Technologies to Improve Ion Propulsion System Performance, Life and Efficiency for NEP

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Potential NEP Missions require major advances in electric thrusters

- Specific Impulse (Isp): 3,000 s → 7,000 s
- Beam voltage: 1,100 V → 5,000 V
- Power: 2,500 W → 10,000 W
- Throughput increase: 200 kg → 1,000 kg
- Life: 3 yrs → 10 yrs

Ion Engines Clear Choice For Potential Near Term NEP Missions

Ion Propulsion Background

NASA’s Solar Electric Propulsion Technology Programs

Nuclear Electric Xenon Ion System (NEXIS) Program

JPL Computer Models: Ion Thruster Design Tools
- Ion optics grid performance & life
- Hollow cathode life

Thruster plume – S/C interactions

Summary
Mission ΔV’s for Potential NEP Missions

Present Systems
<5 kWe

Approximate System Power Required
~ 25 kWe
~ 100 kWe
~ 250 kWe

Missions Enabled by NEP

Mission ΔV Range (km/s)
0 20 40 60 80 100

Gridded Ion Thrusters: Clear Choice For Near Term NEP

- Ion thrusters scale well to high power & Isp
  Voltage & power increase with Isp$^2$
  e.g. NSTAR 3100 s 2.3kW, 7000 s ~ 10 kW

- High Isp readily achievable with ion thrusters
  Increased grid voltage increases ion exit velocity
  Demonstrated in the lab >> 12,000 s Isp

- High efficiency comes naturally at high Isp

- Key challenge is achieving thruster life
  NSTAR Extended Life Test demonstrated 27,000+ hrs
  Life validation must use accelerated tests & analysis

- Grid and Cathodes are the keys to long life
  Grid erosion increases ~ linearly with voltage
  Hollow cathode life models are needed
Gridded Ion Thruster Basics

1. Xenon gas **ionized** in the discharge chamber
2. Ion **accelerated** electric field between grids
3. Ion beam charge and current **neutralized** by neutralizer electrons

Life limiting mechanisms
1. Grid erosion
2. Cathode failure
Deep Space 1 flew by the comet Borrelly in 2001, collecting valuable science data.

Flight ion engine firing on Deep Space 1 spacecraft during solar thermal vacuum test.

World’s longest ion engine endurance test is presently underway at JPL.

- Deep Space 1 Flight Engine Developed by JPL Managed Team
  NSTAR Project (JPL, GRC, industry, universities and international partners)

- Deep Space 1 Ion Engine Life Testing Performed by JPL
  1000 hour validation test
  8200 hour Life Demonstration Test
  Ongoing Extended Life Test (26,000+ hours)

- Deep Space 1 Flight System Integration and Functional Tests
  End-to-end system demonstration in thermal-vacuum test

- Deep Space 1 NSTAR Flight Diagnostics Package

- Deep Space 1 Flight Operations and Successful Mission
  16,265 hours of operation in space
  Hyper-Extended Mission – NSTAR thruster tests
NSTAR Extended Life Test
Data for Ion Thruster Service Life Validation

- Long Duration Tests to Identify and Characterize Failure Modes
  - 10 kWe test (1988)
  - 5 kWe test (1990)
  - Test-to-Failure Test (1993)
  - NSTAR Testing
    - 2000 Hour Test (1994)
    - 1000 Hour Test (1995)
    - 8200 Hour Test (1998)
    - 27000+ Hour Test (Ongoing)

- In-Space Data from the Deep Space 1 Spacecraft to Characterize Failure Modes and Validate Ground Measurements

- Probabilistic Analysis to Assess Service Life
  - Relatively simple analytical models of failure process embedded in Monte Carlo simulation
  - Experimental data and additional modeling to characterize parameter distributions

- Modeling of Plasma and Surface Processes
  - Particle-in-Cell code simulations of ion acceleration and charge exchange process
  - Hollow cathode physics models
  - Surface kinetics modeling of simultaneous sputtering and deposition
Xenon Ion Propulsion Used Extensively on Commercial GEO Communications Satellites

- Boeing has launched 13cm XIPS thrusters since 1997 and 25cm XIPS thrusters since 1999

19 Satellites  
76 Thrusters

- 52 of the 13 cm ion thrusters and 26 PPU's are in-orbit on thirteen 601HP communications satellites
  >55,000 hours of operation accumulated to date
- 24 of the 25-cm ion thrusters and 12 PPU's are in-orbit on six Boeing 702 communications satellites
  >4500 hours of high power orbit insertion
  >9000 hours of low-power station keeping
- Transmitter tubes operate 5,000-10,000V

13-cm Xenon Ion Propulsion System on the HS-601 Spacecraft Bus.

Boeing 702 Satellite 25cm XIPS
The 40cm NEXT thruster is more than twice as powerful as today’s NSTAR thruster.

**Status:** Laboratory Model thruster manufactured and performance characterized. Engineering Model engine under test. PPU beam supply manufactured and tested.

**Developers:** NASA Glenn Research Center (Lead), the Jet Propulsion Laboratory, Boeing Electron Dynamic Devices, General Dynamics-Space Propulsion Systems, Applied Physics Laboratory, Colorado State University, University of Michigan

**Managed by:** NASA/MSFC

**Description of Technology:**

40-cm diameter ion thruster  
Throttle Range: 1 kW – 6.25 kW  
Maximum Isp 4050 seconds  
71% engine efficiency.

**Graph:**

- Data NSTAR 8200 hr test
- Calculation CEX-3D

**JPL leading the service life validation activity**
Advanced carbon grid materials offer dramatic improvements in ion engine technology
- Carbon erosion resistance essentially eliminates grid wear out failure modes

Goals and Objectives
- Develop 30-cm carbon-carbon grids
- Validate the performance and life of the carbon-carbon grids
- Develop and deliver grid life modeling software

Key Challenges
- Achieving required beam extraction characteristics
- Demonstrate ability to survive launch loads
- Demonstrate ability to provide sustained operation with acceptable arcing at the required electric field

Accomplishments
- 30cm Carbon – Carbon Grids
  Running at 5000s Isp!
- Analysis shows CC grid will survive launch loads

Managed by: NASA/MSFC
NEXIS a major advance in ion thruster performance
NEXIS Advances Ion Thruster Technology

- Large Discharge Chamber
- Advanced Ring Cusp Magnetic Field Configuration
- Beam Voltage > 4860 V
- New Grid Design Using Advanced Simulation Tools
- Erosion-resistant Carbon Grids
- High Perveance Margin Operation
- Accelerator Grid Hole Size Tailoring
- Grid Masking

<table>
<thead>
<tr>
<th>Performance Metric</th>
<th>NEXIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kWe)</td>
<td>20</td>
</tr>
<tr>
<td>Isp (s)</td>
<td>7500</td>
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<tr>
<td>Thruster Efficiency</td>
<td>0.78</td>
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<tr>
<td>Specific Mass (kg/kWe)</td>
<td>1</td>
</tr>
<tr>
<td>Throughput (kg)</td>
<td>1000</td>
</tr>
<tr>
<td>Run Time (hrs)</td>
<td>48,000</td>
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</table>

- Reservoir Hollow Cathode Incorporating:
  - Advanced Emitter Material
  - High Capacity Activator Supply Reservoir
  - Improved Activator Transport
  - Decoupled Emitter and Activator Source
  - One Neutralizer Shared By Multiple Engines

- Erosion-resistant Carbon Keeper Electrode
- Operational Control of High Energy Ion Production
Computer models are used to guide design, correlate test data & predict engine life. Validated with lab & flight performance & wear data.

Hollow cathode orifice and discharge chamber models include ionization physics.

Codes model ion trajectories and erosion of a single grid aperture.

Discharge chamber potentials.
**JPL Grid Ion Optics Codes**

**CEX2D** : 2-D R-Z including charge exchange ions (that cause erosion)

**CEX3D** : 3-D right triangular prisms (minimum symmetry region)

- **Physics**
  - Potentials: Poisson’s equation
  - Ion density: tracked trajectories using calculated electric fields
  - Electron density: analytic – assumes Maxwellian’s upstream & downstream
  - Charge Exchange (CEX) collisions

- **Advanced Numerical Techniques**
Fig. 7 Beamlet exit diameters as a function of radius for tests 1 and 2.

George Soulas and Vince Rawlin, Beamlet Diameter Measurements, 3/22/99
• Charge Exchange (CEX) collisions between beam ions and neutral gas produce slow ions that can impact grid surfaces

Barrel Erosion caused by CEX ions generated upstream and in accel grid hole

Pits and Grooves Erosion caused by CEX ions generated downstream

Comparisons with NSTAR Data

Data NSTAR 8200 hr test
Calculation CEX-3D
NEXIS Isp = 7500s Grid Design

- High ISP means high grid voltage
  - Thruster power increases rapidly
  - Discharge chamber doesn’t change
- High Isp grids designed using computer codes
- Laboratory test validate designs

Beamlet Current (mA)

Beam extraction tests with subscale grids show desired beam extraction characteristics.
Hollow Cathode Fundamentals

- Efficient source of electrons
- Partially ionizes a neutral gas
  Input: propellant gas, e.g. Xenon
  Output: electrons, ions, and unionized gas
- Electron current >> ions emitted
  Electrons emitted from low work function Barium impregnated insert
- Failure modes
  Insert Ba depletion
  Orifice erosion or blockage
  Keeper erosion

Figure 1. Drawing of a flight HCA (drawing not to scale).

Figure from “A Review of Testing of Hollow Cathodes for The International Space Station Plasma Contactor” S. D. Kovaleski, M. J. Patterson, G. C. Soulas, T. R. Sarver-Verhey, NASA Glenn Research Center, IEPC-01-271
Increasing Hollow Cathode Insert Life

- Potential NEP Missions require 10 yr cathode life
  - Space Station Plasma Contactor life test demonstrated 28,000 hrs life, very hard to start ~ 24,000 hrs
  - NSTAR Extended Life Test Discharge Cathode presently at 27,400+ hrs, shows no sign of degradation

- Hollow Cathode models provide physical insight
  - Barium is ionized and migrates upstream
  - Orifice dimensions and current control insert temperature

- Methods to increase insert life
  1. More barium
  2. Lower work function
  3. Lower operating temperature

JPL Models of Hollow Cathode Physics

- 40° C Reduction Doubles Insert Life

\[ \begin{align*}
\text{Insert Temperature (°C)} & \quad 1100 \quad 1150 \quad 1200 \quad 1250 \quad 1300 \\
\text{Insert Life (hours)} & \quad 160,000 \quad 140,000 \quad 120,000 \quad 100,000 \quad 80,000 \quad 60,000 \quad 40,000 \quad 20,000 \quad 0
\end{align*} \]
Computer Models Will Be Used to Address EP Thruster Plume - S/C Integration Issues

- **Ion thruster plume components**
  - Energetic beam ions
  - Charge exchange plasma
  - Scattered ions
  - Grid erosion products

- **Plume-Spacecraft interactions**
  - Sputter erosion of surfaces
  - Contamination of radiators, optics, & antennas
  - Plasma optical & RF emissions
  - Plasma dielectric effects
  - Mechanical & thermal loads

Plume model integrated with spacecraft geometry

Calculated material sputtering and redeposition

Thruster plumes have high energy particles at large angles

![Plume model integrated with spacecraft geometry](image)

![Calculated material sputtering and redeposition](image)

![Thruster plumes have high energy particles at large angles](image)
Summary

- Gridded Ion Engines Clear Choice For Potential Near Term NEP Missions
- Potential NEP Missions require major advances in ion thrusters
- Extensive Ion Thruster Heritage
  - Knowledge
  - Flight
  - Laboratory Life Test
- In-Space technology programs don’t address potential NEP Mission requirements
  - NEXT - NASA’s Evolutionary Xenon Thruster
    - Bigger discharge chamber, Modest Isp increase (4000s)
  - CBIO - Carbon Based Ion Optics
    - Low sputter yield material for long grid life, demonstrated at 5000s Isp
- Nuclear Electric Xenon Ion System (NEXIS) Program
  - Advanced Technologies that Enable NEP
    - High efficiency discharge chamber
    - High Isp, long life, carbon based grids
    - Dispenser hollow cathodes for long life
  - Designed using JPL Ion Thruster Codes
    - Ion optics grid performance & life
    - Hollow performance & cathode life