Planned & Future Missions

Human Exploration of the Solar System by 2100

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“Pathways Beyond Low Earth Orbit”
In-Space Chemical Propulsion TIM
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• **Human Exploration of the Solar System by 2100 as a Strategic National Goal**
  – Vision to Revitalize HSF in Service to Security, Economic, & Scientific Interests of Nation
  – Requires Multi-Decade Commitment Employing Radically Advanced Technologies
  – Enormous Costs will Demand Public, Private, & International Collaboration

• **HSF Timeline & Mission Drivers**
  – **Inner Solar System (through 2050)** – Near-Earth, Cis-Lunar & Mars
    – Achievable via Chemical Propulsion, Split–Chemical/SEP, Hybrid-Chemical/SEP or NTP/NEP
    – Facilitate Econo-Space Development & Commercial Opportunities
    – Establish Outposts, Permanent Bases & Colonies
  – **Outer Solar System (2050 to 2100)** – Beyond Mars
    – Requires Highly Energetic Processes/Concepts beyond NTP
    – Harsh Space Radiation Environment & Sustained Zero Gravity Impose Strict Biological Constraints
    – Enable In situ Human Exploration

• **HSF Mission Case Studies**
  – Examine Mission Scenarios to Define Quantifiable Propulsion Capability Needs
    – Duration constrained roundtrip missions
  – Evaluate Advanced Propulsion Technology Landscape
    – Identify advanced propulsion architectures capable of fulfilling mission need

• **Diversified Capability Development Strategy**
  – 2030-2050 Inner Solar System Missions
  – 2050-2100 Outer Solar System Missions
**Destination Types**
- Primitive Bodies
  - Asteroids & Comets
  - Dwarf Planets & Centaurs
  - Trans-Neptunian Objects
  - Plutinos & KBOs
- Inner Planetary Systems
  - Mercury to Mars
  - Moons
- Outer Giants & Icy Planets
  - Jupiter to Neptune
- Moons of Giants & Icy Planets
  - Large Satellites

**Exploration Sequence Modes**
- Flyby Reconnaissance
  - Free Trajectory S/C
- Rendezvous Encounters
  - Orbiters, Probes, Landers
- Robotic In Situ Exploration
  - Roving Labs & SR
- Human In Situ Exploration
  - Habitats & Mobility
KEY DEEP SPACE MISSION MILESTONES
Notable Robotic & Human Spacecraft Heritage

NEW HORIZONS MISSION

Voyager 1 @ 134 au
V-2 @ 111 au
38+ years flight time

New Horizons

Voyager 2
Cassini
Galileo
Pioneer 10
Pioneer 11
Nimbus III
Ulysses
Mars 2020
Viking 1
Viking 2
Apollo Lander Surface Experiments
Curiosity

Orbit
Flyby
Rove
Land
### Space Radiation Sources

- **Solar Energetic Particles (SEP)**
  - Intermittent proton showers from Solar Flares/CMEs
  - Potentially lethal but limited peak energy permits effective shielding solutions – **PRACTICAL**
- **Galactic Cosmic Radiation (GCR)**
  - Near continuous flux of high-energy heavy ions
  - Protective shielding requires an effective depth equivalent to Earth’s atmosphere – **IMPRACTICAL**

### Mission Driving Biological Effects (1 Sievert = 100 REM)

- Annual Allowable Dose for Middle Age Astronaut = **0.4 Sv**
- Lifetime Limit Depends on Astronaut Gender & Age = **1.5 – 3.0 Sv**
5-yr Roundtrip Mission to Callisto*

*NASA-TP-2003-212691
HSF MISSION CASE STUDIES
Assumptions & Analysis Approach

• **Inner Solar System – Mars**
  – NASA Design Reference Architecture 5.0

• **Outer Solar System – Jupiter/Saturn/Uranus/Neptune Systems**
  – 4-yr Roundtrip Flight Time
  – 2-yr Flyout Time
  – Thrust-to-Coast Ratio = 1.0 to 1.3
  – $C_3 = 0$ (km$^2$/s$^2$) at Mission Departure
  – 20% Flyout Payload Mass Fraction
    ➢ Includes habitat, structures, propulsion system, & flyback propellant
    ➢ Baseline analysis assumes no pre-deployments
  – Propulsion System Treated Parametrically
    ➢ Jupiter/Saturn: $P = 100$ MW & $\eta_t = 80\%$
    ➢ Uranus/Neptune: $P = 200$ MW & $\eta_t = 80\%$

Humans to Mars Transportation Architectures
- Split SEP|Chemical
- Split Chemical | Chemical
- Hybrid SEP-Chemical
- NTP
- NEP (Under consideration)
NOTE: DRA-5 Assumes Near-Term NEP Propulsion System Specific Mass ≈ 25 kg/kW
OUTER PLANET MISSION CASE STUDIES
Flyout Trajectories & Velocity Profiles

Jupiter Flyout Trajectory

Saturn Flyout Trajectory

Jupiter Round Trip Velocity Profile

Saturn Round Trip Velocity Profile
## OUTER PLANET MISSION CASE STUDIES

### Analysis Summary

<table>
<thead>
<tr>
<th>Mission Data</th>
<th>Jupiter</th>
<th>Saturn</th>
<th>Uranus</th>
<th>Neptune</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heliocentric Distance (AU)</td>
<td>5.20</td>
<td>9.50</td>
<td>19.2</td>
<td>30.1</td>
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<tr>
<td>Round Trip Flight Duration (yrs)</td>
<td>4.0</td>
<td>4.0</td>
<td>4.0</td>
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<tr>
<td>Flyout Time (yrs)</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
<td>2.0</td>
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<tr>
<td>Flyout Thrust Time (yrs)</td>
<td>1.0</td>
<td>1.2</td>
<td>1.1</td>
<td>1.3</td>
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<tr>
<td>Flyout Payload MF* (%)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Propulsion System Power (MW)</td>
<td>100</td>
<td>100</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Thrust Efficiency (%)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>C₃ (km²/s²)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mission ΔV (km/s)</td>
<td>27.9</td>
<td>59.2</td>
<td>122.1</td>
<td>205.1</td>
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<tr>
<td>Mission Specific Energy (GJ/kg)</td>
<td>0.365</td>
<td>1.45</td>
<td>8.54</td>
<td>18.3</td>
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<tr>
<td>Thrust (N)</td>
<td>8734</td>
<td>4382</td>
<td>3619</td>
<td>2468</td>
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<tr>
<td>Isp (ksec)</td>
<td>1.87</td>
<td>3.72</td>
<td>9.02</td>
<td>13.22</td>
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<tr>
<td>Launch Mass (Mkg)</td>
<td>19.3</td>
<td>5.9</td>
<td>1.9</td>
<td>1.0</td>
</tr>
<tr>
<td>Launch Propellant MF (%)</td>
<td>93</td>
<td>93</td>
<td>93</td>
<td>93</td>
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<td>Earth Return Payload MF (%)</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>(\alpha_{\text{propulsion}}) (kg/kW)</td>
<td>3.47</td>
<td>1.05</td>
<td>0.163</td>
<td>0.090</td>
</tr>
<tr>
<td>(\phi_{\text{propulsion}}) (kW/kg)</td>
<td>0.288</td>
<td>0.952</td>
<td>6.13</td>
<td>11.1</td>
</tr>
</tbody>
</table>

* Includes habitat, structures, propulsion system, and flyback propellant
HSF TRANSPORTATION CAPABILITY NEED
Propulsion System Specific Mass

Inner Solar System ↔ Outer Solar System ↔ Interstellar

now - 2050
2050 – 2100
> 2100

10^{-1} M_0 V M Astroid Belt S U Z
10^0
10^1
10^2
10^3
R (AU)

2017 NASA Authorization Act
1 (d) SENSE OF CONGRESS ON PROPULSION TECH-
2 NOLOGY.—It is the sense of Congress that advancing prop-
3ulsion technology would improve the efficiency of trips
4 to Mars and could shorten travel time to Mars, reduce
5 astronaut health risks, and reduce radiation exposure,
6 consumables, and mass of materials required for the jour-
7 ney.

17 (d) PROPULSION TECHNOLOGIES.—A goal of propu-
18 lation technologies developed under subsection (c) shall be
19 to significantly reduce human travel time to Mars.
ADVANCED PROPULSION LANDSCAPE
Technology Capability Regimes

- Speculative Energy & Motive Physics
- High-Power NEP & Directed Energy EP
- Pulsed Fusion
- Antimatter
- Continuous Fusion
- Electrostatic
- Electromagnetic
- Electrothermal
- Laser/Solar Thermal
- Pulsed Fission
- Thermal Fission (Chemical RBCC)
- Chemical Rockets

Vehicle Acceleration or T/W Ratio (g’s)

Specific Impulse (seconds)

10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^2
10^3
10^4
10^5
10^6
10^7

Unproven Technology (TRL 1-3)
Demonstrated Technology (TRL 4-6)
Operational Systems (TRL 7-9)
Candidate Advanced Propulsion Technology Solutions

- **Multi-MW-Class NEP**
  - NTP Derived LEU/CERMET Reactor – De-rate Temperature to 1850 K with High Burn-Up Fuel Design
  - He-Xe MHD Brayton Cycle for High-Temperature Heat Rejection & Minimized Radiator Mass
  - High-Power EP

- **Multi-MW-Class Directed Energy EP**
  - 100-200 MW Off-Board Laser Array Beaming to 70% Efficient Tuned S/C Photovoltaic Array
  - Direct Drive of On-Board High-Thrust, High-Specific-Impulse, Lithium-Fueled Electric Thruster

- **GW-Class Pulsed Fusion**
  - DT-Driven-DD Pulsed Micro-Fusion in Magnetic Nozzle
  - 2-GW Average Jet Power @ 70,000-sec Isp
STMD STRATEGIC FRAMEWORK

Implementation Waterfall

- **STMD Transformative Themes**
  - Expand Utilization of Near-Earth Space
  - Develop Efficient & Safe Transportation Through Space
  - Increase Access to Planetary Surfaces
  - Enable Humans to Live & Explore on Planetary Surfaces
  - Enable Next Generation of Science Beyond Decadal
  - Grow & Utilize the U.S. Industrial and Academic Base

- STMD Strategic Alignment Framework
  - Core Values
  - Guiding Principles
  - Implementation Goals Flowdown

- STMD Strategic Themes
  - Get There
  - Land There
  - Live There
  - Observe There
  - Invest There

- STMD Transformative Themes (6)

- STMD Thrust Areas

- STMD Quantifiable Capabilities (37)

- Technology Portfolio Integration
  - Crosscutting Strategy
  - Content Prioritization

- STMD Programs
  - Implementation
STMD TRANSFORMATIVE THEMES
Expand Utilization of Near-Earth Space

THEME-1: EXPAND UTILIZATION OF NEAR-EARTH SPACE
• Provide Safe & Affordable Routine Access to Space
• Enable Extension, Reuse, and Repair of Near-Earth Assets
• Expand Near-Earth Infrastructure & Services to Support HSF

THRUSTS

A Satellite Propellant Transfer
B Advanced Robotics & Inspection Systems
C Advanced Launch Vehicle Systems
D Advanced Structures & Materials
E Enhanced Ground Processing & Operations
F Assembly & Aggregation
G Advanced System Development & Testing
H Long-term Propellant Storage & Transfer
THEME-2: DEVELOP EFFICIENT & SAFE TRANSPORTATION THROUGH SPACE

- Provide Cost-Efficient, Reliable Propulsion for Long Duration Missions
- Increase Effectiveness & Applicability of Current Propulsion Options
- Enable Faster, More Efficient Deep Space Missions
- Provide Efficient & Safe In-Space Habitation
### Recommended Technology Prioritization

<table>
<thead>
<tr>
<th>Recommended Technology Prioritization</th>
<th>Mission Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Develop and flight demonstrate <strong>SEP</strong> (12.5 kW HET Quad-Cluster) and establish EMC relevant power extensibility $\geq 150$ kW</td>
<td>Science/Commercial &amp; EMC Hybrid/Split</td>
</tr>
<tr>
<td>2) Develop foundational technology for affordable <strong>Nuclear Thermal Propulsion</strong> and establish viability &amp; feasibility, with good cost &amp; schedule confidence, prior a decision to proceed with full-scale engine system development</td>
<td>EMC NTP &amp; Large Robotics</td>
</tr>
<tr>
<td>3) Mature <strong>in-space cryogenic liquid engine technologies</strong> for the development of integrated MPS/RCS and descent/ascent engines applicable to EMC architecture</td>
<td>EMC Split</td>
</tr>
<tr>
<td>4) Develop and demonstrate <strong>high thrust, low-freezing-point in-space storable propulsion</strong> that reduces spacecraft power burdens and provides for long-duration operation in extreme space environments</td>
<td>Robotic Science &amp; EMC Hybrid</td>
</tr>
<tr>
<td>5) Develop and demonstrate <strong>small-scale launch systems &amp; $\mu$-propulsion technologies</strong> that would enable affordable high-$\Delta V$ small spacecraft missions</td>
<td>Robotic Space &amp; Commercial</td>
</tr>
<tr>
<td>6) Develop and demonstrate <strong>green propellant in-space propulsion</strong> that simplifies ground launch ops, increases performance, reduces spacecraft burdens, and extends extreme environments operability – facilitate green propellant commercialization &amp; infusion</td>
<td>Robotic Science &amp; Commercial</td>
</tr>
<tr>
<td>7) Identify, mature, and execute proof-of-principle demonstrations of <strong>breakthrough propulsion technologies</strong> that could enable more ambitious missions to Mars &amp; beyond</td>
<td>Large Robotics &amp; Crewed Deep Space</td>
</tr>
</tbody>
</table>
## PROPULSION CAPABILITY OBJECTIVES

### Quantifiable Capabilities

<table>
<thead>
<tr>
<th>Capability Objective</th>
<th>Quantifiable Metrics</th>
</tr>
</thead>
</table>
| **High-Power SEP with EMC Extensibility** | • In-Space Demonstration of 12.5-kW Hall Effect Thruster  
• Long Life Thruster enabling Mission Utilization > 1  
• Power Extensibility ≥150-kW EP |
| **EMC NTP Propulsion Architecture** | • Thrust ≥ 25lbf @ Thrust/Weight ≥ 4  
• High Temperature Fuel Element Temp ≥ 2850 K @ Isp ≥ 900 sec  
• ΔV ≥ 10 km/s – Enable Opposition & Conjunction EMC Mission Options  
• Fission Product Leakage << NERVA/ROVER Milestone  
• Run Duration ≥ 2 hrs @ rated temperature  
• Engine Restarts ≥ 10  
• Hydrogen CFM - Zero Boil Off & Liquefaction at Low Power (kW's @ 20k)  
• NTP Engine System Development LCC ≈ Comparable Scale LRE LCC ($1-2B) |
| **EMC LOX/Methane Propulsion Architecture** | • MPS Thrust ≥ 23 kN with 5:1 Throttling Capability  
• RCS Thrust ≥ 100 lbf with Integrated Feed Systems  
• Isp > 360 sec  
• Lifetime > 300 hours  
• LOX/Methane CFM - Zero Boil Off and Liquefaction at Low Power (100’s Watts @ 90K) |
| **Mission Enhancing In-Space Storable Propulsion** | • 100-lbf Class MON-25/MMH Bipropellant Engine (Flight Qualified within 2 years)  
• EMC Scale-Up: RCS Thrust = 100-1000 lbf | MPS Thrust = 25,000 lbf  
• Reduce Propellant Freezing Point < -40 °C  
• Reduce Propulsion System Mass ≥ 80%  
• Reduce Propulsion System Volume ≥ 50%  
• Reduce Propulsion System Cost ≥ 60% |
| **Enabling Small-Scale Launch & Small Spacecraft Missions** | • 5-180 kg payload delivery capacity to 350-700 km (CONUS & Sun Synchronous Ops)  
• Launch Costs < $60,000/kg; m₀ ≥ 50kg  
• Launch Costs < $3M/Launch; m₀ < 50kg  
• Small S/C Sub-KW EP: ΔV > 5km/s @ <1-kW with 7x Increase in Propellant Throughput |
| **Mission Enhancing In-Space Green Propulsion** | • Scale-Up: 22-N Green Monopropellant Thruster (Flight Qualified within 3-5 years)  
• Scale-Up: 110-N Thruster (5-7 years), 440-N Thruster (7-10 years)  
• Increase Density-Isp ≥ 25%  
• Reduce Propellant Freezing Point < -40 °C  
• Reduce Thruster Power Consumption ≥ 50%  
• Increase Propellant Throughput/Lifetime ≥ 125 kg  
• Reduce Ground Operation Costs ≥ 50% (Reduce or Eliminate SCAPE Suit Ops) |
| **Breakthrough In-Space Propulsion** | • Ultra Low Propulsion System Specific Mass: α ≤ 5kg/kW |
CAPABILITY DEVELOPMENT STRATEGY

Diversified Propulsion R&T Investments

### Inner Solar System
**now – 2050**

**IN-SPACE PROPULSION – Near Term Focus (3 ≤ TRL ≤ 6)**
Technology investments in key areas enable evolved capability and modest gains in capability – *PROGRESS IS PREDICTABLE*

- **Advanced Chemical Propulsion**
  - **Key Technologies:**
    - Advanced Propellants
    - Long-term CFM
    - ISRU (LOX/Methane)
  - **Key Challenges:**
    - Extreme Environments
    - Propellant Handling
    - Performance Plateau

- **Combined Chemical-Electric Propulsion**
  - **Key Technologies:**
    - Light Weight Deployable Arrays
    - Extreme Environment Arrays
    - High-Power/isp Thrusters

- **Solar Electric Propulsion**
  - **Key Technologies:**
    - Power Scalability Limit
    - Array Degradation
    - Efficiency/Specific Mass
  - **Key Challenges:**
    - Power Scalability Limit
    - Array Degradation
    - Efficiency/Specific Mass

- **Bimodal Nuclear Thermal-Electric Propulsion**
  - **Key Technologies:**
    - Robust High-Temperature Fuels
    - High Power Density LEU Reactor
    - Affordable Development & Testing
  - **Key Challenges:**
    - Affordability & Viability

### Outer Solar System
**2050 – 2100**

**ADV PROPULSION – Far Term Focus (TRL < 3)**
Sustained research investment enables possibility for new revolutionary technologies – *PROGRESS IS NOT PREDICTABLE*

- **Multi-MW NEP**
  - Fast Mars
  - Tech Push

- **Fission Gas Core or Enhanced Solid Core**

- **Photonic Laser Thruster**

- **Pulsed Fusion**

- **Antimatter**
  - Capability Goal:
    - \( \alpha < 5 \text{ kg/kW} \)

**Revolutionary Unproven Energetic Propulsion Concepts**
- High Power NEP, Advanced Fission, Fusion, etc

**Sustained Low-Level Research Investment**
Research on Advanced Energetic Processes & Concepts
- Tangible Action to Remove “Barriers to Innovation”