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The Status of Ion Propulsion Development and Implementation at JPL in 2003

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The successful demonstration of ion propulsion on NASA's Deep Space 1 (DS1) mission has stimulated substantial interest in the application of this technology to future solar system exploration missions. It has also stimulated interest in the development of more advanced ion propulsion technologies. NASA is involved in a broad spectrum of ion propulsion activities ranging from low Technology Readiness Level (TRL) development to flight implementation. The Jet Propulsion Laboratory (JPL) is participating in these activities at all levels. Flight activities include analyses of the Deep Space 1 Hyper-Extended Mission data; life testing of the Deep Space 1 Flight Spare ion thruster; the development of the ion propulsion system for the Dawn mission (a solar-powered Discovery mission to the main-belt asteroids Vesta and Ceres); and a Phase A study of an ion propulsion system for the nuclear-powered Jupiter Icy Moons Orbiter mission. Mid-TRL activities include the development of carbon-carbon grids for 30-cm, 40-cm, 65-cm, and 75-cm diameter ion thrusters; the development of an advanced 65-cm diameter ion thruster for nuclear electric propulsion applications; the development of advanced hollow cathode technology for ultra-long-life cathodes; and the service life validation of 30-cm, 40-cm and 65-cm diameter thrusters. The life validation activities include the establishment of the service life capabilities for the NSTAR/DS1 and NEXT thrusters through a combination of modeling and test. Current model developments include 2D and 3D ion optics codes; a model of cathode insert life; a 1D model of the discharge region just downstream of a hollow cathode and a 2D model of the discharge chamber. Low TRL research at JPL includes the development of miniature (~3-cm diameter) ion thruster technology; measurements of internal hollow cathode temperatures; and measurements of cathode keeper erosion rates in an NSTAR ion thruster using a surface layer activation technique.

Introduction

The Jet Propulsion Laboratory in partnership with the Glenn Research Center (GRC) and industry partners Boeing Electron Dynamics Division (EDD), Moog Scientific Controls, Inc., and Spectrum Astro, Inc. developed and successfully demonstrated the use of ion propulsion on NASA's Deep Space 1 (DS1) spacecraft [1-5]. DS1 was launched in October 1998 and successfully used the ion propulsion system to provide the ΔV necessary to flyby the asteroid Braille and the comet Borrelly [2]. The DS1 ion propulsion system, based on NASA's 30-cm ion thruster developed under the NSTAR project [3], was also used to provide pitch and yaw control of the spacecraft in order to save hydrazine propellant following the failure of the spacecraft's stellar reference unit in November 1999 [2]. The success of DS1 led directly or indirectly to several significant subsequent activities including:

1. The selection of Dawn, a Discovery Mission to the main asteroid belt and the first full-up science mission to use ion propulsion [6].
2. The initiation of the Next Generation Ion project to develop improved ion propulsion technologies for solar-powered deep-space missions [7].

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3. The establishment of Project Prometheus to develop the technologies necessary for nuclear electric propulsion (NEP).
4. The selection of the Jupiter Icy Moons Orbiter mission as the first mission under the Project Prometheus Program.

Through a combination of directed and competitively won activities JPL is involved in a broad spectrum of ion propulsion technology development ranging from low technology readiness level (TRL) research to the implementation of flight systems. This paper briefly describes the current ion propulsion activities at JPL and identifies the references to papers presented at this conference for many of these activities.

Flight Systems

JPL is currently involved in four flight activities involving ion propulsion. The first is the on-going analyses of the data from the DS1 Hyper-Extended Mission [5]. Second is the Extended Life Test (ELT) of the DS1 flight spare ion thruster [8]. Third is the development of ion propulsion system for Dawn [6], and fourth is the Phase-A study of the ion propulsion system for the Jupiter Icy Moons Orbiter mission.

DS1 Hyper-Extended Mission Analyses

At the end of the Extended Mission for DS1, after the spacecraft successfully flew by the comet Borrelly, the ion propulsion system had been successfully operated for approximately 14,000 hours. This provided NASA with a unique opportunity to investigate how an ion thruster wears in space relative to that expected from ground-based life tests. Therefore, NASA executed what came to be called the DS1 Hyper-Extended Mission. This DS1 mission phase was designed to characterize the wear on the DS1 ion engine after extended operation in space. A series of tests was performed to investigate the condition of the DS1 ion thruster including a "plume mode survey" to map out the operating characteristics of the neutralizer cathode; perveance and electron-backstreaming tests to determine the extent of accelerator grid aperture erosion; direct thrust measurements to compare to similar measurements made earlier in the mission and before flight; discharge chamber performance curves; measurements of the magnetic field produced by the thruster's permanent magnets; and the impact of thruster-produced charge-exchange plasma on the solar array. At the end of the Hyper-Extended Mission the ion propulsion system on DS1 accumulated 16,265 hours of operation and processed approximately 73.4 kg of xenon. The DS1 spacecraft was voluntarily turned off in December 2001. Preliminary results of theses tests are described in [5].

The thrust measured on DS1 shown in Table 1 (reproduced from Ref. 5) indicate a thrust degradation with time that is not well understood, but is currently believed to be a result of a changing number of double ions in the discharge chamber.

The data obtained on DS1 during the Hyper-Extended Mission also included discharge chamber performance curves, solar array interactions measurements, magnetic field measurements, single plenum operation, Plasma Experiment for Planetary Exploration (PEPE) measurements, and the impact of the ion propulsion system on the spacecraft attitude control system. These data are still being analyzed.

Extended Life Test of the Deep Space 1 Flight Spare Ion Engine

An extended life test of the Deep Space 1 (DS1) spare flight ion thruster (FT2) has just been completed at the Jet Propulsion Laboratory. The test was started in September 1998, just prior to the launch of DS1, and was voluntarily terminated on June 26, 2003. The thruster was operated for 30,352 hours, and processed 235 kg of Xenon propellant. The purpose of this test was to determine the ultimate service life capability of the NASA 30-cm-diameter ion thruster technology. Thruster performance data and operational characteristics, over the full DS1 throttle range, were collected and analyzed during the course of the test, to aid in the diagnoses and understanding of the processes of failure and performance degradation in ion thrusters. Diagnostic capabilities of the test included real time measurements of thrust vector, thrust, double and single xenon ion current, beam current density, and screen grid transparency to ions. Additional real-time diagnostic equipment included high-resolution video data of thruster components inside the test chamber, a retarding potential analyzer to characterize the neutralizer plume, as well as a laser profilometer to measure in situ grid erosion.

The test is described by Sengupta in Ref. 8. which presents the performance variations as a function of time and throttle level. Significant observations include discharge cathode keeper erosion and heater power reduction, accelerator

Table 1: Engine thrust measured by Doppler shift in DS1 communications signal at three different times during mission suggests slight decay in performance and thrust loss due to double ion content in beam.

	Measured Engine Parameters			**Thrust (mN)**			
Mission Level	**Beam Voltage (V)**	**Beam Current (A)**	**Discharge Propellant Efficiency**	**Throttle Table**	**IAT1 (16 hrs)**	**IAT2 (1786 hrs)**	**IAT3R (16000 hrs)**
Nominal Conditions							
6	637	.514	.83	20.61	20.8±0.1	20.71±0.08	20.57
13	836	.533	.88	24.47	--	24.23±0.07	23.9
20	1086	.523	.87	27.38	--	26.99±0.07	26.66
27	1086	.614	.91	32.02	31.8±0.2	31.46±0.07	30.17
34	1086	.714	.91	37.25		36.62±0.23	--
48	1086	.915	.92	47.74	47.3±0.1	--	--
69	1086	1.206	.90	63.02	62.2±0.4	--	--
83	1086	1.407	.91	73.42	72.6±0.4	--	--
90	1086	1.497	.91	78.19	77.4±0.4	--	--
Off-Nominal Currents							
6	637	.477	.78	--	--	--	19.24
6	637	.553	.91	--	--	--	21.72
6	637	.574	.94	--	--	--	22.26
6	637	.592	.97	--	--	--	20.44
Off-Nominal Voltages							
27	936	.614	.91	--	--	--	28.84
27	787	.614	.91	--	--	--	26.62
27	637	.614	.91	--	--	--	23.99
27	537	.614	.91	--	--	--	22.14
27	637	.618	.92	--	--	--	24.12
Off-Nominal Flow Rates							
6	637	.517	.47	--	--	--	21.22
6	637	.511	.33	--	--	--	21.23
6	637	.510	.33	--	--	--	21.29
27	1086	.613	.55	--	--	--	32.10
27	1086	.612	.40	--	--	--	32.43
Off-Nominal Flow Rates and Currents							
6	637	.755	.49	--	--	--	31.15
6	637	1.002	.65	--	--	--	40.76

grid barrel erosion, accelerator grid web erosion, deposition of material in the neutralizer orifice and the resultant loss of neutralizer flow rate margin from plume mode (at low power).

The post-test analyses of the thruster has been initiated. Preliminary examinations indicate that none of the known failure modes would have caused near-term thruster failure and no new failure modes were revealed. The propellant processed as a function of run time is given in Fig. 1.

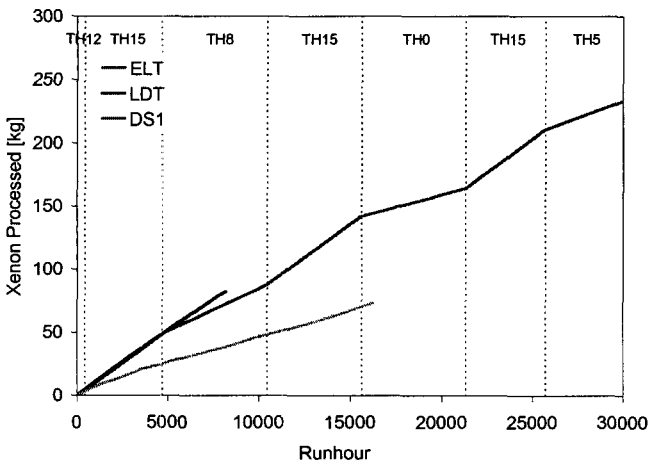

Fig. 1 Xenon processed in the ELT compared to the 8-khr Life Demonstration Test (LDT) of Ref. XX and on DS1.

Dawn Ion Propulsion System (IPS) Development

The successful demonstration of ion propulsion on NASA's Deep Space 1 (DS1) mission has enabled the acceptance of this technology by NASA's Discovery program for low-cost solar system exploration missions. The first of these is the Dawn mission to be launched in 2006. Dawn is a competitively-won Discovery mission to rendezvous with the two heaviest main belt asteroids, Vesta and Ceres. The use of ion propulsion on Dawn makes this mission affordable within the cost constraints of the Discovery program. The ion propulsion system (IPS) for Dawn is based on the ion propulsion technology which flew on DS1. The major differences are that the Dawn system must provide a total delta-V of more than 10,000 m/s (compared to 4,500 m/s for DS1) and will carry 450 kg of xenon (compared to 81.5 kg for DS1). The Dawn IPS and implementation plan is described in Ref. 6. A high-level block diagram of the Dawn IPS is given in Fig. 2.

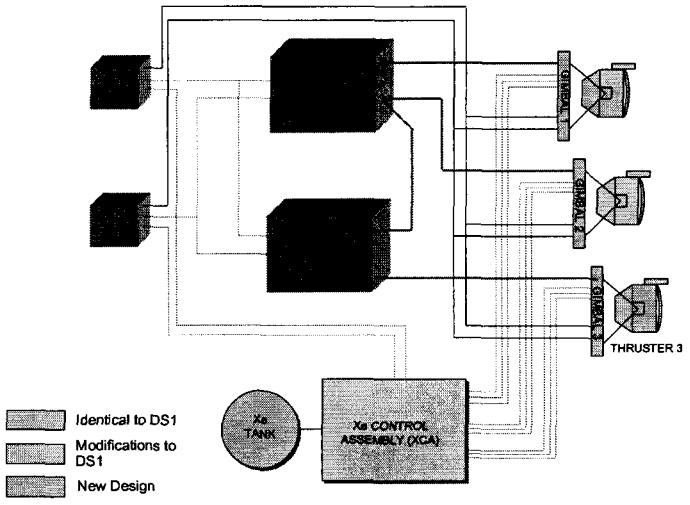

Fig. 2 The Dawn Ion Propulsion System Block Diagram.

Jupiter Icy Moons Orbiter Phase A Study

NASA is currently studying the use of ion propulsion for a Jupiter Icy Moons Orbiter (JIMO) Mission. This concept study is evaluating the use of a nominal 100-kWe nuclear reactor to power an advanced ion propulsion system. This combination is expected to provide a substantial leap in propulsion capability for deep-space exploration. A conceptual configuration for the JIMO vehicle is given in Fig. 3.

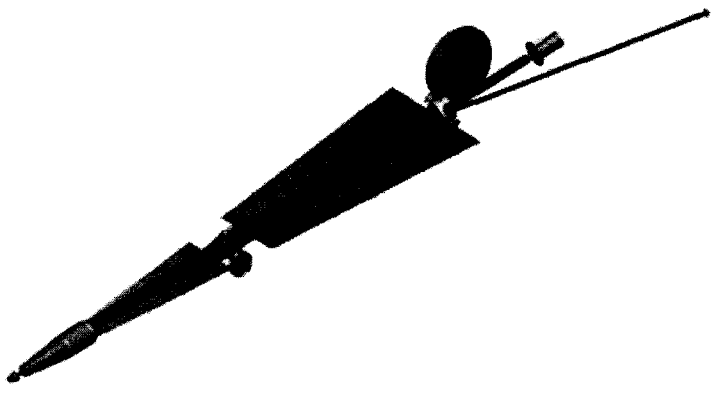

Fig. 3 Conceptual Configuration of an NEP Vehicle for Outer Planet Exploration.

Mid TRL Ion Propulsion Technology Development

Mid TRL activities at JPL include the development of carbon-carbon grids for 30-, 40-, 65-, and 75-cm ion thrusters; the development of an advanced 65-cm ion thruster designed to eliminate all known wear-out failure modes; and the service life validation of the NEXT ion thrusters. To facilitate the grid development and service life validation 2D and 3D ion optics codes are under development.

Carbon-Carbon Grids

The life test of the DS1 flight spare ion thruster demonstrated that its primary life-limiting mechanism is erosion of the accelerator grid by charge-exchange ions. The demand for improved thruster performance – higher *Isp* and longer life – will require the development of ion accelerator systems with improved erosion resistance. JPL is pursuing the development of carbon-carbon composite ion optics for a variety of advanced ion thrusters since this material holds the promise of providing a substantial improvement in erosion resistance while being sufficiently robust that it can survive the launch environment.

Review of Carbon-Based Grid Development Activities for Ion Thrusters. Development of carbon-carbon grids for ion thrusters presents many challenges. Snyder, in Ref. 9, presents a review of previous carbon-based grid development activities, specifically addressing grid manufacturing, optics performance, and launch and operational survivability. The present status of carbon-based grids is assessed and future activities are discussed.

Development and Testing of Carbon-Based Ion Optics for 30-cm Ion Thrusters. JPL is currently developing carbon-carbon grids under the competitively-won Carbon-Based Ion Optics (CBIO) project for 30-cm and 40-cm diameter ion thrusters. The status of this program is presented in Ref. 10. The design and manufacturing methods of the carbon-carbon grids is discussed, and test results for 30-cm flat and dished grids are presented. A photograph of the 30-cm dished carbon-carbon grids is shown in Fig. 4.

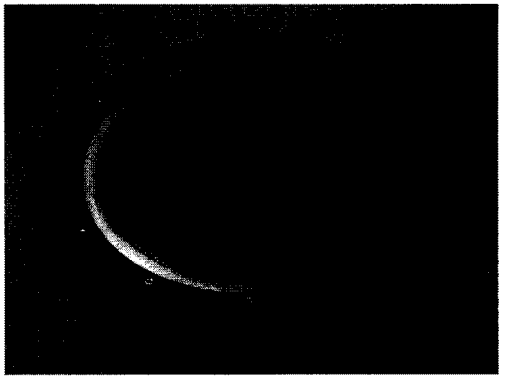

Fig. 4 Photograph of 30-cm diameter, dished carbon-carbon grids developed under the Carbon-Based Ion Optics (CBIO) project.

Grid Development for Interstellar Precursor Missions. Through another competitively-won activity from the XXXX project, JPL is developing 75-cm diameter ion optics for an interstellar-precursor mission. The ion optics for this activity must operate at a specific impulse of 13,000 s with krypton as the propellant, and must have a service life capability of YY years. To meet these goals the grids are being fabricated from carbon-carbon. A photograph of these grids is given in Fig. 5.

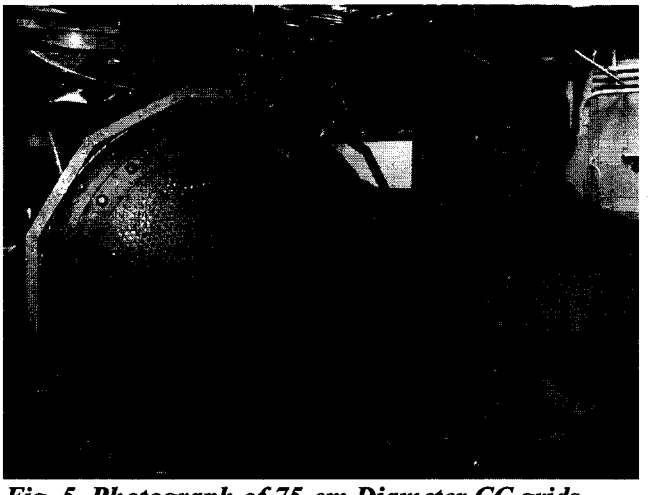

Fig. 5 Photograph of 75-cm Diameter CC grids.

Ion Optics Modeling. Computer modeling is the key to cost-effectively designing advanced ion accelerator systems. JPL is developing two- and three-dimensional numerical simulations to investigate the physics of accelerator grid erosion by charge-exchange (CEX) ions. The computer codes model ion beamlet trajectories through a single pair of screen and accelerator grid apertures in the self-consistent electric potentials found by solving Poisson's equation. The codes follow both primary

ions formed inside the discharge chamber, and ions generated beyond the screen grid by charge exchange between un-ionized propellant atoms and primary ions.

The 2D code results for the calculation of the perveance limit is compared to that measured on a 30-cm NSTAR-like thruster with flat carbon-carbon grids designed for operation at a specific impulse of 5000 s in Fig. 6.

The 2D code is used for determination of the ion optics performance (perveance, cross-over, and electron-backstreaming margins) and the erosion rate of the accelerator hole wall. The 3D code, developed by John Anderson is used for the determination of the erosion pattern and rates on the downstream side of the accelerator grid. An example calculation of the pit & grooves erosion pattern on the downstream side of the accelerator grid is given in Fig. 7.

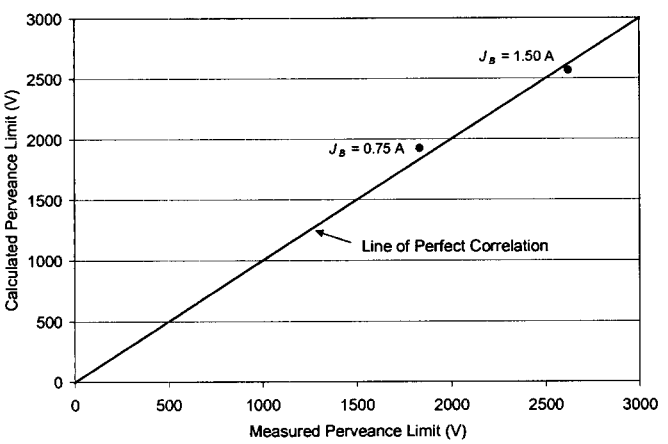

Fig. 6 Comparison of 2D Code perveance calculation with that measured using flat carbon-carbon grids on an NSTAR-like thruster.

Nuclear Electric Xenon Ion System (NEXIS) Technologies. JPL is developing an advanced 65-cm diameter ion thruster for operation at over 20 kW with specific impulses greater than 7000 s under a competitively-won activity. This advanced thruster is designed to eliminate all of the known ion thruster wear-out failure modes and is intended for use on nuclear electric propulsion systems being evaluated under the JIMO mission study. This activity is described by Polk in Refs. 11 and 12. A drawing of the NEXIS thruster is given in Fig. 8.

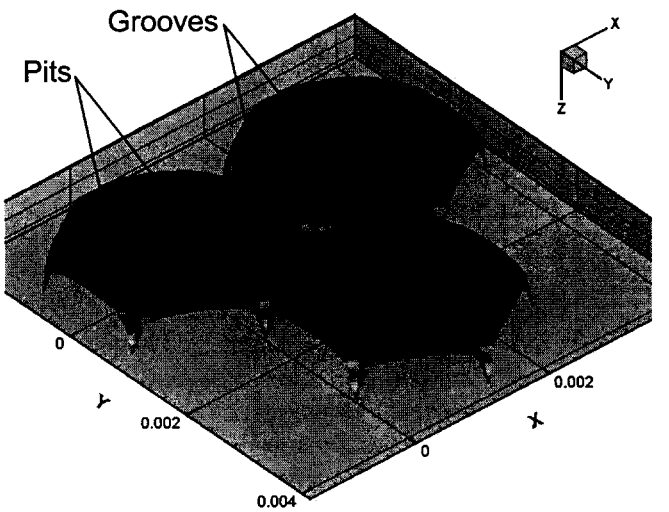

Fig. 7 Calculation of the Pits & Grooves Erosion Pattern on the Downstream Side of the Accelerator Grid from the 3D Ion Optics Code

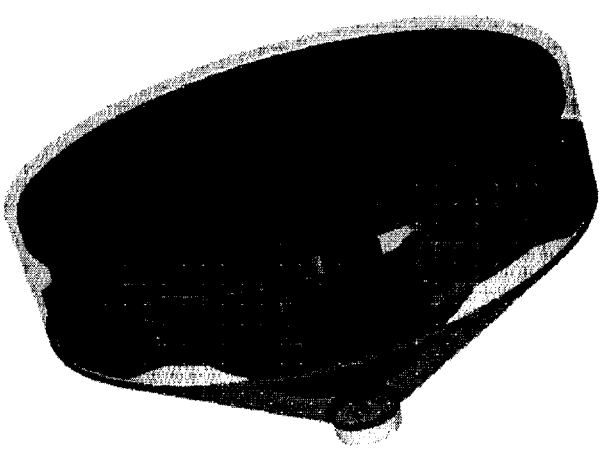

Fig. 8 Drawing of the 65-cm Diameter Advanced-Technology NEXIS Ion Thruster.

NEXT: Service Life Validation; System Integration. JPL is performing the service life validation for NASA's Evolutionary Xenon Thruster (NEXT). This activity is considering all the major know ion thruster wear-out failure modes as identified in Fig. 9 and listed in Table 2.

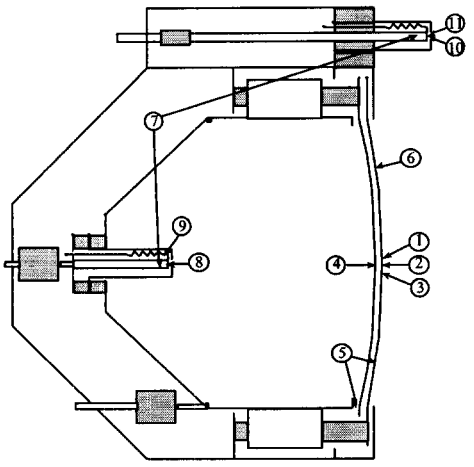

Fig. 9 Wear-out Failure Modes considered in the NEXT Thruster Service Life Assessment.

Table 2 Description of Ion Thruster Wear-out Failure Modes Identified in Fig. 9.

Failure Mode	Description
1	Electron backstreaming due to accelerator grid aperture enlargement from charge exchange ion sputtering
2	Electron backstreaming due to intersection of the accelerator grid aperture and the pits and grooves erosion pattern caused by charge exchange ion sputtering
3	Structural failure of the accelerator grid due to charge exchange ion sputtering
4	Structural failure of the screen grid due to low energy discharge chamber ion sputtering
5	Unclearable short between the grids or between the screen grid and anode due to debris or flakes of sputter-deposited material
6	Rogue hole formation resulting in electron-backstreaming or structural failure of the accelerator grid
7	Cathode insert failure due to exhaustion of activator material
8	Discharge cathode orifice plate structural failure due to low energy ion sputtering
9	Discharge cathode heater failure due to low energy ion sputtering
10	Neutralizer orifice plate structural failure due to ion bombardment from plume mode operation
11	Neutralizer orifice clogging from deposits during low power operation

The results of this evaluation to date suggest that the 40-cm diameter NEXT thruster should be capable of processing more than 400 kg of xenon at specific impulses of up to 4000 s.

Research and Modeling

The success of ion propulsion has resulted in the demand for new and improved ion propulsion capabilities including scaling ion thrusters to very low thrust levels for precision formation flying applications; scaling ion thrusters to very high power and *Isp* levels; and significantly extending ion thruster operating times. To accomplish these goals, as well as to be able to respond to future requirements requires improved understanding of the fundamentals of the ion thruster operation. This section describes the ongoing work to scale ion thrusters down to 3-cm diameter; develop models of the discharge chamber plasma behavior; measure internal hollow cathode temperatures; and measure cathode keeper erosion in short-term tests.

Development Of A Miniature Ion Thruster

It has traditionally been difficult to scale ion thrusters to very small sizes while maintaining good performance. Miniature ion thrusters, however, are well-suited for future space missions that require precision formation flying, attitude control for large inflatable spacecraft, and other applications requiring thrust levels of a few milinewtons. Consequently, a 3-cm diameter miniature xenon ion thruster is currently under development at JPL. This thruster, shown schematically in Fig. 10, uses a compact, lightweight body, low-power cathode technology, permanent magnets, and optimized ion extraction grids to achieve good performance. The JPL miniature ion thruster is capable of providing thrust from 0.1 to >1.5 mN, specific impulses in excess of 3000 seconds, and propellant utilization efficiencies greater than 80% with very high thrust resolution. This activity is described in Ref. 13.

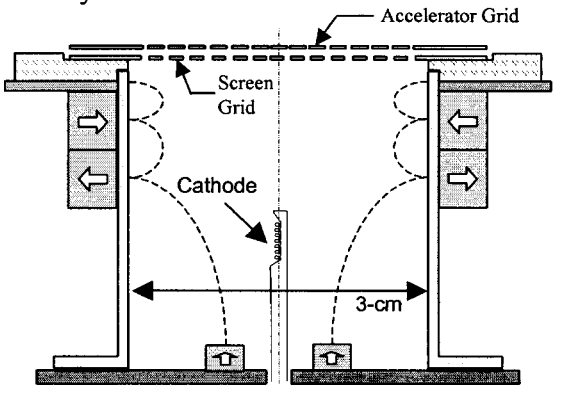

Fig. 10 Cross-section Schematic of a 3-cm diameter Ion Thruster from Ref. 13.

Discharge Chamber Modeling and Experiments

Complete optimization of ion thruster designs to meet future demanding performance requirements will be possible if a robust and flexible computational model of all thruster components can be developed. Recent efforts have shown that the physics of ion optics is relatively well understood and can be modeled accurately. These models have proven effective in the optimization of ion thruster grid design. However, to this date, the design and optimization for ion thruster discharge chambers has been almost entirely based on empirical investigations and has benefited little from computational modeling. There are currently two discharge chamber modeling activities ongoing at JPL. The first is a 1D model of the plasma generation just downstream of the discharge chamber hollow cathode. The second is a 2D model of the entire discharge chamber.

Plasma Generation Near an Ion Engine Discharge Chamber Hollow Cathode. Under certain operating conditions, the environment generated just downstream of the main discharge hollow cathode can result in severe erosion of any thruster components located near the cathode, as well as the cathode itself. In the design of new, higher power thrusters with much longer life requirements it is essential to understand the parameters that impact this erosion phenomena. JPL has initiated a modeling activity of the plasma generated just downstream of the hollow cathode in a DC ion thruster discharge chamber. This activity is described by Katz in Ref. 14. An example of the one of the results from this activity showing that few doubly charged ions are created in this region, is given in Fig. 11.

A 2-D Computational Model Of An Ion Thruster Discharge Chamber. The two-dimensional model currently under development at JPL is designed to predict the behavior of an axisymmetric ion thruster discharge chamber. The model accounts for both primary and Maxwellian electrons and implements a 2.5-dimensional model for the neutral xenon propellant gas flow. Performance of the model is being verified initially with detailed NSTAR experimental data for a 30 cm diameter thruster. This work is described by Wirz in Ref. 15. An example of the calculated neutral gas density distribution in the NSTAR ion thruster is given in Fig. 12.

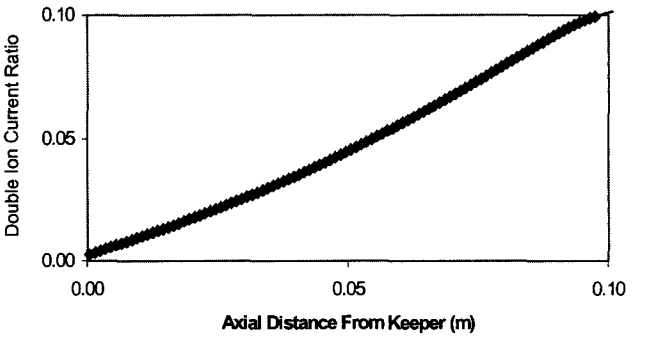

Fig. 11 Ratio of double ion current to single ion current generation as function of distance from the discharge chamber hollow cathode keeper.

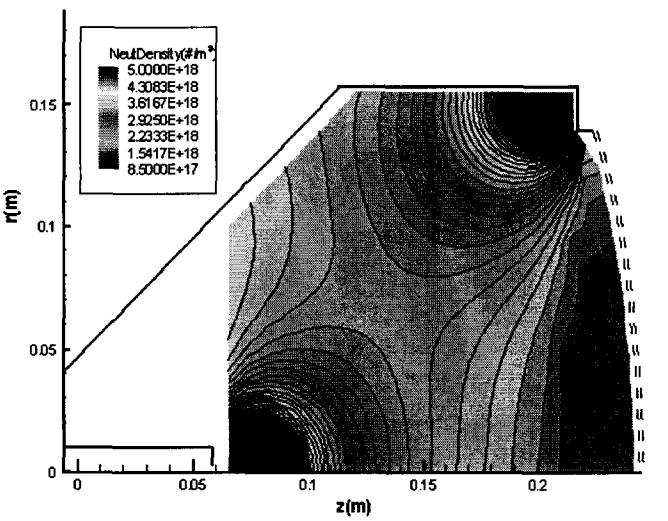

Fig. 12 Calculated Neutral Density Distribution in and NSTAR Ion Thruster at Full Power from Ref. 15

Measurement of Cathode Keeper Erosion in an NSTAR Ion Thruster. The erosion rate of the discharge cathode keeper in a 30-cm diameter NSTAR-configuration ion thruster is measured using a Surface Layer Activation (SLA) diagnostic technique. This technique measures the decrease in the activity of a radioactive tracer material as the keeper surface erodes and correlates this activity to a depth calibration curve, yielding the eroded depth. Using a set of three cathode keepers, each activated at a different radial position from the orifice, the erosion profile measured by conventional means after the 8,200-hour Life Demonstrate Test [16] was

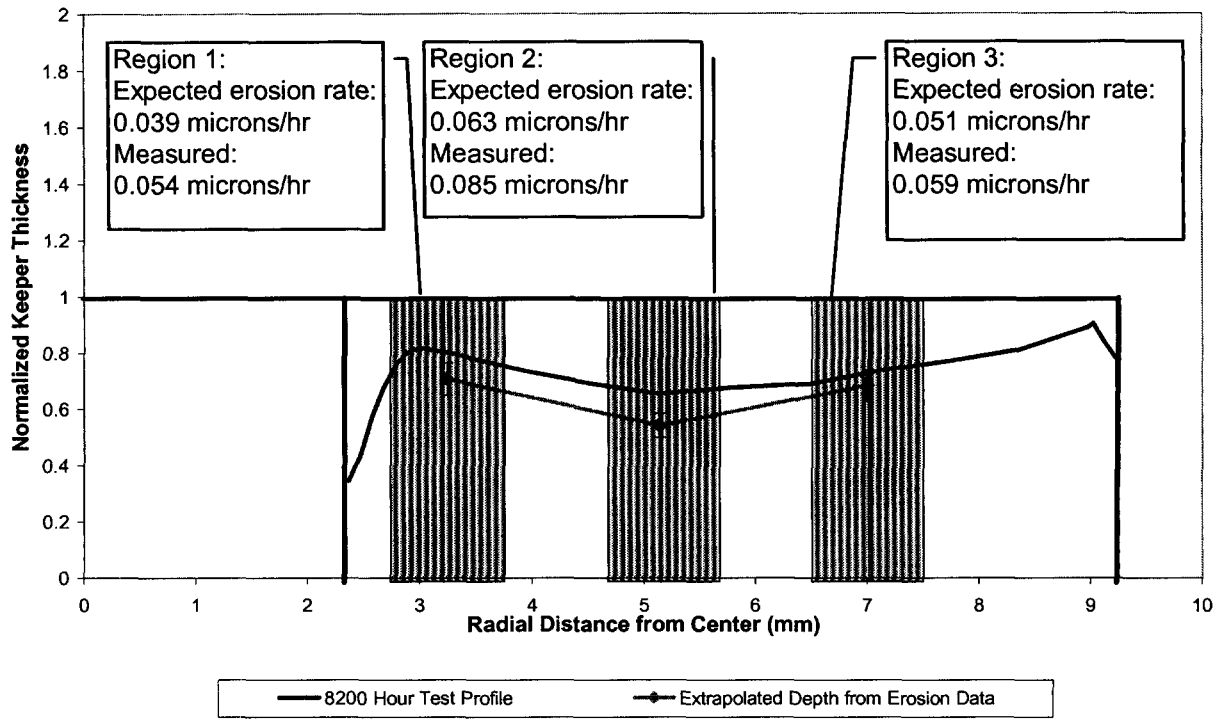

Fig. 12 Comparison of Measured Erosion Rates using Surface Layer Activation with those Obtained from the 8,200-Hour Life Test of the NSTAR Ion Thruster from Ref. 16.

reproduced as shown in Fig. 12. This technique was also used to compare the cathode keeper erosion rates at the NSTAR throttle level TH8 with full power operation, and to measure keeper erosion as a function of the keeper potential relative to the anode. The technique and results are provided by Kolasinski and Polk in Ref. 17.

Summary

The success of Deep Space 1 has stimulated several NASA projects that range from applying this technology directly on near-term science missions to a wide advanced technology development activities. JPL is involved in all of these activities including the implementation of the DS1 ion propulsion technology on a full-up science mission (Dawn); the development of advanced ion thruster technologies that scale this technology up from 30-cm diameter to 65-cm diameter while removing all known wear-out failure modes; the development of a minature ion thruster that scales the technology down to 3-cm diameter while maintaining good efficiency; and the development models that embody the understanding necessary to both efficiently develop new thrusters and to accurately access the service life capability of new and existing ion thrusters.

Acknowledgements

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