Status of Propulsion Technology Development under the NASA In-space Propulsion Technology Program

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NASA’s In-Space Propulsion Technology (ISPT) Program

NASA’s ISPT Program develops critical propulsion, entry vehicle, and other spacecraft and platform subsystem technologies to enable or significantly enhance future planetary science missions.

- Enable access to more challenging and interesting science destinations or benefit future robotic science missions
- By significantly reducing travel times to distant bodies, increasing scientific payload capability, or reducing mission cost and risk.
- The current ISPT focus is TRL 3-6+ product development.

**Propulsion System Technologies**

- AMBR High-Temp Rocket Engine
- 7 kW NEXT Ion Propulsion System
- 4 kW HIVHAC Thruster & Hall Propulsion System

**Entry Vehicle Technologies**

- Aerocapture
- Multi-Mission Earth Entry Vehicle

**Spacecraft Bus & Sample Return Technologies**

- Mars Ascent Vehicle
- Spacecraft Bus Components
- Extreme Environments

**Systems & Mission Studies**

- Mission Analysis Tools
- Mission and System Studies
NASA’s Evolutionary Xenon Thruster (NEXT) Expanding SEP Applications For Science Missions

**Objective:** Improve the performance and life of gridded ion engines to reduce user costs and enhance/enable a broad range of NASA SMD missions

![NEXT Thruster Diagram]

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>300kN (SOA)</th>
<th>NEXT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster Power Range (kW)</td>
<td>0.5-2.3</td>
<td>0.5-6.9</td>
</tr>
<tr>
<td>Max. Thrust (mN)</td>
<td>92</td>
<td>236</td>
</tr>
<tr>
<td>Max. Specific Impulse (sec)</td>
<td>&gt;3100</td>
<td>&gt;4100</td>
</tr>
<tr>
<td>Max. Thruster Efficiency</td>
<td>&gt;61%</td>
<td>&gt;70%</td>
</tr>
<tr>
<td>Total Impulse (x10^6 N-sec)</td>
<td>&gt;5</td>
<td>35.5</td>
</tr>
<tr>
<td>Propellant Throughput (kg)</td>
<td>135</td>
<td>918</td>
</tr>
<tr>
<td>PPU Specific Mass (kg/kW)</td>
<td>6.0</td>
<td>4.8</td>
</tr>
<tr>
<td>PMS Single String Mass (kg)</td>
<td>11.4</td>
<td>5.0</td>
</tr>
<tr>
<td>PMS Unusable Propellant Residual</td>
<td>2.40%</td>
<td>1.00%</td>
</tr>
</tbody>
</table>

* Rated Capability Goal 300Kg ➔ Design/Qualification Goal (1.5x Rated) 450Kg
  Demonstrated Life Limit >900Kg ➔ Potential Rated Capability >600Kg

- NEXT development included critical components for ion propulsion system
- Single-String & Multi-String System Integration Tests completed
- NEXT TRL assessments completed by multiple mission center customers
- Unprecedented diagnostics used for NEXT thruster performance characterization and spacecraft interaction effects testing ongoing
- Thruster and feed system are ready-to-go. 2\textsuperscript{nd} design iteration of PPU being planned.
What the NEXT LDT Demonstrated in 9 yrs of Testing

• NEXT Long Duration Test (LDT) was voluntarily concluded on 1 April 2014
  • Collected end-of-test data with repaired and fully functional diagnostic suite to compare with beginning-of-life data
  • Post-test inspection an analysis is underway
  • The NEXT thruster exceeded design requirements
    • Throttle thruster to a deep space mission profile
      • Goal ≥450Kg qualification level propellant throughput
      • Characterized thruster operation over a wide operating table
    • NEXT LDT sets Throughput and Duration World Records
      • 51,200 hours of operation
      • 918.2 kg Xenon throughput
      • 35.5 MN-s of total impulse delivered

Equivalent Qualification Level: 609.6 kg
Projected Qualification Level: >870 kg
Current throughput projection ≥870±70 kg

Representative Mission Concept Throughput Requirements

Current NEXT Qualification Level [609.6 kg]
Projected Throughput: >870 kg
Original NEXT Qualification Requirement: 450 kg

NEXT LDT Demonstrated (as of 2/12/2014): 914.4 kg
Projected Throughput: >860 kg
Original NEXT Qualification Requirement: 450 kg
What the NEXT LDT Demonstrated in 9 yrs of Testing

- Demonstrated that thruster life-limiting phenomena and wear mechanisms associated with ion thruster operations have been addressed in the NEXT design
  - NEXT LDT post-test inspections/analysis will help confirm
- Improved models for future mission planning and operation
  - Compared measured thruster wear rates with those predicted from life models
  - Carbon back-sputter and enhanced charge-exchange facility impact analysis completed
    - Engineering correction factor on wear-rate test results determined
      - <4% reduction for carbon back sputter
      - ~8-10% increase for charge-exchange
  - Current Life prediction is 870Kg ±70Kg

NEXT thruster has exceeded expectations!
Objective: Develop key components of a HiVHAc Hall propulsion system (thruster, PPU/DCIU, feed system) to TRL 6 to enable/enhance new SMD Discovery missions; expand operational capability to close near-earth mission applications

- The HiVHAc thruster offers improved performance and mission benefits over SOA
- Developing a Power Processing Unit (PPU) with a Digital Control Interface Unit (DCIU) to advance the HiVHAc propulsion system readiness
- A flight-qualified Xenon Flow Control Module (XFCM) was delivered to NASA GRC in March 2012 and has been integrated with the HiVHAc thruster. Designed to work with the above PPU.
HiVHAc Development Status

- Testing of the thruster was performed in NASA GRC’s Vacuum Facility 5 (VF5) during the Fall of 2013
  - Testing of the thruster was performed at various background pressure conditions
  - Measurements included: performance mapping, plasma mapping, and thermal characterization
- Testing of the EDU2 HiVHAc thruster with a brassboard PPU and the VACCO Xenon Feed System was completed in GRC’s VF12 during March of 2014
- A HiVHAc thruster with a modified magnetic circuit was recently tested
  - The discharge erosion starts downstream of the magnetic poles, which protects the poles for a 2 times increase to the projected throughput

Performance Characteristics of HIVHAC vs. SOA Hall (BPT-4000).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>BPT-4000</th>
<th>HIVHAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster Power Range, kW</td>
<td>0.3-4.5</td>
<td>0.3-3.9</td>
</tr>
<tr>
<td>Throttle Ratio</td>
<td>15:1</td>
<td>12:1</td>
</tr>
<tr>
<td>Operating Voltage, V</td>
<td>150-400</td>
<td>200-700</td>
</tr>
<tr>
<td>Specific Impulse, sec</td>
<td>710-2100</td>
<td>860-2700</td>
</tr>
<tr>
<td>Thrust, mN</td>
<td>22-260</td>
<td>20-207</td>
</tr>
<tr>
<td>Efficiency</td>
<td>0.25-0.58</td>
<td>0.32-0.62</td>
</tr>
<tr>
<td>Propellant Throughput, kg</td>
<td>450</td>
<td>&gt;300</td>
</tr>
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</table>
Hall Propulsion Power Processing Unit

• PSD’s In-Space Propulsion Technology (ISPT) Program has been working with a promising Small Business Innovative Research (SBIR) project to develop a low-cost 4.5-kW class wide output range Hall Power Processing Unit (PPU) for Discovery-class planetary missions.

  • Colorado Power Electronics (CPE) has successfully developed a PPU and is poised to take the design to flight certification (TRL 6) by September 2016

  • Qualification Model (QM) PPU will incorporate control electronics for the PPU power modules, VACCOr TRL 7 xenon feed system, and thruster/PPU telemetry

  • CPE has submitted a cost proposal and NASA programs have committed funding to start the effort

  • The PPU is being designed to operate several Hall thrusters:

    • NASA’s High Voltage Hall Accelerator (HiVHAc), Aerojet-Rocketdyne XR-5 (BPT-4000), Space Systems Loral SPT-140.

    • Thruster acquisition and Hall propulsion system development to be addressed by mission proposal teams.
Ultra Lightweight Tank Technology (ULTT) for future planetary missions

Objective:
- Develop a Composite Overwrapped Pressure Vessel (COPV) tanks for propellants and pressurants for Mars Sample Return (MSR) mission
- To design ultra-lightweight propellant and pressurant tanks sized for Mars Skycrane with an option to manufacture and qualify.

Benefits
- 19.5 kg mass savings are achievable for 3 tanks sized for the Skycrane (40% mass reduction)
  - Mass savings can be passed on to the scientific payload or increase mass margin
  - Broad impact to virtually ALL space missions as most use liquid propellants or pressurant
    - Europa Explorer tank mass can be reduced by 60 kg

Accomplishment Status
- Critical Design Review CDR held Feb 2014
- Mars 2020 mission will use build-to-print Skycrane tanks
- Conclude NDI techniques, and no further design or fabrication due to funding limitations and no Mars 2020 adoption
Summary

• Concluded NEXT and Ultra-lightweight Tank development
• Concluded NEXT TRL Assessments and Tech Infusion Study, and identified gaps for customer adoption and improve future technology development
• 2014 concludes all ISPT activities. Wrapping up and documenting remaining ISPT work.
  – HIVHAC Thruster development
  – NEXT LDT post-test characterization, inspection, documenting
  – Will continue to support flight infusion
    – NEXT Thruster and PPU may be offered as Government Furnished Equipment (GFE) on upcoming Discovery Announcement of Opportunity
    – 4.5kW Hall PPU development will continue through other funding
• ISPT investments have expanded Planetary Science mission capabilities
Questions?

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216-433-8709
## NEXT Mission Benefits & Applicability

<table>
<thead>
<tr>
<th>CHARACTERISTIC</th>
<th>NSTAR (SOA)</th>
<th>NEXT</th>
<th>Improvement</th>
<th>NEXT BENEFIT</th>
</tr>
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<tbody>
<tr>
<td>Max. Thruster Power (kW)</td>
<td>2.3</td>
<td>6.9</td>
<td>3x</td>
<td>Enables high power missions with fewer thruster strings</td>
</tr>
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<td>Max. Thrust (mN)</td>
<td>91</td>
<td>236</td>
<td>2.6x</td>
<td></td>
</tr>
<tr>
<td>Throttling Range (Max. / Min. Thrust)</td>
<td>4.9</td>
<td>13.8</td>
<td>3x</td>
<td>Allows use over broader range of distances from Sun</td>
</tr>
<tr>
<td>Max. Specific Impulse (sec)</td>
<td>3120</td>
<td>4190</td>
<td>32%</td>
<td>Reduces propellant mass, enabling more payload and/or lighter spacecraft</td>
</tr>
<tr>
<td>Total Impulse (10⁶ N-sec)</td>
<td>4.6</td>
<td>&gt;35.5</td>
<td>&gt;7x</td>
<td>Enables low power, high ΔV Discovery-class missions with a single thruster</td>
</tr>
<tr>
<td>Propellant Throughput (kg)</td>
<td>150</td>
<td>918</td>
<td>&gt;4x</td>
<td></td>
</tr>
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* NOTE: NSTAR used on DS-1 and Dawn missions
**NEXT Mission Benefits & Applicability**

- **Equivalent Qualification Level:** 612.1 kg
- **Projected Qualification Level:** >580 kg
- **Original NEXT Design Goal:** 300 kg
- **NEXT LDT Demonstrated (as of 3/28/2014):** 918.2 kg
- **Projected Throughput:** >870 kg
- **Original NEXT Qualification Requirement:** 450 kg

**Representative Mission Concept Throughput Requirements**

- 522 kg – Multi-asteroid Rendezvous
- 503 kg – Ceres SR
- 499 kg – Mars Orbiter
- 450 kg – NWO
- 442 kg – Main-belt SR
- 426 kg – Uranus orbiter
- 418 kg – Bepi-Columbo
- 405 kg – CSSR
- 360 kg – Multi-asteroid SR
- 338 kg – Multi-asteroid Rendezvous
- 360.8 kg – Comet SR Qualification
- 275 kg – TSSM
- 263.5 kg – Vesta-Ceres
- 262.7 kg – Neptune DSDRM
- 250 kg – Titan Lander
- 246 kg – Comet Rendezvous
- 242.3 kg – Saturn DSDRM
- 200 kg – EZE
- 176.3 kg – NEAR Mission

**Goals**

- Current NEXT Qualification Level (612.1 kg)
- Next LDT Demonstrated (as of 3/28/2014): 918.2 kg
- Projected Qualification Level: >580 kg
- Projected Throughput: >870 kg

**NEXT Throughput Requirements**

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<td>450 kg – NWO</td>
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<tr>
<td>442 kg – Main-belt SR</td>
<td>442 kg</td>
</tr>
<tr>
<td>426 kg – Uranus orbiter</td>
<td>426 kg</td>
</tr>
<tr>
<td>418 kg – Bepi-Columbo</td>
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<td>176.3 kg – NEAR Mission</td>
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**Propellant Throughput, kg**

- **Current NEXT Qualification Level (612.1 kg)**
- **Original NEXT Design Goal (300 kg)**
- **Current throughput projection >870±70 kg**
Hall Propulsion Priorities for Planetary Science Missions

- Develop common flight Hall Power Processing Unit (PPU) with capabilities for PSD mission needs for any Hall thruster
  - 5 kW class, modular design
  - Qualify unit and procure 3 flight PPU's as GFE

- Evaluate commercial Hall thrusters (i.e. BPT-4000, SPT-140,...)
  - Delta-qual (as necessary) for PSD environments/life
  - Facility effects assessment and develop ground-test-to-flight-modeling protocols

- Complete the High Voltage Hall Accelerator (HiVHAc) system
  - Assess/incorporate Magnetic Shielding (MS), and qualify thruster

- Leverage STMD’s 12-kW Hall system development to address planetary science mission needs

- Maintain Mission analysis capabilities and tool development
  - Community engagement with mission capabilities
Solar Electric Propulsion Market Options

<table>
<thead>
<tr>
<th>ISP/Input Power</th>
<th>&lt;5 kW</th>
<th>5-10kW</th>
<th>NEXT &amp; HiVHAc flexibility &amp; performance envelopes much of the existing market while extending new mission realms (interplanetary, orbit transfer, high mass) for new customers (e.g., international, government &amp; commercial)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;4000</td>
<td></td>
<td>NEXT</td>
<td>BHT-200</td>
</tr>
<tr>
<td>2500-4000</td>
<td></td>
<td>HiVHAc</td>
<td>RIT-22 T6 XIPS 25 NEXT nonmarking return HiVHAc STMD 12.5kW Hall SPT-140 STMD 12.5kW Hall</td>
</tr>
<tr>
<td>1000-2500</td>
<td></td>
<td>HiVHAc</td>
<td>T5 SPT-100 XR-5 (BPT-4000) SPT-140 SPT-140</td>
</tr>
<tr>
<td>&lt;1000</td>
<td></td>
<td>BPT-4000</td>
<td>Arcjet EHT</td>
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