable combination of high deployed strength and stiffness with low stowed volume ($>40\text{kW/m}^3$) and low mass (up to 200W/kg). Both UltraFlex and MegaFlex are compatible with virtually all commonly used space solar cells and have been tested and flown in many unique configurations ranging from 1kW to 20kW wings. Fig. 15 shows examples of three different wings that have been manufactured, ranging from 2m to 10m in diameter. These wings have exceptional deployed

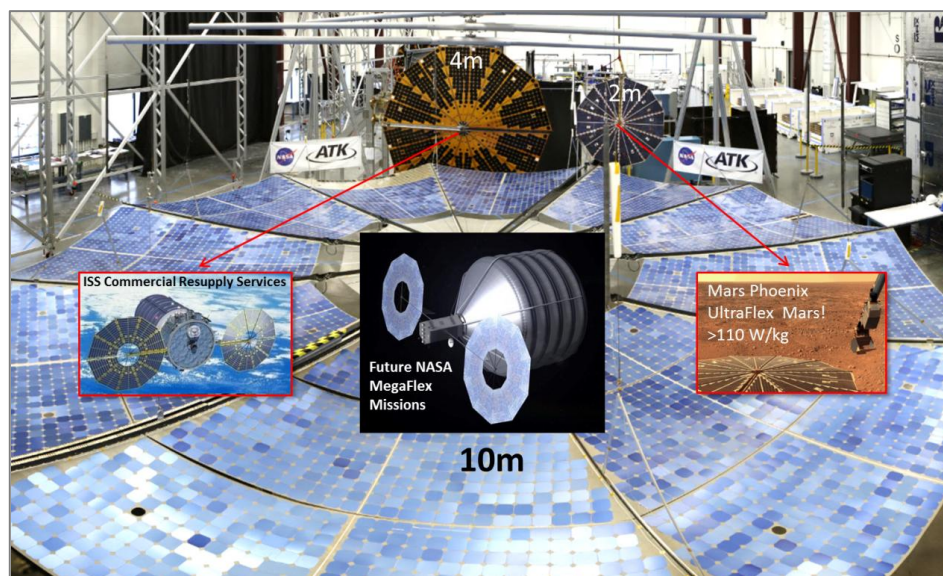


Figure 15. Manufactured UltraFlex and MegaFlex wings.

strength as represented by the Mars Phoenix UltraFlex wing capable of 1g deployed loading and over 110W/kg of specific power and by the Commercial Resupply Services UltraFlex wing capable of a 5g deployed load. Furthermore, the compatibility of the blanket array with high density, energetic, electric propulsion plumes has been demonstrated in NASA sponsored testing where successful operation of solar cell strings up to 600V relative to very dense plasma (10^8cm^{-3}) has been shown²⁵.

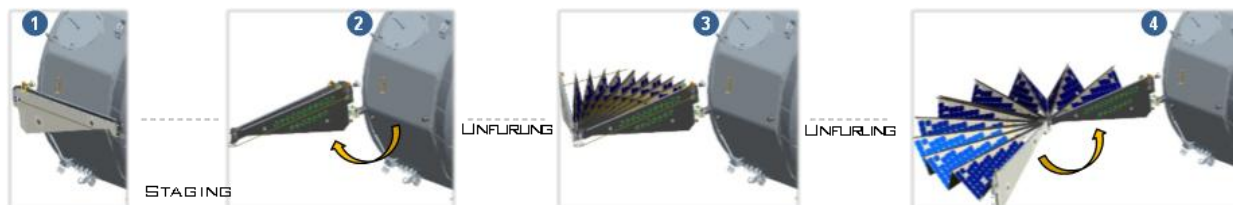


Figure 16. Deployment sequence of an UltraFlex array

When stowed, the solar array is configured as a flat-pack to produce a compact launch volume and a high structural frequency. Preloaded foam layers in the solar blankets sandwiched between graphite composite panels provide exceptional protection for the solar cells during launch. The deployment is driven by an electric motor and, as shown in Fig. 16, occurs like a Japanese-style hand fan where each interconnected triangular-shaped substrate (called a gore) unfolds and expands. Upon full deployment, the circular membrane structure, which is supported by radial spars, becomes tensioned like a very shallow or flat umbrella. At the end of deployment, the panels containing the solar cells blanket latch into a strong/stiff triangular truss assembly that supports the deployed wing away from the spacecraft.

The primary difference between MegaFlex and UltraFlex is that MegaFlex has an articulating panel and spar extenders that reduce its stowed length. This feature allows solar array wings with up to 3 times the deployed area of a standard UltraFlex wing and over 300kW of power to be stowed on a spacecraft in existing rocket fairings with stowed power efficiencies exceeding 40kW/m^3 .

IV. Conclusion

After its initial involvement in ground breaking programs like Deep Space 1 and Dawn, Orbital ATK is charting a course to use electric propulsion for greatest benefit to Orbital ATK's current and future customers, first through the introduction of a hybrid and all-electric geostationary satellite and then through the development of space logistics services that will further push the envelope in terms of throughput and power. To that end, Orbital ATK intends to continue to lead the development of the systems, tools, and products that will enable reliable usage of electric propulsion on these future flight systems.

References

- ¹Herman, D.A., Santiago, W., Kamhawi, H., Polk, J.E., Snyder, S., Hofer, R. and Parker, J.M., "The Ion Propulsion System for the Solar Electric Propulsion Technology Demonstration Mission," *30th International Symposium on Space Technology and Science/34th International Electric Propulsion Conference/6th Nano-satellite Symposium*, IEPC 2015-008/ISTS-2015-b-008, Kobe, Japan, July 2015.
- ²Oh, D., Benson, S., Witzberger, K., and Cupples, "Deep Space Mission Applications for NEXT: NASA's Evolutionary Xenon Thruster," *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA Paper 2004-3806, Fort Lauderdale, FL, July 2004.
- ³Dressler, G., Morningstar, R. E., Sackheim, R. L., Fritz, D. E., and Kelso, R., "Flight Qualification of the Augmented Electrothermal Hydrazine Thruster," *17th AIAA/SAE/ASME Joint Propulsion Conference*, AIAA Paper 1981-1410, Colorado Springs, Colorado, July 1981.
- ⁴Knowles, S.C., Yano, S.E., Aadland, R.S., "Qualification and life testing of a flight design hydrazine arcjet system," *21st International Electric Propulsion Conference*, AIAA Paper 1990-2576, Orlando, FL, September 1990.
- ⁵Zube, D., Lichon, P., Cohen, D., Lichtin, D., Bailey, J. and Chillelli, N., "Initial On-Orbit Performance of Hydrazine Arcjets on A2100TM Satellites", *35th Joint Propulsion Conference and Exhibit*, AIAA Paper 1999-2272, Los Angeles, CA, June 1999.
- ⁶Beattie, J.R., Williams, J.D. Robson, R.R., "Flight Qualification of an 18 mN xenon ion thruster," *23rd International Electric Propulsion Conference*, IEPC Paper 93-106, Seattle, WA, September 1993.

- ⁷Kim, V., "Electric Propulsion Activity in Russia," *27th International Electric Propulsion Conference*, IEPC Paper 2001-005, 2001, Pasadena, CA, October 2001.
- ⁸Gray, H.L., and Kamath, U.P., "Intelsat 10 Plasma Propulsion System Initial Flight Operations," *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, AIAA Paper 2005-3672, Tuscon, AZ, July 2005.
- ⁹Goebel, D.M., Martinez-Lavin, M., Bond, T.A., and King, A.M., "Performance of XIPS Electric Propulsion in Station Keeping of the Boeing 702 Spacecraft," *38th Joint Propulsion Conference*, AIAA Paper 2002-4348, Indianapolis, IN, July 2002.
- ¹⁰Killinger, R., Gray, H., Kukies, R., Surauer, M., Saccoccia, G., Tomasetto, A., and Dunster, R., "Artemis Orbit Raising In-Flight Experience with Ion Propulsion," *Acta Astronautica*, August 2003.
- ¹¹Polk, J., Kakuda, R., Anderson, J., Brophy, J., Rawlin, V., Patterson, M., Sovey, J., and Hamley, J., "Validation of the NSTAR Ion Propulsion System on the Deep Space One Mission – Overview and Initial Results," *35th Joint Propulsion Conference and Exhibit*, AIAA Paper 1999-2274, Los Angeles, CA, June 1999.
- ¹²Kuninaka, H., Nishiyama, K., Funaki, I., Yamada, T., Shimizu, Y., and Kawaguchi, J., "Powered Flight of Electron Cyclotron Resonance Ion Engines on Hayabusa Explorer," *Journal of Propulsion and Power*, Vol. 23, No. 3 (2007), pp. 544-551.
- ¹³Koppel, C., Marchandise, F., Prioul, M., Estublier, D., and Darnon, F., "The Smart-1 Electric Propulsion Subsystem Around the Moon: In Flight Experience," *41st AIAA/ASME/ASEE Joint Propulsion Conference & Exhibit*, AIAA Paper 2005-3671, Tuscon, AZ, July 2005.
- ¹⁴Thomas, V.C., Makowski, J.M., Brown, G.M., McCarthy, J.F., Bruno, D., Cardoso, J.C., Chivilee, W.M., Meyer, T.F., Nelson, K.E., Pavri, B.E., Termohlen, D.A., Violet, M.D., and Williams, J.B., "The Dawn Spacecraft," *Space Science Reviews*, Vol. 163, Issue 1-4, Springer Netherlands, 2011, pp 175-249.
- ¹⁵Garner, C.E., and Rayman, M.D., "In-Flight Operation of the Dawn Ion Propulsion System Through Completion of Dawn's Primary Mission," *52nd Joint Propulsion Conference*, AIAA Paper 2016-4539, Salt Lake City, UT, July 2016.
- ¹⁶Roberts, C. R., "Life Demonstration of an Upgraded Augmented Catalytic Thruster," *19th International Electric Propulsion Conference*, AIAA Paper 1987-0996, Colorado Springs, CO, May 1987.
- ¹⁷Fisher, J., Wilson, A., King, D., Meyer, S., deGrys, K., and Werthman, L., "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System," *39th Joint Propulsion Conference & Exhibit*, AIAA Paper 2003-4551, Huntsville, AL, July 2003
- ¹⁸Bermudez, L.M., Agathon-Burton, C.A., Basak, D., and Glogowski, M.J., "A Comprehensive Numerical Approach to the Modeling and Simulation of Plume Interaction Effects on Solar Electric Propulsion Spacecraft," *35th International Electric Propulsion Conference*, IEPC Paper 2017-238, Atlanta, GA, October 2017.
- ¹⁹Diamant, K.D., Curtiss, T.J., Spektor, R., Beiting, E.J., Hruby, V., Pote, B., Lolencik, J., and Paintal, S., "Performance and Plume Characterization of the BHT-1500 Hall Thruster," *30th International Symposium on Space Technology and Science/34th International Electric Propulsion Conference/6th Nano-satellite Symposium*, IEPC Paper 2015-69/ISTS-2015-b-069, Kobe, Japan, July 2015.
- ²⁰de Grys, K., Mathers, A., Welander, B., and Khayms, V., "Demonstration of 10,400 Hours of Operation on a 4.5 kW Qualification Model Hall Thruster," *46th Joint Propulsion Conference & Exhibit*, AIAA Paper 2010-6698, Nashville, TN, July 2010.
- ²¹Bermudez, L.M. and Jermakian, J.B., "Modeling, Simulation and Validation of the Mo and Mo+ Deposition Imparted by the NASA Evolutionary Xenon Thruster (NEXT)," *35th International Electric Propulsion Conference*, IEPC 2017-281, Atlanta, GA, 2017.
- ²²W.H. Tam, I.A. Ballinger, J. Kuo, W.D. Lay, S.F. McCleskey, P.Morales, Z.R. Taylor, and S.J. Epstein, "Design and Manufacture of a Composite Overwrapped Xenon Conical Pressure Vessel," *32nd Joint Propulsion Conference*, AIAA Paper 96-2752, Lake Buena Vista, FL, July 1996.
- ²³W.H. Tam, A.C. Jackson, E. Nishida, Y. Kasai, A. Tsujihata, and K. Kajiwar, "Design and Manufacture of the ETS VIII Xenon Tank," *36th Joint Propulsion Conference and Exhibit*, AIAA Paper 2000-3677, Huntsville, AL, July 2000.
- ²⁴Murphy, D.M., Eskenazi, M.I., McEachen, M.E., and Spink, J.W., "UltraFlex and MegaFlex - Development of highly scalable solar power," *42nd IEEE Photovoltaic Specialist Conference (PVSC)*, 2015.
- ²⁵Eskenazi, M. I., "Ground Validation of the ATK MegaFlex Solar Array," *23rd Space Photovoltaic Research and Technology (SPRAT) Conference*, NASA Glenn Research Center, October 2014.