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ABSTRACT

The Ballistic Missile Defense Organization sponsors an aggressive program to develop and demonstrate electric propulsion and space power technologies for future missions. This program supports a focused effort to design, fabricate, and space qualify a Russian Hall thruster system-on-a-pallet ready to take advantage of a near-term flight opportunity. The Russian Hall Effect Thruster Technology (RHETT) program will demonstrate an integrated pallet design in late FY95. The program also includes a parallel effort to develop advanced Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET). This synergistic technology will be demonstrated in a flight experiment this summer on the Comet satellite. This paper provides an overview of the RHETT and SCARLET programs with an emphasis on electric propulsion, recent progress, and near-term program plans.

INTRODUCTION

Satellite propulsion and power are critical to the performance of nearly all space missions. The Ballistic Missile Defense Organization's Directorate for Innovative Science and Technology (BMDO) sponsors aggressive programs in these synergistic technology areas. The objective of these programs is to bring high performance technologies to operational status in a timely and cost effective manner. For this, BMDO identifies advanced, high payoff technologies then rapidly moves to fabricate, integrate, qualify, and flight-demonstrate representative systems. At present, BMDO supports a substantial program focused on the development and demonstration of Russian Hall Effect Thruster Technology (RHETT).

Russian Hall effect electric thrusters, shown in Figure 1, provide very high specific impulse compared to state-of-art (SOA) chemical systems. Because of this, these devices offer significant performance advantages for in-space functions such as orbit insertion, repositioning, station keeping, and evasive maneuvering. An example of this is shown in Figure 2. Here, propulsion system wet mass for an Atlas 2AS-class geostationary spacecraft is plotted against time on orbit for a Hall system and a SOA chemical system. In the analysis, the propulsion systems performed both North-South station keeping and two repositions a year (total $\Delta V \sim 100$ m/s). From the figure it can be seen that the Hall system provides significant mass savings for missions longer than 5 years. The wet propellant mass for the Hall system is greater than that for the chemical system up to the 3 year point due to the Hall system's larger dry mass. Recently, the BMDO program has demonstrated the feasibility of Hall thruster technology.[1,2] Concurrently, an effort is directed toward the development of a self-contained thruster-on-a-pallet system ready to take advantage of a near-term flight opportunity. Key contributors to this program include Russian institutes, US industry, universities, the Jet Propulsion Laboratory (JPL) and the NASA Lewis Research Center (LeRC). In addition to the RHETT program, BMDO is sponsoring the development and near-term flight testing of Solar Concentrator Arrays with Refractive Linear Element Technology (SCARLET). Partnered with both U. S. industry and NASA, the SCARLET program will flight demonstrate the first full scale, deployed concentrator array this summer. RHETT and SCARLET are synergistic technologies applicable to multiple space missions. A graphic depicting the BMDO program is shown in Figure 3.

This paper provides a programmatic overview of BMDO's RHETT and SCARLET programs with emphases on electric propulsion, recent progress, and near-term directions. Both programs are international efforts with multiple components. The contributions of organizations pursuing the several subsystems are reported elsewhere.

RHETT

In the early 1990's BMDO took the lead in identifying and evaluating advanced propulsion technologies developed in the former Soviet Union. Hall thrusters where quickly targeted as an area of interest. With over 60 operational units spanning more than 20 years, Stationary Plasma Thrusters (SPT's) appeared to be the most likely candidate for insertion into US commercial and Government space programs.[3,4,5] In 1991, BMDO commissioned a team from three Government laboratories to participate in testing the SPT thruster in Soviet laboratories. With the results obtained through that evaluation at the Scientific-Research Institute of Thermal Processes (NIITP) in Moscow and at "Fakel" Enterprise in Kaliningrad (Kaliningrad region) the team recommended further evaluation in the US. Flight-representative SPT-100, 1.35 kW thrusters manufactured at "Fakel" were obtained for endurance testing at the Jet Propulsion Laboratory (JPL) and evaluation of integration issues at Lewis Research Center (LeRC). At that time commercial interest was increasing, Space Systems/Loral (SS/L) developed a power processor for the thruster and established an international consortium to begin marketing the system for Western spacecraft. To aid the commercialization, the BMDO continued supporting of the SPT-100 evaluation. A 6000 h endurance test was completed at JPL.[6] Integration issues such as plume erosion/deposition, induced torques, and optical emissions were completed.[7,8,9]

The charter of BMDO's Office of Innovative Technology is to continuously advance the state-of-art, and in that capacity BMDO sought to increase the performance of the existing Russian technology through sponsorship of US industry/Russian joint ventures. In 1992 the BMDO sponsored a second trip to Russia by Government electric propulsion specialists to identify second generation Hall thrusters. The NIITP T-100 advanced SPT and the Central Scientific-Research Institute of Machine Building (TsNIIMash) Thruster with Anode Layer (TAL) were identified. At NIITP, BMDO sponsored the development of an advanced versions of the SPT. The thrusters are designated the T-100 (1.35 kW) and T-160 (4.5 kW) and have target lifetimes of 8000 h. Also, under BMDO SBIR sponsorship, Space Power Inc. (SPI) developed a breadboard power processor for the device, and its sister company Inernational Scientific Products (ISP) obtained marketing rights. Three T-100 thrusters were manufactured and obtained for evaluation at JPL and LeRC. With the use of metallic discharge chamber walls and a shorter acceleration zone, the TAL also held the possibility of improved life, and the BMDO obtained two D-55 (nominally 1.5 kW) thrusters for similar evaluation.

The BMDO has completed the evaluation of these advanced Hall thrusters and is focusing its effort on demonstrating the maturity of the technology through a flight demonstration of a system under the program. RHETT is a multiphase program to bring advanced Russian Hall thruster technology to operational status. In the first phase program, designated RHETT I, five years of BMDO investment in electric propulsion component technology is being brought together and demonstrated as a system in ground testing. The system demonstration will take place by the end of FY95 and will lead to rapid transition to the next phase of the program. RHETT II is a flight demonstration of the propulsion pallet leading to operational status in the third and final phase.

The RHETT I design philosophy is to package a compact Hall thruster propulsion system with components which are flight-qualified or engineering models in the process of flight qualification. The RHETT assembly consists of a Hall thruster, a Power Processing Unit, a Propellant Management System, a Xenon Flow Controller, and required structure. Figure 4 shows an isometric view of the propulsion pallet.

The Power Processing Unit (PPU) converts the low voltage available from the spacecraft bus to the 300 V required by the thruster. The Propellant Management System (PMS) provides pressure regulation from the high pressure xenon storage tanks on board the spacecraft to the required input pressure for the flow controller. The Xenon Flow Controller (XFC) is installed inline between the thruster and the PMS. The PPU provides a constant voltage to the thruster. Discharge current is directly proportional to the xenon flow through the thruster. Using closed-loop control from the PPU the flow is regulated by the XFC. In line with a palletized design philosophy structure is minimized.

Because RHETT I is a modular system, all major components can be replaced as technology advances or user requirements change. The thruster to be integrated into the RHETT I package is the NIITP T-100 thruster. Power is provided by an SPI engineering model PPU which provides 300 V at 4.5 A to the thruster at an input voltage is 28 V. The efficiency is estimated to be 0.92. Higher voltage spacecraft busses would allow for weight reduction in future power processors. For cyclic operation, the 140 W of waste heat from the PPU can be handled by a phase-change thermal storage module. The existing design can accommodate one hour of operation every three hours; however, a small component design change increasing the mass of the thermal storage material would allow longer duty cycles. For long duration continuous operation the existing thermal module would be replaced by a heat pipe panel and connected to the spacecraft thermal management system. The PMS is provided by MOOG Space Products Div. and uses a xenon regulator which drops the pressure from the propellant tanks located on the spacecraft to approximately two atmospheres. The XFC was also manufactured by NIITP and uses a thermal throttle to control the xenon flow to the thruster. Major components are used as structure, where possible, to minimize weight and to provide a compact package. The target mass for RHETT I is 20 kg.

The ground demonstration of RHETT I will include both pre-flight qualifications of the system and resolution of integration issues. The RHETT I system will be assembled in August and testing will begin in September 1995. The qualification test plan includes thermal-vacuum environment cycling, random vibration testing, electromagnetic interference assessment, and thruster cold-soak ignition reliability testing. Several RHETT/spacecraft integration issues have been identified. Many of those issues will be addressed during the RHETT I ground demonstration. These include spacecraft surface deposition/erosion from the high energy xenon ions in the plume, optical spectra definition to determine effects on star trackers and sensors, and induced torque determination via measurement of the azimuthal ion velocity. Currently ten integration issues have been identified and are in the processes of being addressed. Some may require the RHETT II flight demonstration test for resolution.

SCARLET

Innovative, high-performance, power technology can benefit mission performance in several ways. Spacecraft power systems are often a major mass driver impacting launch mass, mission life, and/or payload capabilities. As noted above, the application of electric propulsion depends on the availability of space power and coupling advanced array technology with Hall thruster systems can provide substantial benefits for a wide range of missions.

BMDO sponsored the development of concentrator solar arrays for nine years, starting with survivable concentrator arrays to respond to Cold War threats in the late 1980s. More recently, concentrator solar array technology development has focused on low cost, low mass, and radiation hardened designs. Entech's innovative domed fresnel lens concentrators provided a promising pathway to meet these system goals, but development was slow due to fabrication and integration problems with the domed lens. A linear version of the design eliminated these problems and greatly simplified array design and spacecraft integration. This became the basis for the SCARLET program.

At present, BMDO's program is pursuing two complementary approaches to next generation concentrator array development, both involving linear optics. Both approaches provide for practical spacecraft integration due to the increase in pointing error tolerance over previous, point-focus designs. Linear optics reduce critical pointing requirements to a single axis and thus eliminate complex two axis gimbals. Additionally, creative approaches including the design of the convex linear Fresnel lens and the use of secondary reflectors result in pointing tolerances of ±2-3 degrees in the critical axis while still minimizing the area of the expensive, heavy photovoltaic cells. This enables the use of off-the-shelf array components such as gimbals and sun sensors. A major program goal is to provide hardware required for an in-space demonstration of the technology.

A system based on linear reflective concentrator optics is being developed at the Ioffee Institute in St. Petersburg, Russia under BMDO funding. The near term goals of this effort are to fabricate a prototype working concentrator module and to develop high efficiency solar cells for the array. Using single junction GaAs cells, target BOL performance characteristics are 240 W/m^2 at a specific mass of 80W/kg and an operating temperature of 100 C. With tandem cells, the targets increase to 300 W/m^2 and over 90 W/kg at the same operating temperature. The array will use linear compound parabolic concentrators.

In a separate effort, the SCARLET array is being developed by AEC-Able with participation of Entech, Spectrolab, and Composite Optics.[10,11] The concept relies on the same general principles as the mini-dome point-focus device and also offers the potential for low-cost mass production of the concentrator lens material. SCARLET uses either GaAs or higher efficiency multiple band gap solar cells. The array using GaAs cells, will provide part of the power for the Comet satellite. Later advanced versions will use the higher efficiency cells. Technology goals are a specific mass greater than 80 W/kg and more than 300 W/m^2 with a recurring cost below $500/W.

CONCLUDING REMARKS

BMDO's on-going space propulsion and power program sponsors aggressive efforts to advance innovative, high-performance technologies for near-term in-space application in both Government and commercial missions. Presently, BMDO focuses on two major efforts. RHETT will develop and demonstrate an integrated Russian Hall thruster system in ground tests in FY95 and plans to follow this with a near-term flight test. SCARLET will demonstrate a full scale deployed concentrator array in-space for the first time later this summer. It is hoped that RHETT and SCARLET will lead the way to operational use of these high performance technologies in the near future and initiate a bright new era in electric propulsion.

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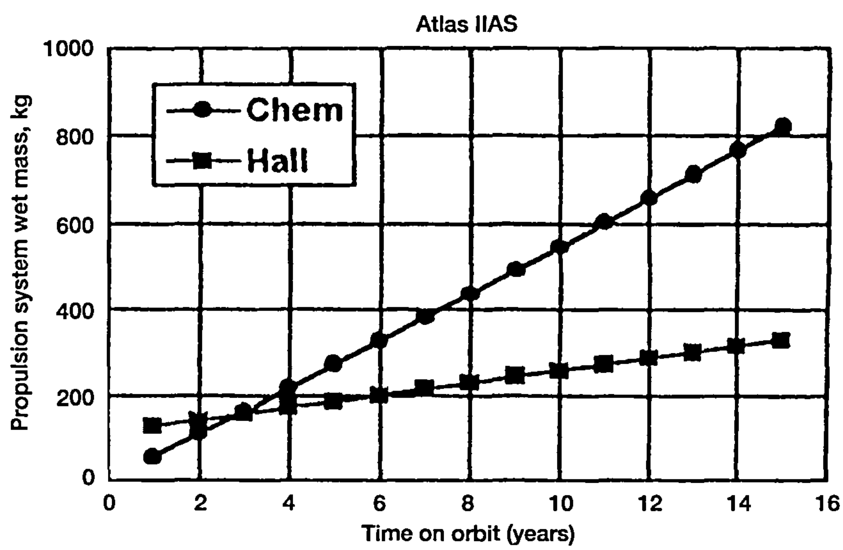

Figure 1.—Representative projection of mass savings achieved for a communications satellite station-keeping propellant.

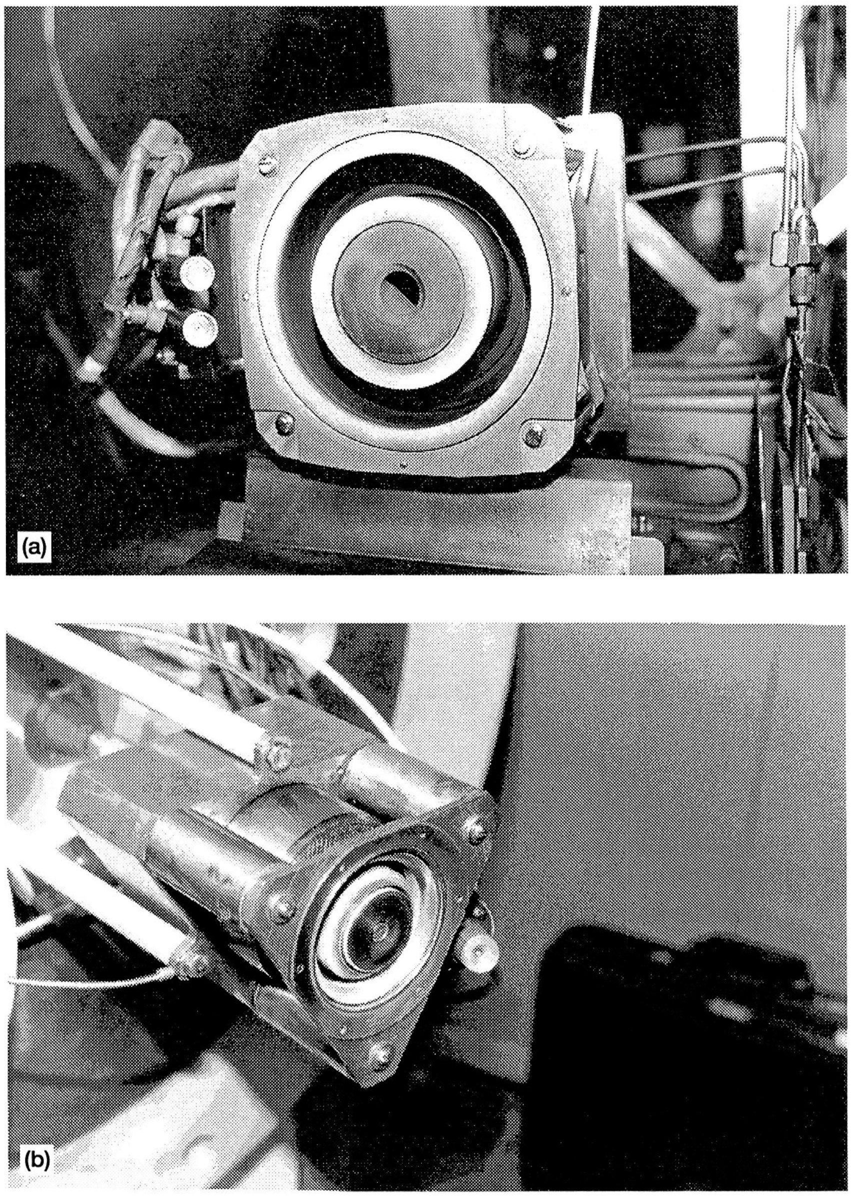

Figure 2.—Two variants of the Russian Hall thruster that incorporate recent improvements. Both thrusters are shown in test stands at NASA Lewis Research Center. (a) NIIP T-100 Hall thruster designed for BMDO for extended ifetime; note the smaller, heaterless cathodes. Thruster has 100 mm discharge passage and operates in the 1.0 to 1.5 kW range. (b) TsNIMash D-55 Anode Layer (Hall) thruster. Its relatively higher thrust density is indicated by the 55 mm toroidal discharge passage and its 1.0 to 2.5 kW operating range.

Figure 3.—International partnership combining advanced Hall thruster and concentrator array technology to usher in a bright new era in electric propulsion.

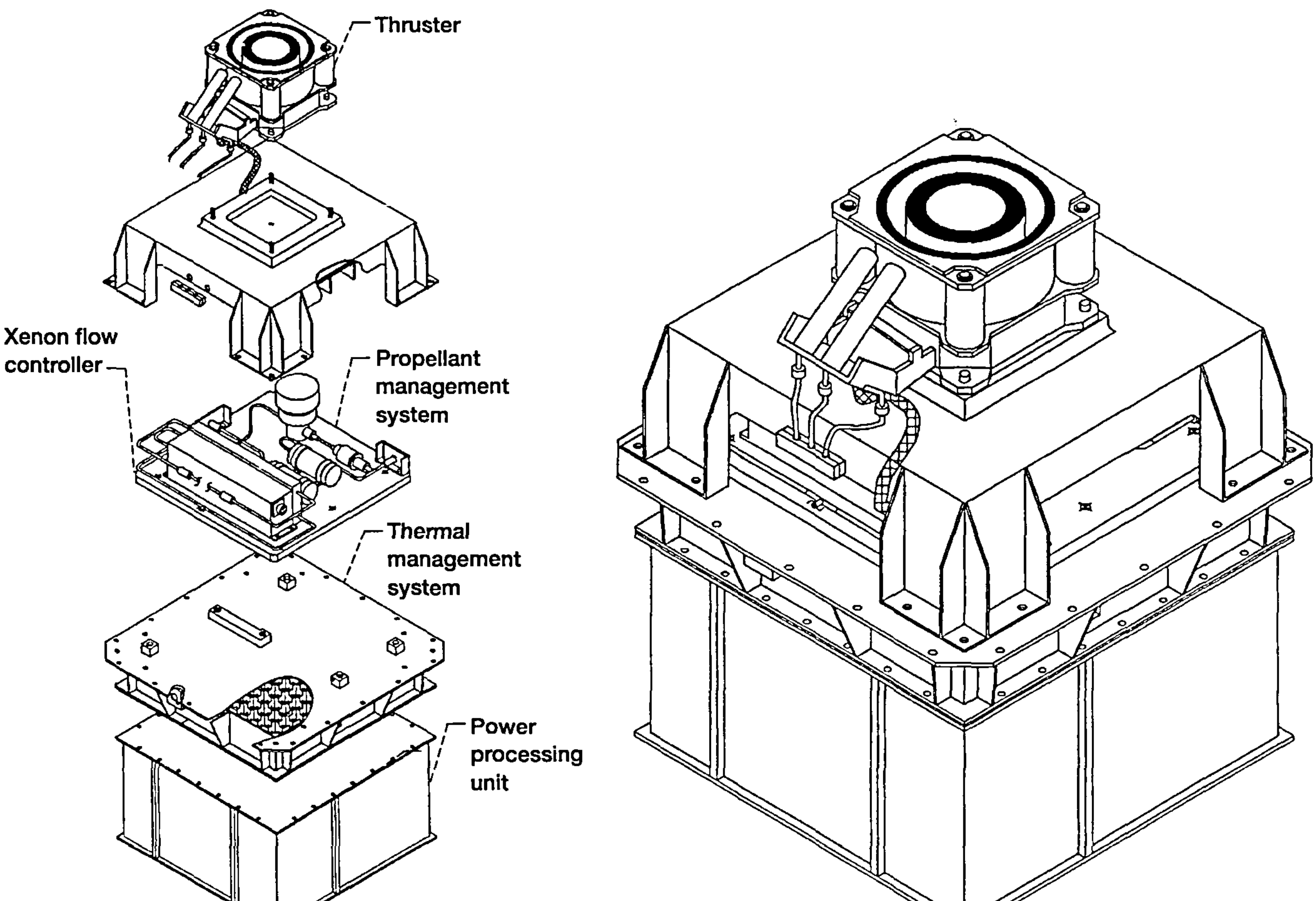

Figure 4.—The RHETT I configuration as being fabricated for the space qualifiaction testing in September 1995. The mass goal is 20 kg and the major dimensions are 32 x 32 cm base and 28 cn high. This second generation configuration represents a mass and volume reduction of 50% compared to the 1993 conceptual design. The centrally located thermal management "plate" is application specific; the phase change system depicted is suitable for intermittent station keeping operation.

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