Candidate Thruster Technologies for NEP

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Near- to Mid-Term

- Thruster Input Power: 20 to 50 kW
- Specific Impulse: 6000 to 9000 s
- Propellant Throughput: 1000 to 2500 kg/thruster

Far-Term

- Thruster Input Power: 100 to 1000 kW
- Specific Impulse: 6000 to 15,000 s
- Propellant Throughput: 50 kg/kW per thruster
### Candidate Thruster Technologies

<table>
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<tr>
<th>Thrusters</th>
<th>Propellants</th>
<th>Specific Impulse Range (s)</th>
<th>Power Range (kW)</th>
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<td><strong>Electrothermal</strong></td>
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<tr>
<td>Resistojets</td>
<td>N2H4</td>
<td>300 to 400</td>
<td>&lt; 1</td>
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<tr>
<td>Arcjets</td>
<td>NH3, N2H4, H2</td>
<td>500 to 1200</td>
<td>&lt; 10</td>
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<td>Microwave Electrothermal Thruster (MET)</td>
<td>NH3, N2</td>
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<tr>
<td>Pulsed Electrothermal (PET)</td>
<td>H2O</td>
<td>&lt; 2000</td>
<td>&lt; 10</td>
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<tr>
<td><strong>Electrostatic</strong></td>
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<tr>
<td>Gridded Ion Thrusters</td>
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<tr>
<td>DC Ion Thrusters</td>
<td>Ar, Kr, Xe</td>
<td>2000 to 15,000</td>
<td>0.01 to 100's</td>
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<tr>
<td>RF/ECR Ion Thrusters</td>
<td>Ar, Kr, Xe</td>
<td>2000 to 15,000</td>
<td>0.1 to 100's</td>
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<tr>
<td>Hall Thrusters</td>
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<tr>
<td>SPT</td>
<td>Ar, Kr, Xe</td>
<td>1000 to 3000</td>
<td>0.05 to 100's</td>
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<tr>
<td>TAL</td>
<td>Ar, Bi, Kr, Xe</td>
<td>1000 to 8000</td>
<td>0.05 to 100's</td>
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<tr>
<td><strong>Electromagnetic</strong></td>
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<tr>
<td>Magnetoplasmadynamic (MPD)</td>
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<tr>
<td>Pulsed</td>
<td>H2</td>
<td>3000 to 10,000</td>
<td>0.1 to 5000</td>
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<tr>
<td>MPD-PET</td>
<td>LH2, LN2</td>
<td>4000</td>
<td>1000</td>
</tr>
<tr>
<td>Steady State</td>
<td>Li, H2</td>
<td>4000 to 8000</td>
<td>500 to 10,000</td>
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<tr>
<td>Pulsed Inductive Thruster (PIT)</td>
<td>Ar, NH3, N2H4, CO2</td>
<td>2000 to 8000</td>
<td>100 to 1000</td>
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<tr>
<td>Electron Cyclotron Resonance (ECR)</td>
<td>Ar, Kr, O2, Xe</td>
<td>TBD</td>
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<tr>
<td>Ion Cyclotron Resonance (ICR)</td>
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<td>Pulsed Plasmoid Thruster</td>
<td>N2, O2, CO2</td>
<td>5000 to 20,000</td>
<td>Not specified</td>
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<tr>
<td>Field Reversed Configuration (FRC) Thruster</td>
<td>N2, O2, CO2</td>
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<td>10 to 1000</td>
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<tr>
<td>Variable Specific Impulse Magnetoplasma Rocket</td>
<td>N2, O2, CO2</td>
<td>1000 to 30,000</td>
<td>1000 to 10,000</td>
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<td>Deflagration Gun</td>
<td>H2</td>
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<td>Rail Gun</td>
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<td>Mass Driver</td>
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<td>Dense Plasma Focus</td>
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High Power Ion Engines

- Ion thrusters scale well to high power at high Isp

- High Isp is readily achievable with gridded ion thrusters

- High efficiency comes naturally as the Isp is increased

- Key challenge is achieving the required thruster life
  - Grid and Cathode designs are the keys to long life
High-Power (Interstellar) Ion Propulsion System

- 30 kW High-Power (Interstellar) Ion Propulsion System (NEP)
- 10-30 kW Power range per engine
- High specific impulse, > 10,000 Sec
- Design and fabrication of large-area discharge chamber completed
- Discharge operation characterized on krypton and xenon propellants
- Performance characterized up to 4 kW input power

- Lessons learned from this engine being applied to current NEP NRA

Glenn Research Center at Lewis Field
NASA 50kW Hall Development

Expected performance
Isp = 2500 sec
Thrust = 2.5 N @ 500V & 100A
Eff = 63%

10x SOA

Developed new heat treat process
Developed magnetic field mapping
Developed 100A cathode

Performance Testing Started in March

Similar Activities at General Dynamics Under Contract to GRC

Glenn Research Center
at Lewis Field
Pulsed MPD Thrusters
HIGH POWER MPD THRUSTER
PROGRAM STATUS AND PLANS

• MPD Program Status:
  - Pulsed test facility operational
  - Baseline thruster tested to 2-MW
  - Minor facility bugs corrected

• FY02 Program Plans
  - 2nd/3rd Quarter:
    Baseline self-field & applied-field thruster tests
    Goal: 40% self-field, >50% applied-field
  - 3rd/4th Quarter:
    Nozzle-anode self-field thruster tests
    Goal: 50% self-field efficiency
Bismuth-fueled Anode Layer Thrusters are a Viable Alternative to Ion Engines for NEP Missions

Near-term NEP Performance Objectives Have Already Been Demonstrated With Bismuth-fed TAL's

Isp up to 8000 s, efficiency up to 70% and power per engine as high as 140 kWe

Average Ion velocity & Efficiency vs Accelerating Voltage

1. Exp. $\langle v_i \rangle \approx 2,7 \cdot 10^6 \sqrt{U_{ac}} \text{ cm/s}$
2. Theor. $\langle v_i \rangle = 3,05 \cdot 10^6 \sqrt{U_{ac}} \text{ cm/s}$
3. Efficiency

25 kWe, radiation-cooled Bi TAL
Steady-State MPD Thrusters

The Self-Field MPDT

- Lorentz force \((j \times B)\) acceleration
- High exhaust velocity, 5-50 km/s
- High thrust density, \(10^4 - 10^5\) N/m²
- Robust and simple design
- Solid cathode
- Gaseous propellant injected at backplate
- Current attachment along entire cathode
Recent Experimental and Theoretical Results Show Path to MWe Plasma Thrusters

**POWER**
- Anode Texturing
- Heat Pipes

**MULTIMEGAWATT TECHNOLOGY**
- Routine Access to the Solar System

**PERFORMANCE**
- η = 60%
- Isp = 8000 s
- Lithium Propellant
- Active Turbulence Suppression

**LIFETIME**
- 100's of Hrs
- At 3000 A
- Multi-Channel Hollow Cathodes
- Barium Addition

**STATE OF THE ART**
- 200 kWe Lithium-fed Thruster

**PLUME CONTAMINATION**
- 10^-8 g/cm^2s at 0.3 m
- Plume Shields
- Booms

**STATE OF THE ART**
- 10^-10 g/cm^2s at 30 m
Steady-State MPD Thrusters
Propulsion Niches for High Power Lorentz Force Accelerators Define Evolutionary Path

- 0.5 -- 1 MWe lithium-fed thrusters are ideal for near-term applications
  - First generation power sources with system power levels of 1-5 MWe
  - Specific impulse of 4000-6000 s
  - Orbit transfer and Mars cargo applications
- 1--5 MWe lithium thrusters fulfill mid-term propulsion requirements
  - Second generation power systems at 10--30 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
Pulsed Inductive Thruster

Operation:
The Pulsed Inductive Thruster (PIT) is characterized by μ-second, MW-power pulsed operation. Thrust is generated by the cross-product interaction of the azimuthal current in the plasma and the magnetic field in the coil generating a Lorentz force, which in turn accelerates the plasma axially away from the coil.

Benefit:
PIT provides high thrust efficiency over a wide range of specific impulse values.

Single Shot Performance:
- Specific Impulse: 2,000 - 8,000 s
- Efficiency: 20 - 50 %
- Discharge Voltage: 20 - 30 kV
- Propellant: Ar, NH₃, NH₄, CO₂

Technical Challenges:
- Switch Technology
  - High repetition rate and extreme long lifetime
  - High peak currents
  - High and rapid initial current rise
- High Power Capacitors
  - Extreme long lifetime
  - Requires space qualification under extreme operating conditions
- Pulse Driver Network and Architecture
  - Recovery of reflected energy
  - Pulse shape control for optimum pulse waveform

Current On-Going Effort:
- NASA MSFC Work:
  - Design and evaluation of innovative powertrain design reducing PIT circuit requirements.
  - Explore innovative switch and capacitor technology for short-pulse, high power applications.
  - Evaluation of Solid-State Switches for High Rep-Rate PIT Operation by TRW.
- MACH2 Modeling of the Pulsed Inductive Thruster by Dr. Pavlos Mikelides, Arizona State University, AZ.
- Development of 2-D nonlinear MHD code at NASA GRC.
Helicon wave thruster concepts

- Compact ion or plasma source
  - 1 cm radius to replace hollow cathode
  - Small radius -> high density
    - $10^{20} \text{ m}^{-3}$ achieved at 1 kG, kW of power in long tube, radius 1 cm
    - Short tube for thruster applications is a departure from long laboratory sources

- ECR thruster
  - Generate helicon wave in chamber
    - $T_{\perp} = T_{||} \sim 3 \text{ eV}$, high ionization
    - Isotropic $T_{\theta}$ reduces plasma losses due to Bohm diffusion ($D \sim T_{\perp}^{\frac{1}{2}} / B$)
  - Expand magnetic field outside of chamber to ECR region
    - Continued magnetic expansion past ECR region to accelerate exhaust
Objective: Investigate the use of a Field Reversed Configuration (FRC) for use as an in-space electric thruster. Thrust is produced by inductively accelerating a magnetized plasmoid.

Payoff: A high specific-impulse, high efficiency, inductive (electrode-less) electric thruster

Potential Performance:
- \( P_{\text{Jet}} = 10 \text{ KW - 1 MW} \)
- \( I_{\text{sp}} = 5,000 - 15,000 \text{ s} \)
- \( \eta = 60 - 80\% \)

Milestones:
- FRC formation experiments FY02
- Translation experiments FY03
- Design/Construction of acceleration stage FY03

Status:
- Facilities in PRC Lab C (Bldg. 4655) complete
- Major components have been bought
- Vacuum system under construction
- Final design of coils / bus-plates / mechanical structure
- Final design of capacitor banks and triggering circuits
- Procurement of Control / DAQ system

Collaborations:
- University of Washington

Points of Contact:
- Adam Martin, MSFC TD40 256-544-5296
- Richard Eskridge, MSFC TD40 256-544-7119
Quick Review of VASIMR System

Variable Specific Impulse Magnetoplasma Rocket Concept

NASA Johnson Space Center, Advanced Space Propulsion Laboratory
There are lots of candidate thruster types
- Many are called, but only a few will be chosen

For thruster power levels of 20 to 50 kW Ion and 2-Stage Hall Thrusters will be hard to beat

The field is wide open for thrusters in the 100’s to 1000’s of kW input power range