REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
14-07-2000	Technical Paper	

4. TITLE AND SUBTITLE

The USAF Electric Propulsion Research Program (Postprint)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
10110011

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
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8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-TP-2000-152

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
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10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-TP-2000-152

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (AFRL-ERS-PAS-2000-102).

13. SUPPLEMENTARY NOTES
Presented at the 36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, 17-19 July 2000. AIAA-2000-3146.

14. ABSTRACT
An overview of the current electric propulsion research and development efforts within the United States Air Force is presented. The Air Force supports electric propulsion primarily through the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL) and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall direction for the programs comes from Air Force Space Command (AFSPC), with AFRL mission analysis used to define specific technological advances needed to meet the AFSPC mission priorities. AFOSR funds basic research in electric propulsion throughout the country in both academia and industry. The AFRL Propulsion Directorate conducts electric propulsion efforts in basic research, engineering development, and space flight experiments. EOARD supports research at European laboratories that will directly feed into the AFOSR and AFRL research programs. Current research programs are well grouped into three categories defined by the thruster power level. All three agencies are currently focusing their research at the low-power regime, in support of the emerging AF microsatellite missions. Emphasis on research in the mid-power range (500W to 5kW) is diminishing with the near-term conclusion of the 4.5 kW HPHS Hall thruster development program, and the high degree of commercialization in this power range. The high power regime (P>3kW) is realizing increased emphasis through such programs as a collaborative AFRL research effort with industry.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Dr. James M. Haas
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	12	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**			N/A

A00-36411

AIAA-2000-3146
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36th Joint Propulsion Conference & Exhibit
16 – 19 July 2000
Huntsville, Alabama

AIAA-2000-3146

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An overview of the current electric propulsion research and development efforts within the United States Air Force is presented. The Air Force supports electric propulsion primarily through the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL) and the AFOSR European Office of Aerospace Research and Development (EOARD). Overall direction for the programs comes from Air Force Space Command (AFSPC), with AFRL mission analysis used to define specific technological advances needed to meet the AFSPC mission priorities. AFOSR funds basic research in electric propulsion throughout the country in both academia and industry. The AFRL Propulsion Directorate conducts electric propulsion efforts in basic research, engineering development, and space flight experiments. EOARD supports research at European laboratories that will directly feed into the AFOSR and AFRL research programs. Current research programs are well grouped into 3 categories defined by the thruster power level. All three agencies are currently focusing their research at the low-power regime, in support of the emerging AF microsatellite missions. Emphasis on research in the mid-power range (500W to 5kW) is diminishing with the near-term conclusion of the 4.5 kW HPHS Hall thruster development program, and the high degree of commercialization in this power range. The high power regime (P>30kW) is realizing increased emphasis through such programs as a collaborative AFRL research effort with industry.

I. Introduction

To provide enhanced satellite maneuvering capability at reduced cost, the United States Air Force (USAF) has developed a coordinated research program within the Air Force Office of Scientific Research (AFOSR), the Air Force Research Laboratory (AFRL), and the AFOSR European Office of Aerospace Research and Development (EOARD). Research direction for these efforts comes primarily from Air Force Space Command (AFSPC) in the form of a Strategic Master Plan (SMP). The SMP provides a 25-year AF plan, detailed in terms of near-term (2000-2007), mid-term (2008-2013), and far-term (2014-2025) development priorities. AFRL and AFOSR perform the mission analysis required to determine the optimal propulsion system for the AFSPC missions, and then promotes research programs to develop the technology needed to achieve these missions. EOARD interacts with AFRL and AFOSR to develop research at European laboratories that will directly feed into the AFOSR and AFRL research programs. Near-term missions are generally served through commercial contracts at the System Program Office (SPO) level. The AFRL role in these decisions is primarily one of technical advice, advocacy and demonstration of new technologies to facilitate technology transfer to the commercial sector. The research role of AFRL and AFOSR is focused on the mid-term and far-term, with AFOSR directed more towards performing the basic research that enables AFRL to meet the far-term mission needs in a future advanced engineering program.

The AFRL technology development advances are baselined and measured through the Integrated High Payoff Rocket Propulsion Technology (IHPRPT) program. IHPRPT is an all-encompassing propulsion development program, which details specific performance advances for each technology area in a 3-phase effort from 1995 to 2005. The IHPRPT baselines and goals were determined through a collaborative effort between AFRL, NASA and industry. All current AFRL electric propulsion funding falls under the guidance of the IHPRPT program.

Although a majority of the resources are used for conventional core funding and in-house research,

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AFOSR and AFRL also manage a number of contracts through the Small Business Innovative Research (SBIR) and the Small-Business Technology Transfer Research (STTR) programs. Contracts under the SBIR/STTR programs are also directed towards achieving the IHPRPT goals. Complimenting the AFOSR and AFRL programs is the European Office of Air Force Research and Development (EOARD), which funds AF-relevant basic research abroad. In all of the efforts, the AF organizations coordinate their respective research programs so as to maximize effectiveness in achieving the AFSPC priorities and the IHPRPT goals.

Historically, AF electric propulsion research has been directed primarily at medium power technologies (500W – 5kW) for stationkeeping, rephasing, and orbit topping applications. Military satellites which may benefit from this research include MILSATCOM, DSP, DSCS, and SBIRs to name a few. Electric propulsion in this class is largely commercialized. Both arcjets and ion thrusters are now seeing widespread use on commercial satellites, indicating their availability for military applications. The exception is the Hall thruster. Whereas the Hall thruster has performance characteristics (specific impulse, thrust density) optimal for the on-orbit USAF satellite missions, it has only seen widespread operational use in Russia. To promote the domestic commercialization of the Hall thruster, AFRL is co-funding the development of a 4.5 kW High Performance Hall System (HPHS) in a cost shared contract with International Space Technology Incorporated (ISTI) with Atlantic Research Corporation (ARC) as the prime contractor. The HPHS has demonstrated performance in excess of the IHPRPT Phase I goals. The final major task is a 7200-hour life test of the qualification model thruster, scheduled to start in November 2000 at AFRL. With the scheduled completion of the 4.5 kW HPHS program in 2001, AFRL and AFOSR research emphasis on mid-power electric propulsion is expected to decline. The technology should be of sufficient maturity, and the commercial payoffs sufficiently large, that further performance advances will be accomplished in the private sector.

With the projected decline in electric propulsion needs for the mid-power range, the AF electric propulsion research emphasis has bifurcated towards both the low-power (1W – 200W) and the high-power (>30kW) regimes. Low-power electric propulsion research responds to the AFSPC priority for highly maneuverable microsatellites performing Modular On-Orbit Servicing (MOOS) or flying in formation to create a sparse aperture Space-Based Radar (SBR). Mission analysis shows that both high specific impulse and high thrust micropropulsion will be required to meet the low-power AFSPC missions. High-power electric propulsion research responds to the AFSPC priority for Orbit Transfer Vehicles (OTV) and the propulsion capability to rescue and reposition marooned assets that failed to achieve final mission orbit. Although not described within this paper, AFRL also supports in-house and contractual research in solar-thermal spacecraft propulsion directed towards the enabling the same AFSPC high-power missions.[1]

For the last few years, research in the low-power regime has received more emphasis than the high-power regime. AFOSR supports industry and university research in technologies such as colloidal thrusters, low power Hall thrusters, and Pulsed Plasma Thrusters (PPTs) for the high specific impulse maneuvers, and research in digital chemical microthrusters for the high thrust maneuvers. EOARD supports 40W – 100W Hall thruster research in Russia, and 100W resistojet research at Surrey, UK. AFRL supports 200W Hall thruster and PPT development, often co-funding these efforts with AFOSR. EOARD and AFRL support separate research efforts in low-power, low-propellant, neutralizer technologies, essential for a low-power Hall thruster system. In-house research at AFRL, partially funded by AFOSR, has focused on miniaturized versions of the PPT and miniaturized chemical motors for high-thrust maneuvers. The AFRL Electric Propulsion Group is also responsible for developing a low-power propulsion system for the TechSat21 spacecraft,[2] scheduled for launch in 2003. The propulsion system is currently in the source selection process with an award announcement expected in August 2000.

The high-power regime is realizing increased research emphasis. AFRL has entered into a commercial partnership to research the effects of assembling several Hall thrusters into a clustered array to achieve high total system power. This follows a year of discussions with industry, universities, and government users to determine the most efficient means of achieving high power electric propulsion capability while minimizing total lifecycle costs. Ongoing AFOSR basic research on Hall thruster physics at the universities has beneficial impact both at the mid-power regime and the high-power regime.

In the following sections, various research programs supported by AFRL, AFOSR and EOARD are summarized with references to more complete descriptions. Summaries of the AFOSR funded efforts at the universities can be found in a companion paper from this same conference.[3]

II. Low Power Electric Propulsion (1W – 200W)

200 Watt Hall Thrusters

Two separate efforts have been supported by AFRL and AFOSR to develop a 200W-class Hall thruster. The Busek Corporation has developed a 200W Hall thruster and power processing unit PPU under AFRL SBIR contracts, and recently improved the PPU under an AFOSR STTR contract.[4, 5] In a similar effort contracted to Space Power Inc. (SPI), AFOSR and AFRL changed roles. AFOSR supported the thruster development, while AFRL managed a BMDO-funded SBIR to develop the PPU.[6]

During spring 2000, both thrusters were brought to AFRL for testing and demonstration for potential industry partners in an effort to facilitate technology transfer of the devices. During summer 2000, AFRL is currently providing extended use of their testing facilities to SPI for research and development of their 200W Hall thruster. AFRL facilities are provided at no cost to SPI, and all SBIR contractors who request use, as available.

100 Watt Hall Thrusters

EOARD supports two projects with Russian institutes investigating low power (<100 W) Hall thrusters. The first effort, contracted to TSNIIMASH Export, Moscow, Russia, characterizes the performance of their existing T-27 thruster, operating at lower than design power conditions. TSNIIMASH investigated the changes in performance due to variations in thruster power, mass flow rate, and magnetic field strength at powers ranging from 40 – 150 W. The goal was to increase the ionization efficiency at a lower mass flow density and voltage. The research showed excessive power and propellant losses, indicating the a thruster redesign was required for competitive performance in the sub 100W power regime. An increased knowledge of the physics of small Hall thruster operation was produced from an understanding of the important variables in this study.

Fakel Design Bureau, Kaliningrad, Russia has developed a new Hall thruster to operate below the 100 W power levels. This thruster was a modification of the T-20 thruster that had been previously developed, but optimized for the 100W operation. The thruster also required the development of a "heaterless" hollow cathode that could operate for up to 1000 hours of operation. The following performance results were measured in tests at Kaliningrad:

Power: 94.5 W
Thrust: 4.7mN
Isp: 1000 sec
η = 24 % (includes cathode and other system power)

The Fakel 100 W thruster has been delivered to Edwards AFB where it will undergo testing at the AFRL Electric Propulsion Laboratory. Follow-on work supported by EOARD is planned with both institutes.

Field Emission Diamond Cathodes

Busek Corp is currently funded under an AFRL Phase II SBIR Program to develop a diamond based field emission (FE) cathode for space propulsion applications. Motivation for a field emission cathode stems from the deleterious impact of hollow cathodes on the performance (efficiency and Isp) of low power electrostatic thrusters including Hall and ion thrusters. The FE cathode is also a candidate for neutralization of the colloid and FEEP thruster beams.

The Phase II effort focuses on the development of cathode emitter materials and cathode designs with sufficient current density to provide discharge and neutralization electron current for a 100 W class Hall thruster, such as those developed in Russia through EOARD. Several materials and fabrication techniques are being investigated. Material emission requirements are influenced by total current, cathode size, and space charge limits. Contractor analysis has resulted in a baseline design for a 1 Amp, 10 cm^2 emission area. The maximum electron current density is governed by the Child-Langmuir space charge equation. At V_a = 20 volts and d = 3.5 micron, the maximum current density is approximately 17 A/cm^2. The electron current density in the contractor design is orders of magnitude less than the Child-Langmuir limit.

100 Watt Water Resistojet

In 1998, AFRL/PRRS contracted with the University of Surrey to build a 100 W water resistojet[7] to fly on MightySat II.1. Due to funding constraints, the propulsion subsystem experiment on the flight was canceled, but the flight thrusters were delivered to Edwards AFB. Under the scope of the present program, funded through EOARD, an endurance test has been conducted of the 100 W thruster. The thruster has recently completed over 400 hours of operation with no anomalies. The endurance test will continue through 500 hours of operation.

A similar design, using nitrous oxide as the working fluid, was demonstrated in space flight during 1999 on the UoSAT-12 spacecraft developed by the University of Surrey. Results of this work and more discussions on the water resistojet tests results are presented in a companion paper at this conference.[8]

Nitrous Oxide Monopropellant

The University of Surrey, Guildford, UK has been developing a nitrous oxide monopropellant thruster under funding from EOARD. This thruster concept is based upon the catalytic decomposition of nitrous oxide and requires input energy at start-up, but then produces a self-sustaining reaction that runs as a function of the catalyst lifetime. Theoretical specific impulse is 206 sec. The University of Surrey has produced a ~ 1 N, 175 sec experimental thruster that has been tested for 76 minutes continuously. An electrical power of 24 W was input for 3 minutes, following which the reaction ran self-sustained for the remaining 73 minutes. The catalyst is rhodium based and the University plans on building a prototype thruster for vacuum testing in Fall, 2000.

Electrothermal Pulsed Plasma Thruster

CU Aerospace, teamed with the University of Illinois at Champaign-Urbana and Unison Industries, designed, fabricated and tested an electrothermal PPT-8 breadboard demonstrator. PPT-8 is a three-module coaxial pulsed plasma thruster that was designed based upon research of the single-module thrusters PPT-4[9] and PPT-7.[10] The thruster uses side-fed Teflon bars, and is driven by low-loss mica capacitors. Performance of individual thrusters in PPT-8 are comparable to the performance characteristics of the PPT-7 thruster. The three-module thruster was designed for operation at 100 W of spacecraft bus power to produce a high-thrust greater than 2 mN. The Unison electronics consisted of a mica-capacitor energy storage unit (ESU), 0.25" diameter semiconductor igniter plugs, a three-channel multiplexed discharge exciter unit, and a microprocessor-controlled power processing unit. PPT-7 and PPT-8 research and development was funded by an AFOSR Phase I STTR, AFRL core funding, and the AFOSR TechSat21 initiative. Research and development of the Unison electronics were funded by NASA on an advanced PPT components development program.

An AFOSR Phase II STTR for the CUA effort was recently awarded. Under the AFOSR Phase II STTR effort, the thruster performance will be further optimized. Qualification testing will be performed, including vibration and thermal-vacuum testing, along with structural and thermal modeling. At the conclusion of the program, the thruster is expected to be in an advanced state of engineering development, suitable for incorporating directly into a future spacecraft flight integration effort with minimal additional engineering required.

MEMS Mega-pixel micro-thruster

A new micropropulsion concept called the MEMS Mega-pixel micro-thruster array intended for stationkeeping of small and micro satellites is being developed and tested by the Honeywell Technology Center and Princeton University's Electric Propulsion and Plasma Dynamics Lab. The effort is supported under an AFSOR STTR contract. The thrusters have very low power and energy thresholds for ignition (~10 mWatts, ~100 μJoules), and no moving parts. The array contains a quarter of a million separate thrusters on a 1.3" x 1.3" silicon die; the thrusters themselves are laid out one a 512 by 512 grid with 51μm by 51μm pitch. Each thruster has its own heater filament, which is co-axially aligned to a hollow fuel-filled cavity directly above it. Each thruster/pixel is individually addressable and ignitable. The goals of the project include 1) modeling the mechanical and thermal properties of the structures, 2) building the micro-thruster arrays, 3) measuring the performance of the thrusters using Princeton's new micro-thruster stand, and 4) generally advancing the fundamental understanding of how explosions occur in very small structures.

Presently the following tasks have been accomplished successfully: 1) numerical modeling of the structures, 2) processing the igniter wafers, 3) building walls around the individual igniters, 4) coating the filaments with a Self-Assembled Monolayer (SAM) to facilitate good wetting by the lead styphnate (which will serve as the thermally-detonatable first stage) 5) preparing and applying the lead styphnate igniter suspension to the igniter filaments, 6.) creating the hollowed-out cavity wafers, 7) bonding the styphnate-coated filament wafers to the cavity wafers and 8) mounting the 2-layer structures onto appropriate packages. Presently the cavities are being loaded with the nitrocellulose fuel at the Atlantic Research Corporation and readied for testing at Princeton.

Diamond Field Emission Electron Beam Sublimation Thruster

A new micropropulsion concept called the Diamond Field Emission Electron Beam Sublimation Thruster, based on the idea of a self-consuming microsatellite, is under investigation at UHV Technologies Inc., in collaboration with Princeton University's Electric Propulsion and Plasma Dynamics Lab. The effort is supported under an AFOSR STTR contract. The concept relies on efficiently generating an electron beam from a small device that is capable of focusing, scanning and bending the beam in complex patterns over variously shaped targets for sublimating unneeded microspacecraft structures and ejecting the products thermally to produce thrust. The overall objectives of the Phase I project were to demonstrate the feasibility of fabricating an efficient, compact and lightweight field emission (FE) electron-beam, determine its operational characteristics and estimate the thrust capabilities of the concept. A diamond cold cathode needle sources were produced from molybdenum wires by graduated electrolytic etching. These needle cathodes produced electron beams in excess of 1mA current with 3-7 V/μm electrical field. Using these needle type field emission sources, the feasibility of ablating gold, AuSn alloy and aluminum in a diode configuration was demonstrated. The ablation rates were measured directly by ablating material deposited on quartz crystal monitor. Based on these measurements, the thrust and specific impulse for gold-based sublimation thruster is predicted to be 0.5 μN and 35 sec using a single needle source without any electron focusing optics. It is expected that a proper selection of sublimation materials, electron focusing optics and large area electron emitter geometry, diamond field emission electron beam based sublimation thrusters would attain higher specific impulses and be optimized for use in the .5 μN to 100μN thrust range.

Micro-PPT

AFRL mission analysis indicates that propulsion devices that can provide precise impulse bits in the 10-μN range may be enabling for several AFSPC microsatellite missions. In response to this need the Air Force Research Laboratory has been developing a miniaturized propulsion unit: the Micro Pulsed Plasma Thruster (Micro-PPT). Like a standard PPT, The Micro-PPT uses a surface discharge across the face of a solid Teflon™ propellant to create and accelerate a combination of plasma and neutral vapor. The Micro-PPT substantially differs from the standard design by using a self-igniting discharge and eliminating the separate igniter circuit from the thruster. This simplification enables the order-of-magnitude reductions in the thruster size and operational power level required to meet microsatellite propulsion requirements. The primary attractive features are the use of a solid inert propellant (Teflon™), expected high-I_{sp} due to the use of electromagnetic acceleration, and a simple, lightweight design based largely on previously flight-qualified electronic components. Prototype Micro-PPTs have been fabricated and several designs have demonstrated extended lifetime in laboratory tests. Thus, the Micro-PPT is believed to be a near-term design that could be made available for flight with a modest amount of engineering.

The past year has witnessed three significant accomplishments in Micro-PPT development at AFRL. The most recent design has decreased the dry mass of the thruster to about 60 grams while demonstrating operability in the 15W range. This is a mass decrease of about 2 orders of magnitude from the LES 8/9 PPT, generally used as a baseline comparison within the AF research program. Second, propellant geometries and firing configurations have been identified which result in steady-state propellant ablation patterns. Steady-state propellant ablation behavior is expected to be critical for achieving sufficient thruster lifetime for the microsatellite missions. In one configuration the propellant is observed to recede back into the outer anode shell, with the inner cathode electrode ablating at a rate equal to that of the propellant. Thus over time the accelerated propellant will have to travel increasing distance through the anode shell to reach the thruster exit plane. This configuration is preferable from a spacecraft interaction standpoint, since the exhaust location remains fixed, but may cause a thrust decrease over time due to viscous effects. A second configuration has shown operation whereby both the inner and outer electrodes recede with the propellant. The optimal configuration will likely be determined by the spacecraft integrator on a case-by-case basis. The third significant accomplishment is that AFRL has established methods to measure the Micro-PPT thrust levels. The technique involves simply changing the operating mode of the existing PPT thrust stands. Normally the thrust stand damper is energized to damp the oscillations. Displacement are then measured and compared to the displacements due to calibration masses. For the Micro-PPT thrust measurement the damper circuit is turned off, and the thrust stand is allowed to oscillate with about an 8 second period. The thruster is then fired in 4-second bursts with a 50% duty cycle to force a resonant oscillation in the thrust stand displacement. Calibration weights are applied with the same duty cycle using small weights lifted and dropped using an electromagnet. Details on the Micro-PPT developmental status and performance measurements can be found in an accompanying paper at this conference.[11]

TechSat21 Propulsion Flight Demonstration

A primary goal of the AF research programs is to transfer developed technologies to the private sector for commercialization. The fundamental approach is to provide sufficient risk reduction for a new technology, that it will become attractive for a commercial company to complete the engineering development. For a demonstrated technology such as a Hall thruster, which benefits from a strong flight heritage in Russia, sufficient risk reduction can be accomplished using ground tests. This approach is currently being employed in the AFRL High Performance Hall System program, as will be described in a later section. For more radical technologies, such micropropulsion or very high power operation, a flight demonstration is often needed to provide sufficient risk reduction for technology transfer. This approach was used in the recently completed AFRL ESEX program, where a 30-kW arcjet was developed and flown aboard the AF ARGOS satellite in 1999. A present example is the AFRL development of low-power propulsion for the TechSat21 flight.

TechSat21 is an AFRL/VS (Space Vehicles Directorate, Kirtland AFB, NM) mission to demonstrate the formation flying of 3 microsatellites. Other capabilities to be demonstrated include sparse aperture phased array sensing from a space-based platform, autonomous control, and microsatellite bus technologies. The mission is scheduled for launch in 2003. As a critical part of the TechSat21 team, the AFRL/PRRS Electric Propulsion Group is providing propulsion for the mission.

The mission requirements for TechSat21 propulsion system are a wet mass below 8.5 kg, power between 100 and 200 W, stationkeeping Delta-V of 40 m/s, and a cluster maneuver Delta-V of 30 m/s. A total impulse of 8800 N-s will be delivered by the propulsion system. The system must also be able to provide impulse bits as low as 2 mN-s for precision maneuvering. The possibility for a significant orbit raise Delta-V also exists, depending on the launch vehicle. No altitude adjustment will be needed if launched from an OSP, EELV, or Arianne V. If launched as a DMSP secondary, the propulsion system will provide 200 m/s Delta-V to lower the spacecraft from 1000 km to the operational altitude of 650 km. For a Shuttle launch, a Delta-V of 100 m/s will be required to raise the orbit.

In 1999 AFRL conducted an extensive mission analysis and trade study to optimize the propulsion requirements and to identify leading candidate technologies. An open competition for the propulsion contract was held in Spring 2000, which included all offerors demonstrating laboratory models of their proposed technologies at the AFRL Electric Propulsion Laboratory. An award and announcement of the winner is expected in late July to early August 2000.

III. Mid-Power Electric Propulsion Research

High Performance Hall System

The High Performance Hall System (HPHS) program supports the development and flight qualification of a 4.5 kW electric propulsion system that includes the SPT-140 Hall thruster. AFRL and ISTI are co-funding this cost-shared contract (56% government, 44% contractor) under the auspices of the IHPRPT initiative. Atlantic Research Corporation (ARC) is the prime contractor. The propulsion system includes the thruster, power processing unit (PPU), propellant management assembly (PMA), and simulated spacecraft hardware. The Experimental Design Bureau/Fakel, a Russian designer and manufacturer of over 110 flight Hall thrusters, is developing the SPT-140 thruster. Space Systems/Loral (SS/L), leveraging their flight qualification experience with the 1.35 kW SPT-100 Hall system, is designing and manufacturing the Power Processing Unit (PPU). An existing, MOOG Inc built, flight qualified Propellant Management Assembly (PMA) will complete the major system components. The target performance of the system is a specific impulse of 1800 s, overall system efficiency of 51%, specific mass (thruster, PPU) of 6.0 kg/kW, and a lifetime of 7200 hours. To ensure US government access to SPT-140 thruster technology, ARC will deliver a thruster design package, including engineering drawings, processes, and procedures to a US-based escrow agent.

The Fakel SPT-140 thruster preliminary design review (PDR) and critical design review (CDR) were successfully completed in December 1997 and March 1999, respectively. During an extended 1200-hour test at Fakel, the thruster demonstrated thrust efficiency of over 58% (including cathode flow, magnet power, and vacuum correction). This efficiency exceeds the contractual goal of 55%.

The PPU PDR and CDR have also been successfully completed in November 1998 and October 1999, respectively. A delta CDR is currently being scheduled to authorize design changes prior to qualification model (QM) fabrication.

During testing with the breadboard unit, SS/L demonstrated an efficiency of 95.1% on the main discharge supply and a 94.4% overall PPU efficiency. PPU total mass is less than 13kg including all required housekeeping and switching functions, modules to control the Xenon flow controllers and the cathodes, plus all required telemetry functions. The unit is capable of operating either of two thrusters via a thruster selection module.

In order to ensure that the SPT-140 HPHS will meet USAF requirements, an extensive series of tests is being conducted by AFRL in conjunction with other research and development groups. The test plans, written by ISTI and SS/L, are based on previous US SPT-100 qualification experience.

The first test series was conducted at NASA Glenn Research Center (GRC) during August 1999. The tests included measurements of the thruster performance, electromagnetic interference (EMI), and potential plume contamination. These tests were co-funded by AFRL and NASA under an Interagency Agreement. In these tests a slightly lower thrust efficiency was measured, nearer to the 55% contractual goal. Details of the tests are presented in a companion paper.[12]

In a second series, ground tests were performed to characterize modes of interaction between the SPT-140 Hall thruster and spacecraft components. The experiments were performed at NASA Glenn Research Center and at the University of Michigan. Measurements were made of thruster plume current density, electromagnetic interference (EMI), and surface sputtering and contamination. Diagnostics included Faraday probes, collimated sputter/deposition targets, and radio-frequency detectors. Ion current density measurements showed exponential decay with off-axis angle up to approximately 30 degrees. At off-axis angles greater than 30 degrees, results varied with chamber background pressure, presumably due to ambient charge exchange plasma. Sputter rates of solar cell coverglass, Kapton, and RTV were accurately measured 1 meter from the thruster exit for off-axis angles less than 60 degrees. At off-axis angles greater than 60 degrees, the sputter rate was on the order of the measurement uncertainty. EMI tests found very little emission in the traditional RF communication bands. At the lowest frequencies, one band of E-field emission (10 kHz to 20 MHz) was detected which exceeded the MIL-STD-461C specification by up to 53 dB. Details of these tests are described in a companion paper.[13]

Fakel is awaiting approval to proceed with fabrication of the flight qualification model thruster. The QM thruster and brassboard PPU will undergo an integrated life test scheduled to begin in November 2000 and continue to late 2001. The test will consist of a simulated life of a 15-year GEO-type satellite including orbit topping and stationkeeping burns. Total thruster operation will be 7200 hours.

The life test will be performed at the AFRL Electric Propulsion Laboratory located at Edwards AFB, CA. Initial checkout of the 3.3-m diameter, 8-m long Chamber 3 has been successfully completed. The Xe pumping speed, measured with NIST traceable instrumentation, was found to be 150,000 l/s with a thermal load of 7.5 kW applied. The test was continued over a 24-hour period with no measurable variation in pumping speed. Currently the chamber is being outfit with graphite sputter suppression panels in preparation for the HPHS SPT-140 life test.

IV. High-Power Electric Propulsion Research

8kW Bi-Modal Hall Thruster

Busek Corp, under an AFRL Phase II SBIR, is developing a novel, high-power Hall thruster capable of bi-modal operation over a broad range of specific impulse and thrust. For bi-modal operation the thruster, while operating at constant power, should deliver continuously increasing thrust with decreasing specific impulse.

Busek has developed, constructed, and tested as 8 kW thruster and associated high-power cathode designated BHT-8000 and BHC-500 respectively. The thruster/cathode assembly was successfully tested in Busek's cryogenically pumped (T8) test facility. At 8 kW with a 300 V discharge, the thruster delivered 512 mN of thrust at 63.5% anode efficiency and 2024 seconds specific impulse.[14]

Very High Power Clusters of Hall Thrusters

AFRL has initiated a program to develop Hall thruster systems that operate at power levels well in excess of current state-of-the-art. Current program goal is for operation in the 100kW to 150kW range. The program addresses the AFSPC priority for orbit transfer vehicles (OTV) and rescue vehicles capable of repositioning and rescuing of marooned space assets that have failed to achieve final mission orbit. The power range is based on that expected from proposed AFRL Space Vehicle programs using deployed sails of thin-film solar arrays, and will adapt as predicted power availability changes.

During the past year, AFRL has sought to define the optimal method of approaching the mission need through discussion with industry, other government agencies and universities. The study resulted in the following design criteria:

- The high-power system should use Hall thrusters, as opposed to ion thrusters, due to their superior specific mass (2 kg/kW for Hall versus 8 kg/kW for ion thrusters)
- The high power system should be assembled from a cluster of low-power devices to reduce qualification and testing costs. A clustered system also offers the flexibility needed to meet varied power budgets on future missions. Changing the number of units in the cluster varies system power.
- The unit thruster should be a commercial flight-qualified thruster. To minimize dry mass, it should also be the highest power Hall thruster expected to be used for GEO stationkeeping.
- An even number of thrusters should be clustered, in opposite magnetic polarity, to cancel out the Hall thruster torques.
- The unit thruster power should be sufficiently low so as to allow testing in current ground test facilities. Test facility costs for a monolithic 100kW Hall thruster could dominate the program costs.
- Based on these considerations, the unit thruster power level is expected to be in the

8kW to 10kW range. Hall thrusters in this range are currently in development under both NASA and AFRL programs.

- The individual Hall thrusters must be independent (i.e. no sharing of magnetic circuits or structure) so that the base units can be individually flight-qualified prior to integration into the cluster.
- Both the thruster and the PPU should be modular to minimize qualification costs. Optimal design for the propellant management system is an open issue.

In general the primary advantage of a clustered approach to 100kW-class power levels concedes performance in favor of cost. The relative advantages of each approach are summarized in Table 1.

With the high power scenario determined, several technical challenges are apparent. Foremost is the ability to flight-qualify a cluster of Hall thrusters based on the qualification of each individual unit. Specific issues are:

- The effects of combined beam divergence and plume behavior on spacecraft interaction. Can the plume of the cluster be simulated from an understanding of the plume of a single unit?
- Does possible electrical cross talk through the external plasma affect the uniformity of the power distribution?
- Is the lifetime of the individual unit affected by placement within the cluster?
- Can the Hall thruster torque be effectively cancelled by assembling the cluster from an even number of thruster units?
- What is the optimal method of neutralizing the clustered plasma? Should the cathodes be modular, or can a single large electron source be used to neutralize the entire cluster?

These issue, and others, will be addressed using subscale (P<1kW) thrusters arranged in a cluster to enable research in existing test facilities.
To facilitate the Hall cluster research effort, AFRL has entered into a collaborative research and development effort with Busek Corporation. An existing AFRL Phase II SBIR effort has been augmented with AFRL core funding. Busek will provide thrusters of various cluster geometry with cathodes. Testing will be performed both at Busek and in AFRL Chamber 6. Testing in AFRL Chamber 3 will be used for higher power testing upon completion of the HPHS lifetest scheduled later this year.

Table 1: Trade-offs between a clustered and monolithic approach to high-power electric propulsion

Criteria	*100 kW class Monolithic*	*Clustered 10 kW*
Performance		
Efficiency	Higher	Lower
Specific Impulse	Same	Same
System Dry Mass	Lower	Higher
Reliability		
Thruster	About the Same	About the Same
PPU/PMA	Higher	Lower (more parts)
System Overall	Lower	Higher (redundancy)
Operational Flexibility		
Throttling	Lower	Higher
Orbit raise (Full power)	Same	Same
Station-keeping Suitability (Low power)	Lower	Higher
Suitability for Maneuvering/Vectoring	Lower	Higher
Scalability (up and down in power)	Lower	Higher
Developmental Cost	Very High	Low
Test Facility	Not Available/Very High	Availability/Very Low

V. Summary

The Air Force supports electric propulsion primarily through AFOSR, AFRL and EOARD. Overall direction for the programs comes from AFSPC, with AFRL mission analysis used to define specific technological advances needed to meet the AFSPC mission priorities. Current programs are well grouped into 3 categories defined by the thruster power level. All three agencies are currently focusing their primary research in support of the emerging AF microsatellite missions, due to the current lack of high performance flight-qualified propulsion at very low power levels. Emphasis on research in the mid-power range (500W to 5kW) is diminishing with the near-term conclusion of the 4.5 kW HPHS Hall thruster development program. AFRL has recently begun to increase emphasis on very high power levels (P>30kW) through a collaborative research effort with industry.

VI Acknowledgements

The authors appreciated contributions to this paper from Vlad Hruby, Busek, David Gibbon, Surrey, David Carroll, CUA, Edgar Choueiri, Princeton, Mark Cappelli, Stanford, and the researchers at AFRL, Edwards AFB.

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