NASA's Electric Propulsion Program

John W. Dunning, Jr., Scott Benson, Steven Oleson
National Aeronautics and Space Administration
John H. Glenn Research Center at Lewis Field
Cleveland, Ohio USA 44135
216-433-5298
john.w.dunning@grc.nasa.gov

IEPC-01-002

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. The benefits of high performance electric propulsion systems are recognized, and new technologies have been accepted. Electric propulsion enables aggressive science missions and provides an economic advantage for commercial ventures. NASA recognizes the need for new, high performance, electric propulsion technologies for future solar system missions and is sponsoring aggressive efforts in this area. These efforts are conducted under the Office of Aerospace Technology and the Office of Space Science. Technology activities are broadly based to support all of NASA. The majority of the work is focused on technology for planetary science missions. The Glenn Research Center leads the Electric Propulsion activities for the agency and is supported by JPL, JSC, and MSFC. Plans include the development of next generation ion thrusters for end of decade missions. Additional efforts are planned for the development of very high power thrusters. Clusters of ion and high power Hall thrusters are being studied. 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. 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.

INTRODUCTION

The benefits of high performance electric propulsion systems are now recognized and new technologies have been accepted across the user communities. After 40 years, NASA ion propulsion has been added to the propulsion portfolio. Deep Space-1 with the NSTAR ion system was the first flight of a xenon ion system as primary propulsion on a deep space NASA mission. On the commercial side, Hughes has flown their XIPS-13 on the 601HP bus and the XIPS-25 is operational on the 702 bus. Hall thrusters are routinely used on Russian communication satellites for both East-West and North-South station keeping and are about to be flown on a US manufactured geo-comsat. NASA has been heavily involved in transitioning the Russian developed Hall thruster technology for use on US spacecraft. NASA has supported the efforts of all US providers and users of Hall thruster systems by providing test facilities and expertise at both its Glenn Research Center (GRC) and Jet Propulsion Laboratory (JPL). In the area of control propulsion NASA GRC and the Goddard Space Flight Center (GSFC) have developed a pulsed plasma thruster that is awaiting operation on the Earth Observing-1 spacecraft. The system will serve as a precursor for future NASA missions, requiring precision attitude control.

Spacecraft propulsion system mass fractions continue to drive mission performance across a wide range of Earth-orbital and deep space missions. Increasing the performance of those systems is key to enable planned NASA science missions and provide technology spin-offs to the commercial space sector. NASA's electric propulsion effort is centered on providing products to its three mission enterprises: Space Science, Earth Science, and Human Exploration and Development of Space. The major support for the technology has been NASA's Aerospace Technology Enterprise. Technical participation is provided from several centers including, GRC, GSFC, JPL, Johnson Space Center

Presented as Paper IEPC-01-002 at the 27th International Electric Propulsion Conference, Pasadena, CA, 15-19 October,2001

(JSC), and MSFC. To advance the technology into higher technology readiness levels and to mission acceptance, the technology programs seek partners from the mission enterprises. A significant amount of planning and content development of the electric propulsion portion of both the Space Base and the Advanced Space Transportation Program was completed with identification of key products and technology milestones. The plans encompass the next six years and will move NASA's electric propulsion effort in new directions. NASA's emphasis in the next decade will focus on technology development to enable missions planned at the end of the decade and beyond and technology enhancements to current systems. A major emphasis will include development of the next generation of electrostatic systems for planetary and near Earth operations with power levels of 10's of kilowatts. A second exciting area of emphasis is centered on very high power electric propulsion. NASA is again planning on conducting research and development of 100kW ->1MW electric propulsion concepts for solar system exploration.

ION THRUSTER

The largest technology investment for NASA in electric propulsion continues to be the area of ion propulsion for deep space missions and is being developed by NASA GRC with participation of JPL. Ion propulsion technology for primary spacecraft propulsion was successfully demonstrated for the first time on the Deep Space-1 (DS1) mission following its launch in October 1998. As of September 2001, the thruster on DS1 had accumulated about 14,000 hours of operation. The DS1 ion propulsion system is currently being used for both primary propulsion and for pitch & yaw attitude control of the spacecraft in order to save hydrazine propellant for the September 2001 encounter with the comet Borrelly. The ion thruster will accumulate a total of approximately 14,000 hours of operation by the planned end of the mission. From telemetry, the ion engine appears to have the same performance now as at the beginning of the mission.

A long-duration test with the DS1 flight spare ion engine is ongoing at JPL and has accumulated nearly 19,000 hours of operation. Over this time the engine has processed 152 kg of xenon, almost double the engine design life.

Advanced ion propulsion technology is considered mission enabling or strongly mission enhancing for a wide variety of deep space missions contained in the Code S strategic plan such as comet and asteroid explorers, Titan Explorer, Venus Sample Return, Neptune Orbiter, Saturn Ring Observer, and Europa Lander. Systems / mission studies indicate that an advanced, multi-engine version of the DS1 ion propulsion technology is needed to take full advantage of the performance benefits of ion propulsion. Future missions need an ion engine with a total impulse capability significantly greater than the NSTAR / DS1 design point in order to reduce the required number of required.

The objective of NASA's near-term ion propulsion system technology activity is to develop an advanced multi-engine, ion-propulsion-system in order to retire the risk for deep-space missions requiring the use of advanced solar electric propulsion (SEP) systems. The IPS technology developed under this task will enable significantly more difficult deep-space missions by increasing the total impulse, specific impulse and maximum thrust capability of the ion engine. In addition, the multi-engine SEP system developed will provide a fault tolerance capability that is highly desirable for flag-ship deep-space science missions.

In addition to the DS-1 / NSTAR activities, NASA's ion technology efforts are focused on base technology research including long-life optics, neutralizers, discharge chambers, and diagnostics and four main areas of thruster system development: 10 kW class, 300 W class, micro-ion, and 30 kW-class /14,000 s Isp engine technology.

10kW engine

The goal of this effort is to develop a high-performance 10kW ion engine that is throttleable down to 2.5 kW, along with the associated power processing technology. The target customer for the technology is the ambitious class of NASA deep-space exploration missions beyond 2007. With deep throttle capability and an Isp range of 2500-5000 s, the goal is to develop an engine with application both to commercial Earth Space operations and for NASA deep space science.

To accomplish that overall objective several goals have been established. These include:

- Variable specific-impulse capability of ~2500-5000 seconds specific impulse for Earth-space mission applications, and 4000 seconds and 70% efficiency for deep-space applications
- 525kg of Xenon throughput
- mechanical design envelope comparable to that of the NASA NSTAR 30 cm thruster
- mass on the same order as the NSTAR thruster
- PPU specific mass less than that of NSTAR PPU
- PPU efficiency > 92%

This development activity has been pursued aggressively in FY01. This activity has been performed in-house at GRC and includes thruster design and performance analysis, completion of detailed mechanical design of thruster components, fabrication of thruster components, and assembly of prototype thruster. Preliminary thruster performance testing has been conducted. University participation includes the University of Michigan for both ion optics erosion modeling and engine erosion diagnostics development.

Boeing (Hughes Electron Dynamics) was selected in a competitive procurement as the contractor to conduct a design study of innovative approaches to simplified ion power processing units (PPU). The purpose of this procurement is to advance the systems technology of electrostatic (ion) propulsion power processing, beyond the state-of-the-art NSTAR technology.

The result is an ion PPU design that can operate at high power (approximately 5 kW) and high efficiency (greater than 92%), while yielding a low mass (less than the 15 kg flight-packaged PPU, less cabling). The PPU has been operated and meets all expectations.

Sub-kilowatt

A need for lightweight, low power, ion thruster technology has been identified for small spacecraft. To address the requirements, an effort continues to examine scaling relationships and design criterion for low power ion systems. The development effort to date has led to the fabrication of a small 8 cm diameter, 0.25 kW class laboratory model thruster for testing and optimization. Performance goals include 50% efficiency at 0.25 kW input power, representing a 2x increase in efficiency over SOA A second generation lightweight breadboard PPU has been fabricated and integrated with the engine. Four power converters are used to produce the required six electrical outputs. The component mass of this breadboard is 0.9 kg and the total mass is 1.8 kg.

Boeing (Hughes Electron Dynamics) and General Dynamics (Primex Aerospace Company) were awarded contracts to perform a design study that is to include a user survey (identifying potential mission applications), top-level drawings, and detailed system and performance requirements. The manufacturing of engineering model thrusters and power processors is anticipated.

Micro-ion

Performance objectives for the GRC Hollow Cathode Micro Thruster (HCMT) activities are an efficiency exceeding 25% at > 1500 seconds specific impulse, operating over an input power range of about 1 to 25 Watts.

A general need for high specific impulse (> 1000 sec), low-power (~10 W) propulsion has been identified for 2nd generation NASA Micro-spacecraft. This thruster fills the gap between micro Newton concepts and ~100W class electric propulsion thrusters, and has the potential to be used on a variety of micro-spacecraft for prime propulsion, station keeping, and formation flying.

The GRC HCMT will provide thrust by accelerating ions produced by a miniature hollow cathode utilizing a high-voltage acceleration stage. The thruster overcomes the technological roadblocks that prevent shrinking conventional ion engines and Hall-Effect Thrusters (HETs) because the ionization process eliminates the issues of neutral loss and magnetic confinement. Recent advances enabling this concept include the development at NASA GRC of small hollow cathodes that are capable of supporting high ionization efficiencies, and the quantitative understanding developed via computer models of hollow cathode ion production. SAIC has supported the modeling aspects of this effort

An HCMT has been built and tested at GRC as part of the base technology effort.

JPL is pursuing a different approach to micro-ion thrusters based on field emitter array technology.

Interstellar Precursor Ion

This activity is long-range and seeks to develop 10-30 kW krypton ion engine technology in support of high specific impulse (>10,000 seconds) applications such as the Interstellar Probe Mission. The activity is being conducted in-house by GRC and includes university participation from Colorado State University in the area of ion optics design analysis and the Ohio Aerospace Institute for engine test support.

The design and fabrication of a 76 cm diameter discharge chamber has been completed. The discharge chamber was integrated with an ion extraction system and neutralizer. Discharge operation was subsequently characterized on krypton and xenon propellants, and engine performance was characterized on xenon propellant up to approximately 4 kW input power.
Three 30-cm diameter NSTAR-type ion optics sets were affixed to the forward end of the discharge chamber. Perveance data obtained from this ion optics system indicates that each of the 3 ion optics sets is functioning on the 76 cm diameter discharge chamber in the same manner as they would individually mounted to 30 cm diameter discharge chambers.

This is an important finding, demonstrating that the use of multiple ion extraction systems on a common discharge chamber will function stably; and yield an increase in beam current extraction capability proportional to the increase in total beam area. This is especially significant for engine scaling considerations

The second-phase effort has concentrated on development of the high-voltage ion optics and will include operation of the engine on krypton propellant at high (> 10,000 s) specific impulse. Activities will include design analyses and fabrication of large-area high-voltage ion optics, completion of design modifications to discharge chamber to accommodate high-voltage beam extraction operation, and to develop control sequence for high-voltage arc breakdowns. Finally, engine performance tests with beam extraction on krypton propellant will be initiated.

5kW 30cm Testbed Engine

A significant level of activity is being expended on ion component technology development with broad application for missions before 2007. To enable the technology development, NASA GRC has fabricated a 30-cm test-bed engine. This engine has the capability to operate up to 5 kW. The engine is identical in design to the NSTAR flight thruster to provide a test-bed for the development of components (ion optics, discharge and neutralizer cathodes, propellant isolators, etc.). The test-bed allows for detailed investigations of performance and erosion processes relative to the NSTAR thruster, for which a large database has been established. It also accommodates experimental activities focused to improve the DS-1 / NSTAR thruster performance.

High Performance, Long Life Ion Optics

Several options, including advanced-molybdenum, titanium, and carbon materials, with potential for 2x-10x increase in propellant throughput capacity over that demonstrated with NSTAR 30 cm ion optics, are being pursued at GRC and JPL in-house and under grant and contract. These options, through materials selection, design, or both, should yield a reduction in sputter erosion due to ion bombardment, and hence increase in grid life.

30 cm diameter ion optics have been fabricated and tested using 50% thicker molybdenum and titanium. Both have been successfully tested up to 4.6 kW input power on the test-bed thruster. Performance (perveance, and electron backstreaming margin) for the titanium ion optics compare favorably to that measured for NSTAR ion optics. Either design appears to be a candidate for applications requiring up to ~170 kg propellant throughput and 3+ kW.

Under grant to Colorado State University, the use of ion-implantation processes to reduce the sputter yield of molybdenum is being investigated. To date a 15% reduction in sputter yield via implantation of nitrogen, and a 40% reduction in sputter yield via implantation of carbon, has been demonstrated on sample materials.

The development of ion optics manufactured from carbon is being pursued under contract with North Carolina State A&T. Carbon provides the highest-payoff in the near term for grid life enhancement, and is a leading candidate for high-thrust density engines. Multiple sets of ion optics (electrodes and mounting system) have been delivered, compatible with the design of the NASA sub-kilowatt (8 cm beam diameter) ion thruster. After performance evaluations, the contractor will fabricate and deliver multiple sets of ion optics compatible with NASA's 30-cm test bed thruster. An additional contract has been awarded to Minteq Inc. for the manufacture of pyrolytic graphite grids. This approach has the potential benefit of eliminating carbon fibers that disturb the hole geometry.

Under an award from a previous NRA, JPL is having fabricated carbon-carbon grid sets for the 30 cm engine. GRC will test those grid sets on the test bed engine.

High-Efficiency, Long-Life Neutralizers

For improved-efficiency, improvements in neutralizer performance (reduction in propellant and power consumption) are warranted. An effort has been initiated to develop an improved-performance neutralizer specifically for the NSTAR 30 cm thruster.

A series of design-optimization tests were conducted on prototype cathodes, examining the affect of cathode and keeper orifice plate geometries on neutralizer function. Significant benefit was gained due to a parallel development activity being conducted for a reduced flow rate cathode for the Space Station plasma contactor system. This activity culminated in the manufacturing of two identical engineering model neutralizer assemblies, both of which have been successfully integrated on NASA 30 cm thrusters, and performance characterized up to about 3.1 kW thruster input power. Use of the improved neutralizer increases thruster efficiency by about 3 and 5 percentage points at 2.3 kW and 0.5 kW respectively.

Additional work will be required to further improve performance, and to validate the lifetime, for a low-flow neutralizer product.

Improved Discharge Chamber Design

An effort was initiated to investigate the thermal-limits of NSTAR-derivative 30 cm thrusters, and to examine discharge processes with the intent of developing an improved-performance thruster capable of 5 kW operation. To examine temperature limits, the test-bed thruster was outfitted with thermocouples distributed over the discharge chamber, discharge and neutralizer keepers, high-voltage propellant isolators, thruster mounting system, and plasma screen to document the thruster thermal behavior. All temperatures were well within material operating limits.

Internal plasma measurements at the anode of the test-bed thruster were measured and used to estimate the upper limit of electron flux collected between the magnetic cusps. This upper limit suggests that about 30% of the discharge current flows to anode surfaces between the cusps. It was also found that the majority of both ion and electron collection between cusps occurred in the downstream cylindrical section of the discharge chamber.

It was found that the electron temperature was on average 3 eV higher in the cylindrical section as compared with the upstream conic section of the discharge near the hollow cathode. This finding suggests that the thermalization rate of primary electrons in the cylindrical section may be higher than in the conical section of the thruster. The thermalization of primaries in the cylindrical section may be enhanced due to electron confinement associated with the negatively biased screen grid electrode.

Discharge and Beam Diagnostics

The research at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan has focused on measuring discharge cathode erosion using laser-induced fluorescence (LIF), and explaining the physical mechanism behind this erosion. The LIF diagnostic has demonstrated three-component ion (Xe^+) velocimetry and has successfully interrogated Xe, Xe^+, Mo and W species.

The investigation of the generation of ions capable of causing the erosion observed in the NSTAR 2000 hour wear test has made significant progress. A NASA GRC 30 cm ion thruster, modified to provide optical access to the discharge chamber was used for these tests, and assessments were made over the entire 2.3 kW NSTAR throttling range. Internal LIF of the thruster discharge indicates the presence of a small potential hill and back-flowing ions near the unkeepered discharge cathode. Ion energies, especially of Xe^{++} and Xe^+ coupled with a potential drop across the sheath around the cathode appear sufficient to generate the observed erosion.

Detailed Xe+ velocity mapping indicates significant radial and, at the upstream edge, noticeable back-flowing velocities that are consistent with the erosion patterns observed in the 2000 hr wear test. Tungsten LIF signals as a function of radial position across the face of the unkeepered cathode has also been obtained, and agrees with the observed erosion. Both sets of data were taken with the thruster operating at 2.3 kW input power and 12.1 A discharge current. A detailed correlation between Mo and W LIF signal, Xe+ velocities, thruster operating condition, and cathode erosion rates has been developed.

Validating new thrusters is a costly prospect, with the cost of qualifying thrusters for space flight measured in millions of dollars. To reduce the risks associated with new ion propulsion systems, ground based lifetests will continue to be conducted for the foreseeable future. Life-limiting operating conditions must be identified and mitigated prior to initiating long duration tests to increase the probability of success. Consequently, accurate and timely evaluations of thruster performance and predicted life are critical to the development of advanced ion thruster systems.

Research is currently being conducted at NASA GRC, with the assistance of the Ohio Aerospace Institute, to develop real-time, spatially-resolved erosion diagnostics in support of advanced ion thrusters. As a preliminary step toward developing real-time erosion diagnostics, emission spectra have been collected in the discharge chamber and the beam of the test-bed 30 cm thruster.

Detailed plume measurements of the test-bed thruster have also been documented, using both Faraday and Langmuir probes. It was found that the beam profile becomes more peaked with increasing thruster power. Beam divergence measurements revealed that the beam divergence angle was fairly narrow, with 90% of the beam included within 25 degrees (for conventional NSTAR ion optics). It was also found that the radial electric field component in the plume is not capable of imparting significant off-axis energy to those ions born on centerline, to sputter typical spacecraft materials. Plasma measurements in the plume were also used to estimate relative contributions to low energy ion production in the plume due to charge-exchange and direct ionization

PULSED INDUCTIVE THRUSTER

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. In its basic form, the PIT consists of a flat spiral coil covered by a thin dielectric plate. A pulsed gas injection nozzle distributes a thin layer of gas propellant across the plate surface at the same time that a pulsed high current discharge is sent through the coil. The rising current creates a time varying magnetic field, which in turn induces a strong azimuthal electric field above the coil. The electric field ionizes the gas propellant and generates an azimuthal current flow in the resulting plasma. The current in the plasma and the current in the coil flow in opposite directions, providing a mutual repulsion that rapidly blows the ionized propellant away from the plate to provide thrust. The thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and propellant mass flow, and there is minimal if any erosion due to the electrodeless nature of the discharge. Prior single-shot experiments performed with a 1-meter diameter version of the PIT at TRW demonstrated specific impulse values between 2,000 seconds and 8,000 seconds, with thruster efficiencies exceeding 50% for ammonia propellants.

The PIT is an electrodeless device in which the plasma does not directly contact material surfaces, thus minimizing erosion and increasing thruster life. A single thruster design can be used for a variety of mission applications, ranging from orbit transfer to deep space exploration as additional on-board power becomes available. In collaboration with TRW, the NASA Marshall Space Flight Center, and OAI the NASA GRC technology development program seeks to understand the physics behind this versatile thruster performance, and to extend the technology to the high power, multiple-repetition rate operation required for NASA and DOD missions.

State of the art performance measurements for the PIT were obtained by TRW under single-shot discharge conditions. Using ammonia propellant and a 16-kV capacitor bank charging voltage, 1-m diameter thruster efficiencies of 35% to 55% were achieved for specific impulse values of 2000 to 8000 s, respectively. The ultimate goal of the proposed technology program is to demonstrate efficient pulsed inductive thruster performance under high frequency, multiple repetition rate operation. The specific goal is to demonstrate a thruster efficiency of at least 60% for repetitively pulsed discharges of 10 to 100 pulses discharged at 10 Hz or higher with peak power levels exceeding 1-MW.

Initial work has focused on thruster physics simulation. A simple equivalent circuit model of the PIT acceleration mechanism has been developed by TRW and GRC has developed a physics-based numerical model to understand and improve thruster performance.

MAGNETOPLASMADYNAMIC THRUSTER

The high power magnetoplasmadynamic (MPD) thruster is a robust and versatile electromagnetic propulsion device with the potential to meet a variety of high-power, near-Earth and deep space mission requirements. In its basic form, the MPD thruster consists of a central cathode surrounded by a concentric cylindrical anode. A high-current arc is struck between the anode and cathode, which ionizes and accelerates a gas propellant. In the self-field version of the MPD thruster, an azimuthal magnetic field produced by the return current flowing through the cathode interacts with the radial discharge current flowing through the plasma to produce an axial body force. In applied-field versions of the thruster, a solenoid magnet surrounding the anode is used to provide additional radial and axial magnetic fields that can help stabilize and accelerate the discharge plasma.

The specific impulse (Isp) of the thruster is a function of the discharge current and propellant species. Low molecular weight propellants such as hydrogen and lithium can provide Isp values in excess of 5,000 s, while heavier propellants such as argon and krypton are generally limited to below 2,500 s. Although thruster efficiencies as high as 70% were reported in the early 1970’s using lithium propellant, more recent performance measurements have demonstrated lower efficiencies of around 45% with lithium and 15-30% for most other propellants. In addition, the stability of the MPD thruster plasma discharge is limited by the onset of voltage oscillations that can lead to enhanced electrode erosion and a rapid reduction in thruster life. Nevertheless, the MPD thruster is unique in its ability to process megawatts of power, and the technology continues to hold significant promise as a high power plasma propulsion system. Both NASA GRC (non-Li) and JPL (Li) are conducting development efforts on MPD thrusters.

High power, lithium-fuelled Lorentz Force Accelerators (LFA's) or MPD thrusters are under development at JPL for ambitious future MW-class missions. Lithium propellant yields very high engine efficiency because it has low frozen flow losses. Lithium has a very low first ionization potential and a high second ionization potential and very little power is expended in creating the plasma. Lithium LFA's can operate efficiently at power levels from 150 kWe up to tens of MWe and are therefore ideally suited for a variety of future missions requiring high power levels.

A steady state, radiation-cooled, applied-field thruster developed by the Moscow Aviation Institute (MAI) under JPL sponsorship has been operated at up to 188 kWe and has demonstrated 49 percent efficiency at an Isp of 4500~s. The primary life-limiting component appears to be the cathode, which must operate at very high temperatures to emit high current levels thermionically. Tests at MAI demonstrated that the addition of barium vapor to the lithium propellant could significantly extend cathode life by reducing cathode temperatures. Recent work at JPL has focused on designing and fabricating a 500 kWe-class steady state, radiation-cooled self-field thruster and developing the capability to test lithium-fed engines at high power. Calibration tests of a lithium feed system developed by Princeton University and JPL demonstrated controllable flows over a range of 10 to 110 mg/s with an uncertainty of 0.22%. This feed system will be used to obtain performance measurements at Princeton on a 30 kWe-class thruster built by MAI. Additional work at Princeton includes the development of an MHD code to model MPD thruster discharges using a novel solution technique and the investigation of anode phenomena in lithium-fed thrusters.

Non-Lithium MPDs

NASA GRC’s efforts are focused on non-Li propellants. Numerical codes developed at GRC have been used to design self-field MPD thrusters that can operate with inert gas propellants at predicted efficiencies in excess of 35%. It is anticipated that higher thruster efficiencies will be obtained with the addition of applied magnetic fields, leading to the development of MPD thrusters capable of achieving over 50% efficiency with inert propellants. Such designs would mitigate the safety and spacecraft contamination issues associated with condensable propellants such as lithium. Numerical models developed by the Ohio State University (OSU) and further developed by OAI indicate that applied-field MPD thrusters may be able to operate at even higher efficiencies with any propellant by using the applied magnetic field as a true magnetic nozzle downstream of the plasma discharge. These combined results lend confidence that a robust, efficient MPD thruster can be built, and the primary goal of the high power MPD program is to demonstrate efficient, long-life thruster performance at the specific impulse values and power levels required by NASA mission applications.

The effort has several goals over the next 6 years, through a cooperative agreement with the Ohio Aerospace Institute. The first is to establish an MPD thruster modeling effort to simulate applied-field MPD thrusters using a modified version of the MACH2 MHD code. With help of the design codes, pulsed self-field and pulsed applied-field MPD thrusters from 100-kW to 10-MW have been designed, with the goal of achieving over 50% thruster efficiencies. Initial code verification has been on inert gas operation. Based on the OAI models, design and testing will be performed of a quasi-steady MPD thruster in which the primary applied magnetic field is positioned downstream of the electrodes. The performance of this design will be evaluated using inert gas propellants over a range of discharge currents and magnetic field strengths. The experimental results will be compared with the OAI simulations to validate the MPD magnetic nozzle concept.

The next phase will develop a water-cooled, steady state MPD thruster operating in both self-field and applied-field mode. The steady-state thruster will be operated over a power range of 100-500 kW, with the goal of demonstrating thruster efficiencies of at least 50% with an inert gas propellant. Component wear will be measured, and techniques to mitigate electrode erosion will be evaluated. The goal will lead to the design and development of efficient, MW-class MPD thrusters with limited ground testing at 100-kW-class, steady state power levels. If the technology development is successful, an augmented program will provide for the development of steady-state MW-class thrusters and long duration ground testing in a simulated space environment.

Specific program goals to be achieved using augmented funding include several parts. Development of electrode voltage and thermal distribution models is needed to fully understand the performance of an MPD thruster. Electrode sheath models used to predict total voltage and electrode thermal models used to predict component wear would be developed and integrated into the numerical simulations. Steady-state thruster performance at power levels up to 1-MW will be measured, and new designs will be evaluated with the goal of achieving over 50% efficiency in a steady state, MW-class device. Finally, a long-duration (minimum 500 hr), MW-class MPD thruster endurance test will be conducted to validate thruster designs and to establish the feasibility of long term thruster operation in a space environment.

VASIMR THRUSTER

NASA under the leadership of Dr. Chang-Diaz at JSC is also 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 in a magnetic nozzle. This magnetic configuration is called an asymmetric mirror. The forward end-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 end-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 (typically hydrogen) is injected at the forward end-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 end cell to provide modulated thrust. The VASIMR concept is envisioned as eventually evolving to power levels up to 100 MW.

HALL THRUSTER

Hall effect thrusters offer many advantages for Earth orbital and space transfer vehicles 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. The key development paths for increased performance, reduced mass, and longer life have been identified. Goals include the life test of a 10kW thruster and a demonstration of a 50 kW thruster.

For a given mission, reduced propulsion system wet mass will enable a smaller launch vehicle and/or increased mission margin/capability. The near term programs are focused at applying and incrementally improving the SOA Hall thruster systems. The longer-term program is pursuing dramatic improvements in the efficiency, and thrust level with innovative approaches to both the thruster designs and power systems.

NASA's efforts in Hall thrusters consist of four parts, high-power engine development for primary propulsion, ground/space operation effects, research in new thruster concepts including multimode operation, and basic physical understanding of physical processes in a Hall engine.

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

In-house system studies have identified high power / high Isp (>10 kW/>=2000 s) Hall thruster systems as candidates for very ambitious Earth-space orbit transfer missions and as stepping-stones for HEDS-class missions. A 10kW engine has demonstrated an Isp of 2340 s with an efficiency of 57%. The 10 kW T-220 engine successfully completed a 1000 hour life test. The life test included erosion measurements that would predict lifetimes in excess of 8000 hours.

NASA partnered with the BMDO to flight-demonstrate a 5kW Hall system under the Express/T-160 Project. The Express/T-160 flight is an extension of the decade long NASA GRC collaboration with the BMDO in Hall thrusters. Although the flight date was missed, the thruster / PPU combination have been tested and prove that the PPU architecture and thruster technology are valid.

Ground/Space Correlation

The implementation of Hall thruster propulsion requires evaluation of the effect the plasma plume has on the spacecraft. Measuring ion current density and ion energy at various places within the plume during ground tests and calculating spacecraft integration effects based on these data traditionally accomplish this. The validity of this approach is being investigated comparing specific ground test measurements with an SPT-100 to in-orbit plasma measurements taken during operation of SPT-100 thrusters onboard the EXPRESS A-2 and A-3 Russian geosynchronous communication satellites. An early result has confirmed ground test trends that suggest that background pressure has significant effects on ground measurements. Cooperative testing with the Air Force has provided an opportunity to collect ground test data for different chamber backpressures and thrusters. This provided an initial assessment of the effect of the ground test facility on the performance measurements being made.

Multi-Mode Hall Thruster Research

Hall thrusters development has often been done in an Edisonian / evolutionary way stepping off from a known design into a family of thrusters of varying size and power. State-of-art thrusters operate at power levels between 0.75 – 4.5 kW, discharge voltages are nominally 300V, and discharge chamber geometries are circular. Fundamental Hall thruster processes are being investigated in order to push Hall thruster understanding and technology to meet the requirements for future generations of Hall thrusters. These investigations will consider, but are not limited to, reduced beam divergence, increased range of efficient throttleability and increased thrust density at high power.

Innovative two-stage thruster configurations have been investigated so that a spacecraft could have both high thrust and high Isp in its mission profile from the same thruster. Two engines were fabricated under contracts to Boeing/Rocketdyne/Tsniimash and ARC/Fakel. Both were tested at GRC and exceeded their performance specifications. A subsequent area of investigation will be the characterization of a high power thruster at modest Isp.

The NASA D-80 multi-mode Hall thruster has been evaluated at GRC. It was operated over a power range of 1 to 8 kW and in both single and two stage modes. Performance ranged from 1500 seconds to over 3300 s at greater than 50% efficiency. It confirmed the possibility of high-efficiency, deeply throttleable Hall thruster.

The continued effort consists understanding how to manipulate the ionization and acceleration processes within Hall thrusters by modifying the electron temperature and electric field distribution. This information will be used to design the next generation of thrusters to operate more efficiently over a greater operating range.

Discharge chamber materials and geometry will be in investigated and optimized in regimes previously of limited interest. Thrusters operating at voltages other than the SOA 300 volts will require understanding the influence higher and lower voltages have on surface chemistry and modification to the electron energy distribution over the life of the thruster. Specifically, low power thrusters will be used for cost effective limited erosion and performance characterization. The type and configuration of ceramic material, along with the operating parameters, will be varied. A model will also be used to understand the influence these changes have on the distribution of losses within the thruster (ie ionization, radiation, etc.). Based on the results innovations such as composite discharge chambers and hybrid anode designs will be considered.

A split anode TAL will be studied along with two hybrid concepts (The University of Michigan and Busek Co.) to understand the internal processes of the thruster. Understanding and manipulating the electric field within a thruster holds the promise of increase ionization and acceleration efficiency over a wide range of discharge voltage. In the out years concepts such as linear thrusters, racetrack designs, and thrusters with concentric channels will all be considered along with new concepts that come from the fundamental understanding gained the year before.

High Power Engine Development

Over the past several years NASA has been investing in the development of high-power Hall engines for primary propulsion. The first phase of this effort focused on 10 kW engine technologies. That effort culminated in FY00 with the 1000 h demonstration by NASA GRC of the T-220 10 kW engine developed by Pratt & Whitney (formerly Space Power Inc.) under contract to TRW. This is the longest operation ever achieved on a high power Hall thruster. This test indicates the availability of 10kW Hall thruster technology for future NASA, commercial, and military missions. The thruster provided over 500mN thrust at 2450 seconds specific impulse (Isp) and 59% total efficiency with 10 kilowatts input power.

The primary objectives of the life test were to determine the rate of erosion that occurs on the ceramic discharge chamber in order to refine future designs, and to demonstrate the overall durability of high power Hall thrusters. Quantitative measurements of material erosion were made throughout the test using a novel laser profiling technique. Erosion measurements project a useful life of approximately 8000 hours. Performance parameters showed less than 2% variation through the 1000-hour test.

High power Hall effect thrusters offer many advantages for Earth orbital and space transfer vehicles 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 primary objective of the High Power Hall Thruster effort is to develop and demonstrate Hall thruster systems for primary propulsion. Goals include the demonstration of a 50 kW thruster engineering models for transition to flight system development over the next 6 years.

Contracts with General Dynamics and Busek are to produce designs for 50kW class thrusters. An in-house effort has designed and is in the process of building a 457mm diameter test bed 50kW thruster. A thrust-stand capable of carrying the weight and discharge current anticipated is being modified. In

FY02 the test-bed thruster will be assembled and tested for baseline performance.

Recent interest in technologies applicable to human exploration and development of space has also focused on Hall thruster technology and significant mission and system analyses have identified a solar electric/ chemical/ aero-brake (i.e. non-nuclear) 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 is extremely synergistic. The Space Solar Power Exploratory Research and Technology program is supporting 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, lightweight, low power feed system will provide benefits to both Ion and Hall thruster applications.

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 integration aspects. PPT-specific systems analysis is performed to continually upgrade our understanding of the technology drivers.

PPTs have several unique attributes that make them enabling for several 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 most 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. Further, very small impulse bits can be attained for precision pointing applications. Use of a solid polymer propellant results in a very simple (i.e., one moving part), 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. The near term effort sought to reestablish a commercial source for Teflon PPTs with a specific impulse levels of >1100s and efficiencies of >0.10 at a power levels of 50W. An initial product from the program will be demonstrated on NASA's Earth Observing-1 (EO-1) S/C. 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. The GRC Prime Contractor for the PPT, General Dynamics (Primex Aerospace Co.), was tasked with the hardware fabrication. The flight system has been built, delivered to the spacecraft, integrated, fully tested, and launched. An on-orbit checkout indicated that the PPT survived the launch. The PPT will provide pitch axis control for a limited time after the primary spacecraft mission has been completed. An intermediate program goal is to develop the propulsion 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 must be 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 will be 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 primary 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. GRC 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.

CONCLUDING REMARKS

Spacecraft propulsion continues to be a significant performance driver for many mission applications. To meet known and anticipated mission performance goals in the future, innovative electric propulsion systems will be required. To this end, NASA sponsors aggressive programs to develop new electric propulsion systems for a wide variety of space systems. The scope of the program extends from low power systems (sub-0.1 kW) for miniature/micro spacecraft for space exploration and MTPE-class missions to very high power (50 - 100 kW) systems for HEDS-class endeavors. Significant emphasis will be on the future evolution of NSTAR ion technology and on the development of next generation ion systems for deep space exploration. 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.

Continuation of much of this effort is subject to awards of “contracts” from an upcoming Code S openly competed NRA.

PARTICIPATING ORGANIZATIONS

NASA: GRC, GSFC, JPL, JSC, MSFC

Industry: ARC, Boeing/CP, Boeing/Hughes, Busek, Ceramic Composites Inc., CU Aerospace, General Dynamics, 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

ACKNOWLEDGEMENTS

The author would like to thank all the NASA electric propulsion task managers whose inputs provided the bulk of the paper: Robert Jankovsky, Michael LaPointe, and Michael Patterson Eric Pencil (NASA GRC); John Brophy and Jay Polk (JPL); Franklin Chang-Diaz (NASA JSC) and Ivana Hrbud (NASA MSFC).