The Ion Propulsion System for the Asteroid Redirect Robotic Mission

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Outline

• EMC, SEP TDM, and ARRM

• Ion Propulsion System Overview

• NASA In-House Technology Development Status
  – 12.5 kW HERMeS Thruster
  – 13.3 kW HP-120V PPU

• Transition-to-Flight
  – Advanced Electric Propulsion Contract
  – ARRM Spacecraft

• Conclusions
High-Power SEP Critical to NASA Exploration Vision

- High-Power SEP systems required to move large masses in interplanetary space
  - Leveraged in a multi-use, evolvable space infrastructure

50kW-class spacecraft w/advanced solar arrays and electric propulsion

- Transportation capability with fuel efficiency 10x chemical systems
- Reduces trip times by 5x relative to existing SEP systems
- Scales to higher power to support beyond LEO human exploration

1998 Deep Space 1
Technology Demonstrator
374kg dry/82kg Xe
2.5 kW power system
2.5kW EP system
1900-3200s specific impulse

2007 Dawn
Deep-Space Science Mission
747kg dry/425kg Xe
10 kW power system
2.5kW EP system
1900-3200s specific impulse

~2020 SEP TDM
Asteroid Redirect Mission
4,500 kg dry/5,000kg Xe
50kW power system
40kW EP system
2000-3000s specific impulse

≥ 2025 Beyond LEO Human Exploration
Prepositioning of assets
~7000kg dry/16,000kg Xe
~200kW power system
150kW EP system
2000-3000s specific impulse
High-power SEP can be enabling for both near-term and future exploration architectures and science missions.

NASA is maturing mission design for a 50kW-Class SEP Demonstration:
- Most mature concept is the Asteroid Redirect Robotic Mission
  - Dec. 2021 launch
  - 2026 asteroid boulder return to cis-lunar space
  - Reference asteroid: 2008 EV5
  - Electric propulsion used for:
    - Maneuver for LGA
    - Heliocentric transfer to and from asteroid
    - Orbit capture/transfer at asteroid
    - Planetary defense demo
    - Departure/escape from asteroid
    - Insertion into lunar DRO
    - Pitch and yaw control of vehicle during EP operation
• Ability to utilize multiple advanced, deployable solar array technologies currently being matured
  – MegaFlex and ROSA wings shown
• EP thrusters shown on gimbal with boom
  – Reduce plume impingement on the vehicle (especially docking ring and solar arrays)
  – Beneficial for large off-axis thrusting for planetary defense demonstration
• Capability of carrying in excess of 10 tons of xenon, but loaded only to 5.3 tons
• Leverages synergy with Restore-L service mission: rendezvous and proximity operations sensors, dexterous robotics, hybrid flight computing algorithms, and servicing avionics
• Collect high-value plasma plume data
  – Validate models of high-power SEP operation and spacecraft plasma interactions
  – Improve design tools that are critical to enabling high-power SEP spacecraft to support future human and robotic missions to Mars
  – Provide in-flight SEP system performance measurements and thruster characterization tool
  – Measure surface erosion and material re-deposition

• Government-led development of package provided as GFE to mission
  – Utilizes high-heritage instruments flown on prior NASA and other government spacecraft
NASA is developing the requisite technologies for a 50kW-Class Solar Electric Propulsion Demonstration to enable SEP missions and applications at higher power levels.
Ion Propulsion System and Thruster Requirements

- Key ARRM Requirements for Ion Propulsion System (IPS)

<table>
<thead>
<tr>
<th>Capability</th>
<th>Value</th>
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<tbody>
<tr>
<td>Total system power</td>
<td>40 kW</td>
</tr>
<tr>
<td>Maximum specific impulse</td>
<td>2600 s</td>
</tr>
<tr>
<td>Xenon throughput</td>
<td>5,000 kg</td>
</tr>
<tr>
<td>String fault tolerance</td>
<td>Single</td>
</tr>
<tr>
<td>Solar range</td>
<td>0.8 – 1.7 AU</td>
</tr>
<tr>
<td>Input voltage range</td>
<td>95 – 140 V</td>
</tr>
</tbody>
</table>

- Simplified EP String throttling utilized in ARRM mission design
  - ARRM mission analyses shown that maximum boulder return mass and xenon propellant required vary by less than 5% and 2%, respectively over 2,600 – 3,000 s specific impulse range

<table>
<thead>
<tr>
<th>EP String Total Input Power (kW)</th>
<th>Discharge Voltage (V)</th>
<th>Thrust (mN)</th>
<th>Mass Flow Rate (mg/s)</th>
<th>System Efficiency</th>
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<tr>
<td>13.3</td>
<td>600</td>
<td>589</td>
<td>22.9</td>
<td>0.57</td>
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<tr>
<td>11.1</td>
<td>500</td>
<td>519</td>
<td>22.0</td>
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<tr>
<td>8.9</td>
<td>400</td>
<td>462</td>
<td>22.1</td>
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<td>6.7</td>
<td>300</td>
<td>386</td>
<td>21.7</td>
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<tr>
<td>3.4</td>
<td>300</td>
<td>200</td>
<td>11.9</td>
<td>0.49</td>
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</table>
**Government-Furnished Electric Propulsion String**

- **GFE Electric Propulsion String consists of:**
  - Flight Thrusters (FT)
  - Power Processing Unit (PPU)
  - Xenon Feed System (XFS)
  - Harnesses between the above elements

- **Thruster gimbal is not considered part of the GFE EP string**
  - Gimbal design specific to spacecraft configuration still being matured

**Legend:**
REU: Remote Engineering Unit  
TGA: Thruster Gimbal Assembly  
FT: Flight Thruster  
XFC: Xenon Flow Controller  
PMA: Propellant Management Assembly  
28V: Low Voltage Bus
• 3+1 EP Strings consisting of four elements
  – Flight Thrusters (FT)
  – Power Processing Unit (PPU)
  – Xenon Feed System (XFS)
  – Mechanical Integration Hardware (MIH)

• Thruster gimbal is part of spacecraft structures and mechanisms
NASA GRC and JPL developed 12.5 kW Hall Effect Rocket with Magnetic Shielding (HERMeS) to demonstrate viability and address mission risks.

First Technology Demonstration Unit (TDU-1) fabricated and extensively tested:
- Operating envelope (blue) spans 300-800 V, 8.9-31.3 A (3.5:1), & 6.25-12.5 kW
- TDU-1 testing has demonstrated operating points (red) as low as 300 V, 2 A
  - Performance and plume mapping: including facility effects characterizations, magnetic field strength optimization, magnetic field symmetry assessment, cathode flow fraction characterization, and plume flux, energy, and charge state
  - Multiple thermal characterizations to quantify thermal margin
  - Wall probe measurements to verify magnetic shielding require for long-life
- TDU-1 is approximately 1,000 hours into a 2,000 hour wear test in VF5
A second Technology Demonstration Unit (TDU-2) was fabricated at NASA GRC for an environmental test campaign at JPL with the following modifications:

- Improved thermal management relative to TDU-1
- Structural modifications for surviving dynamic environments
HP-120V PPU Development Status

14 kW HP-120V Full-Bridge Topology Power Processing Unit (PPU)

System Control Board (SCB) developed and undergoing integration in HP-120V PPU
- EP string command, control, and telemetry interface
Brassboard unit developed and tested over operating range 2 – 14 kW, 95 – 140 V input, and 200 – 800 V output

- Ambient functional testing
- Vacuum performance characterization: 5 – 50 °C cold plate range
- Integrated testing with TDU-1 HERMeS thruster: ignition, transient and steady-state characterization; output filter optimization; and input power quality characterization
• Monday [July 25]

• Tuesday [July 26]
  – [5:00 – 5:30] W. Huang, “Facility Effect Characterization Test of NASA’s HERMeS Hall Thruster”
  – [5:30 – 6:00] W. Huang, “Plasma Oscillation Characterization of NASA’s HERMeS Hall Thruster via High Speed Imaging”

• Wednesday [July 27]
  – [5:00 – 5:30] P.Y. Peterson, “2,000 Hour Wear Assessment of the HERMeS BaO Hollow Cathode”
A competitively-selected cost-plus fixed fee including incentives contract was initiated to develop and procure the EP strings that will be provided as GFE to ARRM:

- Draft Request for Proposals (RFP) issued on May 5, 2015
  - Base Period of Performance includes:
    - (1) Engineering Development Unit (EDU) EP String including GSE & (1) additional EDU Hall thruster
  - Option Period of Performance includes:
    - (1) Qualification Model (QM) EP String
    - (4) Flight Model (FM) EP Strings including GSE & (1) Spare FM PPU

The Advanced Electric Propulsion System (AEPS) $65M contract plus up to $2M incentives was awarded to Aerojet Rocketdyne with subcontractors ZIN Technologies and VACCO Industries:

- May 16, 2016 Authority to Proceed

### Notional AEPS contract schedule shown against ARRM milestones (subject to change)

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<tr>
<th>CY16</th>
<th>CY17</th>
<th>CY18</th>
<th>CY19</th>
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<td><strong>Milestones</strong></td>
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<td></td>
<td><strong>Contract Effective Date</strong></td>
<td><strong>CDR</strong></td>
<td><strong>Final EP String Delivery</strong></td>
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<td><strong>Need to Receive Thruster Assembly</strong></td>
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<td><strong>Activity of AI</strong></td>
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<tr>
<td><strong>EP Contract</strong></td>
<td><strong>System Design Verification Review</strong></td>
<td><strong>8/18</strong></td>
<td><strong>7/19</strong></td>
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<td><strong>Base</strong></td>
<td><strong>4/17 SDR</strong></td>
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<td><strong>SDR</strong></td>
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<td><strong>System Design Verification Review</strong></td>
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<td><strong>Activity of AI</strong></td>
</tr>
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</table>
Asteroid Redirect Vehicle Acquisition

- Asteroid Redirect Vehicle (ARV) Acquisition strategy leverages commercially available U.S. industry capabilities to reduce costs
  - Procurement of ARRM spacecraft occurs in two phases

- Phase 1: Fixed price design study contracts were awarded for to support mission formulation in cooperation with ARRM
  - Lockheed Margin Space Systems
  - Boeing Phantom Works
  - Orbital ATK
  - Space Systems / Loral

- Phase 2: Competitive selections for the development and implementation of the flight spacecraft bus by one of the study participants
  - Request for Proposals for potential procurement in planning phase
  - AEPS GFE String description document and plasma plume description included to define EP string components and interfaces/interactions with vehicle
Conclusions

- NASA is developing high-power SEP systems required to move large masses in interplanetary space as part of a multi-use, evolvable space infrastructure.
- NASA is maturing mission design for a 50kW-Class SEP Demonstration
  - Most mature concept is the Asteroid Redirect Robotic Mission.
- NASA is developing the requisite technologies for the SEP TDM, including ARRM, to enable these SEP missions that is extensible to applications at even higher power levels
  - Joint NASA GRC and JPL in-house development of the 12.5 kW HERMeS thruster and 13.3 kW HP-120V power processing unit.
- The AEPS contract for the development and delivery of 4 flight Electric Propulsion Strings was awarded on May 16, 2016 to Aerojet Rocketdyne
  - Acquisition initiated during ARRM mission formulation to meet the Dec. 2021 ARRM launch date.
  - EP strings will be provided as GFE to ARRM.
- Phase 1 of ARRM vehicle acquisition completed and Phase 2 in planning
  - Leverages commercially available U.S. industry capabilities to reduce costs.
  - EP string description documents detail interfaces between EP string and ARV.
The support of the joint NASA GRC and JPL development of HERMeS by NASA’s Space Technology Mission Directorate through the Solar Electric Propulsion Technology Demonstration Mission (SEP TDM) project is gratefully acknowledged.
SEP TDM supported papers at 2015 JANNAF, IEPC, & JPC


