Revolutionary Space Transfer Propulsion Technologies for Human Exploration and Development

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Decadal Planning Team

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In-Space Propulsion
Solar Thermal and Solar Sails

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Solar Thermal	Transfer cargo from LEO to GEO or nuclear safe orbit	Ability to inflate concentrator and control focal point location during the mission	Reliable High Temperature material engine Accurate inflatable concentrators/supports Cryogenic fluid management for 30 days	5
Solar Sails	Cargo vehicles for Piloted exploration of the solar system; piloted sailcraft for intersteller and Solar system exploration	Feasibility of making sails that are 100m to 100-km-dia and 1-20 g/m^2; Feasibility of making >1000-m-dia Sails 0.1 g/m^2 and using 10^9-10^{12} W of space-based laser power	1-20 g/m^2 , 100- m2 sails to deploying up to 100-km-dia sails 0.1 g/m^2 10^9-10^{12} Wspace-based laser power 0.1-20 g/m^2 tear-resistant materials High temperature sail materials Deployment of Gossamer structures	0-3

In-Space Propulsion
Multimegawatt Electric Propulsion

Propulsion Option	Benefit	Issues	Technology 1	TRL Robotic/Human
• Ion Thruster	-high specific impulse -long lifetime -high efficiency -applicable to interplanetary and interstellar missions	-high/extremely high voltage -high-voltage solar arrays if solar power is used -PMAD, PPU -propellant management -ion grid design and material	-molybdenum grids -carbon-carbon grids -field emitter array cathodes -lightweight engine body -low flow cathodes -advanced materials -high power PPU and PMAD	•TRL 7-9 (present status, DS-1) •TRL 2-4 human •TRL 3-6 robotic
• Hall Thruster	-high specific impulse -high efficiency -high thrust (compared to Ion) -orbit-raising heavy payloads -applicable to fast Mars precursor, interplanetary and interstellar missions	-PPU (magnets/engine) -propellant management -electrode erosion/material issues	-high power PPU and PMAD -low flow cathodes -lightweight engine body -advanced materials	•TRL 4-6
• MPD	-extremely high thrust -low specific mass -orbit-raising heavy payloads -fast robotic outer planet missions -moderate specific impulse -high efficiency operates with a variety of propellants	-high currents -cathode lifetime -S/C contamination if lithium is used -propellant management (lithium/hydrogen) -PPU -power management and distribution -high power thermal management	-advanced materials for electrodes and body (refractory metal) -high power PPU and PMAD	•TRL 3-4
• PIT	-high specific impulse -variable specific impulse -operates with a variety of propellants -high efficiency -applicable to interplanetary and interstellar missions -orbit-raising heavy payloads -low specific mass -potential for high thrust	-extremely high voltages and currents (very high power system) -switch repetition rate -PMAD, PPU -propellant feed system and management -pulsed power network/architecture -thermal management -component wear	-switch technology -high repetition switching -high power capacitors -propellant valves with extreme sharp rise times -propellant delivery and distribution system -PMAD -materials	•TRL 2-4

In-Space Propulsion

Multimegawatt Electric Propulsion, Continued

Propulsion Option	Benefit	Issues	Technology 1	TRL Robotic/Human
• VaSIMR	-variable thrust -variable specific impulse -high specific impulse -high thrust -applicable to interplanetary and interstellar missions		-superconductors -	TRL 2-4 (present status)
• Helicon				

In-Space Propulsion
Aeroassist

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Aeroassist Aerocapture	•Up to 35% mass reduction •G-limited entries •Precision landing	• Higher L/D (> 0.25) vehicles • Efficient packaging and CG control • Accurate atmospheric models	•GN&C, Structures, Thermal Protection, Aero/aerothermal	•Aerocapture: 5 / 3 •Aeroentry: 6 / 4 •Precision Landing: 6 after MSP '01/ 3
Aerogravity	•No human mission applications foreseen	•High L/D vehicles with sharp leading edges required	•Thermal Protection, High-Temp Structures, GN&C	•Currently 2 / n/a
Solar Environment				
Solar Thermal				
Solar Sails				
Minimagnetospheric				
Magsails				

In-Space Propulsion
Tethers

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Electrodynamic	Propellantless Earth and Jovian Orbit Propulsion	High Current Emission Tether Survivability	Field Emitter Array Cathodes Long-Life Tethers	6/6
Momentum Exchange	Propellantless, reusable space infrastructure for LEO-to-beyond missions	High facility cost Rendezvous and Capture (for some apps) Tether Survivability	Long-life, high strength-to-weight tethers Automated Rendezvous and Capture	5/5
Orbit-to-Orbit Elevators	Low-cost atmosphere to higher-orbit transportation	High facility cost Tether survivability Orbit maintenance	Long-life, high strength-to-weight tethers	2/2

Fission Based Propulsion

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Nuclear Electric	- Advanced NEP systems enable rapid access to all points in solar system.	High specific power (>0.1 kW/kg) required for crewed applications.	Coupling fission energy to propellant. Waste heat rejection.	5 / 3
Nuclear Thermal	- NTR reduces launch mass and complexity of inner solar system missions.	Demonstrated fuels enable 850 s Isp. Solid-core Isp limit < 1000 s.	High-temperature, long-life fuel. System integration.	6 at 850 s Isp 3 at 950 s Isp
Nuclear Ramjet	- Nuclear Ramjet greatly increases effective ETO Isp, potentially yielding high-performance SSTO.	Operations / reusability. Ultra-high power density core design. Safety during launch accidents.	Fuels, materials, heat transfer.	4
External Pulsed Plasma	- Nuclear pulse gives rapid access to any point in solar system. High thrust, potential Isp >> 10,000 s.	Efficient system must utilize large (>1E14 J) pulses.	Efficiently coupling pulse to spacecraft.	4

In-Space Propulsion
Magsails

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Solar wind acting on magnetic "sails"	High specific impulse for space transportation in the inner solar system, potential high speed transportation	Control of thrust magnitude and direction, deployment and operation of large superconducting loop, power source for loop current	Large high temperature superconducting material for "sail" loop (carbon nanotubes), deployment deployment and spacecraft control systems, power supply for loop current	6/3
Minimagnetospheric				

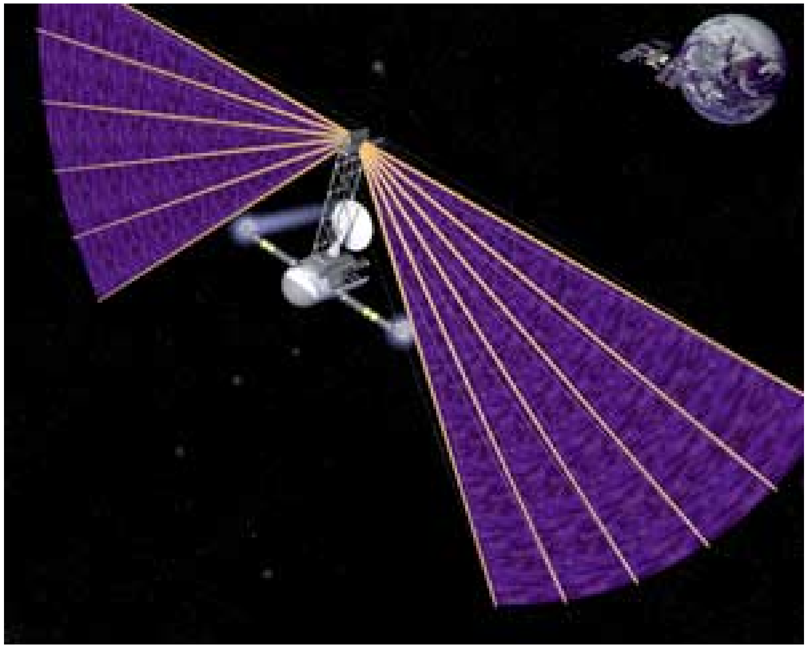
Fusion Based Propulsion

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Fusion Plasma (direct fusion to propulsion conversion)	• Very high Isp capability (> 50,000 s) • Very short trip time • Non-radioactive • Environmentally benign • Inexhaustible, low-cost fuel from Earth • Fuel collectible from lunar base, other planets and asteroids	• Attainment of practical fusion gain (> 1) • Active NASA's engagement in developing fusion science and technologies pertinent to propulsion application	• Fusion • Pulsed power • Energy storage • High magnetic fields • Magnetic nozzle • Plasma acceleration • Stable magnetic and plasma structures • Disposable first wall (liquid wall)	3/3 5/5 4/4 3/3 3/3 3/3 3/3 2/2
Fusion Electric	• High Isp capability (> 10,000 s) • Short trip time • Non-radioactive • Environmentally benign • Inexhaustible, low-cost fuel from Earth • Fuel collectible from lunar base, other planets and asteroids	• Attainment of practical fusion gain (> 1) • Active NASA's engagement in developing fusion energy pertinent to propulsion application	• Fusion • Pulsed power • Energy storage • High magnetic fields • Plasma acceleration • Stable magnetic and plasma structures • Disposable first wall (liquid wall) • High efficiency direct plasma-electric conversion	3/3 5/5 4/4 3/3 3/3 3/3 2/2 3/3

Fusion Assist Nuclear Propulsion

Propulsion Option	*Benefit to Human Exploration*	*Issue*	*Technologies*	*TRL Robot/Human*
Fusion Assist Fusion/fission hybrid Q-less-than-1 fusion schemes	• Moderately high Isp capability (> 5,000 s) • Greatly reduced trip time over nuclear fission based rockets • Reduced radioactivity • Environmentally more acceptable • Extensive, low-cost fuel reserves from Earth • Shorter R&D path	• Attainment of required fusion gain • Fusion/fission engineering interface	• Fusion • Pulsed power • Energy storage • Neutronics • Plasma acceleration • Stable magnetic and plasma structures • Disposable first wall (liquid wall)	3/3 5/5 4/4 4/4 3/3 2/2

Electric Propulsion



- Description
  - Electric propulsion provides high performance systems using solar or nuclear energy conversion
    - Ion systems provide highest delta-V for deep space missions
    - Hall thrusters provide higher thrust than ion systems, good application for orbit raising missions and some planetary transfer missions.

- Application(s)
  - LEO to GEO, Lunar, interplanetary, Mars
- General Benefit(s)
  - High Isp, up to 3600s
  - Multiple applications
- Limitations/Issues
  - Low thrust systems, applicable to mission phases up to human transportation
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **6 - 8**
  - **Potential for non-minimum energy propulsion?**
  - **Benefit for human exploration?**
    - **Potential for providing orbit raise to GEO, rendezvous with Crew for remainder of mission.**
    - **Can provide cargo transfer to planetary destinations, to await crew arrival**

Aeroassist

- Description
  - Use of aerodynamic forces during atmospheric flight to accomplish transportation functions
  - Disciplines involved include:
    - Aero/aerothermodynamics
    - Guidance, Navigation and Control
    - Structures
    - Thermal Protection Systems
    - Vehicle Design/Configuration
- Application(s)
  - Aerocapture for orbital insertion about a planet (robotic and human) - first use by MSR '05 Orbiter
  - Aeroentry for descending to a surface (robotic and human) - common at Earth, but aeromaneuvering at Mars will be first performed by MSP '01
  - Aerobraking for adjusting orbits (robotic, human cargo missions due to long time) - used by Mars Global Surveyor
  - Precision Landing for acquiring specific sites (robotic and human) - first use by MSP '01 (10 km accuracy)
  - Aerogravity Assist for diminishing flight times to outer planets (robotic missions)
- General Benefit(s)
  - Aerocapture enables some robotic missions to outer planets
  - Aerocapture reduces LEO mass by up to 35% (over propulsive capture) for humans
  - Enables G- and heat-rate-limited profiles
- Limitations/Issues
  - Higher L/D (> 0.25) vehicles needed
  - Efficient packaging and CG control
  - Dependent on accurate atmospheric models

Near-Term (within 10 years) Impact If Adequately Funded

TRL Status for Human Exploration Use:

TRL=7 by 2009 if shape and H/W are human-like

Benefit for human exploration?

35% mass reduction in low Earth orbit
Safe landing near predeployed surface resources
Enables G-limited trajectories

Solar Thermal Propulsion

- Description
  - Uses solar concentrators to heat propellant (LH_2) and provide high performance (Isp ~ 900 sec) thrust.
    - Uses lightweight thin-film concentrators deployed on orbit, lowers system mass.
    - High temperature thruster, no combustion, simple propellant heating and expansion to produce thrust
  - Flight demonstration funded by Air Force for orbit transfer system, 2002

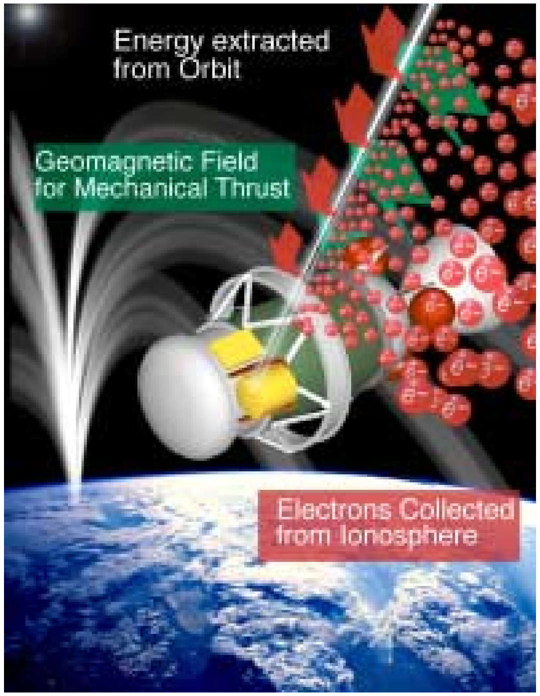
- Application(s)
  - LEO-to-GEO, Lunar Transfer, other applications need study
- General Benefit(s)
  - Bi-Modal system can provide both Propulsion and power
  - Low mass system reduces launch costs
- Limitations/Issues
  - Low thrust system - 50lbf, slow human mission
  - Missions limited to close solar distances
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **9**
  - **Potential for non-minimum energy propulsion? NO**
  - **Benefit for human exploration?**
    - **Potential for cargo transfer vehicle to support human missions**

Solar Sail Propulsion

- Description
  - Solar photon pressure used to push (via photon momentum transfer) a large, thin sail
  - Sail diameters > 70 m required; 0.1 - 20 g/m^2 density

- Application(s)
  - Light-weight payloads (~200 kg) to solar system destinations
  - Non-Keplerian 'hanging orbits' near Earth and/or L1
- General Benefit(s)
  - Requires no propellant
  - Enables rapid travel with close solar approach trajectories (> 15 AU/year)
- Limitations/Issues
  - Sail sizes may be practical for only small payloads (< 500 kg) - TBD
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **7 - 8**
  - **Potential for non-minimum energy propulsion? YES**
  - **Benefit for human exploration?**
    - **Potential for rapid payload transfer throughout the solar system using existing Earth launch infrastructure.**

Electrodynamic Tether Propulsion



- Description
  - Long (>5 km) thin tether deployed from spacecraft to interact with magnetic field and ionosphere
  - Power supply used force current through tether
  - Downward current **I** produces thrust force **F** to boost spacecraft or change its inclination
  - Current **I** produces magnetic force d**F** on each tether section dl: $d\mathbf{F} = dl\mathbf{I} \times \mathbf{B}_{North}$

- Application(s)
  - Low Earth orbit boost, deboost and inclination changes (<2300 km)
  - Jovian Exploration
- General Benefit(s)
  - Requires no propellant
  - Reusable
  - Low-cost
- Limitations/Issues
  - Can only operate in low orbits
  - Operations complexity during rendezvous
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **8 - 9**
  - **Potential for non-minimum energy propulsion? NO**
  - **Benefit for human exploration?**
    - **Orbit maintenance of large, high-power facilities in Earth orbit (space station; assembly stations)**

Momentum Exchange Tether Propulsion

- Description
  - Rotating tether in orbit can catch a payload in a lower orbit and "toss" it into a higher orbit or Earth escape
    - Tether "gives" some of its momentum & energy to payload
  - Use ED tether, SEP, or return traffic (energy conservation) to restore orbit

- Application(s)
  - LEO-to-MEO, GEO, Lunar (orbit and/or surface) or Mars
    - Circularization and/or course correction propulsion also required
- General Benefit(s)
  - Requires little propellant
  - Reusable over many missions
  - Allows system for forward and return traffic by establishing an in-space infrastructure.
- Limitations/Issues
  - Rendezvous is challenging
  - Human safety
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **7 - 8**
  - **Potential for non-minimum energy propulsion? YES**
  - **Benefit for human exploration?**
    - **Potential for near-propellantless in-space infrastructure of rotating tether facilities passing payloads to and from 'destinations'**

Nuclear Electric Propulsion

Module test for potential first-generation fission energy source.

An 8200 Hour Test of an Ion Thruster (courtesy JPL).

- Description
  - Energy from fission is converted to electricity. Electricity is used to accelerate propellant to velocities up to (and exceeding) 30 km/s.
  - Numerous options exist for both the fission energy source and the propulsion subsystem.
- Application(s)
  - Any desired payload to any solar-system destination.
  - High-efficiency orbit changing / maintenance.
  - Rendezvous and sample return.
- General Benefit(s)
  - Requires very little propellant.
  - Safe, virtually non-radioactive at launch.
  - Unaffected by solar proximity or orientation - full thrust capability at all locations.
- Limitations/Issues
  - Political concerns with use of any nuclear technology (fission, fusion, antimatter).
  - First-generation systems relatively low-cost. Man-rated systems will require significant development.
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **6 - 8**
  - **Potential for non-minimum energy propulsion? YES**
  - **Benefit for human exploration?**
    - **Second or third generation systems (< 10 kg/KW) enable rapid, efficient trips to Mars and other solar-system destinations.**
    - **Highly efficient cargo transfer.**

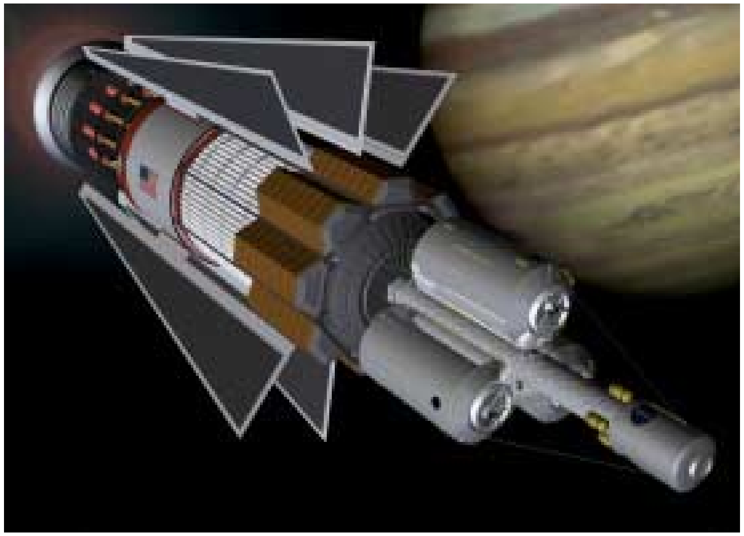
Nuclear Thermal Propulsion

Phoebus 2A (1968)

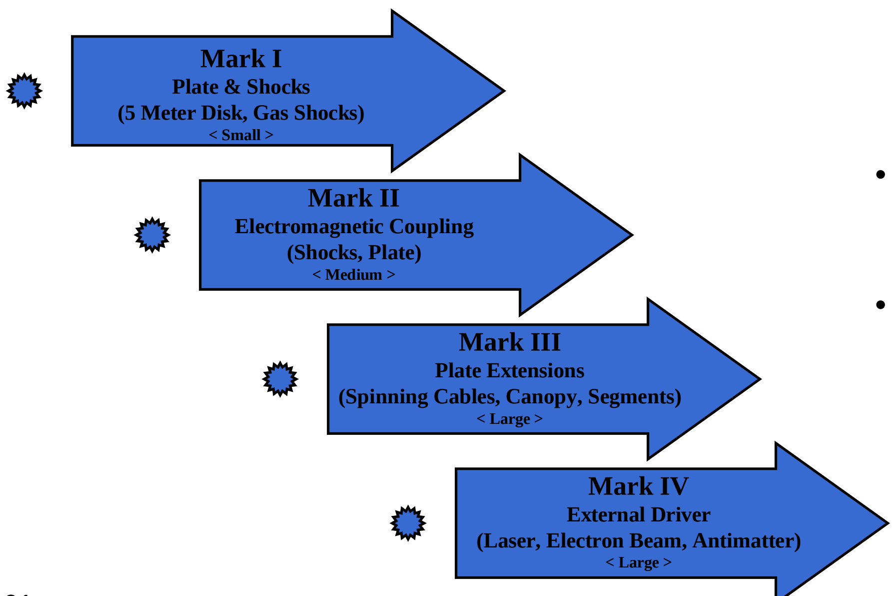
Bimodal Module Test (1999)

- Description
  - Energy from fission used to heat propellant, no chemical reaction required. Low molecular weight propellant (e.g. H_2) yields high Isp (>800 s).
  - Potential for thrust-to-weight >5.
- Application(s)
  - Moderate thrust (> 100 N) applicable to unmanned missions. Planetary exploration, asteroid rendezvous.
  - High thrust (> 10 kN) applicable to human Mars exploration, lunar and asteroid missions.
- General Benefit(s)
  - Double Isp of chemical systems.
  - Safe, virtually non-radioactive at launch.
  - Reduce mission time and launch mass.
- Limitations/Issues
  - Political concerns with use of any nuclear technology (fission, fusion, antimatter).
  - First-generation systems relatively low-cost. Second-generation systems will require significant nuclear-fuels and other development.
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **Use of first-generation system on unmanned mission. Man-rated system brought to TRL 6 - 8.**
  - **Potential for non-minimum energy propulsion? YES**
  - **Benefit for human exploration?**
    - **Reduce mission time and/or launch mass for human missions to the moon, Mars, or asteroids.**

External Pulsed Plasma Propulsion

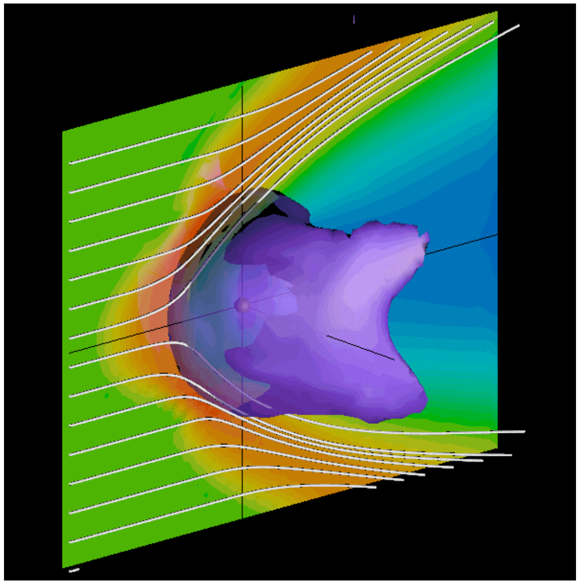


GABRIEL Mark I



- Description
  - High energy nuclear pulse units are ejected from vehicle, producing a thin plasma shell expansion that is coupled to the vehicle by a mechanical or magnetic momentum transfer mechanism.
  - Specific Impulse of 3000 sec. Minimum, with 10,000 sec. possible and thrust-to-weight ratios of 1 to 5.
- Application(s)
  - GABRIEL class vehicle (<50 tons) fast manned Mars missions, asteroid/comet rendezvous and deflection, lunar heavy transport and solar system exploration.
  - Large vehicle (hundreds of tons) applicable to manned and unmanned missions for deep solar system exploration and interstellar travel.
- General Benefit(s)
  - Best thrust and Isp with known technology.
  - Fast, reliable, reusable and least Mars mission cost.
  - Order of magnitude performance increase in future versions (scales “bigger is better”)
- Limitations/Issues
  - Political concerns with use of any nuclear technology (limited nuclear operation near Earth).
- **Near-Term (within 10 years) Substantial Impact If Adequately Funded**
  - **Man-rated system brought to TRL-7.**
  - **Potential for non-minimum energy propulsion? YES**
  - **Benefit for human exploration?**
    - **Increased safety for humans through reduced trip times.**

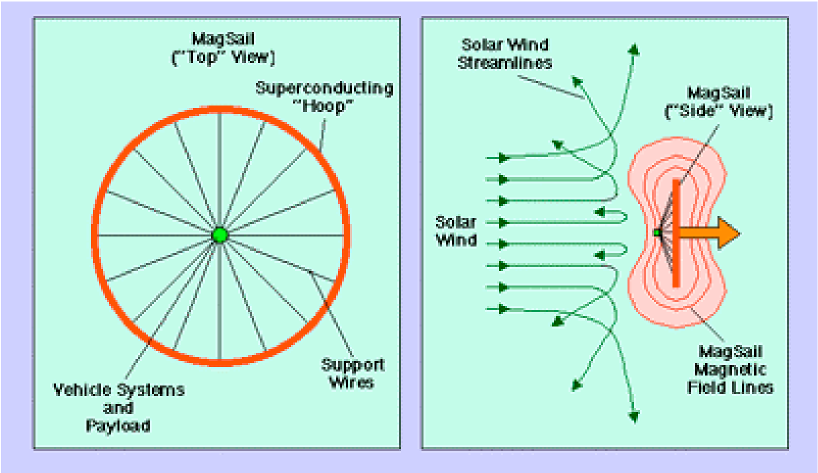
Mini-Magnetospheric Plasma Propulsion



- Description
  - Create a magnetic bubble around and attached to a spacecraft that will then be carried by the solar wind.
  - Low energy plasma is used to inflate the magnetic field to produce a large cross-section (15-30 km) for a force of about 1 N and an ISP of 30,000-80,000
  - Use SEP with an innovative plasma and magnetic field configuration.

- Application(s)
  - Interstellar Precursor Mission
  - Faster, cheaper missions to the planets, including Mars
  - Sun-Synchronous Orbiter
- General Benefit(s)
  - Light weight and requires power that can be handled by existing SEP systems
  - Easy implementation with no mechanical parts
  - High speeds of between 50-100 km/s can be attained
- Limitations/Issues
  - EM noise, efficiency of systems
  - Navigation
- Near-Term (within 10 years) Impact If Adequately Funded
  - TRL Status for Human Exploration Use:
    - 6 - 7
  - **Potential for non-minimum energy propulsion? YES**
  - Benefit for human exploration?
    - Facilitate easy access to the planets and beyond the solar system

Magsails

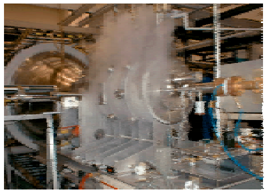


- Description
  - Cable of superconducting material, millimeters in diameter, which forms a hoop that is tens to hundreds of kilometers in diameter.
  - The current loop creates a magnetic dipole which diverts the background flow of solar wind. This deflection produces a drag-force on the MagSail radially outward from the sun.
  - Proper orientation of the dipole may produce a lift-force which could provide thrust perpendicular to the radial drag-force.

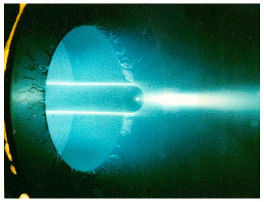
- Application(s)
  - Interplanetary Propulsion
- General Benefit(s)
  - Requires no propellant
  - Potentially reusable
- Limitations/Issues
  - Thermal control, structures, radiation, superconductor technology, attitude control, and deployment
- **Near-Term (within 10 years) Impact If Adequately Funded**
  - **TRL Status for Human Exploration Use:**
    - **6**
  - **Potential for non-minimum energy propulsion?**
  - **Benefit for human exploration?**
    - **Potential for rapid payload transfer throughout the solar system**

Very High Power Electric Thrusters

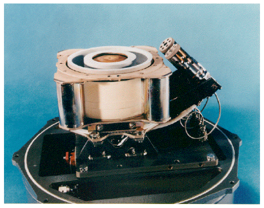
- Multi-Mega Watt Class Electric Thrusters
  - May have relatively high thrust levels, Isp and alpha (kg/kW) to enable robust and routine interplanetary human missions



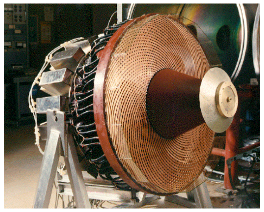
- VASIMR (Variable Specific Impulse and Thrust at maximum power)



- Magnetoplasmadynamic (MPD) thrusters



- Inverse Hall Thruster (a Russian concept for a megawatt Hall thruster)
- Helicon



- Pulsed Inductive Thruster

  - All of these concepts need significant work