The Application of Advanced Electric Propulsion on the NASA Power and Propulsion Element (PPE)

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Space Policy Directive 1: To the Moon, then Mars

- Lead an innovative and sustainable program of exploration with commercial and international partners
- The United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations

The Artemis Program

Artemis is the twin sister of Apollo and goddess of the Moon in Greek mythology. Now, she personifies our path to the Moon as the name of NASA's program to return astronauts to the lunar surface by 2024.
The Artemis Program

Artemis Phase 1: To the Lunar Surface by 2024

Artemis 1: First human spacecraft to the Moon in the 21st century

Artemis 2: First humans to orbit the Moon in the 21st century

Artemis Support Mission: First high power Solar Electric Propulsion (SEP) system

Artemis Support Mission: First pressurized module delivered to Gateway

Artemis Support Mission(s): Human Lander System delivered to Gateway

Artemis 3: Crewed mission to Gateway and lunar surface

Commercial Lunar Payload Services - CLPS delivered science and technology payloads

Early South Pole Mission(s) - First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles

Large-Scale Cargo Lander - Increased capabilities for science and technology payloads

Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions

LUNAR SOUTH POLE TARGET SITE

2019

2024
TRANSPORTATION & OPERATIONS:
• Common rendezvous sensors and docking systems for deep space
• Transfers and maneuvers in low-gravity regimes

IN-SPACE POWER & PROPULSION:
• High-efficiency, long-life SEP extensible to Mars cargo missions
• Power enhancements feed forward to deep-space habitats and transit vehicles

LANDING SYSTEM DEPLOYMENT:
• Aggregation, automated docking, and deployment of Human Landing System from an orbiting platform

OPERATIONS:
• Extended operations in lunar orbit in preparation for missions farther into deep space
• High-efficiency propulsion demonstration for deep-space trajectory and navigation techniques

TRANSPORTATION & OPERATIONS:
• Common rendezvous sensors and docking systems for deep space
• Transfers and maneuvers in low-gravity regimes

High-Efficiency Solar Electric Propulsion
Refuelable tanks
Landing System
Deep-Space Rendezvous Sensors & Docking Capabilities
Gateway Phase 1

Gateway Phase 1 Status

- **Power and Propulsion Element (PPE)**
  - Based on a commercial satellite bus
  - Recently awarded to Maxar Technologies
  - Scheduled to launch in 2022

- **Habitation and Logistics Outpost (HALO)**
  - Recently awarded to Northrop Grumman
  - Scheduled to launch in late 2023

- **Logistics Element**
  - Being modeled after ISS Commercial Resupply Services
  - Scheduled to launch in 2024, just ahead of Orion crewed flight, Artemis 3
Approach for Power and Propulsion Element

• NASA and its PPE partner Maxar began upon contract award May 24, 2019
  – Public-private partnership leveraging U.S. industry capabilities
  – Target launch date December 2022, followed by Maxar-owned demonstration up to 1 year
  – Includes contract option to acquire residual asset (PPE) for NASA use, after demonstration completion

NASA Demo Objectives
• Demonstrate in relevant space environment:
  – 50-kW class solar array and electric propulsion
  – Deployment and successful long-term, deep-space operation of high-power next-generation SEP system
  – High-data throughput uplink / downlink Comm system
  – PPE insertion into a crew-accessible Near Rectilinear Halo Orbit (NRHO)
• Obtain design, development, and flight demonstration data to determine acceptability of the Gateway PPE
• Observe and characterize performance of integrated end-to-end high-power SEP system

Maxar Demo Objectives
• Demonstrate Next-Generation Commercial Communications Capabilities
  – Demonstrate lunar lander communications relay services at the moon
  – Demonstrate high-power SEP capabilities for commercial communications satellites
• Demonstrate Next-Generation Commercial Space Transportation Capabilities
  – Demonstrate high-power SEP-enabled cargo transfer
  – Demonstrate heavy-lift launch vehicle capability
• Demonstrate Next-Generation Commercial Satellite Servicing Capabilities
  – Demonstrate detailed spacecraft inspection capability
  – Demonstrate xenon transfer capability
Leverage heritage reliability, proven development approach, and the scalable 1300-class platform as the basis for a PPE demonstration mission culminating with delivery of PPE to NASA in the target NRHO.

- **Power** – 60 kW+ provided by Roll Out Solar Array (ROSA) and Maxar’s 1300 commercial power subsystem

- **Propulsion** – Combined 49 kW of EP spread over 6 EP strings that leverage NASA development of 12.5 kW Electric Propulsion (EP), and internal Maxar advanced 6 kW EP development, with Maxar expertise in system accommodation of EP elements

- **Communications** – Ka-band relay from Lunar vicinity to Earth, accommodations for future optical communications payloads

- **Guidance Navigation and Control** – Utilize proven approaches for station keeping, momentum management, and autonomous low thrust electric orbit transfer

- **Payload Transfer** – 1000 kg for lunar lander or science instruments
Leverage Maxar SEP expertise having manufactured and flown 38 satellites equipped with 152 Hall thrusters and accumulated more than 100,000 hours of on-orbit firing time

- **Two 12.5 kW AEPS EP Strings** – Provided by Aerojet Rocketdyne
  - Under development through the AEPS Contract
- **Four 6 kW EP String – BHT-6000 Hall Thruster provided by Busek, 6 kW PPU provided by Maxar**
  - Under development through Maxar-Busek internal investment and NASA Tipping Point Contract
- **Two 825 L Xenon Tanks** – Provided by Keystone
  - Capability to store 2500 kg xenon at pressures below 2000 psi and temperatures below 55 C
- **On-Orbit Propellant Refueling** – Two dissimilar refueling interfaces for xenon and hydrazine
  - Government-furnished NASA Docking System with 2 xenon and 2 hydrazine ports interfaces with next module in the Gateway
  - Commercial docking berths and refueling valves based on Restore-L or Robotic Servicing of Geosynchronous Satellites (RSGS) type refueling

Maxar proposal baseline PPE electric propulsion subsystem block diagram
PPE Ion Propulsion Subsystem Performance

- Subsystem Preliminary Performance Estimates for 5 Electric-Orbit Raise (EOR) Configurations

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Thruster Power (kW)</th>
<th>Thrust (N)</th>
<th>Flow Rate (mg/sec)</th>
<th>Mass Used / Day (kg)</th>
<th>Specific Impulse (sec)</th>
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</thead>
<tbody>
<tr>
<td>x2 AEPS</td>
<td>25</td>
<td>1.18</td>
<td>46</td>
<td>4.0</td>
<td>2620</td>
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<tr>
<td>x2 BHT-6000</td>
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<td>x4 BHT-6000</td>
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<td>1.16</td>
<td>47</td>
<td>4.1</td>
<td>2505</td>
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<td>1.17</td>
<td>47</td>
<td>4.0</td>
<td>2560</td>
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<tr>
<td>x2 AEPS, x4 BHT-6000</td>
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<td>2.34</td>
<td>93</td>
<td>8.0</td>
<td>2560</td>
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</tbody>
</table>

Preliminary AEPS and 6 kW EP Strings Performance Assumptions

**Throttle Curves**

- AEPS
- BHT-6000 (High Isp/P)
- BHT-6000 (High T/P)

**Specific Impulse Curves**

- AEPS
- BHT-6000 (High Isp/P)
- BHT-6000 (High T/P)
Aerojet Rocketdyne is completing engineering model (EM) hardware fabrication, beginning EM testing, and is on the path to an AEPS system CDR in summer 2020.
6 kW EP Strings

Dual-mode 6 kW EP string operates at 300 V (high thrust/power) and 600 V (high Isp/power)

- **Busek BHT-6000 Thruster**
  - BHT-6000 is an extension of the BHT-5000 thruster currently in its life qualification test
  - NASA Tipping Point contract initiated to complete thruster development

- **Maxar 6 kW PPU**
  - An extension of the 4.5 kW SPT-140 PPUs based on 300 V, 5 A Zero-Voltage Switching (ZVS) trays
  - Utilizes a 4th discharge tray to operate a 6 kW
  - Includes relays to place the trays in parallel or series
  - Controls XFC solenoid and PFCV valves

- **Moog XFC**
  - Qualified up to 23 mg/s flow rates
  - To be flown on Psyche spacecraft
  - Mounts on DSM to minimize line length to thruster

- **Maxar Dual-axis SEP Module (DSM) Thruster**
  - Provides 100 degree rotation in both axes for 6 kW EP string pairs
  - Modified version of the DSM flown with pairs of SPT-140 thrusters
GFE Plasma Diagnostics Package (PDP)

<table>
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<th>Probe types</th>
<th>Measured Plume Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>PP (Planar Probe – total 5 in TPA)</td>
<td>Time-resolved ion flux, electron temperature, plasma potential</td>
</tr>
<tr>
<td>HS – RPA (High-Speed Retarding Potential analyzer – total 3 in TPA)</td>
<td>Ion energy distribution, Time-resolved/energy-filtered ion characteristics</td>
</tr>
<tr>
<td>HPA (Hemispherical Potential Analyzer - total 2 in TPA)</td>
<td>Ion energy distribution</td>
</tr>
</tbody>
</table>

Government-Furnished Plasma Diagnostics Package (PDP) placement relative to EP thrusters
Conclusions

• To meet the ambitious SP1 mandate, NASA is implementing Phase 1 of the Gateway and has (or will shortly) awarded contracts for the defined elements including the Maxar award for PPE in May 2019.

• Maxar’s PPE Demonstration meets the combined NASA and Maxar objectives, including (but not limited to):
  – Two advanced, high-performance electric propulsion strings
  – High xenon propellant storage and refueling capability
  – Implements a GFE Plasma Diagnostics Package to characterize on-orbit EP system behavior and interactions with the spacecraft

• The AEPS and 6 kW EP systems are in advanced development and are on a path for qualification to meet the planned 2022 PPE launch.
WE GO
Evolution of Electric Propulsion

SOLAR ELECTRIC PROPULSION – EVOLUTION OF APPLICATIONS

- 2030-2040: 200 - 500 kW Class (25 T, 10 T Xe)
  - Crewed Deep Space Transport—hybrid architecture
  - Mars Cargo Transport—split architecture

2020-2030: 50 kW (5-8 T wet mass, 2-5 T of Xe)
- Deep Space Gateway – Power & Propulsion Element
- Mars Orbiter & sample return
- Geo orbit Insertion & orbital servicing


2003 SMART-1: 1.5 kW ESA Tech demo mission, lunar science

2003 Hayabusa: 2 kW JAXA Tech demo, asteroid sample/return

2007-2016 Dawn: 2 kW (10 kW @ 1AU) NASA science mission, asteroidal rendezvous

1998: Geostationary Communication Satellites: kW-class solar electric propulsion used for
  North-South station keeping by all foreign and domestic satellite manufacturers

Using SEP increased operational lifetimes up to 18 years
Substantially increased payload capability
Emerging use of SEP for final orbit insertion
Multiple qualified system utilizing either arcjets, gridded ion thrusters, or Hall thrusters
100's of spacecraft and tens of thousands hours of successful on-orbit operation
STRATEGIC PRINCIPLES FOR SUSTAINABLE EXPLORATION

• FISCAL REALISM
  Implementable in the near-term with the buying power of current budgets and in the longer term with budgets commensurate with economic growth;

• SCIENTIFIC EXPLORATION
  Exploration enables science and science enables exploration; leveraging scientific expertise for human exploration of the solar system.

• TECHNOLOGY PULL AND PUSH
  Application of high TRL technologies for near term missions, while focusing sustained investments on technologies and capabilities to address the challenges of future missions;

• GRADUAL BUILD UP OF CAPABILITY
  Near-term mission opportunities with a defined cadence of compelling and integrated human and robotic missions, providing for an incremental buildup of capabilities for more complex missions over time;

• ECONOMIC OPPORTUNITY
  Opportunities for U.S. commercial business to further enhance their experience and business base;

• ARCHITECTURE OPENNESS AND RESILIENCE
  Resilient architecture featuring multi-use, evolvable space infrastructure, minimizing unique developments, with each mission leaving something behind to support subsequent missions;

• GLOBAL COLLABORATION AND LEADERSHIP
  Substantial new international and commercial partnerships, leveraging current International Space Station partnerships and building new cooperative ventures for exploration; and

• CONTINUITY OF HUMAN SPACEFLIGHT
  Uninterrupted expansion of human presence into the solar system by establishing a regular cadence of crewed missions to cis-lunar space during ISS lifetime.
Gateway Benefits

- Supports the acceleration of landing Americans on the surface of the Moon in 2024, while preserving the ability to evolve for a longer-term human presence
  - Provides power, propulsion, and communication for surface landing systems
  - Port for landing system vehicle aggregation, checkout, & crew safe haven
  - Provides a temporary home for crew who remain in orbit during surface expedition
  - Accessible for many rockets on the market
  - Provides access to the entire lunar surface
- Enables reusability and sustainability
  - Early Utilization opportunities are being protected for simple payloads
  - Serves as a reusable command module and port for logistics delivery and landing system aggregation
- Is a stepping stone to Mars exploration
  - Allows for deep space systems testing

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