An Overview of Current NASA Activities in Electric Propulsion Technology

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ABSTRACT

The use of electric propulsion is expanding in all space sectors with systems being used, or readied for use, for orbital insertion, deorbit, station-keeping, precision positioning and repositioning, attitude control, and primary and secondary propulsion for planetary exploration. NASA clearly recognizes the need for new, high performance, electric propulsion technologies for the near-, mid- and far-terms and sponsors aggressive efforts in this area. These efforts are mainly conducted under the Office of Space Science Cross Enterprise Technology Development Program (CETDP) through the Advanced Power and On-Board Propulsion Thrust Area and the Aero-Space Technology Enterprise Advanced Space Transportation Program (ASTP). The ASTP also provides resources for the development of high performance, high power systems for very ambitious missions including human exploration. 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. In addition to the in-house technology efforts, 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. This paper provides an overview of NASA's activities in the area of electric propulsion with an emphasis on program directions and recent progress.

INTRODUCTION

In-Space 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 a key element in allowing NASA to lower the cost of space transportation which will enable planned 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 of Earth Science, Human Exploration and Development of Space, and Space Science. Low Technology Readiness Level (TRL) projects are supported by the Office of Space Science Cross Enterprise Technology Development Program (CETDP). To advance the technology into the mid-TRL range the CETDP program seeks technology development partners from the enterprises. The key partner for propulsion is the Aero-Space Technology Enterprise (ATE) with Access to Space as its third pillar and enabling In-Space Propulsion as its tenth goal. Under the ATE Marshall Space Flight Center managed Space Transportation Program, the lead for electric propulsion has been assigned to the Glenn Research Center with participating centers including the Jet Propulsion Laboratory and the Marshall Space Flight Center. The Johnson Space Center is also participating in the development of an advanced plasma thruster. Planning of the electric propulsion portion of the Advanced Space Transportation Program is well underway with technology product development roadmaps assembled, identifying key products to meet/exceed Access to Space goals. The plans take electric propulsion technology from core research under CETDP through ASTP In-Space Focused development funding, and then onto flight demonstration via the FutureX program. The industry/Government/ entrepreneur/academia Space Propulsion Synergy Team has recently completed a comprehensive study of propulsion system technologies required for future In-Space transportation systems and has ranked electric propulsion at the top of several categories. In addition, in the area of electric propulsion NASA is involved in projects with the Department of Defense, including Air Force, Ballistic Missile Defense Organization, Defense Advanced Research Projects Agency, and the Navy. Transition of the technology to US commercial industry is continuing successfully and the unique capabilities of the NASA electric propulsion testbeds are continuing to be utilized by the US commercial satellite industry.

The benefits of high performance electric systems are now widely recognized and new technologies have been accepted across the community. Arcjets have been operational on two generations of Lockheed-Martin commercial communications satellites for several years

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now. Hall thrusters are routinely used on Russian communication satellites for both East-West and North-South Station Keeping. The October 1998 flight of the RHETT2/EPDM Thruster with Anode Layer on the NRO STEx spacecraft was the first Western flight of a Hall thruster. SS/Loral is committed to fly the SPT Hall thruster. NMP Deep Space-1 with the NSTAR ion system is 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 with plans of the XIPS-25 on the 702 bus. NASA has played an active role in the development and demonstration of new technologies for these near-term missions and will continue to identify and validate key technologies for the future.

NASA's efforts in electric propulsion consist of a healthy mix of core research, technology development, and flight demonstration with attention being paid to both near-Earth space and Deep Space applications. This paper briefly describes major NASA electric propulsion activities with an emphasis on-going efforts and anticipated directions over the next several years.

ION

This technology activity addresses the need for high specific impulse ion systems across a broad range of Deep Space mission applications. After the invention of the ion engine at GRC by Harold Kaufman in the late 1950's, NASA demonstrated ion propulsion in the 1960's and 1970's on the SERT1 and SERT2 flight experiments. In the 1980's a low power Ion Auxiliary Propulsion System (IAPS) was built for demonstration on a US Government satellite. During the 1990's NASA focus was on 30 cm xenon technology for deep space science and resulted in the 2.5 kW NSTAR system. The NSTAR system consists of a 30-cm ion engine, a power processing unit, digital controls interface unit, and a propellant storage and delivery system. The system is designed to operate between 0.5 to 2.6 kW at an overall efficiency of 55% and a nominal Isp of 3100 s. NSTAR-like systems will enable launch vehicle class reductions and/or significant trip time savings for planetary exploration.

The NSTAR program has both ground and space elements and is designed to provide the information necessary for flight program managers to baseline solar-powered ion propulsion systems for high delta-V missions. The NSTAR project is managed by JPL and sponsored jointly by the CETDP and the ASTP. GRC was responsible for the thruster, power processor, and interface electronics development and flight hardware delivery with industry partners of Hughes and Spectrum Astro. JPL had responsibility for the spacecraft integration, life testing of the GRC hardware, and feed system development with industry partner Moog Space Products. NSTAR was launched in October 1998 on Deep Space 1 and has completed its mission after over 3000 hours of operation. Every performance metric has been achieved. Currently the Deep Space-1 extended mission has been approved and is being implemented, and the plan is to accumulate over 12,000 of operation by April 2001. In addition to the space operation, a mission profile life test is continuing at JPL with the flight spare hardware and will continue through at least the next year.

The current technology push areas are to develop key technologies for advanced NSTAR-derivative high-power ion, lightweight low power high-performance ion, "micro" ion propulsion, and component technologies for high-power electric propulsion (EP) for very ambitious missions. Products include: a 5-kW, 400 kg-throughput ion thruster and power processing technology; extremely-lightweight high-efficiency sub-kilowatt ion thruster and power processor; a 1-25 W high-specific impulse ion engine; and component technologies for high-power (25-kW+ class) ion and Hall engines.

High-power (5-kW) NSTAR-derivative thruster technology

It is the goal of this activity to develop a high-performance 5 kW-class ion thruster with 400 kg propellant throughput capability (5x increase over NSTAR), and a lightweight (15 kg; 2x reduction in specific mass compared to NSTAR) power processor.

Near and far term program elements include: 1) high performance, long life accelerator systems (several options including advanced-Molybdenum, Titanium, and Carbon-Carbon, with 2x-10x increase in propellant throughput capacity); 2) highly-efficient, long-life neutralizers; 3) improved discharge chamber thermal design; 4) magnetic containment optimization; and 5) advanced lightweight power processing. Near-term activities include the development of a prototype 5-kW thruster (in-house), and a lightweight breadboard power processor (under contract).

The majority of the effort is being supported in-house at GRC; however, industry and academia are a major contributors. Under contract to Ceramic Composites, Inc., an industry source for low-cost carbon-carbon optics is being developed. Fundamental ion engine processes are being better understood via grants to Colorado State University, the University of Michigan, Tuskeegee University, and the Ohio Aerospace

Institute. CSU is assessing the life-enhancement capability of using ion-implantation processes to modify sputter yield of molybdenum. To date they have demonstrated 50% reduction in sputter yield. UM is developing a fundamental understanding of cathode erosion processes in the discharge chamber of high-power ion thrusters utilizing Laser Induced Fluorescense spectroscopy. To date they have measured ion velocities and neutral temperatures downstream of the discharge cathode. TU is measuring low energy sputter yields of materials relevant to electric propulsion. To date they have measured sputter yields of Mo-Xe between 200-500 eV utilizing Secondary Neutral Mass Spectroscopy and Rutherford Backscattering Spectrometry. OAI is evaluating accelerator grid lifetimes for different materials by direct measurement of erosion products in real-time. In addition, they are establishing an ion diagnostics capability for high-power ion thrusters which will provide laser profilometry, optical emission spectroscopy, and LIF.

Low-Power (sub-kilowatt) high performance lightweight ion thruster , power processor, and component technologies

It is the goal of this activity to develop a lightweight (1.5 kg combined mass; 10x reduction from SOA), sub-kilowatt thruster and power processor. Performance goals include 50% efficiency at 0.25 kW, representing a 2x increase over SOA.

To address these requirements, an effort continues to examine scaling relationships/design criterion for low power ion systems. This effort to date has been conducted in-house at GRC and has led to the fabrication and performance assessment of a small (0.25 kW class) laboratory model thruster. A miniature, high efficiency cathode has been developed and is being tested extensively under this program. Advanced grid development is also on-going in a joint GRC/industry effort. This activity will leverage the high power development effort. Near-term activities include the development of a second-generation light-weight thruster with a 100-500 W power throttling envelope, and a second-generation lightweight breadboard power processor.

Industry proposals for conducting a design study of innovative approaches to simplified low-power (sub-kilowatt) ion thruster and power processors were solicited in FY99, with the selection of two contractors, Hughes and Primex Aerospace. Proposal winners were selected based on approaches which would reduce the parts count, mass, volume, and manufacturing costs of ion systems, and yield a combined thruster/power processor efficiency of > 50% at all input power levels, with a 10x mass reduction over SOA. The product of the design study is to include a user survey, top-level drawings, and detailed design requirements. A follow-on option to manufacture engineering-model hardware is anticipated.

"Micro" ion engine technology

Currently there are two "micro" ion concepts being pursued. JPL under the sponsorship of the ASTP Space Transportation Research Program and with FY00 sponsorship from the CETDP has been pursuing physically scaling ion engines to micro-scale. The efforts has been focusing on the feasibility of such an approach, including voltage stand-off, fabrication, and performance predictions.

A second approach is being taken by GRC which is based upon low power cathode technology. That approach an overall performance of >25% efficiency at > 1500 seconds specific impulse, operating over an input power range of ~1W – 25W. To address this need, a laboratory investigation has been initiated to examine the basic physics controlling ionization processes of low power cathodes, and a contracted effort is underway to develop computer models of this process. This will result in the fabrication of high-efficiency hollow cathodes (≥ 50% ionization efficiency; SOA is ~ 3%), and identification of the controlling design parameters. Near-term activities include the design and fabrication of a prototype hollow cathode micro-thruster (HCMT) along with experiments to verify the models and design concepts. Maxwell Laboratories has been brought in as an industry partner to assist in using models of cathode ionization processes to develop the hardware design.

Component technologies for high-power electric propulsion

It is the goal of this long-range activity to develop high-current (100-Ampere class) cathode technology for high-power (> 30 kW) ion and Hall engines, and examine plasma production and ion accelerator system issues associated with large-scale high-power ion engines. Near-term activities include the fabrication and testing of high-current (40-100 Ampere) cathodes, and experimental investigations of novel approaches to large-area ion optics. The activity builds on the significant Space Station Program investment in NASA cathode capability at GRC.

In the far term, the program seeks to develop a 100-kW class ion system for very deep space "precursor Interstellar mission" which would be nuclear powered and require specific impulse levels greater than 10,000s. The planning activity is in support of the Interstellar Propulsion Project lead by MSFC. Many

of the technologies required for that mission are synergistic with requirements for lower power applications.

HALL

The Hall thruster technology is an area of major near term pay-off for Earth orbit missions and with the long term potential to impact the cost of deep space missions. NASA GRC, acting as agent for the Ballistic Missile Defense Organization's (BMDO) Directorate for Science and Technology, has been deeply involved in the development and validation of Hall devices under the Russian Hall Electric Thruster Test (RHETT) program. A major success of the program was the October 1998 firing of the first Hall thruster system on a Western spacecraft. A low power flight system was assembled in a joint program by NASA GRC and the Naval Research Laboratory (NRL) under respective sponsorship of the BMDO and the NRO. The program included both Russian and U.S. industry (Specifically TsNIIMASH, Primex Aerospace, and MOOG, Inc.) The NRL Electric Propulsion Module Demonstration (EPDM) utilized technologies developed/adapted under RHETT including a Thruster with Anode Layer Hall thruster, a cathode developed under the NASA ISS Plasma Contactor Program, a PPU from industry, and a propellant system developed by NRL with components from industry. The EPDM unit was assembled and tested extensively in the large space simulation facilities at GRC. In orbit performance on the STEx spacecraft matched NASA ground test data.

NASA and BMDO are currently collaborating to develop and demonstrate a higher power (~ 3-5 kW) Hall system for orbit transfer applications. This near-term program will once again merge technology programs in the U.S. and Russia to develop new capabilities for future missions. Development of very low cost power processing using commercial, off-the-shelf parts is underway with a flight demonstration on a Russian Express A3 Communications Satellite. BMDO provided initial support for development of the advanced power processor and flight planning. NASA under the FutureX program is supporting flight demonstration. Space Power Inc. is serving as the prime contractor. TRW is responsible for PPU hardware fabrication, Keldysh Research Center in Moscow is providing the 4.5 kW T-160E thruster, and NPO-PM in Krasnoyarsk, Russia is providing the spacecraft integration and operations. The NASA SBIR program is supporting upgrading the power modules to "S" level quality and radiation standards.

While the NASA efforts in 5kW Hall technology focus on system integration and low-cost power processor technology, the AF effort at 5kW seeks high performance in the power processor efficiency. Under IHPRPT the AFRL is sponsoring the development of a different 5 kW system with Atlantic Research Corp and its contractor team. To assist the AF, NASA GRC is providing performance, plume, and EMC testing for the program via an Interagency Agreement.

The program goal is to develop key technologies for advanced Hall thrusters in three distinct application ranges: (1) high Isp--"gridded" ion thruster type performance (2) low power-high-thrust Hall thrusters, and (3) High power-high thrust Hall. Products in those areas include a 2.3-kW, 3200 s Isp, 100 mN thrust Hall thruster and power processing technology; 100 W-class high thrust sub-kilowatt Hall thruster, 10 kW high thrust Hall thruster; and propellant management component technologies for Hall and ion engines.

Low-Power (sub-kilowatt) High Thrust Hall Thruster

In response to inputs from GSFC, industry, and DOD, it is the goal of this activity to develop a sub-kilowatt Hall thruster and power processor. Performance goals include P~100W, T~6 mN at Isp> 1000s. It is also a goal of this effort to gain insight in to the physics and failure modes of all Hall thrusters and investigate new designs and materials to extend the life of Hall thrusters into the ~15,000 hr range. To address these requirements several Space Act Agreements were initiated. Under these Space Act Agreements industry is providing hardware in exchange for performance and life data. In-house fabrication of a modular power processor is in progress. Additionally, a miniature, high efficiency cathode has been developed in-house and is being tested extensively under the low-power ion thruster program. Near-term activities include the performance and life testing of the state-of-the-art 100W Hall thrusters and comparison to life prediction models.

High-Isp Hall Thruster

It is the goal of this activity to develop a Hall thruster that can operate in two modes. First, it is desired to operate with Isp and thrust equivalent to that of a "gridded" ion thruster, and in a second mode to operate with the thrust and Isp of a state-of-the-art Hall thruster. A Hall thruster is inherently simpler and cheaper than a "gridded" ion thruster and does not have the scaling limitations that "gridded" ion thrusters have due to the manufacturing limitations of the grids. It is envisioned that this thruster could replace most "gridded" ion thruster interplanetary applications if required lifetimes can be demonstrated. Near and far term program elements include:

1) Demonstration of 2-stage accelerator geometries; 2) thrust throttling at constant power; 3) 2-stage power electronics; 4) life determination/limitations. Near-term activities include the investigation of 2-stage thruster designs at 2.3 kW power level.

The initial technology target is 3200 s Isp at 2.3kW power. Contracts have been awarded to Atlantic Research Corp and to Boeing. The contracts are both in the first phase which includes building and testing hardware to evaluate the feasibility of reaching the performance target. The second phase consists of the development, fabrication, and testing of engineering model hardware including thruster, power processor, and propellant management assembly.

High Power- High Thrust Hall Thruster

It is the near term goal of this long-range activity to develop a high power-high thrust Hall thruster for Space Transportation applications (multiple 10's of kW). This activity led by GRC is sponsored by the ASTP and directly works toward achieving low-cost space access. These near-term activities concentrate on a 10kW Hall thruster development (P=10kW, T>600mN, Isp>2000s). This activity will assess the scalability of the technology while providing a thruster for near term applications. The effort is part of the Integrated High Payoff Rocket Propulsion Technology Program (IHPRPT) with TRW and Space Power Inc. as industry partners. In the breadboard stage, this engine has demonstrated an Isp of 2340 s at 10kW with an efficiency of 57%. This activity will evolve into a 10-50 kW thruster development effort that will concentrate on a high thrust device with innovative designs. These innovative designs will concentrate on maximizing thrust density while maintaining life.

A technology flight demonstration is being developed in which the 10kW high power system would be used for orbit raising on a JSC/GSFC spacecraft launched from Shuttle. The spacecraft will also demonstrate the Johnson Space Center VASIMR electric propulsion technology which is discussed in a later section.

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 are in progress in a joint JSC/MSFC/GRC effort to develop a solar electric/chemical/aerobrake (i.e. non-nuclear) option for Mars exploration. The JSC Exploration Program has supported low level feasibility assessments of HEDS-class 25 to 50 kW devices. With the assistance of Texas Tech University, a 50kW-class TsNIIMASH TM-50 Hall thruster was tested at GRC in FY98. Thrust of several Newtons was measured at 3300 s and ~30kW 26 kW. Arcing of the device prevented further testing; however, the performance justifies future investment. In FY99, 50kW class thruster development support was continued under SSP SERT.

PULSED PLASMA THRUSTERS

PPTs have several unique attributes that make them enabling for several NASA science missions, including 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 0.001 and 0.2 kW. Thus, 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.

The NASA effort in PPT's was restarted in the mid-1990's as a technology "push" program with the perceived future need to low-cost, high precision, spacecraft attitude control systems to meet the needs of future NASA science missions. The initial goal of that phase were to reestablish commercial sources for Teflon PPTs with a specific impulse levels of >1100 s and efficiencies of > 0.10 at a power levels of 50 W. An initial product from the program was sponsored by the Office of Space Science CETDP and the New Millennium Programs and will be demonstrated as a Category 3 experiment on NASA's Earth Observing-1 (EO-1) S/C. The PPT for EO-1 PPT will provide pitch axis control for a limited time and was developed by GRC with its industry partner Primex Aerospace and its customer the Goddard Space Flight Center (GSFC). The flight system has been built, delivered to the spacecraft and integrated, and awaits launch in January 2000. As with all new technologies, high quality system characterizations and integration impact assessments are primary concerns.

Space-based interferometers will require extreme position control as well as aperture filling. To achieve that requirement, technology advances beyond the EO-1 PPT must be made in mass and life of the capacitor and discharge electronics. In addition, spacecraft

integration concerns including optics contamination, plume emission spectra, and electromagnetic compatibility must be addressed. The far term focus of the program is on revolutionary technology improvements 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. The PPT technology goals can be summarized by three categories: (1) lightweight multi-thruster systems, (2) high-efficiency single-axis systems, and (3) micro-PPT technology.

Lightweight Multi-Thruster PPT Systems

A low volume/low mass multi-axis PPT system would be competitive with current small spacecraft attitude control propulsive and non-propulsive actuation systems. The target PPT system would consist of a centralized power processing unit (PPU) driving 4 to 6 thruster modules, each with 1 to 3 throttleable thrust axes. Such a system could provide attitude control and translation maneuvers at selectable thrust, total impulse and impulse bit levels. Near-term technology goals will support medium life missions, far-term technology focuses on extending life and increasing performance parameters.

Metric	SOA	Near-Term Goal	Far-Term Goal
System Architecture	Distributed Electronics	Centralized Electronics	Centralized Electronics
Thrust Axes	Single-Thruster, 2-axis	Up to 6 thrusters, 1 to 3 axes/thruster	Up to 6 thrusters, 1 to 3 axes/thruster
System Mass	5 kg/distr. Thruster, 30 kg system @100W	15 kg system @ 100W input power	15 kg system @ 300W input power
Life	4M pulses	50M pulse system	100M pulse system
Impulse Bit Accuracy	85%	95%	98%
Throttle Range	100 – 800 μN-s Ibit	50 – 1000 μN-s Ibit	10 – 1000 μN-s Ibit
Efficiency	10%	10%	20%

High Efficiency Single Axis PPT

Application of PPTs to orbit raising/drag make-up functions is currently limited by the low efficiencies of SOA PPTs, resulting in inadequate thrust at low power levels. This technology goal focuses on increasing the efficiencies of a single axis PPT, while extending life to support longer duration LEO missions. High efficiency single-axis mechanical thrusters can also be integrated into multi-thruster systems to provide higher rate translation/rotation maneuver capability.

Metric	SOA	Program Goal
Mass	5 kg dual-thruster	3 kg dual-thruster
Life	4M pulses	25M pulses
Efficiency	10%	20%
Maximum Thrust	850 μN @ 70W	4.2 mN @ 100W

Micro-PPT Technology

Very low mass actuators are required for micro-/nano-satellite attitude control, particularly when these satellites are combined in constellations requiring control of relative positions and attitudes. With the current SOA, cold gas systems, orbit life is severely restricted by propellant mass. Development of high Isp Microelectromechanical Systems (MEMS)-class or micro-PPTs (< 0.5 kg) would enable life extension of micro-/nano-satellite life and improve constellation maintenance metrics.

In addition to the in-house activities at NASA GRC in the three areas, several industry partners and universities are contributors to the program. The largest outside effort is with a team lead by Unison Industries which includes Primex Aerospace and CU Aerospace. That contract is for technology development of electrical/electronic elements, including energy storage units, discharge initiation components and power processing units, to move beyond the EO-1 design. The first phase is underway and will develop breadboard articles for extensive testing at GRC. Included in the technology selections are capacitors, spark plugs and electronics topologies. The follow-on phase will develop flight-like engineering model articles for complete characterization. Under another contracted effort, the Dynacs Engineering Co., Atlantic Research Corp., and the Research Institute of Applied Mechanics and Electrodynamics have recently completed a comprehensive assessment of past Russian PPT efforts which identified other paths for potential improvements of current baselines.

Current academic partnerships are with Ohio State University and Worcester Polytechnic Institute. The OSU effort aims to understand heat flux, model ablation, characterize optical emissions, evaluate alternate hydrocarbon propellants, eliminate current reversal, all in order to design a higher efficiency thruster. The OSU effort models PPT operation using the MACH2 magnetohydrodynamics code, guided by analytical solutions, and has identified and quantified the mechanisms that cause inefficient propellant utilization. OSU is also quantifying the optical output of the PPT, in order to assess potential interference with optical payloads. To allow comparison of the resultant spectroscopic data with numerical simulations, requires a coaxial version of the PPT. Using MACH2, annular and direct-pinch versions have

been explored. Due to poor predicted performance of those concepts, OSU has designed, built, and operated an inverse-pinch system, for which MACH2 predicts substantially lower propellant temperature and greatly improved propellant use. The WPI effort will build on past investments and will provide test-validated plume model. Operational code with algorithm for charge exchange, neutral-neutral, and ion-neutral particle interactions were put in place in FY99. Future work will continue code development and correlate models with GRC-provided contamination test data.

Targets for future technology demonstration include the NASA New Millennium program. JPL has shown great interest on using the technology on the Space Technology–3 Mission (formerly Deep Space-3). In addition, NASA is partnering with the USAF for intermediate technology development with the Unison team to provide an PPT for orbit raising on the MightySat II.2 mission.

ARCJETS

Prior NASA OBP investments in arcjet technology have led to significant impacts in the commercial communications industry and opened the door for other electric propulsion systems. Arcjets are now operational on many GEO communications satellites such as the LMC's A2100 Series spacecraft. The most advanced arcjet the MR510 resulting from the NASA GRC Arcjet Technology Program was flown for the first time in September 1996. In FY97, PAC fabricated and demonstrated a low power arcjet system (LPATS) for small and/or power limited spacecraft under NASA sponsorship. This was the culmination of a joint multiyear effort and the LPATS system is now ready to be qualified for specific applications. As part of the LPATS effort, MOOG Space Products Division developed a miniaturized liquid hydrazine flow regulator. The regulator is approximately the size of a 35-mm film canister and may find application in a range of spacecraft propulsion systems. Mainline NASA arcjet development efforts for conventional spacecraft have now been concluded. The program still lends support where appropriate to assure further technology transfer.

Currently, the only effort in arcjet technology is being supported by the BMDO under that agency's SBIR program. Under NASA GRC management, BUSEK Co. and its partners are seeking to develop an arcjet capable of operation on Monomethyl Hydrazine (MMH). Traditional arcjets must operate on pure hydrazine. The carbon in the MMH causes rapid plugging of the throat. Several Government spacecraft utilize MMH/NTO bipropellant systems, and performance enhancement of an MMH arcjet would be significant. Phase I demonstrated excellent potential and leveraged technology sponsored by the USAF at BUSEK to develop a methane arcjet. Phase II has just been approved and is awaiting contract award.

RESISTOJETS

The program is also sponsoring a small effort in developing a resistojet operating on xenon. Under contract to MOOG, NASA is developing a 100 W-class thruster to provide auxiliary propulsion for spacecraft. System trades have shown the need for the device when a Hall thruster system is primary. The advantage of a common feed system is significant. In addition the device could provide limited propulsion for Shuttle-launched small satellites. The first phase of the contract will result in delivery of an engineering model xenon resistojet in the 220 mN, 80 watt power range by end of FY 00. The thruster is expected to obtain 55 s of specific impulse for short pulses, and 50 s under steady state operation. Weight of the flight unit is to be no more than 200 grams.

ADVANCED HIGH POWER CONCEPTS

The Pulsed Inductive Thruster (PIT) is a high power electromagnetic propulsion system with the potential for performing a wide range of mission applications. The thrust and specific impulse can be tailored by adjusting the discharge power, pulse repetition rate, and injected propellant mass, and there is minimal, if any erosion, due to the electrode-less nature of the discharge. Because the performance can be varied as a function of the power, repetition rate and propellant mass, the thruster can be used for precision orbit maneuvering in support of NASA earth and space science missions or as a versatile primary propulsion system for planetary and deep space exploration. Design studies have been carried out for power levels ranging from tens of kilowatts to several megawatts, allowing a smooth evolution to higher power electric propulsion systems as in-space power capabilities improve. In the early 1990s, NASA GRC funded TRW to test the single-shot performance of the PIT for a variety of gas propellants.

With GRC, MSFC and TRW partnered, the near term objectives of the high power PIT program are to validate the TRW single-shot performance measurements using GRC vacuum facilities, investigate thruster performance using multiple-pulse discharges to identify and address thermal design issues. MSFC will provide assistance in evaluating new power circuits for high repetition rate thruster operation. Farther term objectives are to integrate the

high rep-rate power system with a thermally cooled version of the PIT to demonstrate long-life performance, leading to a Pulsed Inductive Thruster design capable of meeting the propulsion requirements for a variety of NASA missions.

NASA is also building on its past efforts in the area of high-power magnetoplasmadynamic thrusters. The MPD was an outgrowth of NASA GRC and AF in-house and contracted efforts in high power arcjets in the 1960's. From then to the early 1970's, under NASA and AFOSR support 30 kW-class MPD's operating on various propellants including hydrogen and lithium showed promising performance along with a 500-hr life demonstration by McDonnell-Douglas. 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. During that time period GRC developed a strong program and was assisted by JPL in MW-class MPD's. After the termination of SEI, NASA efforts in MPD's ceased with the exception of a small effort of work with Moscow Aviation Institute supported by the Space Transportation Research (STR) program through JPL. That effort worked on leveraging past Russian investments in lithium MPD's and centered in the 100-kW class thrusters. Partnered in that effort was Princeton University. With recent NASA HEDS interest in MW-class electric thrusters and national policy issues with continuing the MAI work, NASA GRC has rekindled its MPD program from the SEI baseline seeking to develop US engines ranging from 0.1MW-10 MW. Under SSP support, 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 are near completion. Planned future activities include completion of fabrication and testing of the steady-state concept. 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.

NASA under the leadership of Dr. Chang-Diaz at JSC is also developing the advanced VASIMR concept. The VASIMR system is a high power, electrothermal 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. Current efforts are focusing on a flight opportunity on a Radiation and Technology Demonstration (RTD) mission with JSC, GSFC, and GRC teamed. The mission is in the study phase. The mission would demonstrate both 10 kW VASIMR and 10kW Hall thrusters.

CONCLUDING REMARKS

In-space 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 technology development efforts to develop new electric propulsion systems for a wide variety of space systems. The scope of the activity extends from low power systems (sub-0.1 kW) for miniature/micro spacecraft for space exploration and Earth science missions to very high power (50 - 100 kW) systems for HEDS-class endeavors. To date, multiple technology transfers from NASA's electric propulsion activities have occurred and several are in progress. Strong emphasis on technology transfer continues with efforts directed toward the development of commercial technology sources and the demonstration of program technologies to the level required by potential users. NASA technology activities 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. NASA will continue to identify and develop new electric propulsion technologies and invites the participation of innovative members of the community in the coming years.