NASA's Electric Propulsion Program

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ABSTRACT

This paper provides an overview of NASA's activities in the area of electric propulsion with an emphasis on program directions, recent progress, and a view of future program directions. Electric propulsion enables aggressive science missions and provides an economic advantage for commercial ventures. NASA has recognized the need for new, high performance, electric propulsion technologies for future missions and is sponsoring aggressive efforts in this area. Recent completion of two EP demonstration flights has reinforced the benefits. These efforts are conducted under the Office of Aerospace Technology and the Office of Space Science. The OAT activities support all of NASA. The OSS work is focused on technology for solar system science missions. OSS has recently embarked on a nuclear powered spacecraft program that includes reactor and radioisotope sources. Associated electric propulsion projects include the development of next generation ion and Hall thrusters for both nuclear and solar powered missions. Additional efforts are planned for the development of very high power thrusters and precision pulsed plasma thrusters. The performance of clusters of ion and Hall thrusters is being revisited. Mission analyses guide the technology programs and indicate new capabilities to mission designers. NASA continues to work closely with both supplier and user communities to maximize the acceptance of new technology in a timely and cost-effective manner. The Glenn Research Center leads the Electric Propulsion activities for the agency and is supported by the Jet Propulsion Laboratory, Johnson Space Center, and Marshall Space Flight Center. NASA's electric propulsion efforts are closely coordinated with Department of Defense and other national programs to assure the most effective use of available resources.

NASA's Electric Propulsion Program is providing products to the three mission enterprises: Space Science, Earth Science, and Human Exploration and Development of Space. NASA funding has been provided by Code R through the Energetics Program and by Code S through the In-Space Program. The bulk of the In-Space budget is competed via NASA Research Announcement including NASA center participation. Glenn Research Center is the lead for electric propulsion and works cooperatively with the Jet Propulsion Laboratory, the Johnson Space Center, and the Marshall Space Flight Center. Activities in electric propulsion range from base research through advanced development to flight demonstration. In addition, in the area of electric propulsion, NASA is involved in projects with the Department of Defense, including Air Force, Missile Defense Agency, Defense Advanced Research Projects Agency and the Navy. Transition of the technology to US commercial industry is a continuing effort. The unique capabilities of the NASA electric propulsion test-beds are being utilized by the US commercial satellite industry.

Increasing the performance of satellite propulsion systems enables ambitious NASA science and exploration missions, lowers the cost of space transportation, reduces trip times, and provides technology spin-offs to the commercial space sector.

The program has a deep commitment to mission studies and trades with industrial and academic involvement. In-house mission analysis capabilities as well as mission studies conducted with APL, GSFC, JPL, JSC, and MSFC guide the directions of the technology program. Innovative studies of low thrust trajectories for missions to outer solar system bodies have resulted in time saving options for fly-by and orbiting spacecraft.

Innovative propulsion systems that provide significant benefits over state-of-art devices can provide substantial gains in mission performance by reducing launch vehicle requirements, improving payload fractions, and/or increasing spacecraft life. New systems can often also provide dramatic improvements in functionality, enhancing or enabling new missions requiring, for example, precision positioning and/or formation flying.

Industry involvement is designed to assure that commercial sources of new technologies are available and that all critical aspects of the technology, including both hardware development and spacecraft integration are addressed. This paper briefly describes major NASA electric propulsion activities with an emphasis on-going efforts and anticipated directions over the next several years.

ELECTO-STATIC

Ion

The NASA Ion propulsion program is addressing the need for high (3000-15000s) specific impulse propulsion systems and technologies. Mission studies indicate that several broad categories of engine systems are desirable. These categories span power ranges from 100W to >10kW with clustering to achieve higher powers. Missions range from visits to relatively near-by bodies to trips as far as 100AU. A program goal is to develop key technologies, thrusters, and systems for this range of missions.

Products include: an NSTAR engine with greater life (throughput), a next generation ion engine, an extremely lightweight and efficient sub-kilowatt ion thruster, and a high-power (100-kW class), high Isp engine. Each product is complete with technology efforts in power processors, system components, and spacecraft integration. Underlying the engine system development activities are base research activities to understand the physics associated with ion engine systems.

The successful demonstration of the NSTAR Ion thruster has provided future mission planners with an off-the-shelf 2.3 kW ion thruster capable of processing about 100kg of Xenon. The DAWN asteroid science mission has selected a spacecraft with three NSTAR engines. This is the first NASA science mission to implement electric propulsion.

While the NSTAR thruster is appropriate in terms of power level and lifetime for Discovery Class missions, its application to larger missions such as outer solar system explorers and sample return missions is limited due its power and total impulse capability.

Studies of the Europa Lander, the Saturn Ring Observer, and the Neptune Orbiter missions, have identified a higher power, higher throughput capability, ~8 kW ion propulsion system as enabling. Studies of comet and Mars sample return missions as well as outer body orbiters such as Titan explorer have all shown the need for a higher power, higher total impulse capability thruster to minimize the propulsion system size, mass and complexity. A Code S In-Space NRA process selected GRC to develop a next generation throttle-able ~8 kW ion thruster capable of processing 400 kg of Xenon based on the lessons learned from NSTAR. Even at the 8 kW level, clustering of engines may be necessary to attain the total thrust and total impulse necessary. The next generation ion project will revisit the clustering work performed at Glenn in the 80's. The same NRA selected Boeing to develop carbon based grids for high power engine systems.

GRC was also selected in a separate NRA activity to develop a 6000 – 9000 s >20kW ion engine system.

A 76 cm diameter, 30 kW engine had been previously built and has been tested at GRC as part of the Code R Energetics program. The discharge chamber has been characterized on both Xenon and Krypton. Engine performance has been characterized on Xenon. The engine will be used to test carbon grids under development by JPL under an NRA contract from the Code R Energetics program.

Mission studies have identified a need for lightweight, low power, ion thruster technology for small spacecraft. An 8 cm diameter, 0.25 kW class thruster system was fabricated for testing and optimization. Performance goals include 50% efficiency at 0.25 kW input power. This represents a 2x increase in efficiency over SOA. Aerojet has performed a manufacturability study of the engine and identified many improvements that should lead to lower cost units. A second generation lightweight breadboard PPU has been fabricated and integrated with the engine. Combined with a newly discovered trajectory, small outer body orbiting spacecraft are enabled.

Development work is implemented by a combination of in-house activities, competitively procured contracts with U.S. industry, and grants with universities.

The in-house ion propulsion activity takes advantage of the NASA GRC resident expertise and unique electric propulsion infrastructure that has been established over the past 40 years.

Several research activities at GRC address base technologies. These elements include: 1) high performance, long life ion optics with > 2x increase in throughput capacity; 2) highly-efficient long-life cathodes and neutralizers; 3) improved thermal design; 4) improved magnetic circuit; 5) advanced power processing, 6) advanced grid materials; and 7) electrode-less plasma production. The efforts in ion optics include titanium grids, thick molybdenum, ion-implanted grids, and graphite grids. The effort has produced PPU stages with greater than 95% efficiency. Several of the evolving technologies could be incorporated into the next deep space mission to enhance performance and provide margin

An additional area of concentration, dealing with fundamental erosion processes, crosscuts all product areas, and is also pursued using both in-house expertise and university expertise via grants.

Hall

Hall effect thrusters offer many advantages including an attractive combination of high specific impulse (as compared to chemical thrusters) and high thrust-to-power ratio (as compared to ion thrusters). The net result is a fuel-efficient transfer with a reasonable trip time. The objective of the Hall Thruster effort is to develop and demonstrate systems for primary propulsion while conducting studies to understand the physics associated with Hall thruster operation. High power thruster development is being emphasized because recent mission analyses have shown a need for higher power electric propulsion systems for both orbital and deep space applications. Orbital applications such as space tugs, spacecraft orbit insertion, etc. benefit from higher thrust systems to reduce trip time. Deep space, large delta V, missions typically require higher specific impulse to reduce fuel loading. Power rich spacecraft architectures provide an opportunity to take advantage of propulsion systems that provide both high power and high specific impulse. As allowable mass is allowed to increase for a mission, the optimum specific impulse tends to decrease. The application of Hall thrusters to these missions requires substantial technology advancements from state-of-the-art thrusters. Key development paths for increased performance, reduced mass, and longer life have been identified.

Two tasks are central to the NASA Hall thruster program: 1.) the development of a laboratory Hall thruster capable of providing high thrust at high power; 2.) investigations into operation of Hall thrusters to understand optimization criteria for new designs.

The first task resulted in investigations of the issues associated with scaling a single thruster to power levels substantially in excess of the state-of-the-art. A 50-kW class Hall thruster was designed, built and operated over the range of 9-72 kW. The second task has focused on investigating factors critical to higher specific impulse operation. This year the investigation has considered the role of magnetic field topography on high voltage operation.

In addition to these two primary activities, there are a number of other on-going activities. These additional activities are related to issues such as thruster lifetime, high-power power processor architecture and spacecraft integration. Thruster lifetime issues were investigated by considering the impact of high voltage Hall thruster operation. Breadboard power system tests were conducted with a single power converter that is applicable to high-power power processing unit (PPU) architecture studies. Impedance measurements of a Hall thruster are to be made in an effort to develop an electrical model of a Hall thruster to enable optimum and cost effective PPU design. Finally, a new effort to consider the dynamic electrical behavior of Hall thruster discharges was initiated. This was deemed necessary due to the importance of electro-magnetic interference (EMI) concerns as a spacecraft integration issue.

The NASA program has been working, often with industry, to assess critical integration issues associated with high performance electrostatic technologies. These assessments include EMI, communications impacts, erosion, and, contamination. Under Space Act Agreements, US industry has received access to the Electric Propulsion testbeds and technical expertise at GRC.

An additional area of investigation will be the characterization of a high power thruster at reduced Isp. Engines with those characteristics may have mission advantages in low orbits and orbit raising.

Recent interest in technologies applicable to human exploration has also focused on Hall thruster technology. Significant mission and system analyses have identified a solar electric/ chemical/ aero-brake option for Mars exploration.

A cooperative agreement with MIT for Hall thruster modeling will provide a better theoretical understanding of the physical processes occurring in a Hall thruster and provide a better basis for design and scaling.

Related Activities

Neutralizer / Cathode Technology

Cathode technology is key to long life and performance enhancement at deep throttling levels. Cathode development activities for electric propulsion seek to reduce required propellant flow, size, and propellant cleanliness requirements. The International Space Station Plasma Contactor activity development was extremely synergistic. The Space Solar Power Exploratory Research and Technology program has supported development of high current (100 A-class) hollow cathodes for both high power Hall and ion. Efforts are being expended investigating zero flow cathode concepts.

Feed System Technology

A contract with VAACO to develop a small, light weight, low power feed system will provide benefits to both Ion and Hall thruster applications.

ELECTROMAGNETIC

Pulsed Plasma Thrusters

Pulsed plasma thrusters (PPTs) have potential for application to a range of spacecraft control functions, including attitude control and translation propulsion, momentum management, drag make-up, orbit raising, and large space structure dynamic control. Users include the three NASA space mission enterprises, as well as the commercial satellite industry. The five sub-elements of the program, energy storage, electronics, thruster, system integration and micro-concepts, include low TRL, intermediate TRL and flight. PPT-specific systems analysis is performed to continually upgrade our understanding of the technology drivers.

PPTs have unique attributes that make them enabling for NASA science missions that include precision control of deep space interferometers constructed of formation flying spacecraft and primary propulsion for NASA micro-science spacecraft. Most PPTs utilize solid propellant and provide over 1000 s of specific impulse while operating at average power levels between 1-200 W. PPT systems offer excellent fuel economy and fit the power range available to many small, power limited spacecraft. Unlike steady state devices, the pulsed nature of the PPT system allows power throttling over a wide range without loss in performance simply by adjusting the pulse repetition rate. Very small impulse bits can be attained for precision pointing applications. The use of a solid, inert polymer as propellant results in a very simple, lightweight, low-cost, modular propulsion system that eliminates the need for toxic propellants and costly, complicated propellant distribution systems.

A three-phase program for advanced pulsed plasma thruster development has been implemented. One effort has reestablished a commercial source for Teflon PPTs with specific impulse levels of >1100 sec. and efficiencies of >0.10 at a power levels of 50W. A PPT has been flown and is continuing to operate on NASA's Earth Observing-1 (EO-1) spacecraft. It has controlled the pitch of the spacecraft during operation of sensitive imaging sensors. Results have shown no adverse interaction between the PPT and the rest of the spacecraft. NASA Glenn Research Center was responsible for the development of the flight hardware and delivery to the Goddard Space Flight Center (GSFC) for spacecraft integration and operation. Aerojet, the prime contractor, was tasked with the detailed design and hardware fabrication. An intermediate program goal is to develop the component technology required for operational sparse aperture Space-Based Interferometers that will require extreme position control. To achieve that goal, technology advances must be made in mass and life of the energy storage and discharge electronics. In addition, spacecraft integration concerns, including optics contamination, plume emission spectra, and electromagnetic compatibility is being addressed. The third phase of the program will focus on revolutionary technology improvement to enable new missions. These will include micro-propulsion versions of a PPT and increases in PPT performance via the use of propellants other than Teflon.

These efforts are being carried out with industry and are coordinated with the on-going efforts in the Air Force to assure accessible, low cost solutions for future small spacecraft propulsion requirements. As with all new technologies, high quality system characterizations and integration impact assessments are program concerns. Beyond the first generation, NASA program efforts are geared for the realization of a high performance system for distributed, high resolution imaging missions that will also be applicable to a range of formation flying missions. Researchers are continuing to assess plume contamination both with direct measurements and with a plume model being developed by the Worchester Polytechnic Institute. Fundamental work to understand the physics governing PPT operation and to develop a model to be used as a design tool is the content of a grant to Ohio Aerospace Institute. Unison Industries has delivered hardware to GRC that demonstrates advances in the electronics, ignition, and energy storage technology.

Those efforts will support technologies for the development of miniaturized, high total impulse devices for micro-spacecraft primary and auxiliary propulsive functions for longer-range applications. A midterm goal is to provide a PPT with an I-bit of 50-1000 micro N-s at an Isp levels >1000 s, with >0.2 efficiency, <2.5 kg system mass, and >20,000 N-s total impulse. Of far term interest is the concept of a PPT for micro-propulsion providing 1000 s Isp with <1 micro N thrust.

Advanced High Power Concepts

NASA is funding, at low levels, a number of advanced high power concepts. They tend to be electro-magnetic in nature.

NASA is building on its past efforts in the area of high-power magneto-plasma-dynamic thrusters. The MPD was an outgrowth of NASA GRC and AF efforts in high power arcjets in the 1960's. During the 60's and early 1970's, under NASA and AFOSR support, 30 kW-class MPD's operating on various propellants including hydrogen and lithium showed promising performance. With the exception of efforts at US academic institutions, MPD research in the US ceased until the late 1980's when it was reinvigorated under NASA's Space Exploration Initiative. JPL continues to work on leveraging past Russian investments in lithium MPD's and is pursuing original work with condensable fueled MPDs. Princeton University is an academic partnered in that effort. GRC has concentrated on gas-fueled engines ranging from 0.1MW-10 MW. Domestic numerical design capability has been refined and designs for both a 0.1-1 MW steady-state breadboard engine and a 1-10 MW pulsed engine have been completed and the engines built. Performance and life challenges include thermal rejection, power management and distribution, electrode erosion at high currents, and improving engine efficiency at Isp levels above 2000 s.

The pulsed inductive thruster (PIT) is a high power electromagnetic propulsion system that can provide high thrust efficiency over a wide range of specific impulse values. Theoretically, the thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow. There should be minimal erosion due to the electrode-less nature of the discharge. Single-shot experiments performed with a 1-meter diameter device at TRW demonstrated specific impulse values between 2,000 seconds and 8,000 seconds, with thruster efficiencies exceeding 50% using ammonia as the propellant. In collaboration with TRW, the NASA program seeks to understand the physics and engineering behind this potentially versatile thruster.

Dr. Chang-Diaz at JSC is developing the advanced VASIMR concept. The VASIMR system is a high power, plasma rocket that is capable of exhaust modulation at constant power. It consists of three major magnetic cells: "forward," "central," and "aft." where plasma is respectively injected, heated and expanded through a magnetic nozzle. The forward cell handles the main injection of propellant gas and the ionization subsystem; the central cell acts as an amplifier to further heat the plasma to the desired magnetic nozzle input conditions. The aft cell is a hybrid two-stage magnetic nozzle that converts the thermal energy of the fluid into directed flow, while protecting the nozzle walls and insuring efficient plasma detachment from the magnetic field. During VASIMR operation, neutral gas is injected at the forward cell and ionized. The resulting plasma is heated with RF energy in the central cell to the desired temperature and density, by the process of ion cyclotron resonance. After heating, the plasma is magnetically (and gas-dynamically) exhausted at the aft cell to provide modulated thrust. The VASIMR concept is envisioned as eventually evolving to power levels up to 100 MW. To date, thrust measurements have been inferred from other experimental data.

NASA Marshall is pursuing several concepts that could be adapted as electric propulsion devices. They stem from basic work at MSFC on fusion power concepts. One concept is a megawatt plasma accelerator with characteristics needed for a fusion engine with fusion gain >1. A second concept is a two stage pulsed plasma accelerator derived from MSFC electromagnetic accelerator research. The proposed thruster would utilize a valve-less liquid Lithium fed thermal plasma injector followed by a high energy pulsed accelerator.

Concluding Remarks

Space propulsion continues to be a significant performance driver for many mission applications. To meet known and anticipated mission performance goals, advanced electric propulsion systems are required. To this end, NASA sponsors aggressive programs to develop new electric propulsion systems for a wide variety of space missions. The scope of the program extends from low power systems for small spacecraft to very high power systems for exploration endeavors. Strong emphasis on technology transfer continues with program efforts directed toward the development of commercial technology sources and the demonstration of program technologies to the level required by potential users. NASA programs are cross cutting and closely allied with other major national development efforts to ensure that a broad range of users are provided with new technologies in a timely and cost effective fashion. The NASA program will continue to identify and develop new electric propulsion technologies and invites the participation of innovative members of the community in the coming years.

Participating Organizations

NASA: GRC, GSFC, JPL, JSC, MSFC

Industry: Aerojet, ARC, Boeing, Busek, Ceramic Composites Inc., CU Aerospace, Jaycor, SAIC/Maxwell Labs, Minteq International, Pratt Whitney, TRW, Unison, VAACO

University: Colorado State University, Kettering University, MIT, North Carolina A&T University, Ohio Aerospace Institute, Ohio State University, Princeton University, Stanford University, Toledo University, Tuskegee University, University of Illinois, University of Michigan, Whitworth College, Worchester Polytechnic Institute