High Power Electric Propulsion for Deep Space Missions

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An Overview of Electric Propulsion for Deep Space Missions

- An Electric Propulsion Primer
- The Flexible Path and the Electric Path
  - A New Plan for Human Exploration
  - The Role of Electric Propulsion
- High Power Electric Thrusters
  - Hall Thrusters
  - Magnetoplasmadynamic Thrusters
- Challenges for the Next Generation of Advanced Propulsion Technologists

Electric Propulsion 101 (limited enrollment)

Opening up the Solar System For Exploration
Electric Propulsion Provides High Exhaust Velocity for Improved Fuel Efficiency

Aerojet Bipropellant Thruster

\( I_{sp} = 323 \text{ sec} \)
Throut = 445 N
Thrust Power = 705 kW

NSTAR Ion Thruster

\( I_{sp} = 1800-3000 \text{ sec} \)
Throut = 0.02-0.09 N
PPU Power = 0.6-2.5 kW

**Chemical Propulsion**

- **Electric Propulsion devices operate at much higher specific impulse than chemical thrusters**
  - High specific impulse = much lower propellant mass

- **EP devices require electric power produced by external power system**
  - Thrust limited by power available from spacecraft
  - Low thrust results in very long burn times

**Electric Propulsion**

\[
\frac{m}{m_0} = e^{-\frac{\Delta V}{V_{exhaust}}} = e^{-\frac{\Delta V}{I_{sp} g}} = e^{-\frac{\Delta V}{9.8 I_{sp}}}
\]

Electric Propulsion’s high Isp increases delivered mass for missions that require large \( \Delta V \)
Ion Thrusters Use Electrostatic Forces to Accelerate Ions to Produce Thrust

1. Xenon gas **ionized** in the discharge chamber
2. Ions **accelerated** by voltage between grids
3. Ion beam **neutralized** by neutralizer electrons
Hall Thruster Operation is Similar, but the Processes Overlap In a Near Continuous Fashion.

1. **Electrons** from the cathode are trapped in an azimuthal drift by the applied electric (E) and magnetic fields (B).

2. **Neutral** propellant gas is ionized by electron bombardment.

3. **Ions** are accelerated by the electric field producing thrust.

4. **Electrons** from cathode neutralize ion beam.
Solar Electric Propulsion (SEP) System Elements

Solar Array

Propellant Storage

Digital Interface & Control Unit

Power Conditioning

Thruster

Gimbal

Exhaust

S/C C&DH

Note: Structural and Thermal Hardware Not Shown
Electric Propulsion-That Crazy Futuristic Technology
Hall Thruster Space Flight Heritage

241 thrusters on 51 s/c have flown since 1971 with 100% success

1960 - 1971
Early US/USSR Hall Thruster Development

1971 - 2010
241 Hall thrusters flown on 51 Russian, US, & European s/c.

Dec 1971
Fakel SPT-60 flies on Soviet Meteor s/c.
1st Hall thruster spaceflight.

Nov 1998
Russian D-55 flies on NRL STEX.
1st flight on US s/c.

Early 1990 s
Russian Hall thrusters introduced to US.

Sep 2003
SNECMA PPS-1350 flies on lunar orbiting ESA SMART-1.
1st Hall thruster used for primary propulsion on a science mission.

Mar 2004
Russian SPT-100 flies on Loral MBSAT.
1st commercial flight on US s/c.

Aug 2010
Aerojet BPT-4000 flies on Advanced EHF.
1st flight of US Hall thruster on GEO s/c.

Dec 2006
Busek BHT-200 flies on TacSat-2.
1st flight of US Hall thruster.
Electric Propulsion Has Been Used on 4 Deep Space Missions by NASA, ESA, and Japan

**NASA**
- Deep Space 1 launch in 1998
  - GRC/L-3 NSTAR ion thruster/PPU
  - Tech demo mission integrated by JPL
- DAWN launched September 27, 2007
  - JPL mission with 3 NSTAR thrusters
  - Science mission to Vesta and Ceres

**International**
- Hayabusa launch in 2003 (0.34 kW)
  - ISAS/JAXA microwave ion thrusters
  - Science mission to Itokawa
- SMART-1 launch in 2003 (1.2 kW)
  - Snecma SPT derived thruster
  - ESA tech demo mission to moon

**Future**
- Bepi-Colombo: ESA mission to Mercury
- Multiple Discovery/NF proposals likely to use electric propulsion (EP) for primary propulsion
Flexible Path for Human Exploration of Multiple Destinations

Review of U.S. Human Space Flight Plans Committee (Augustine Committee) defined "Flexible Path" as:

"Steadily advancing...human exploration of space beyond Earth orbit...successively distant or challenging destinations..."

Destination options include:

- Low Earth orbit (LEO) and the International Space Station (ISS)
- High Earth Orbit (HEO), Geosynchronous Orbit (GEO)
- Cislunar space (Lagrange/Libration points, e.g., L1, L2), lunar orbit, and the surface of the moon
- Near-Earth asteroids (NEAs), near-Earth objects (NEOs)
- The moons of Mars (Phobos, Deimos), Mars orbit, surface of Mars

Can multiple paths get us where we want to go?

Can the program keep its basic shape despite unforeseen events?

Can milestones stretch out without the program breaking?
Notional Incremental Expansion of Human Space Exploration Capabilities

- Lunar Surface Missions
- "Gaining the High Ground" Human Access to Cis-Lunar Space
- New LEO Missions
- GEO/HEO Missions
- Lunar Flyby & Orbit
- "Minimal" NEA Mission
- "Exploring Other Worlds" Access to Low-Gravity Bodies
- "Full Capability" NEA
- "Planetary Exploration" Access to Planetary Surfaces
- Mars

Key
- Candidate Destination

Increments in technology, systems, flight elements development and operational experience

Surface Capabilities Needed

Long Duration Habitation Needed

High Thrust in-Space Propulsion Needed

Advanced Propulsion Needed
SEP Stages with system power levels of 100-300 kW are achievable with near-term technology development.

New solar array technologies (e.g. FAST, Ultraflex, SLASR) could provide the power for a high-power SEP stage (with specific powers of 130-220 W/kg).

DARPA/Boeing FAST array modularity could enable scaling from basic 15-kW modules to > 100 kW systems.

50 kW Hall Thrusters have been demonstrated in the lab (at NASA GRC) that could be clustered together for high-power SEP stages.

“Immortal” Hall Thrusters can now be made that will eliminate wall erosion, the principal life time limiter of past Hall Thruster designs [Mikellides et al., Paper AIAA 2010-6942]
The “Electric Path”
An Architecture for Human Exploration of the Inner Solar System

**Electric Path** human missions to asteroids in the 2020s can be realized with the demonstrated capabilities of high-power Hall thruster technology.

- Uses Solar Electric Propulsion (SEP) boost stages to pre-position caches of supplies and cryogenic chemical propulsion boost stages for human transport.
- Flexible-path architecture that scales from lunar flybys to asteroid missions to Moon and Mars surface
- Requires only EELV class launch vehicles
- Missions to 6 large asteroids (> 200 m) are available in 2020s
- Uses 200 kW SEP system with Hall thrusters and chemical boost stages
  - High-thrust (10 N) & high specific impulse (2000-3000 s) of a 200 kW Hall thruster system optimum for these missions

Example: 1-year SEP Mission to 2008 EV5 (Type-C, 450 m) in 2024
Staging Prior to Earth Departure

• A SEP Boost (SB) stage is used to spiral the uninhabited Deep Space Vehicle (DSV) to a High Earth Orbit (HEO)
• The crew uses an Orion-like Crew Module (CM) and a Chemical Boost (CB) stage to rendezvous in HEO
• A second CB stage is used with the inhabited DSV to escape

Which HEO?

• A C3 of -1 km²/s² (29 d period), is assumed in the paper but orbits with a C3 from -2 to -0.5 km²/s² would also work
• Lunar Gravity Assists (LGAs) are used to move perigee above the Van Allen belts and to rotate the HEO’s line of nodes and change its inclination as needed prior to crew launch
• A LGA is then used to lower the perigee to 200 km before crew arrival for efficient Earth escape.
<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Assumed Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habitation Module (HM)</td>
<td>Module providing life support and accommodations for 4 astronauts</td>
<td>22,000 kg</td>
</tr>
<tr>
<td>Chemical Boost Stage (CB)</td>
<td>Cryogenic fuel booster with active cooling to prevent propellant boil off (20% inert mass for stage)</td>
<td>22,000 kg (wet)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4,400 kg (dry)</td>
</tr>
<tr>
<td>Crew Module (CM)</td>
<td>Orion-like crew capsule for trip from ISS to DSV and for Earth re-entry</td>
<td>9,000 kg</td>
</tr>
<tr>
<td>SEP Boost Stage (SB)</td>
<td>Stage with 250 kW solar arrays, electric propulsion system, and Xenon tanks (20 kg/kW inert mass for stage)</td>
<td>22,000 kg (wet)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5,000 kg (dry)</td>
</tr>
<tr>
<td>Fuel Module (FM)</td>
<td>Module for additional Xenon Fuel needed by Phobos mission (14% inert mass)</td>
<td>22,000 kg (wet)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3,000 kg (dry)</td>
</tr>
<tr>
<td>Provisions</td>
<td>Consumables and supplies to support a crew of 4 for one year (5.5 kg/person/day)</td>
<td>8,000 kg</td>
</tr>
</tbody>
</table>

Components sized to 22 ton capability of Delta IV Heavy to ISS
Architecture 1: Pre-Placed CB Stages

- SEP Boost (SB) stages are used to stage the DSV in HEO prior to Earth departure
- SB stages are used to pre-position Chemical Boost (CB) stages for use by the crewed DSV
- When crew is on the DSV, all maneuvers are done with the CB stages and the SB stage is only used for uninhabited elements
- This architecture allows the CB stages to be sized just to push the DSV mass for a maneuver and the SB stages are used to push the propellant needed for future maneuvers
Architecture 2: Piloted SEP

- Like Arch. 1, SB stages are used to stage the DSV in HEO prior to Earth departure
- The only CB stage is used for the Earth Departure Maneuver (EDM)
- SB stages are used to push the DSV with crew on board
- If there is enough power for the SB stages, this architecture offers significant performance benefits over Arch. 1
- Arch. 1 can be used as a technology fallback if it turns out it is more difficult than expected to develop a SB stage at the desired power level
NEO (2008 EV5) Trajectories

Pre-Placed CB Trajectory

2008 EV5 Departure: 27-DEC-2024
2008 EV5 Arrival: 23-NOV-2024

35-day Stay

Chem. Maneuvers
1. EDM: 974 m/s
2. AOI: 930 m/s
3. ERM: 850 m/s

Return: 25-JUN-2025
Launch: 25-JUN-2024

Piloted SEP Trajectory

2008 EV5 Departure: 23-DEC-2024
2008 EV5 Arrival: 23-NOV-2024

30-day Stay

Chem. Maneuvers
1. EDM: 1046 m/s

250 kW SEP Stage; 2000 sec. Isp

SEP Thrusting

Return: 25-JUN-2025
Launch: 25-JUN-2024
Phobos Trajectories

Pre-Placed CB Trajectory

Launch: 24-DEC-2030
Return: 2-SEP-2033

Chem. Maneuvers
1. EDM: 527 m/s
2. MOI: 1930 m/s
3. POI: 1088 m/s
4. ERM: 1887 m/s

Mars/Phobos Departure: 27-JAN-2033
Mars/Phobos Arrival: 2-OCT-2031

Piloted SEP Trajectory

Launch: 7-DEC-2030
Phobos Departure: 28-AUG-2032
Phobos Arrival: 1-MAY-2032

Chem. Maneuvers
1. EDM: 281 m/s

Return: 28-OCT-2033
Mars Departure: 6-DEC-2032
Mars Arrival: 22-JAN-2033

Phobos Departure: 28-AUG-2032
Phobos Arrival: 1-MAY-2032

2 x 250 kW SEP Stage; 2000 sec. Isp
### Injected Mass to Low Earth Orbit (IMLEO)

<table>
<thead>
<tr>
<th></th>
<th>IMLEO [tons]</th>
<th>No. of 22 t Launches</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEO All Chem</td>
<td>244.6</td>
<td>12</td>
</tr>
<tr>
<td>NEO: Pre-Placed CB</td>
<td>137.9</td>
<td>7</td>
</tr>
<tr>
<td>NEO: Piloted SEP</td>
<td>93.3</td>
<td>5</td>
</tr>
<tr>
<td>Phobos All Chem</td>
<td>722.0</td>
<td>33</td>
</tr>
<tr>
<td>Phobos: Pre-Placed CB</td>
<td>259.3</td>
<td>12</td>
</tr>
<tr>
<td>Phobos: Piloted SEP</td>
<td>167.6</td>
<td>8</td>
</tr>
<tr>
<td>NEO to Phobos Delta: Pre-Placed CB</td>
<td>232.9</td>
<td>11</td>
</tr>
<tr>
<td>NEO to Phobos Delta: Piloted SEP</td>
<td>134.0</td>
<td>7</td>
</tr>
<tr>
<td><strong>NEO+Phobos Total: All Chem</strong></td>
<td><strong>966.6</strong></td>
<td><strong>44</strong></td>
</tr>
<tr>
<td><strong>NEO+Phobos Total: Pre-Placed CB</strong></td>
<td><strong>370.8</strong></td>
<td><strong>17</strong></td>
</tr>
<tr>
<td><strong>NEO+Phobos Total: Piloted SEP</strong></td>
<td><strong>227.3</strong></td>
<td><strong>11</strong></td>
</tr>
</tbody>
</table>
Conclusions

- One-year Human NEO missions are possible with SEP stages at 140-250 kW power levels.
- Three-year Human Phobos missions are possible with SEP stages at 500 kW power levels.
- To do a NEO and Phobos mission, the Piloted SEP architecture requires ¼ of the IMLEO and number of launches of an all chemical approach.
- High-power SEP modules at powers of 150-250 kW are achievable in the near term and have a clear potential to reduce the cost, complexity, and risk of human deep space missions to asteroids and to Mars.
HIGH-POWER HALL THRUSTERS
**High-Power Hall Thruster Technology Readiness**

Hall thruster technology has a demonstrated 1000X range of power from 100 W to 100 kW.

<table>
<thead>
<tr>
<th>Range</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 5 kW (TRL 8-9)</td>
<td>Hall thrusters are routinely used on commercial GEO communications satellites for orbit raising and stationkeeping. Over 130 SPT-100 Hall thrusters are on-orbit, including several satellites built by Space Systems Loral. Aerojet BPT-4000 on DOD AEHF s/c launched Aug 14, 2010.</td>
</tr>
<tr>
<td>5 – 50 kW (TRL 4)</td>
<td>Thrusters in this range have achieved 3N thrust, &gt;70% efficiency, and specific impulses of 1000-5000 s. NASA lab thrusters tested from 2000-2005. - NASA-457M operated to 100 kW. - NASA-400M operated to 5000 s. - Engineering model 457M fabricated. AFRL has developed 20 kW technology to TRL 4. Could be leveraged for near-term flight demos.</td>
</tr>
<tr>
<td>50 – 200 kW (TRL 3)</td>
<td>Concentric channel thrusters identified by NASA as one path to very large thrusters. Sub-scale models have been tested at U of Michigan. Designs for a 150 kW thrusters were developed under ESR&amp;T in 2005 before program was ended. A 600 kW system was awarded to Aerojet in 2005 under ESR&amp;T based on the 150 kW thruster.</td>
</tr>
<tr>
<td>200 – 1,000 kW (TRL 2)</td>
<td>Clustering of 200 kW thrusters is a credible path to reaching &gt;1 MW. Clustering has been demonstrated at power &lt;10 kW. Largest single thruster size that could be practically tested and built for flight is unknown due to limited research performed to date.</td>
</tr>
</tbody>
</table>
Hall thruster technology is very scalable in power and specific impulse

• Power scaling
  - Assuming we desire clusters to consist of no more than four thrusters ...
    • Annular Hall thrusters can be fabricated up to ~100 kW per thruster, allowing for 0.4 MW clusters
    • Nested Hall thrusters can be fabricated up to ~250 kW per thruster, allowing for 1 MW clusters
  - Hall thruster systems spanning 0.1-1.0 MW can meet ESMD mission requirements in the near- to mid-term while the MW-class thruster and power technologies are brought to flight readiness (20+ years)

• Specific impulse scaling
  - 2000 s Isp xenon Hall thrusters are flight qualified (TRL 9)
  - 3000 s Isp xenon Hall thrusters under development (TRL 4)
    • Can be flight qualified in three years
  - High-Isp Hall thrusters can be realized in the mid-term through propellant changes
    • 5000 s Krypton Hall thrusters (TRL 3) have been demonstrated at high-power
    • 5000-8000 s Magnesium Hall thrusters (TRL 2) could form the basis of an ISRU architecture for NEO and Mars exploration
Lifetime

- Hall thruster lifetime is primarily limited by erosion of the discharge chamber walls due to impact of high-energy ions.
- Other failure modes, such as cathode erosion, anode deposition, magnet shorting, etc. have not been observed to be significant life-limiting factors in American Hall thrusters.
  - Cathode erosion and magnet shorting have been observed in Russian (SPT-100) and French (PPS-1350) Hall thruster life tests.
- Channel erosion tends to be localized to a region near the exit plane, on the order of 1 cm in length. In this region, the ions have sufficient energy to sputter erode the walls.
- Upstream of the erosion zone, redeposition of sputtered wall material can occur. The rate of redeposition, like the rate of erosion, decreases with time as the walls recess causing the angle of the ions with respect to wall to become increasingly shallow, which reduces the erosion and redeposition rates.
Soft vs. Hard Failures

- Hall thruster life is primarily limited by erosion of the discharge chamber walls due to high-energy ion sputtering that eventually exposes the magnetic circuit.
- Hall thrusters continue operating long after the magnetic circuit is first exposed [1-3], often without significant performance changes, and for this reason this moment in time is sometimes called a “soft failure.”
- Whether or not a spacecraft can tolerate deposition from the metallic sputter products of the now exposed magnetic circuit is mission dependent.
- Given a sufficiently long enough time the gradual erosion of the magnetic circuit would presumably lead first to performance degradation and eventually to difficulties starting and maintaining the plasma discharge. However, to our knowledge this hard failure point has never been documented in a long duration life test, but is known to be at least several thousand hours of additional operation [1,2].

Immortal Hall Thrusters
A Major Breakthrough in EP Technology

- Qualification life testing showed that the BPT-4000 exhibits the unique behavior that it erodes to a steady-state geometry and then essentially stops eroding.
- This behavior represents one of the most significant technological breakthroughs ever in electric propulsion history.
- Through physics-based modeling, JPL has identified the mechanism responsible, which we call Magnetic Shielding, and developed the design tools to apply this technology in future thrusters.
- Hall thrusters with magnetic shielding technology are essentially immortal and will lead to radically expanded mission capabilities.

Insulator ring erosion by high-energy ion impact is the primary life limiting mechanism in Hall thrusters. Recent advances may eliminate this erosion mode completely.

JPL physics-based model explains how “Magnetic Shielding” works:
Erosion stopped when the channel eroded to a local shape of the magnetic field that had the “right” curvature and field strength.

Erosion Rate in the BPT-4000 Observed to Effectively Stop

<table>
<thead>
<tr>
<th>Location along channel erosion zone</th>
<th>BOL Geometry</th>
<th>Steady-state Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream</td>
<td>2.2x</td>
<td>77x</td>
</tr>
<tr>
<td>Middle</td>
<td>47x</td>
<td></td>
</tr>
<tr>
<td>Downstream</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Nested Hall Thrusters
A credible path to MW-class propulsion systems

CURRENT STATE OF THE ART (SOA) IN ELECTRIC PROPULSION (EP) SYSTEMS.
- Power < 10 kW
  - NSTAR 2.3kW ion thruster (TRL 9)
  - BPT-4000 4.5kW Hall thruster (TRL 8)
  - NEXT 7kW ion thruster (TRL 5)
- Power > 10 kW
  - AFRL HPPS 20 kW Hall thruster (TRL 4)
  - NASA-400 series 50kW Hall thrusters (TRL 4)
  - NEXIS, HiPEP 20kW ion thrusters (TRL 4)

FIRST KEY INSIGHT.
- High-power (0.1-1.0 MW) and high-thrust (5-50 N) EP systems are currently within reach of Hall thruster technology.

SECOND KEY INSIGHT.
- As Hall thruster power levels are scaled higher, key design philosophies emerge that enable the Hall thruster alpha (kg/kW) and footprint area to decrease with power.
  - Hall thruster propulsion technology is not only limited to low power missions.

MAIN ACHIEVEMENT:
By expanding on the successful flight history of Hall thruster and implementing the concentrically Nested Hall Thruster (NHT) design philosophy new low alpha and footprint high power propulsion option is possible.

ASSUMPTIONS AND LIMITATIONS:
- Maximum power that can practically be processed by an NHT likely limited by manufacturing and thermal constraints.

QUANTITATIVE IMPACT END-OF-TASK OBJECTIVES

- Achieve a 250 kW thruster
- Demonstrate a 1 MW cluster

END-OF-TASK OBJECTIVES
Partners: U of Michigan, EDA, JPL, GRC, AFRL

Scaling analysis provided by Electrodynamics Applications, Ann Arbor, MI
Magnetoplasmadynamic Thrusters (MPDTs) or Lorentz Force Accelerators (LFAs)
Overview of Accelerator Geometries

- All geometries rely on high currents to ionize propellant and a combination of JxB and gasdynamic forces to accelerate plasma.
- Crossed Field Accelerator employs externally applied magnetic field.
- Coaxial thrusters use self-field generated by discharge current.
Operating Characteristics of Self-field Thrusters
Operating Characteristics of Self-field Thrusters
- Two force components:
  - \( j_r B_\theta \) blowing forces
  - \( j_z B_\theta \) pumping forces (radial pressure gradients)
- Calculation of blowing force component:
  - \( B_\theta(r, z) = \frac{\mu J}{2\pi r} \left( 1 - \frac{z}{z_0} \right) \)
  - \( f_z(r, z) = j_r B_\theta = \frac{\mu J^2}{4\pi^2 r^2 z_0^2} (z_0 - z) \)
  - \( F_z = \frac{\mu J^2}{4\pi^2 z_0^2} \int_0^{z_0} \int_0^{2\pi} \int_{r_c}^{r_a} \frac{z_0 - z}{r^2} r dr d\theta dz = \frac{\mu J^2}{4\pi} \ln \frac{r_a}{r_c} \)
  - Including current into face of cathode (uniform \( j_r \))
    - \( F_z = \frac{\mu J^2}{4\pi} \left( \ln \frac{r_a}{r_c} + \frac{1}{2} \right) \)
  - Including \( F_c = 2\pi \int_0^{r_c} (p - p_0) r dr = \frac{\mu J^2}{8\pi} \) of cathode \( (j_r \sim 1/r) \):
    - \( F_z = \frac{\mu J^2}{4\pi} \left( \ln \frac{r_a}{r_c} + \frac{3}{4} \right) \)
- Estimate of pumping force on cathode
"Onset" Phenomenon Limits MPDT Performance

- High magnetic Reynolds number leads to convection of magnetic field downstream
- As current pattern gets blown downstream, \( j_z B_\theta \) forces pinch plasma toward centerline
- Depletion of plasma in anode region increases Hall parameter, resulting in higher \( j_z \) component
- Lack of charge carriers in anode region causes onset phenomenon
  - Higher anode fall voltage required to conduct electron current
  - Anode spots form to supply additional plasma

Enclosed current contours for a quasi-steady thruster operating at 15.3 kA and 6 g/s of argon

Anode damage at the onset current limits the achievable thrust, Isp, and efficiency in MPD thrusters
Lorentz Force Accelerators are Ideal for Very High Power Applications

Lorentz Force Accelerators are under investigation because:

- Physics of operation yield high power processing capability
- Lithium propellant has potential for very high efficiency—low first ionization potential, high second ionization potential, and high first excited state of the ion yield low frozen flow losses

Very high power propulsion systems may enable many far-term missions:

- Orbit-raising heavy payloads in Earth orbit
- Fast robotic outer planet missions
- Lunar and Mars cargo missions
- Piloted Mars missions
- Piloted outer planet missions

Electromagnetic acceleration allows >80 times the power of the NSTAR ion engine to be processed in the same volume.
Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path

- 250-500 kWe lithium-fed thrusters give large mass savings for cargo missions
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Lunar and Mars cargo applications
- 1--5 MWe lithium thrusters fulfill mid-term propulsion requirements
  - Second generation power systems at 5 MWe
  - Specific impulse of 4000-6000 s
  - Initial piloted Mars missions
- 5--10 MWe hydrogen or deuterium-fed thrusters open up the solar system
  - Third generation (very low alpha) power systems at 100’s of MWe’s
  - Terminal voltage with lithium is too low to process very high power levels; hydrogen appears to provide required efficiency at Isp’s of 10000-15000 s
  - Piloted missions to Mars and the outer planets
Second Generation Propulsion and Power Systems Can Enable Fast Piloted Mars Missions

- 1 year round trip time possible with 20-30 MWe system
- All NEP missions consistently show the lowest IMLEO of all options
## Large Experience Base For Very High Power Self-Field MPD Thrusters

<table>
<thead>
<tr>
<th>Organization</th>
<th>Power (kWe)</th>
<th>Current (kA)</th>
<th>Specific Impulse (s)</th>
<th>Efficiency</th>
<th>Typical Operating Period</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIITP</td>
<td>300-1000</td>
<td>6-15</td>
<td>3500-5000</td>
<td>40-60</td>
<td>5 min</td>
<td>NIITP design</td>
</tr>
<tr>
<td>Fakel</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>500</td>
<td>9</td>
<td>4500</td>
<td>55</td>
<td>500 hours</td>
<td>Endurance test of Energiya design</td>
</tr>
<tr>
<td>Energiya</td>
<td>250-500</td>
<td>5-8</td>
<td>3000-4500</td>
<td>35-55</td>
<td>30-60 min</td>
<td>Coaxial thruster with long cathode. Stopped because of cathode failure</td>
</tr>
<tr>
<td>MAI</td>
<td>300-500</td>
<td>6-9</td>
<td>3500-4500</td>
<td>40-60</td>
<td>30 min</td>
<td>Energiya design</td>
</tr>
</tbody>
</table>

- Development of high power Li-fed thrusters also occurred in Russia.
- Capabilities required for human exploration missions largely attained.
  - High performance verified at 3 different institutions.
  - 500 hour lifetest at 500 kWe successfully completed.
  - Several thousand hour life projected.
Conclusions

- Electric propulsion is an enabling technology for demanding deep space missions
- We are in the transition from an era of technology development to one of flight applications
- There are still a number of interesting research problems that require a multi-disciplinary approach
  - Advanced materials
  - Plasma physics
  - Plasma-surface interactions
  - Plasma chemistry