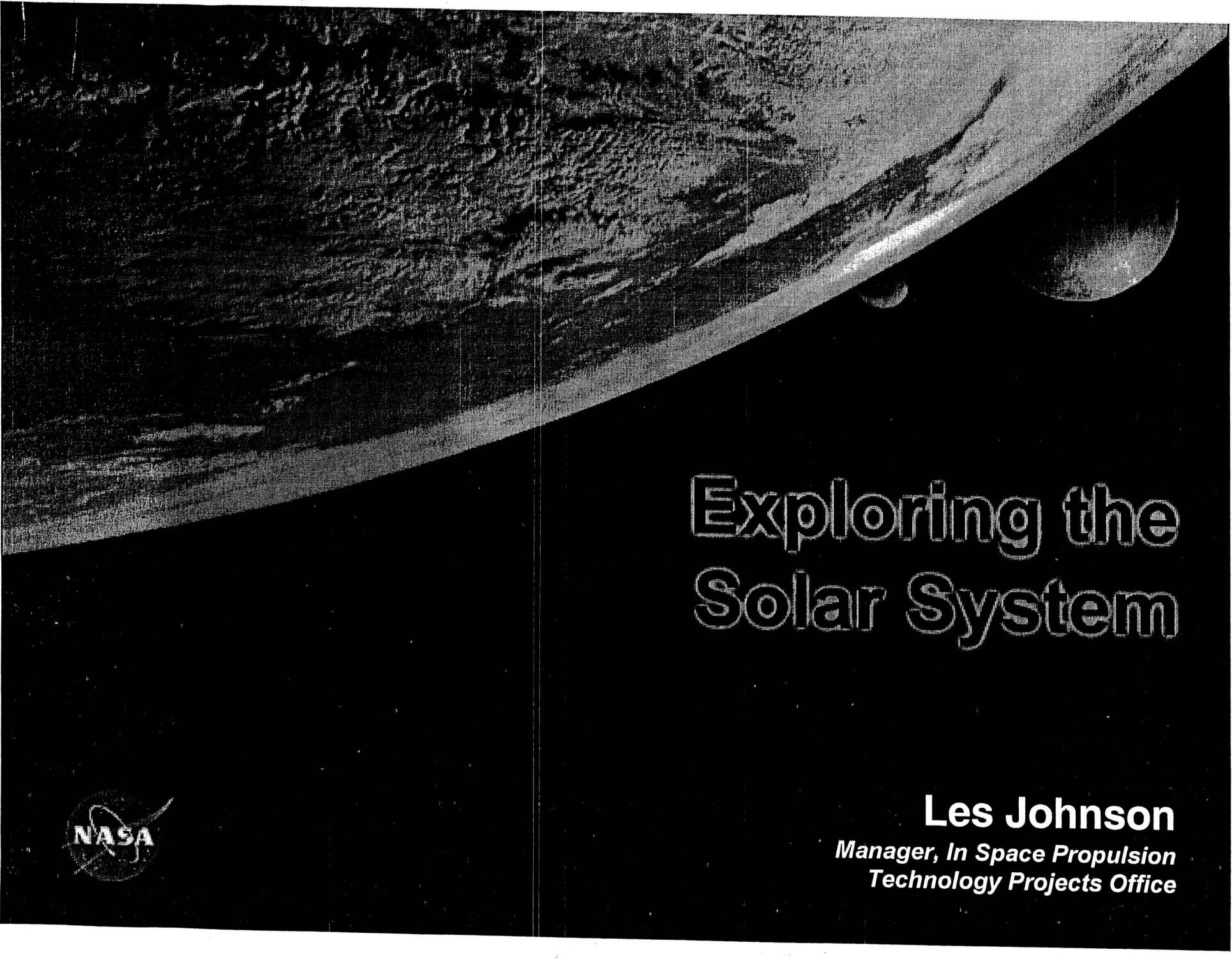


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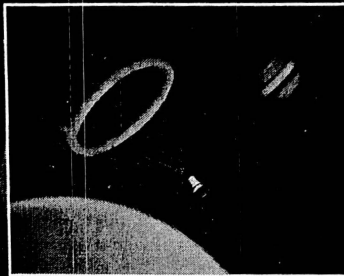
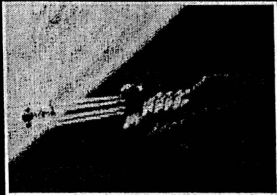


Exploring the Solar System

Les Johnson

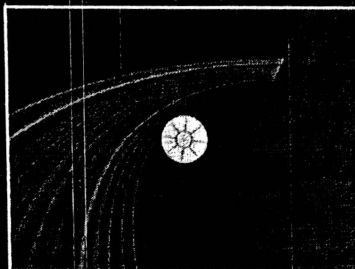
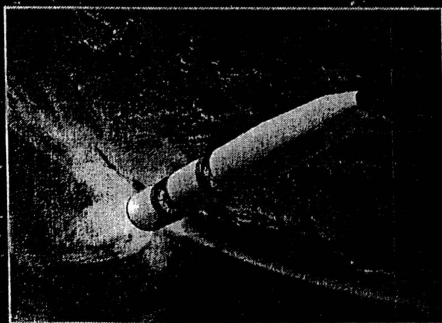
*Manager, In Space Propulsion
Technology Projects Office*



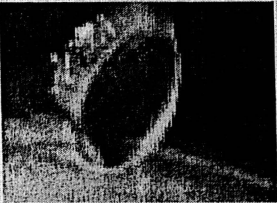
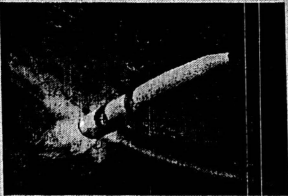
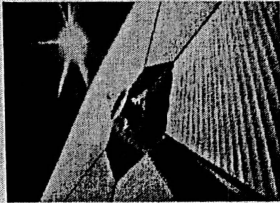
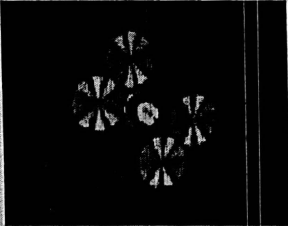
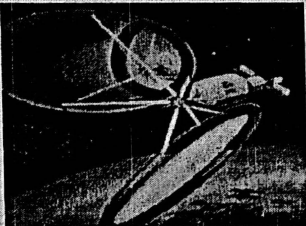
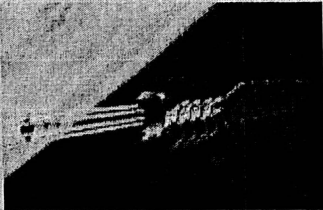
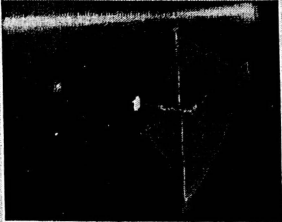
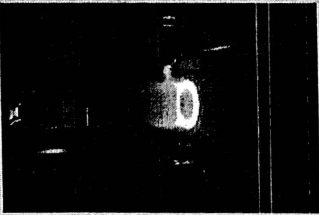


Objective:

To develop in-space propulsion technologies that can enable and/or benefit near and mid-term NASA science missions by significantly reducing cost, mass, and/or travel times.

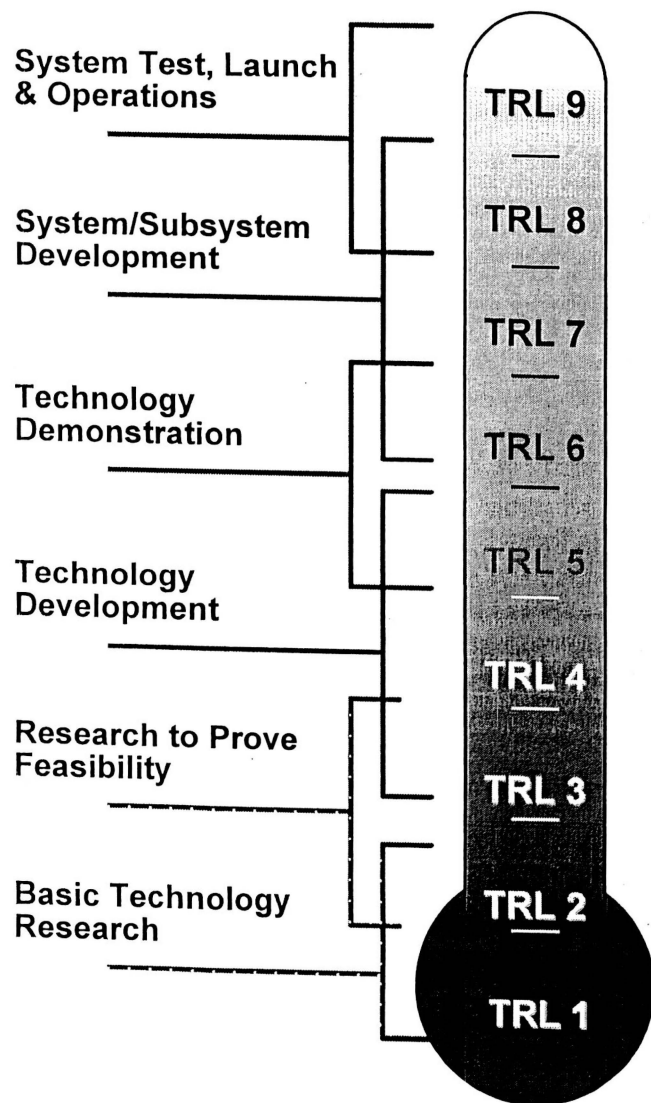
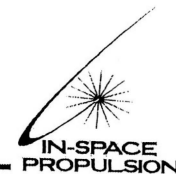




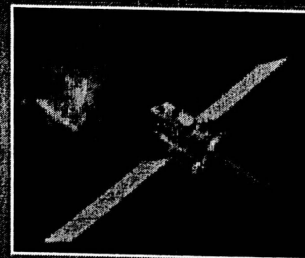
High Priority	Medium Priority	Low Priority	High Payoff/High Risk
Aerocapture 	Advanced Chemical 		1 g/m2 Solar Sails 
Next Generation Ion (5/10 kW) 	Solar Electric 	Solar Thermal 	Momentum Exchange Tethers 
Solar Sails 	Solar Electric Propulsion - Hall - (100 kw) 		Plasma Sails 



In-Space Propulsion Program Will Advance Mid-TRL Technologies to Support NASA Mission Applications



NASA Implementation: (Deep Space One Ion Engine Example)

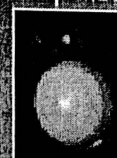


In-Space Propulsion Technologies

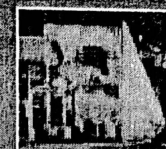
Aeroassist



Adv. Electric Propulsion



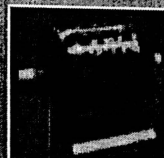
Solar Thermal



Adv. Chemical



Tethers



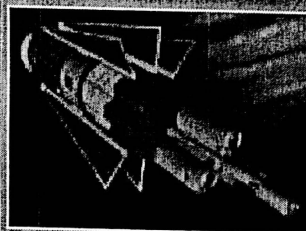
Solar Sails



Plasma Sails



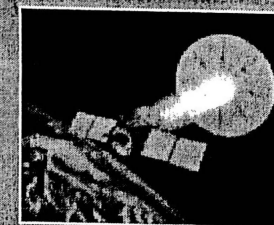
Low-TRL Technologies For the Future



External Pulsed Plasma

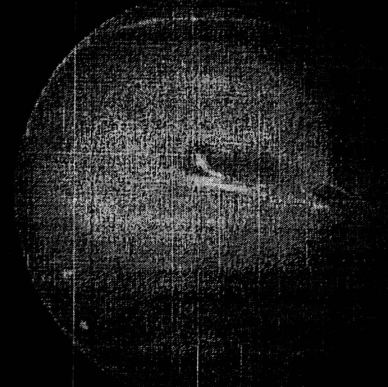
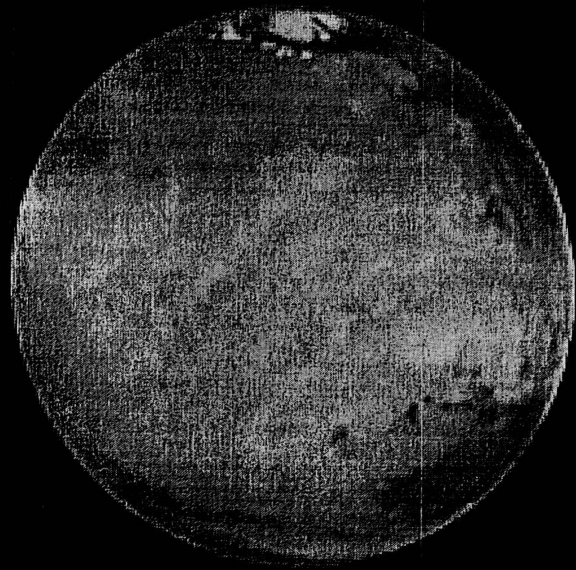


Fusion & Antimatter



Beamed Energy

AEROCAPTURE



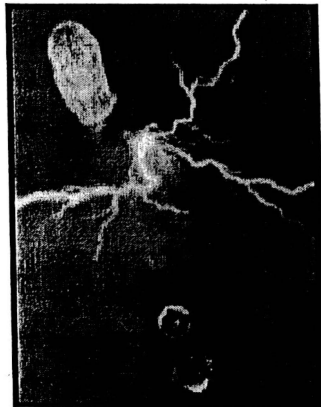


Aeroassist / Aerocapture

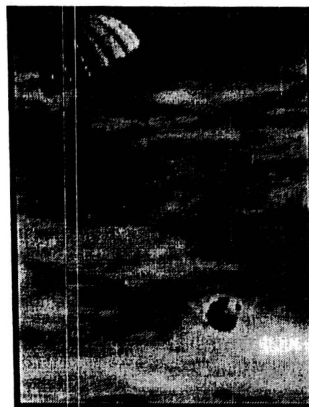


Apollo -1960's

Experience with the Aeroassist “blunt body” shape was gained in the missions pictured here. Utilizing this experience, new materials, and detailed atmospheric modeling, Aerocapture will allow for multi-g deceleration and orbital capture using the atmospheres of destinations such as Titan.



Pioneer Venus - 1970's



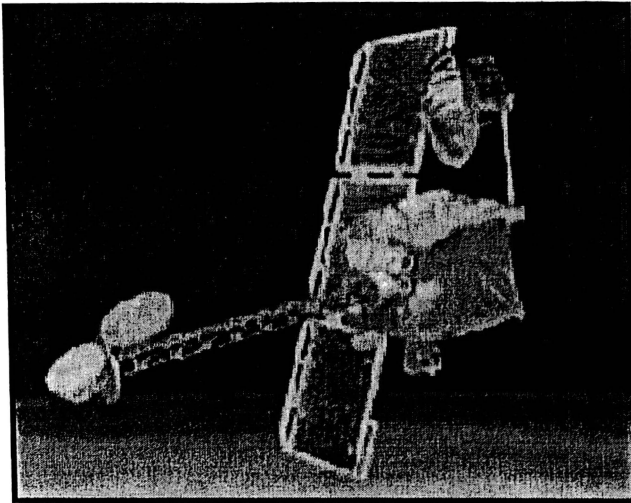
Galileo Probe - 1990's



Mars Pathfinder - 1990's

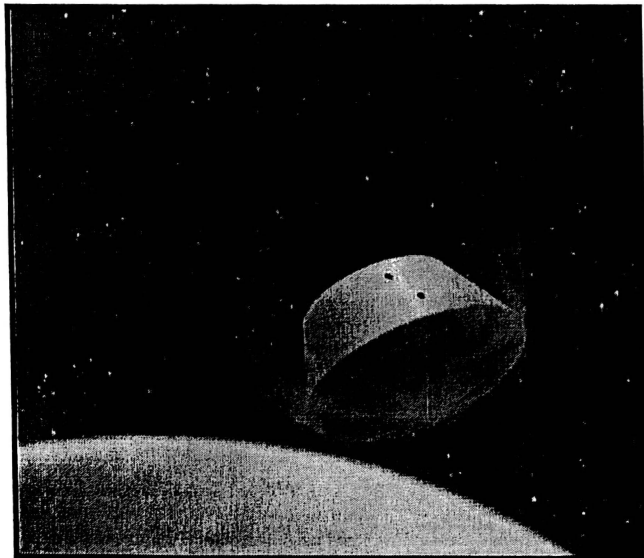


Aerobraking / Aerocapture



Mars Odyssey (2001-02)

- **Aerobraking:** Saves a portion of orbit capture fuel mass and is used when time is not a driving constraint; science orbit is achieved over weeks or months (no aeroshell needed)



Titan Mission Blunt Body Shape

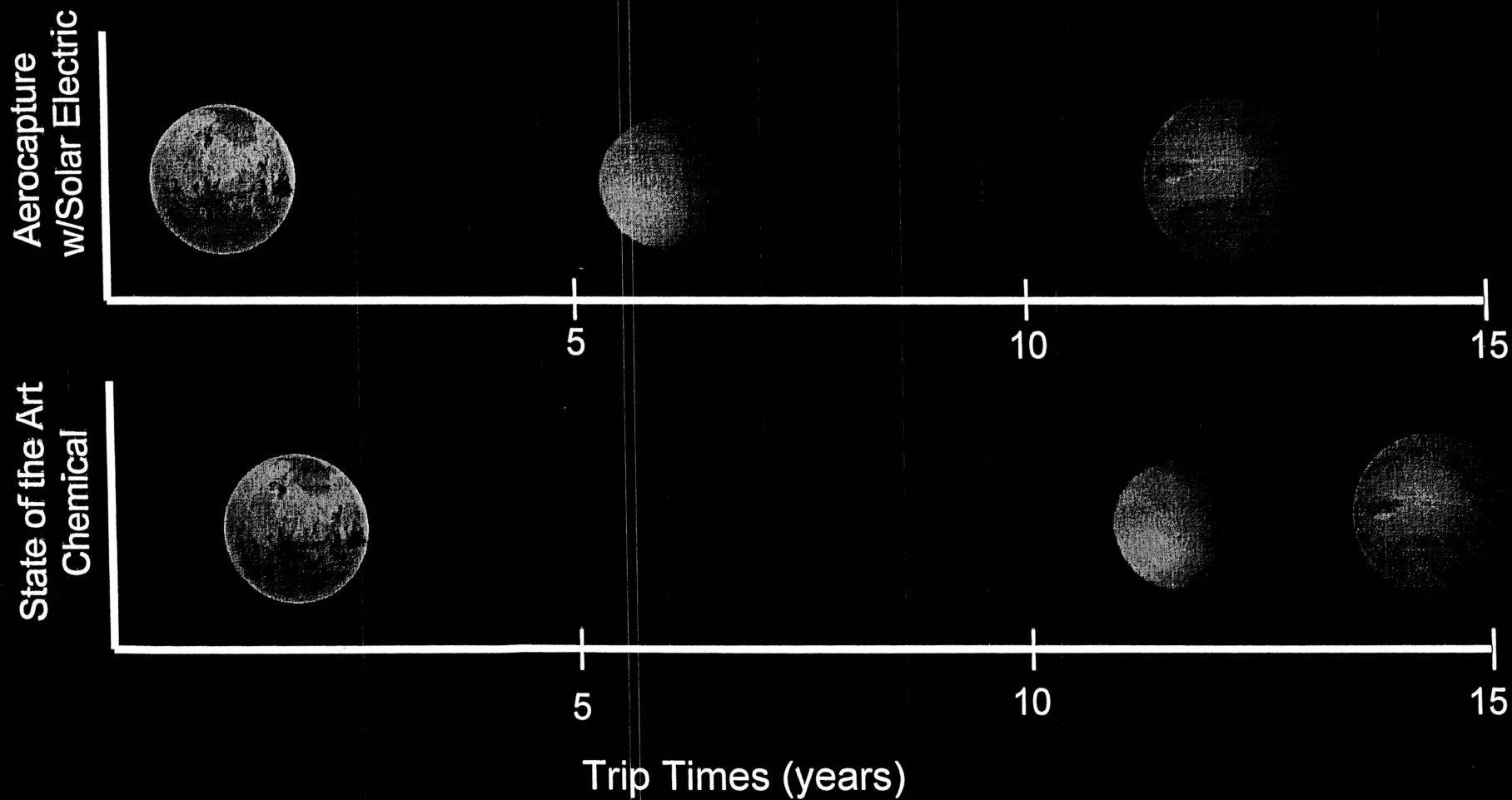
- **Aerocapture:** Saves almost all orbit capture fuel mass and can, in a matter of hours, achieve a scientifically useful orbit (aeroshell and guidance and control system necessary)



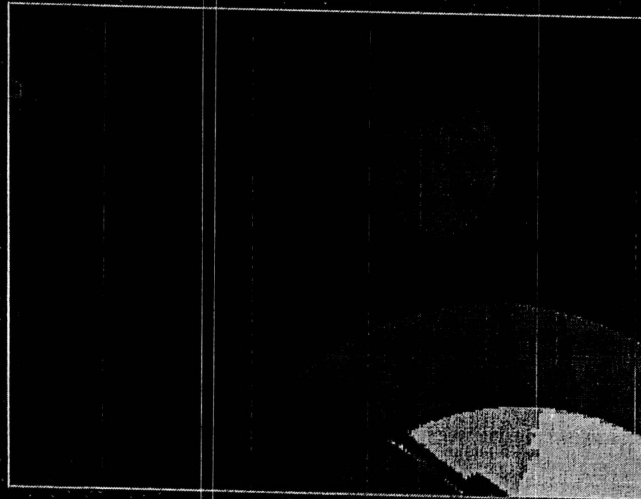
Aerocapture



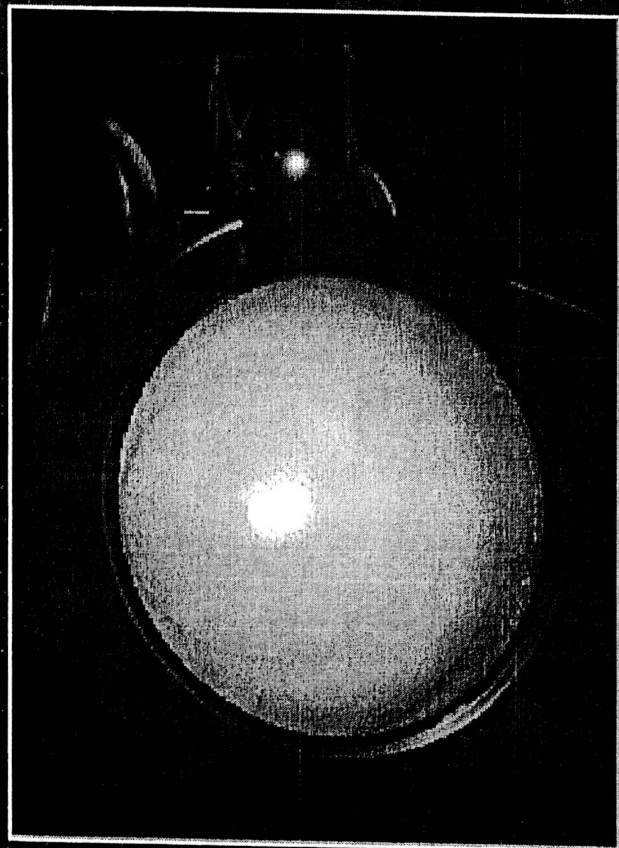
Trip Time and Launch Vehicle Benefits For Potential Destinations



Mission to Titan

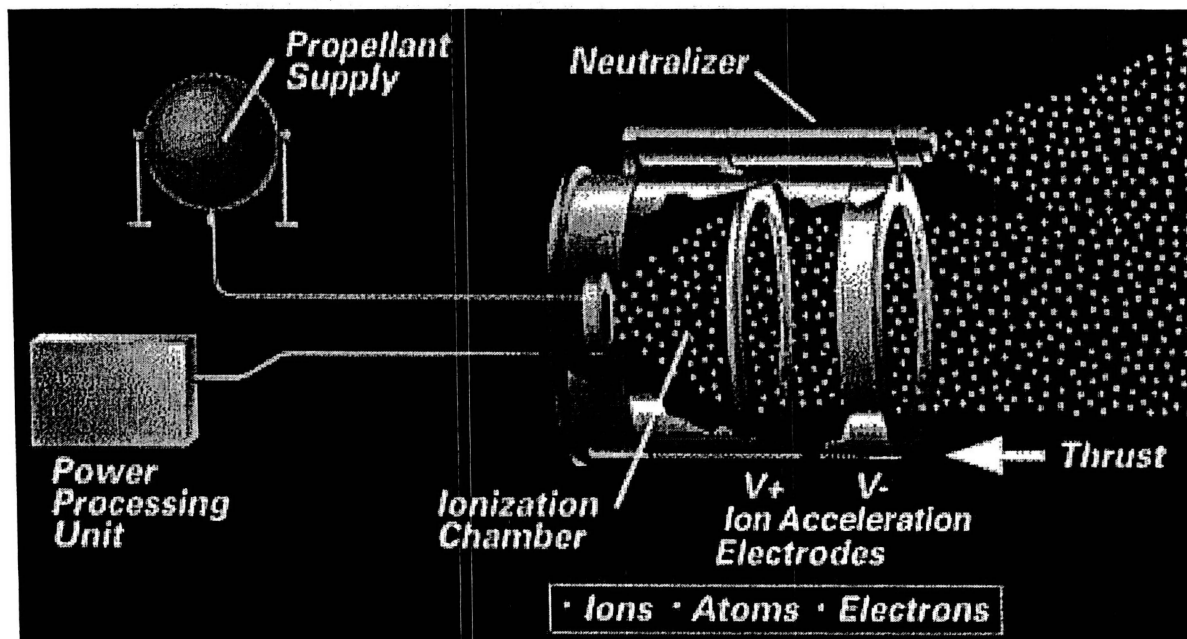


Next Generation Ion Electric Propulsion



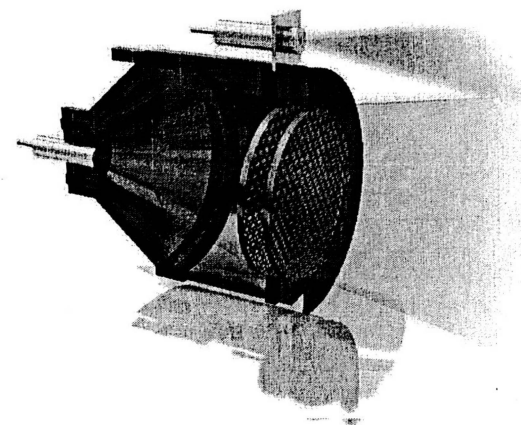


Next Generation Ion Electric Propulsion



Next Generation Ion Electric Propulsion

Is an In Space Propulsion technology that utilizes electrical energy to produce an electrostatic reaction (with a propellant) to obtain thrust. May utilize Solar or Nuclear generated power.





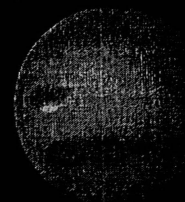
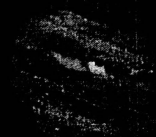
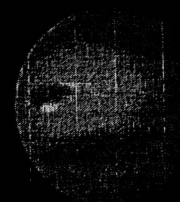
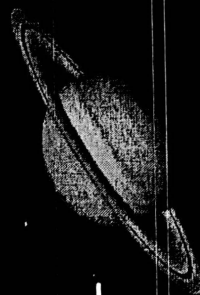
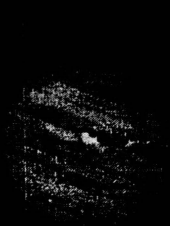
Next Generation Ion Electric Propulsion



Trip Time and Launch Vehicle Benefits For Potential Destinations

Next Generation
Ion Propulsion w/AC

State of the Art
Chemical



5

10

15

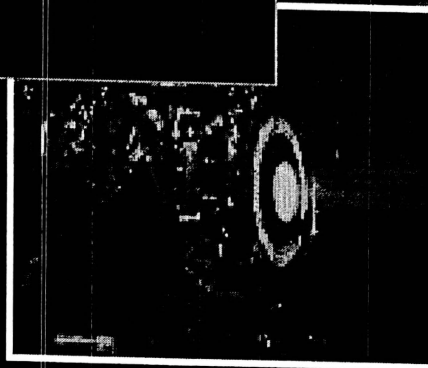
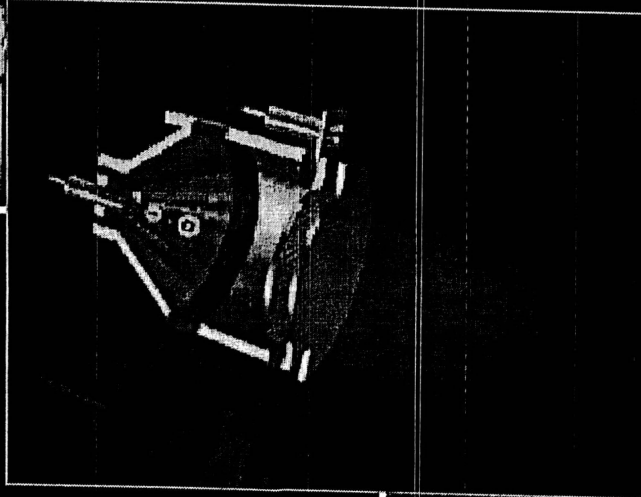
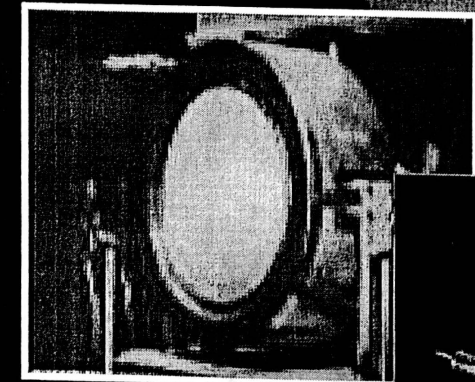
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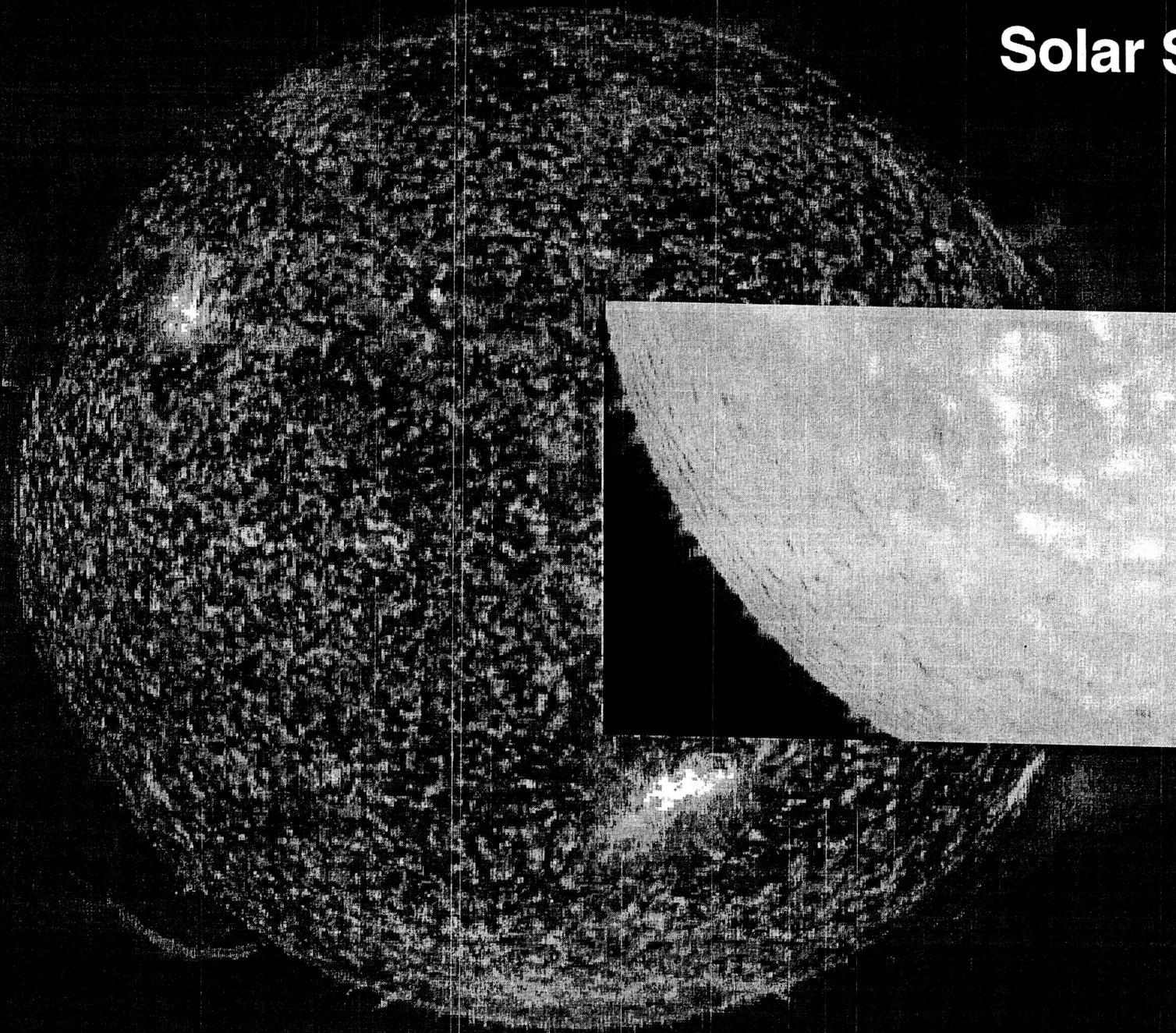
15

Trip Times (years)

Next Generation Ion Electric Propulsion



Solar Sails

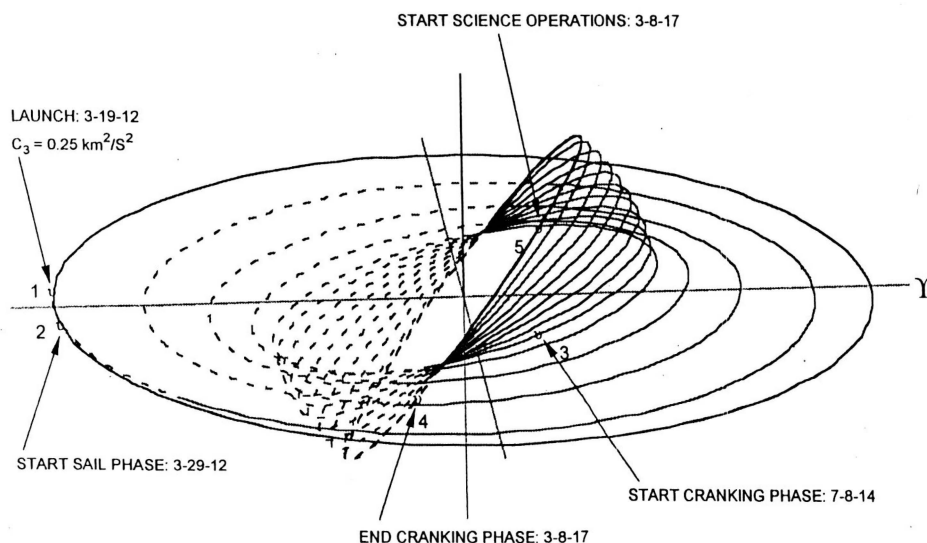
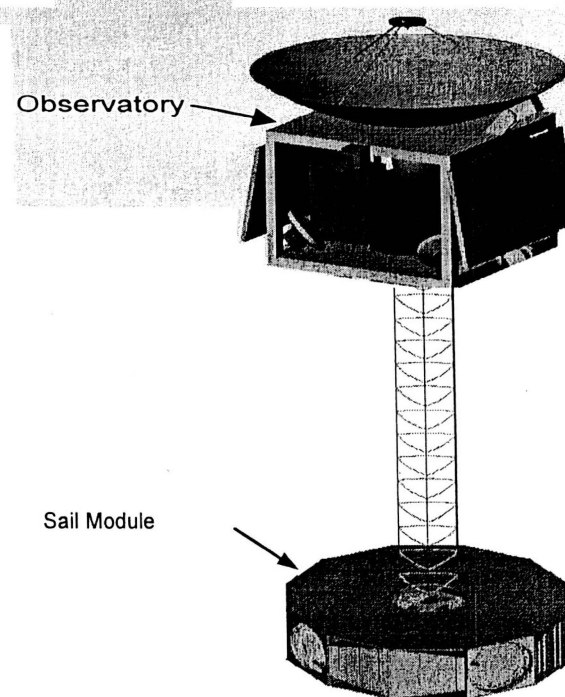
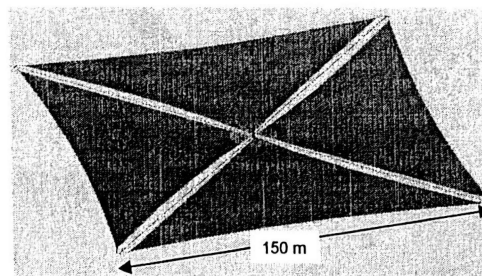
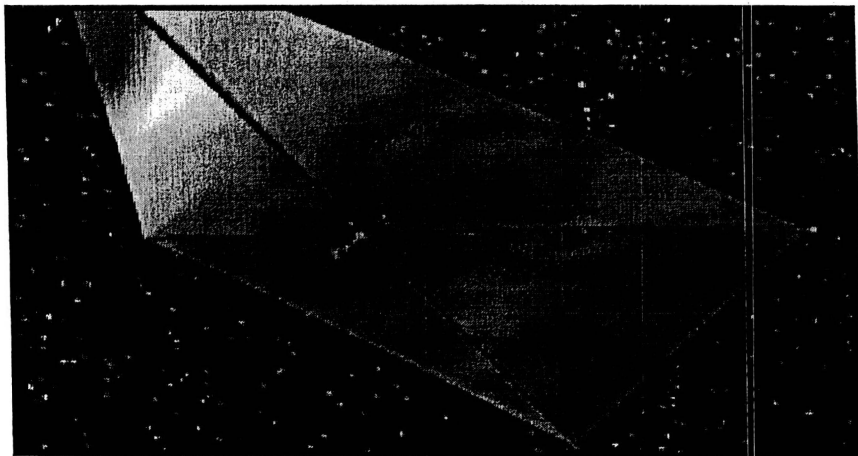




Solar Sails

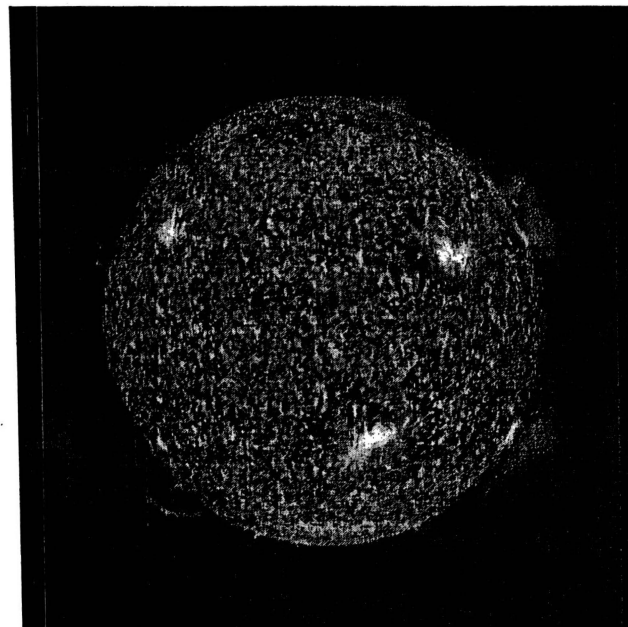
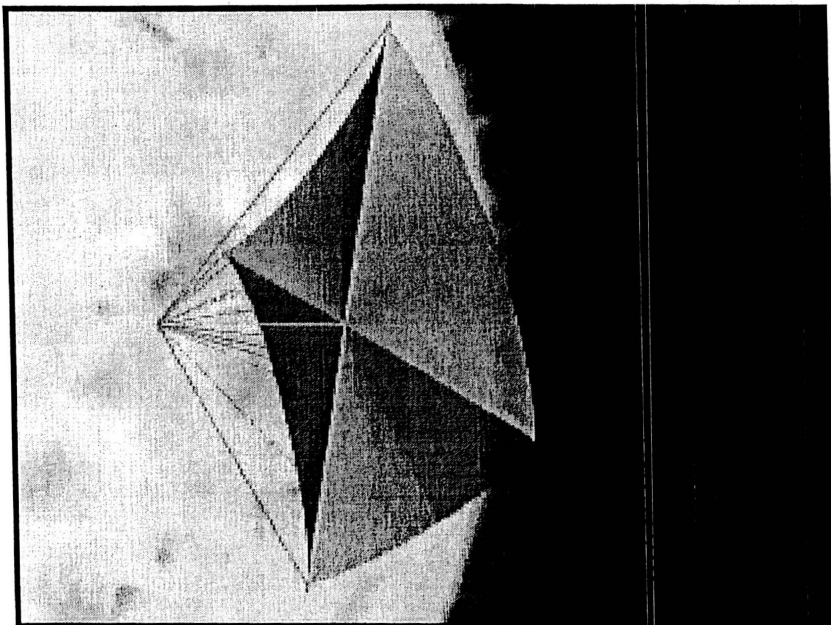


Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust. Sails can open up new regions of the solar system to accessibility for important science missions, with no propellants required.





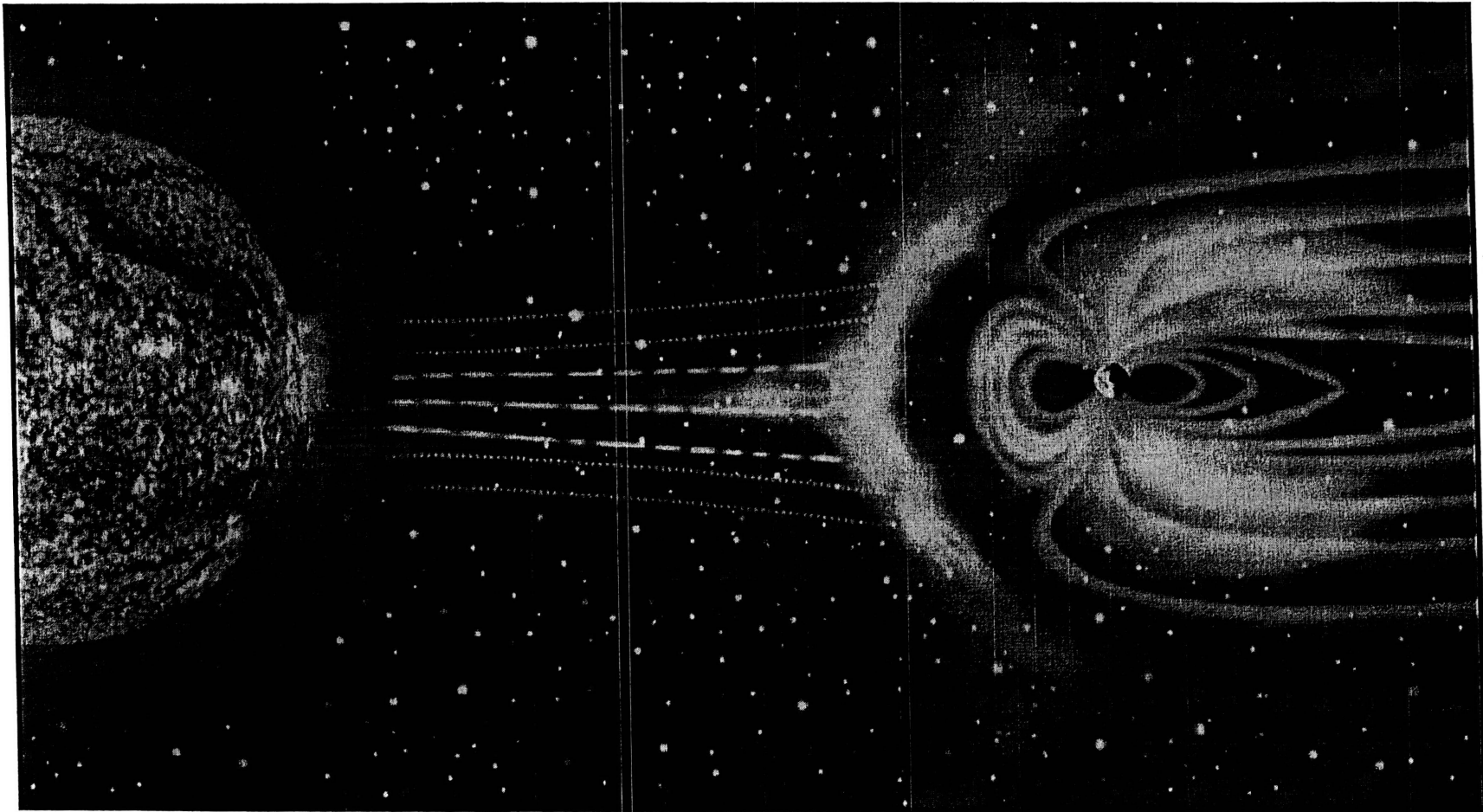
Solar Sails — Geostorm



Geostorm is a mission that provides real-time monitoring of solar activity; it operates at or inside the Earth's L1 point and increases the warning time for geomagnetic storms compared to a vantage point closer to the Earth. Geostorm would double the warning time of the current system, making possible the reconfiguration and securing of defense and civil systems including electrical power grids.

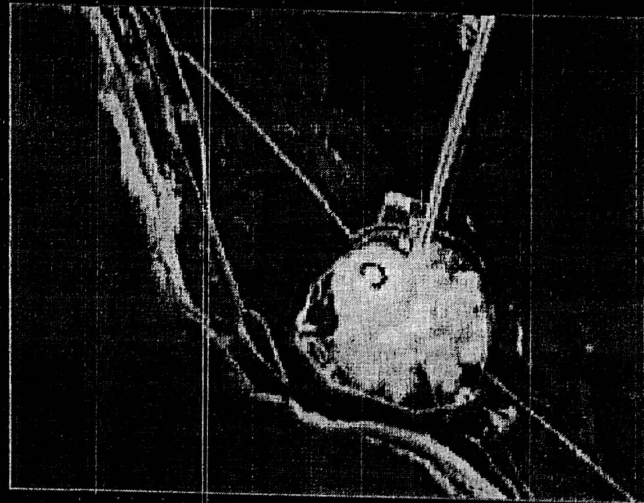


Space Weather



The Effects of Solar Activity on the Near Earth Space Environment

Solar Sails Animation



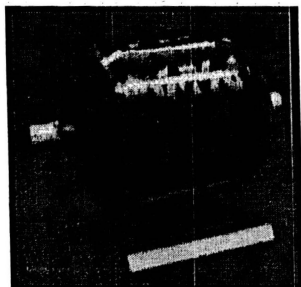
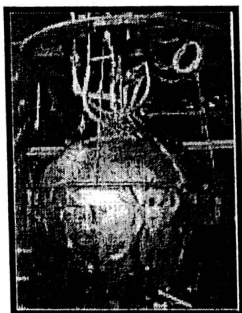


In-Space Transportation Technology Products

Medium / Low Priority Technologies



Medium Priority:

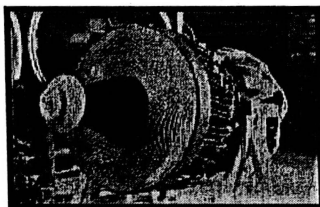


◆ Advanced Chemical

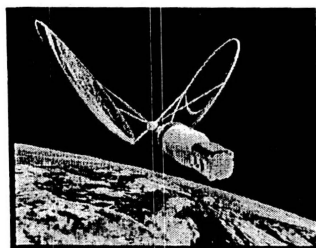
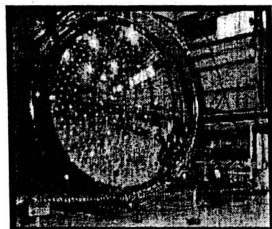
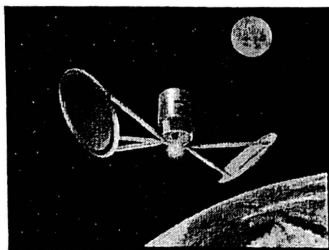
- Fuels development
- Cryogenic Fluid Management
- Lightweight components

◆ kW Solar Electric Propulsion

- Laboratory demonstration of 50kW Hall thrusters
- Competitively select thruster technology advancement based on application



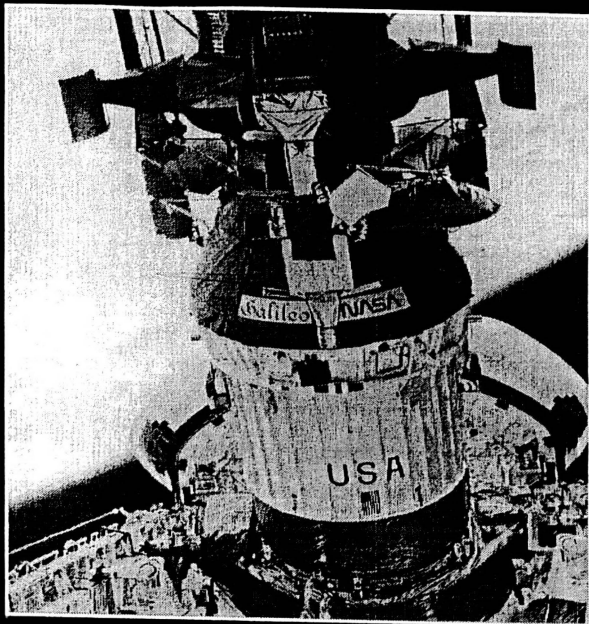
Low Priority:



◆ Solar Thermal Propulsion

- Technology investments under further study
- Directed tasks focused toward fundamental performance questions

Advanced Chemical Propulsion

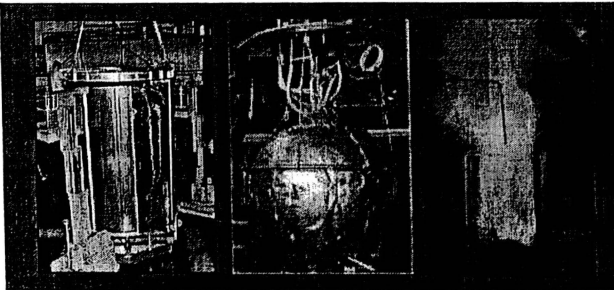




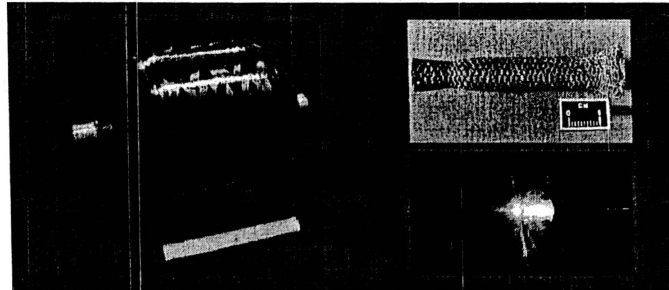
Advanced Chemical Propulsion



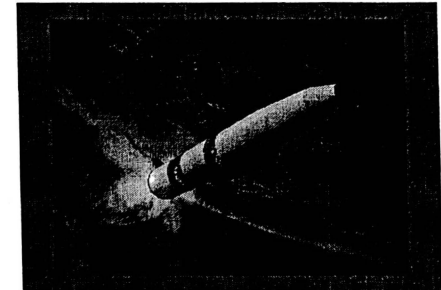
Cryogenic Fluid Management



Lightweight Components

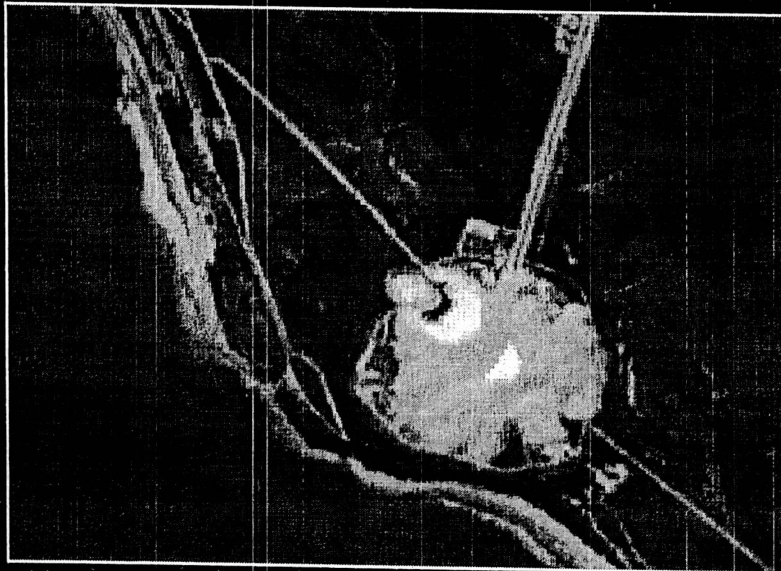


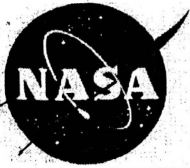
Advanced Fuels



Chemical Propulsion systems have historically been the primary means for transportation of payloads in space because they generate the tremendous amount of thrust required to overcome the effect of Earth's gravity. Advanced Chemical Propulsion incorporates new or enhanced propellants, cryogenic propulsion and lightweight component technology to provide benefits which are cross-technology at the system level, as well as the component level.

kw SEP





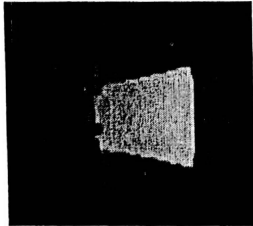
Solar Electric Propulsion



Three Fundamental Acceleration Systems

Applications: Primary propulsion – earth orbit and planetary, orbit insertion, station-keeping, precision control, maneuvering

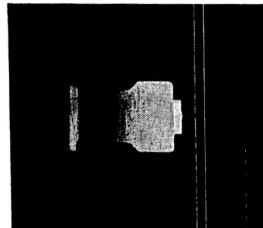
Electromagnetic



Ions created and accelerated by interaction between current and magnetic field



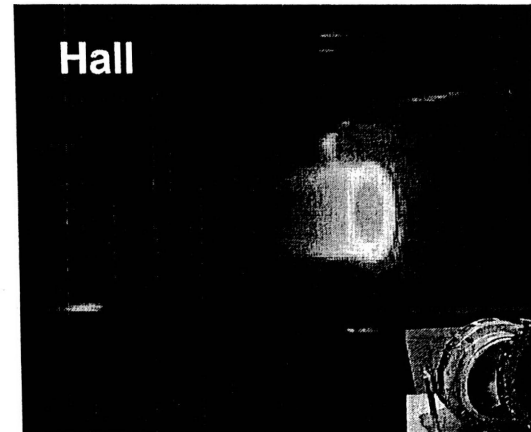
Electrothermal



Propellant heated thermally (physical heater, arc, μ wave, etc.) and exhausted through nozzle

Electrostatic

Hall



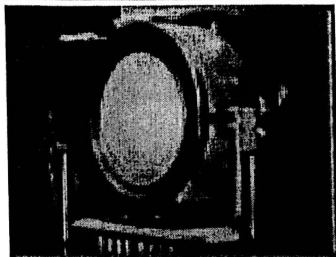
Ions created and accelerated by electric field.

General Description: This area pursues technologies to increase the performance of SEP systems by going to higher power levels, longer life technologies, and by increasing overall system efficiencies.

Objectives: to build on NSTAR heritage to develop a long life, high power, Ion Engine System for future science missions, and significantly Improve performance and reliability of Ion Propulsion systems.

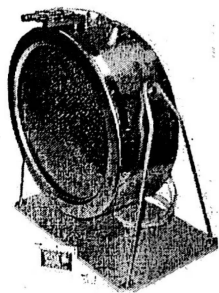


Solar Electric Propulsion

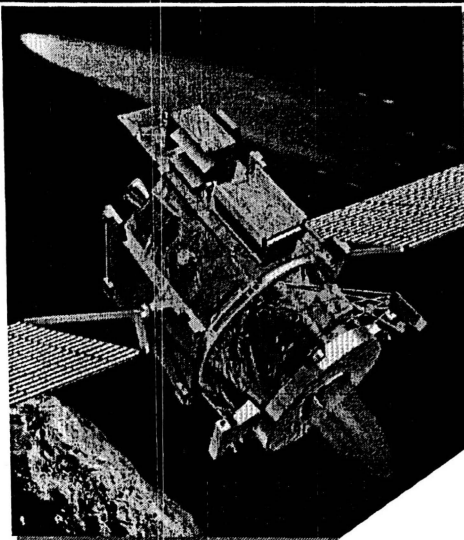


NSTAR Life Test
T = 29,000+ hours

Ion

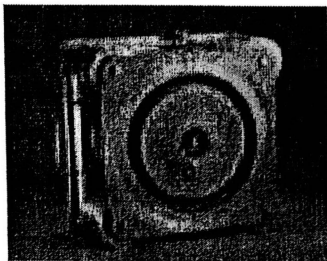


NEXT

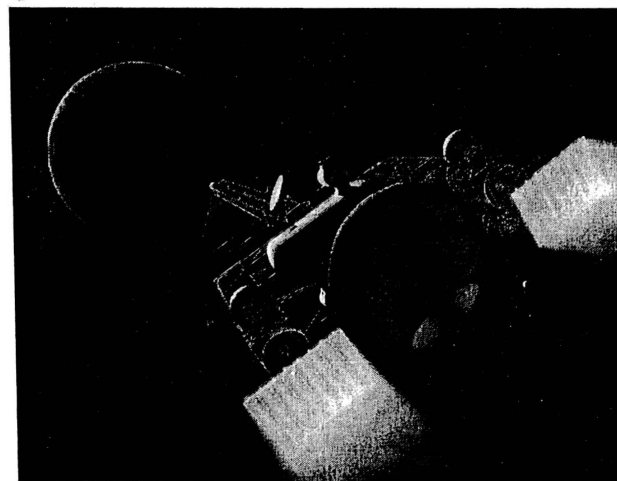
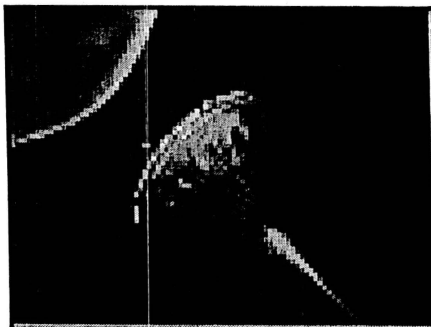


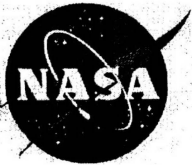
Now...

... And in
the Future.



Hall





Solar Electric Propulsion

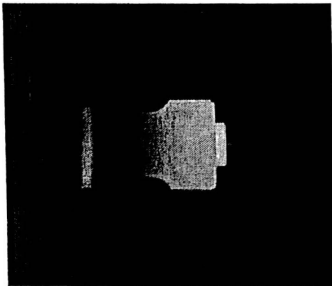


General Description: This area pursues technologies to increase the performance of SEP systems by going to higher power levels, longer life technologies, and by increasing overall system efficiencies.

Applications: Primary propulsion – earth and planetary orbit insertion, station-keeping, precision control, maneuvering

Three Fundamental Propulsion Systems

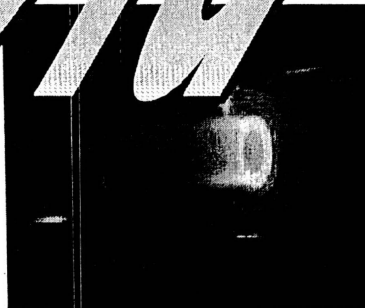
Electrothermal



Propellant heated thermally (physical heater, arc, μ wave, etc.) and exhausted through nozzle

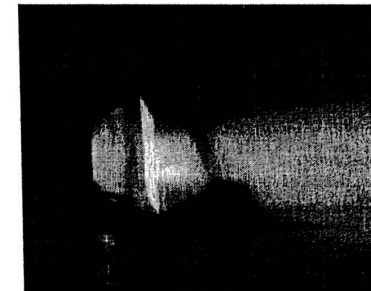
Status: NASA investments paved way for extensive use (Approx. 100 arcjets on orbit) and opened the door for higher performance systems

Electrostatic



Ions created & accelerated by electric field

Electromagnetic

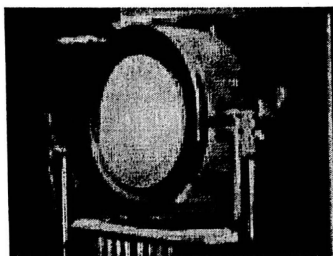


Ions created and accelerated by interaction between current and magnetic field

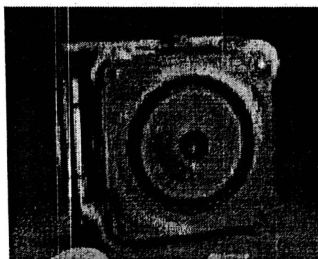
Status: Pulsed Plasma Thruster (PPT) for precision positioning recently demonstrated on Earth Observer 1



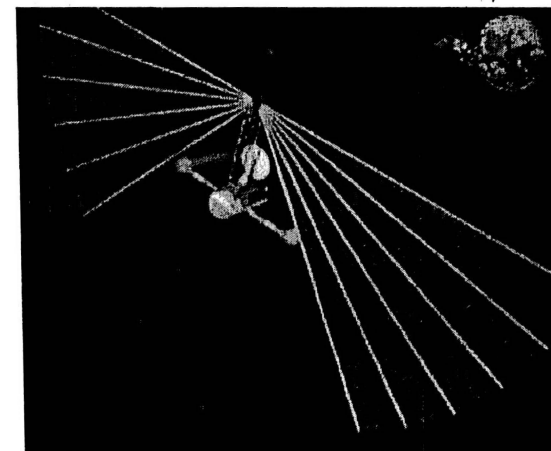
Solar Electric Propulsion Challenges



Ion

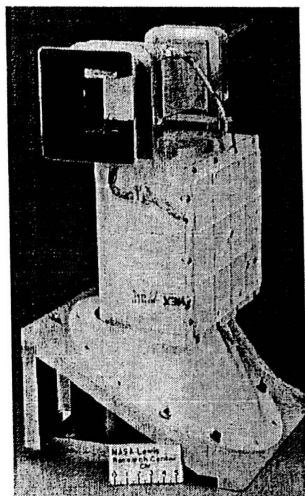


Hall

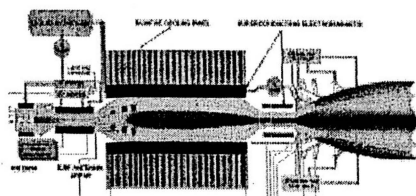


Challenges for SEP applications:

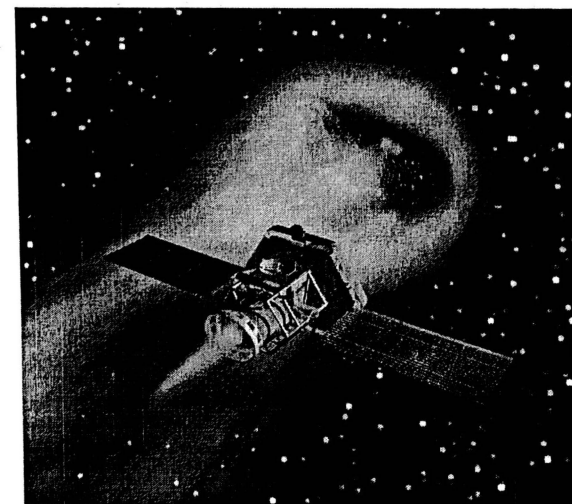
- 'Linerless' composite propellant tanks
- High-temperature, high-voltage isolating materials
- Materials for long life cathodes and insulators
 - Low sputter yield materials
 - Efficient electron emitters
- Low-power cathodes



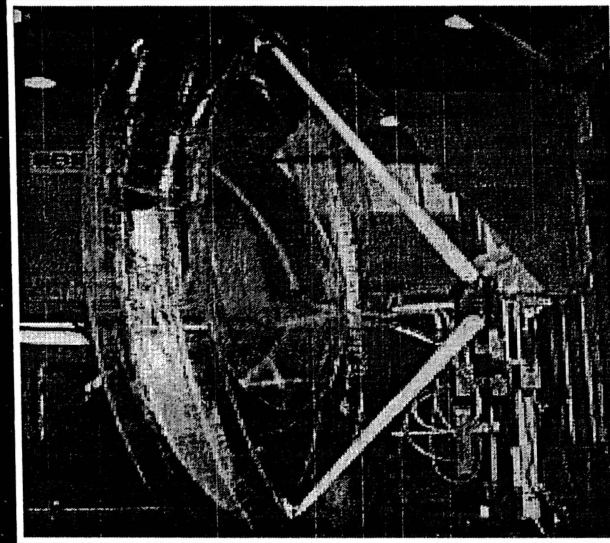
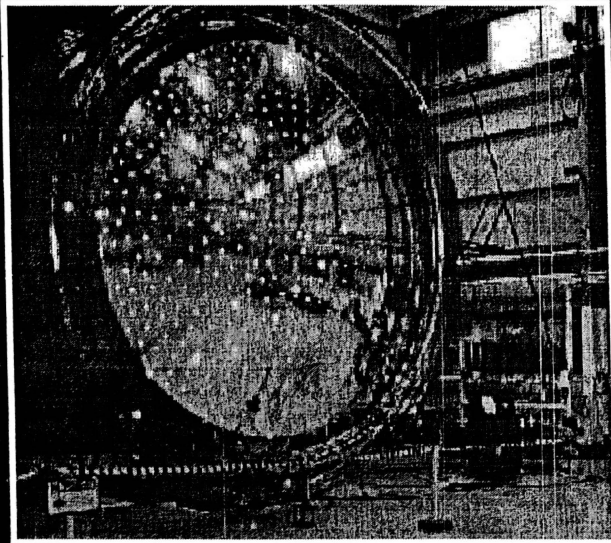
Pulsed Plasma Thruster



VASIMR



Solar Thermal Propulsion



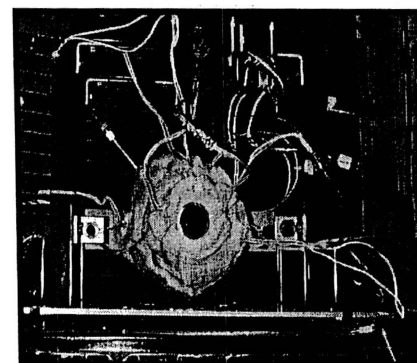
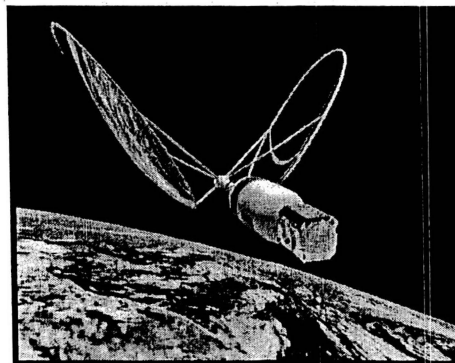
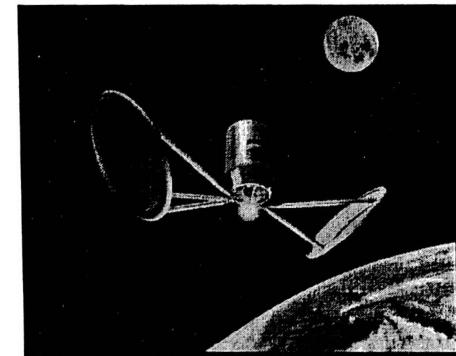


Solar Thermal Technologies



The Solar thermal engine serves as a high temperature heat exchanger and nozzle. Concentrated solar radiation (sunlight) heats mono-propellant without combustion.

Applications include orbit transfer and as the primary propulsion stage, for LEO to GEO, Cargo missions, etc. Solar Thermal would enable relatively short 30-day trips from low earth orbit to geostationary Earth orbit.

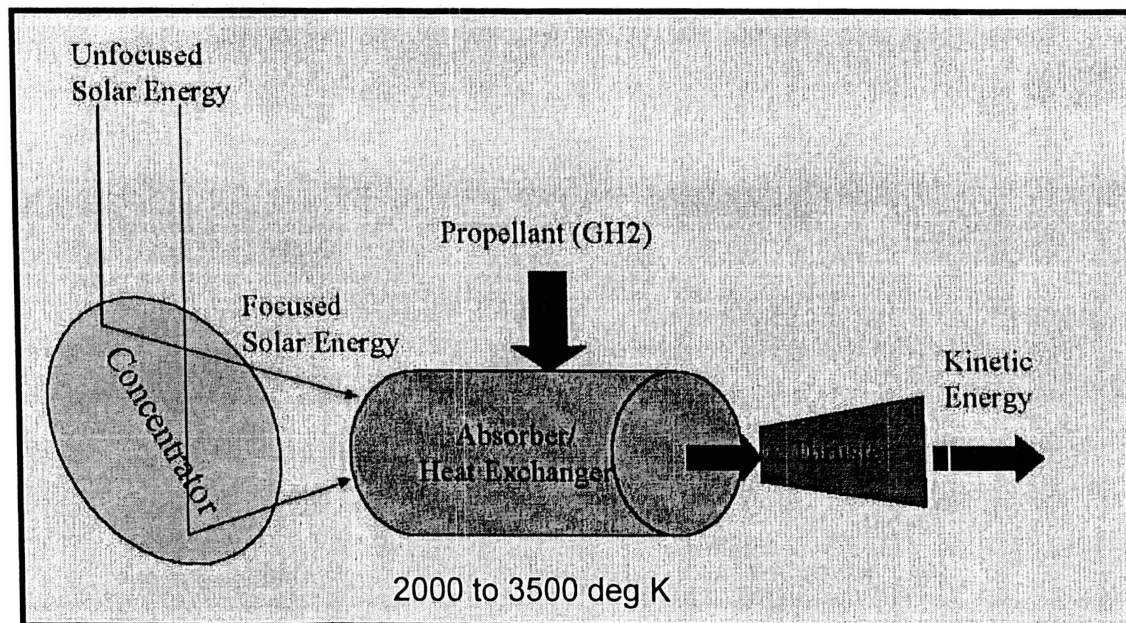


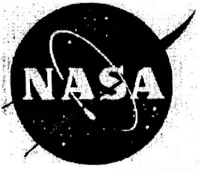


Solar Thermal Propulsion



A solar thermal-powered propulsion (STP) system consists of three basic elements: a Concentrator which focuses and directs incident solar radiation, a Thruster/absorber which receives solar energy, heats and expands propellant (hydrogen) to produce thrust, and a Propellant system which stores cryogenic propellant for extended periods and passively feeds it to the thruster/absorber.

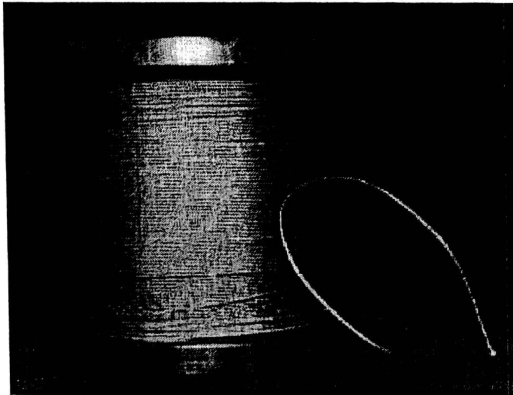




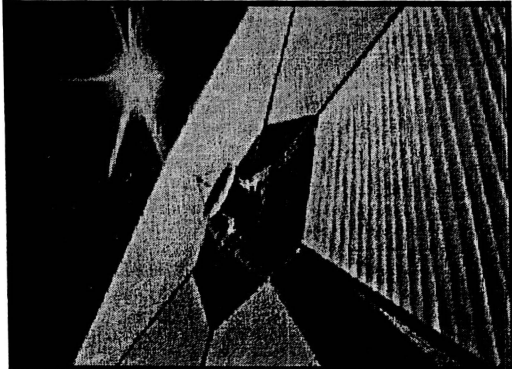
In-Space Transportation Technology Products High Risk/High Payoff & Lower Priority Technologies



◆ Plasma Sails



◆ Momentum Exchange Tethers



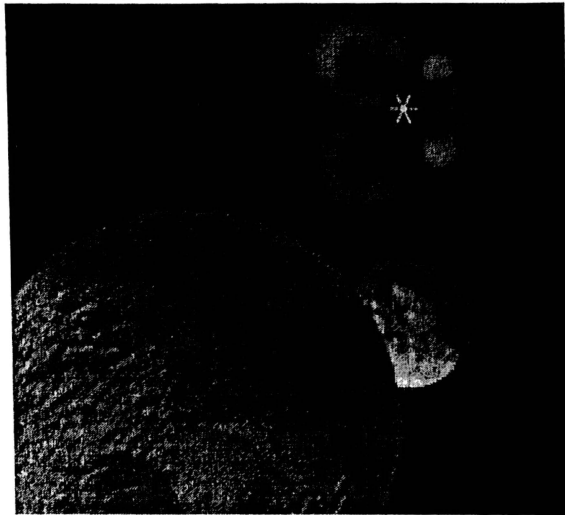
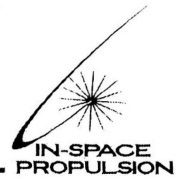
◆ Ultralight Solar Sails ($< 1\text{g/m}^2$)

Plasma Sails





Plasma Sails



This technology is based on the transfer of momentum from the solar wind to an artificial magnetic field structure, similar to the Planetary Magnetosphere that naturally occurs at all magnetized planets in the solar system. Electromagnetic / electrostatic fields are used to create and stabilize an area that exchanges momentum with solar wind, solar photons, or both.

Benefits of Plasma Sails:

This concept would provide dramatic reduction in trip times to the Outer Planets and beyond.

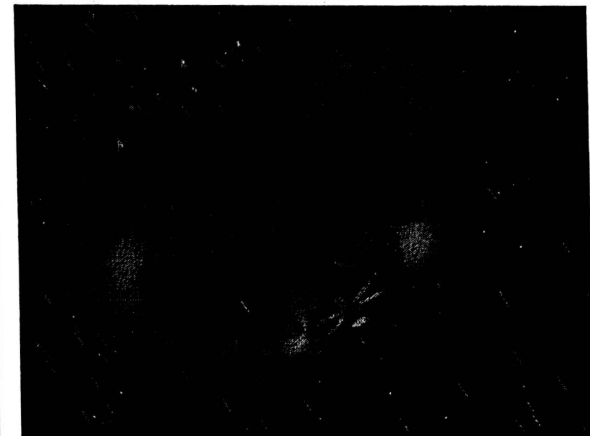
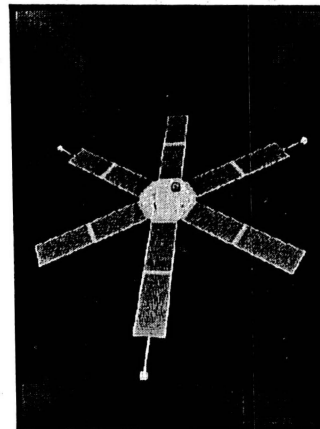
Pluto (fly by) Trip time = 6 years

Saturn (magnetosphere insertion) = 5.6 years

Jovian (magnetospheric insertion) = 1.2 years

Heliopause Trip time = 10 years

The plasma sail in operation may also provide spacecraft radiation shielding. Basic Plasma Sail concepts utilize low cost component technology.

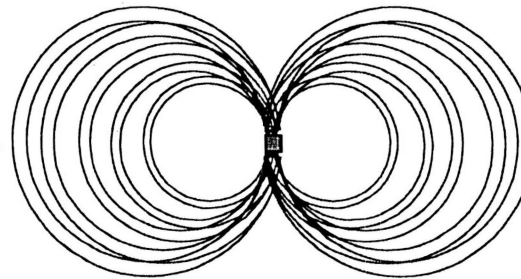
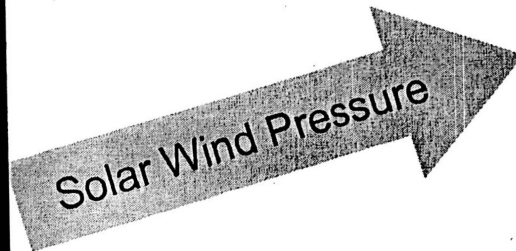
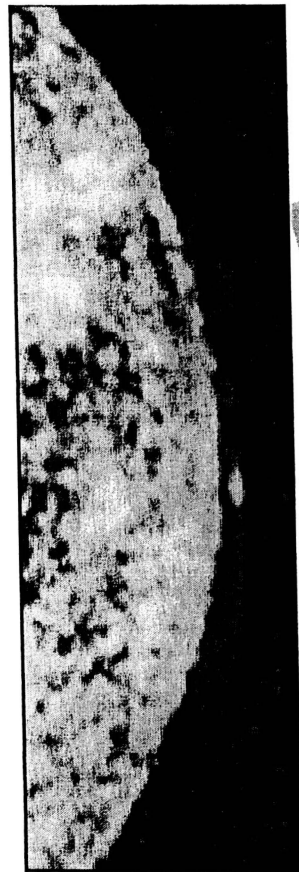




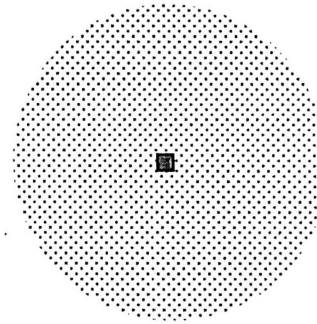
Plasma Sails



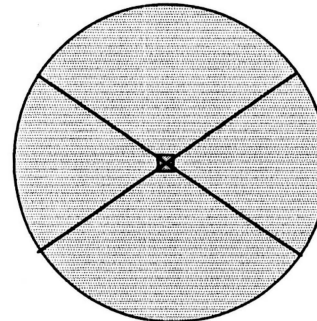
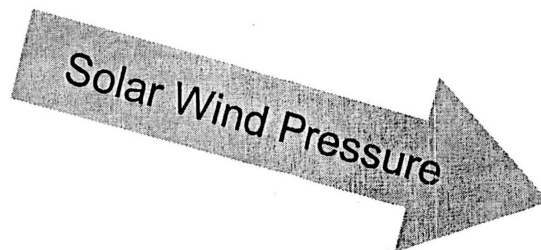
A plasma sail differs from a solar sail in that electromagnetic / electrostatic fields are used to create and stabilize an area that exchanges momentum with the solar wind, solar photons, or both. Here are a few different concepts:



Trapped plasma in an a large (~30 km) inflated dipole magnetic field.
("M2P2")

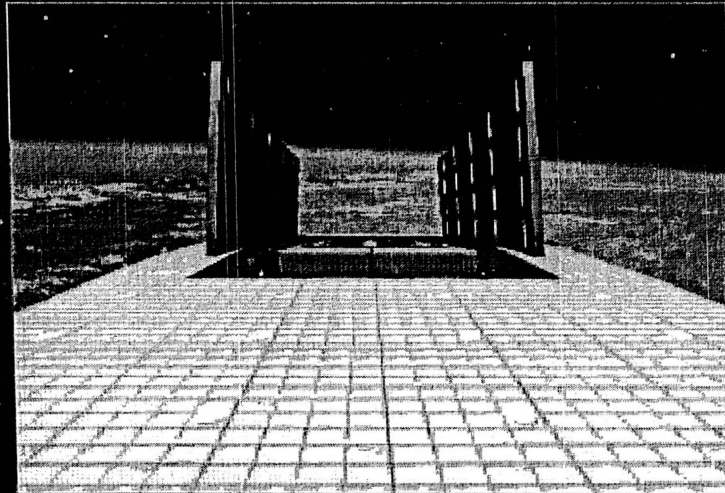


Suspended dust in a small (~300 m) magnetic field.
("Dusty Sail")

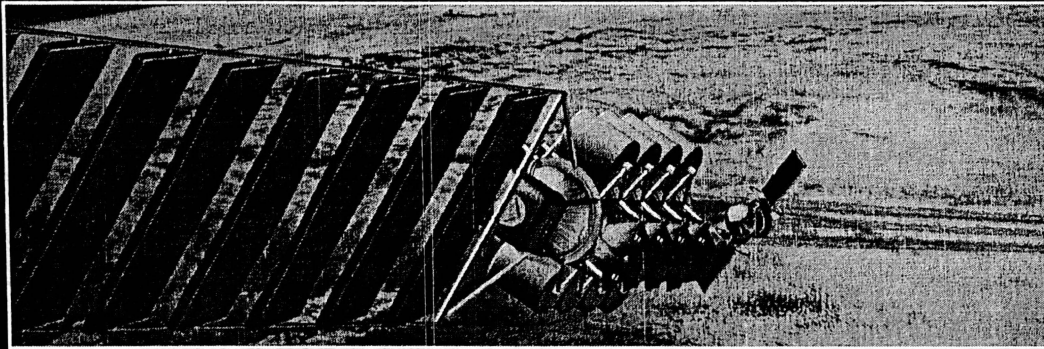


"Electrostatic sail"

Mission to Neptune

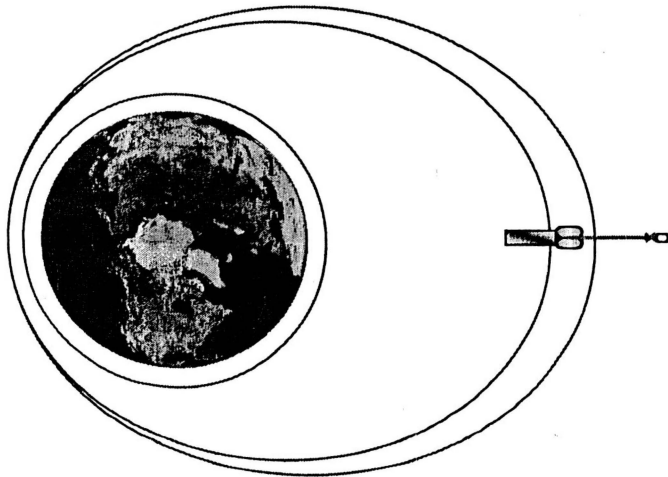
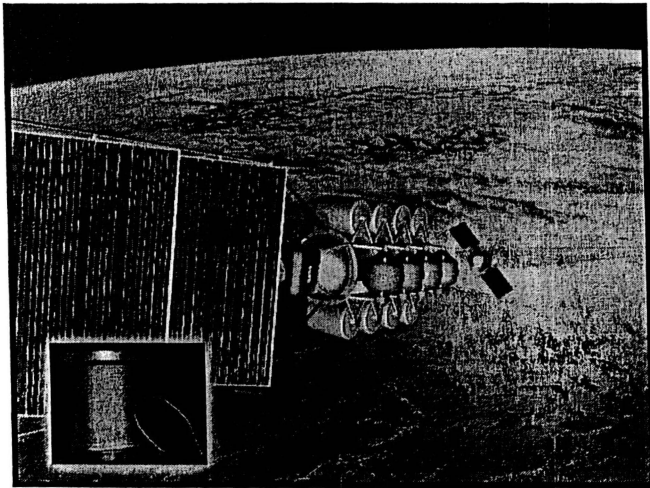


MXER Tether





Momentum Exchange Tethers



◆ General Description

- Momentum-exchange/electrodynamic reboost (MXER) tether facility in Earth orbit boosts spacecraft to high-energy, pre-escape trajectories
- High-thrust propulsion conducts ΔV at perigee to target hyperbolic C3
- Low-thrust propulsion (Solar Electric Propulsion, Nuclear Electric Propulsion, sails) uses lunar swingby to achieve low-C3 heliocentric orbit

◆ Benefits

- ~90% of Earth escape ΔV provided by tether
- Electrodynamic propulsion can reboost tether without propellant
- MXER tether facility supports commercial Geosynchronous Earth Orbit missions as well as interplanetary spacecraft



MXER Mission Benefits

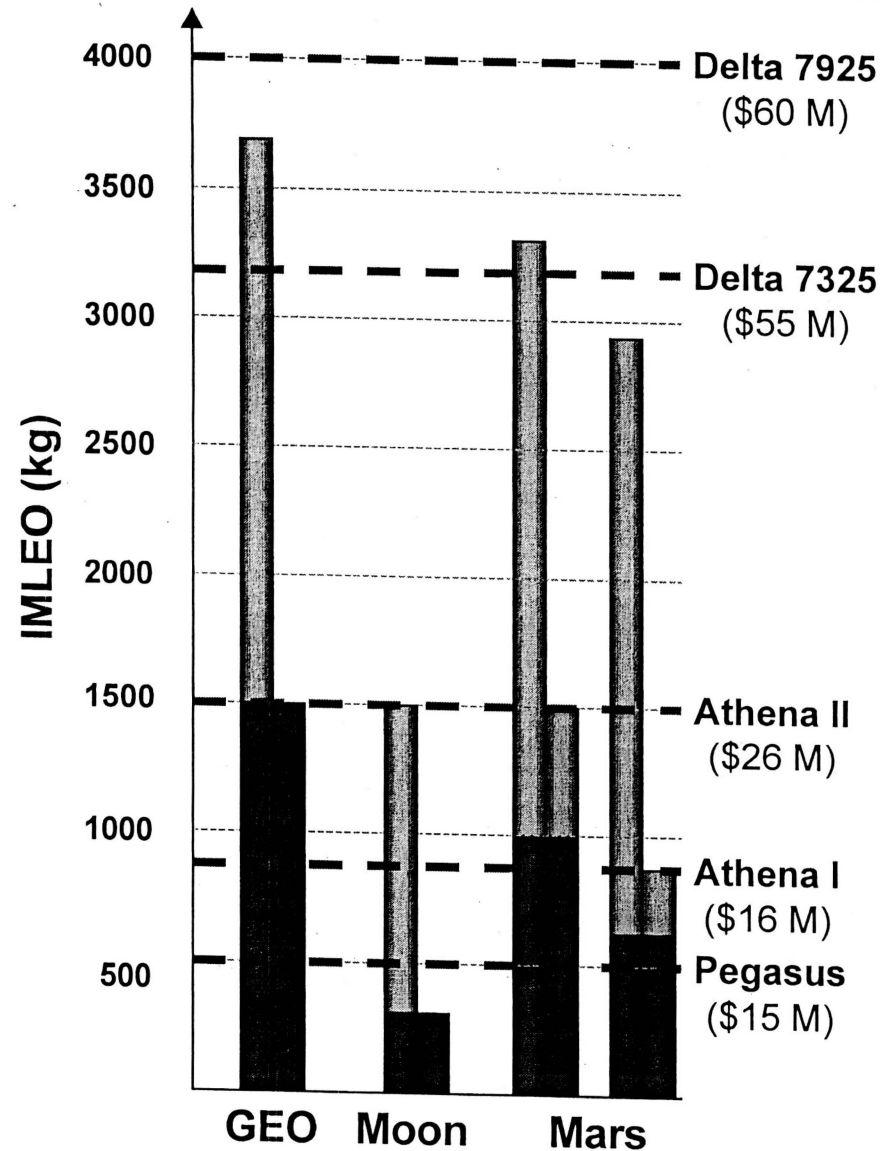


MXER Tether dramatically reduces launch vehicle size. This enables the mission to be launched on a smaller, lower-cost launch vehicle.

The only high thrust, reusable, high-Isp upper stage!



- Spacecraft w/SEP thrusters and propellant
- Injection stage mass (propellant and dry)

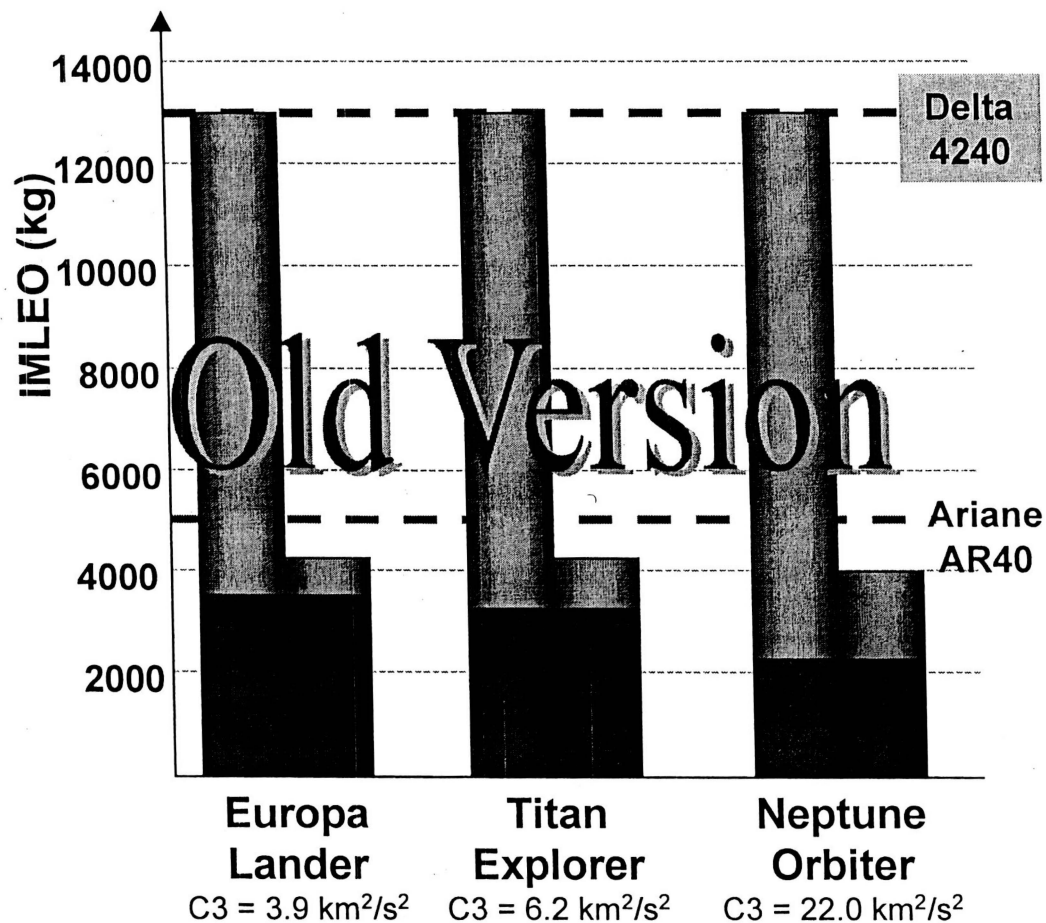




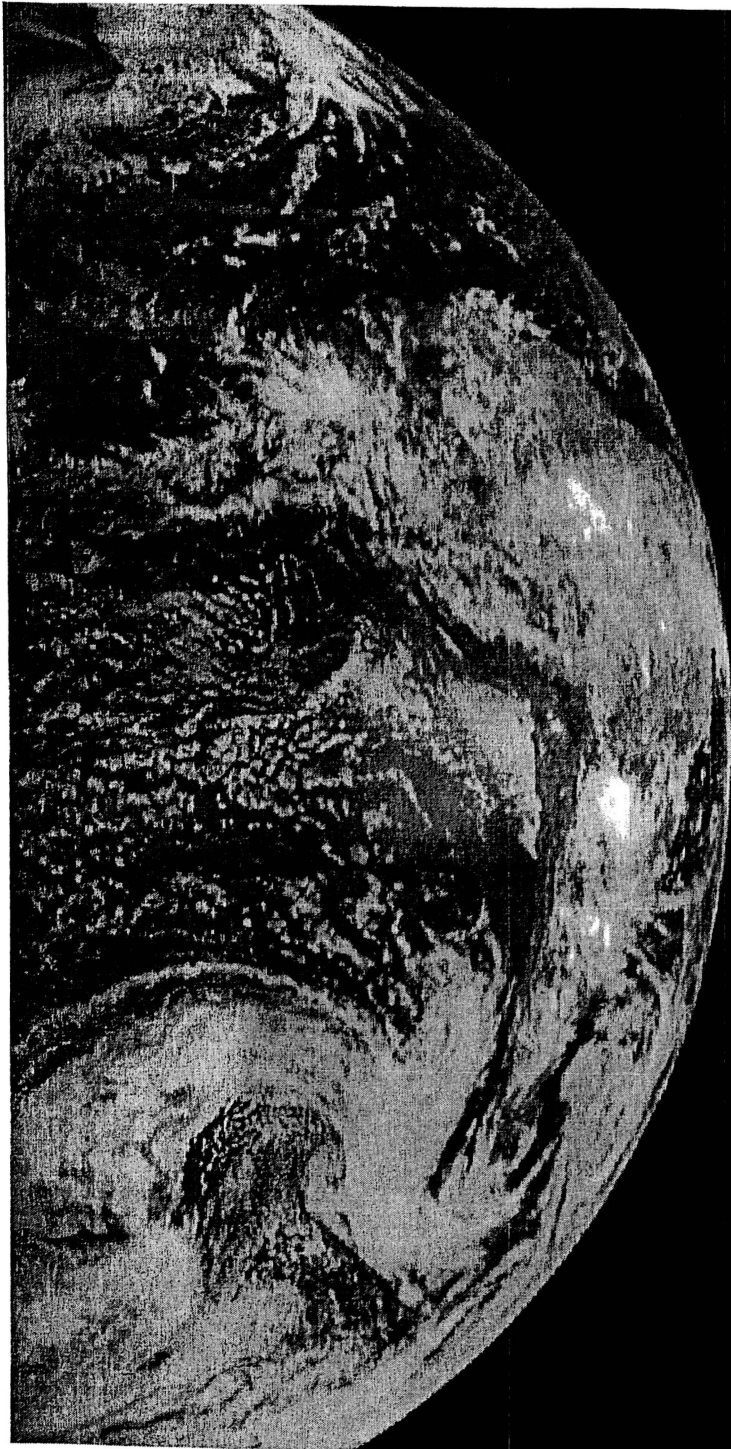
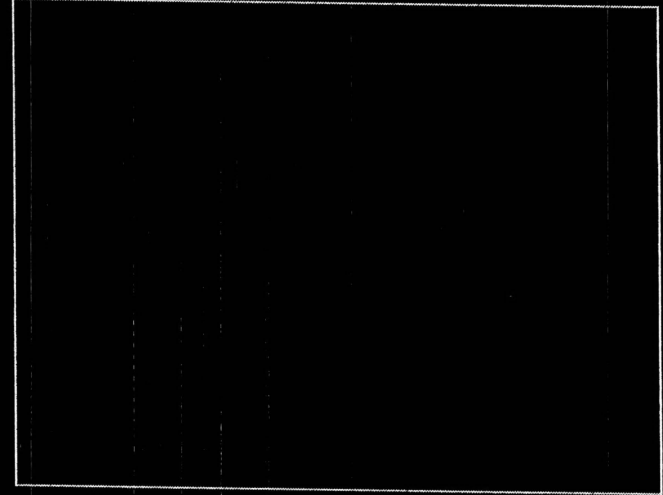
Momentum Exchange Tethers



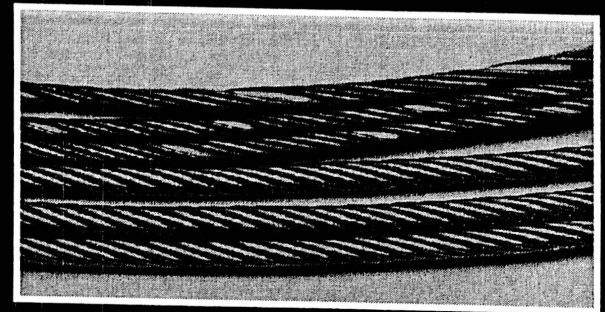
MXER Tether dramatically reduces launch vehicle size. This enables the mission to be launched on a smaller, lower-cost launch vehicle.



MXER Tether

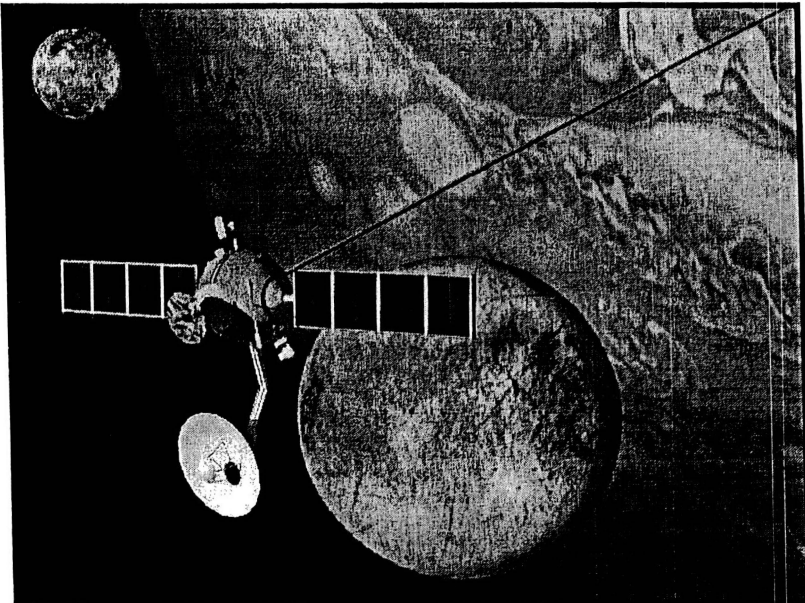
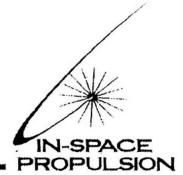


Electrodynamic Tethers





Electrodynamic Tethers Offer Propulsion and Power Without Fuel

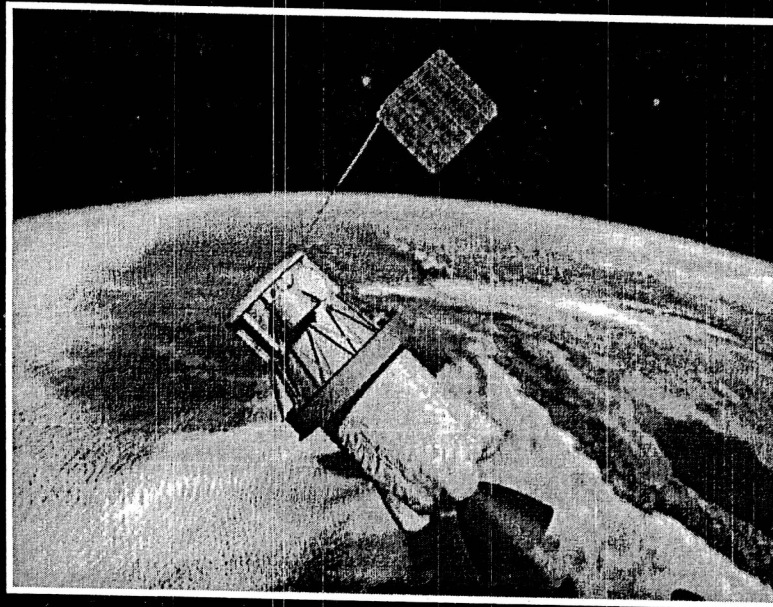


The conducting Electrodynamic Tether (EDT) produces an induced Electromagnetic Field (EMF) as it passes through a planetary magnetic field and when the electric circuit is completed through the ionosphere it produces thrust and/or power. The gaseous giants have ideal environments for EDT operations because of their rapid rotation rates and intrinsic magnetic fields.

Benefits of Electrodynamic Tethers:

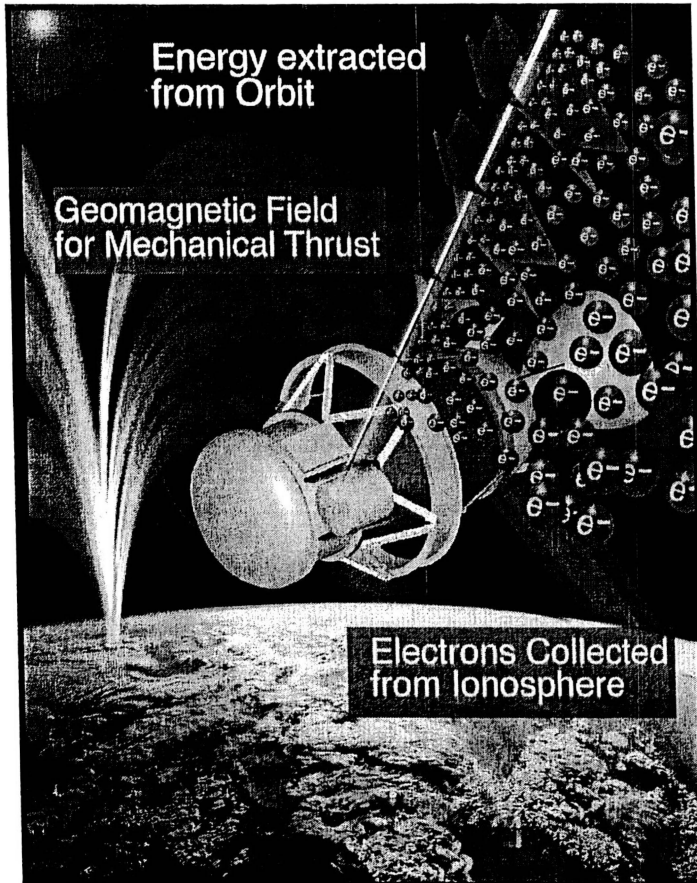
- Braking force merely requires resistive dissipation of energy
- Propellantless propulsion and continuous power (kW to MW) at gas giants (Jupiter, Saturn)
- No need to preserve onboard fuel for deorbit at end of life
- Allows all rocket fuel to be used for orbit insertion; results in higher efficiency system
- Increases efficiency of upper stages and the stationkeeping lifetime of orbiting spacecraft
- Enabling technology for MXER tethers

ProSEDS



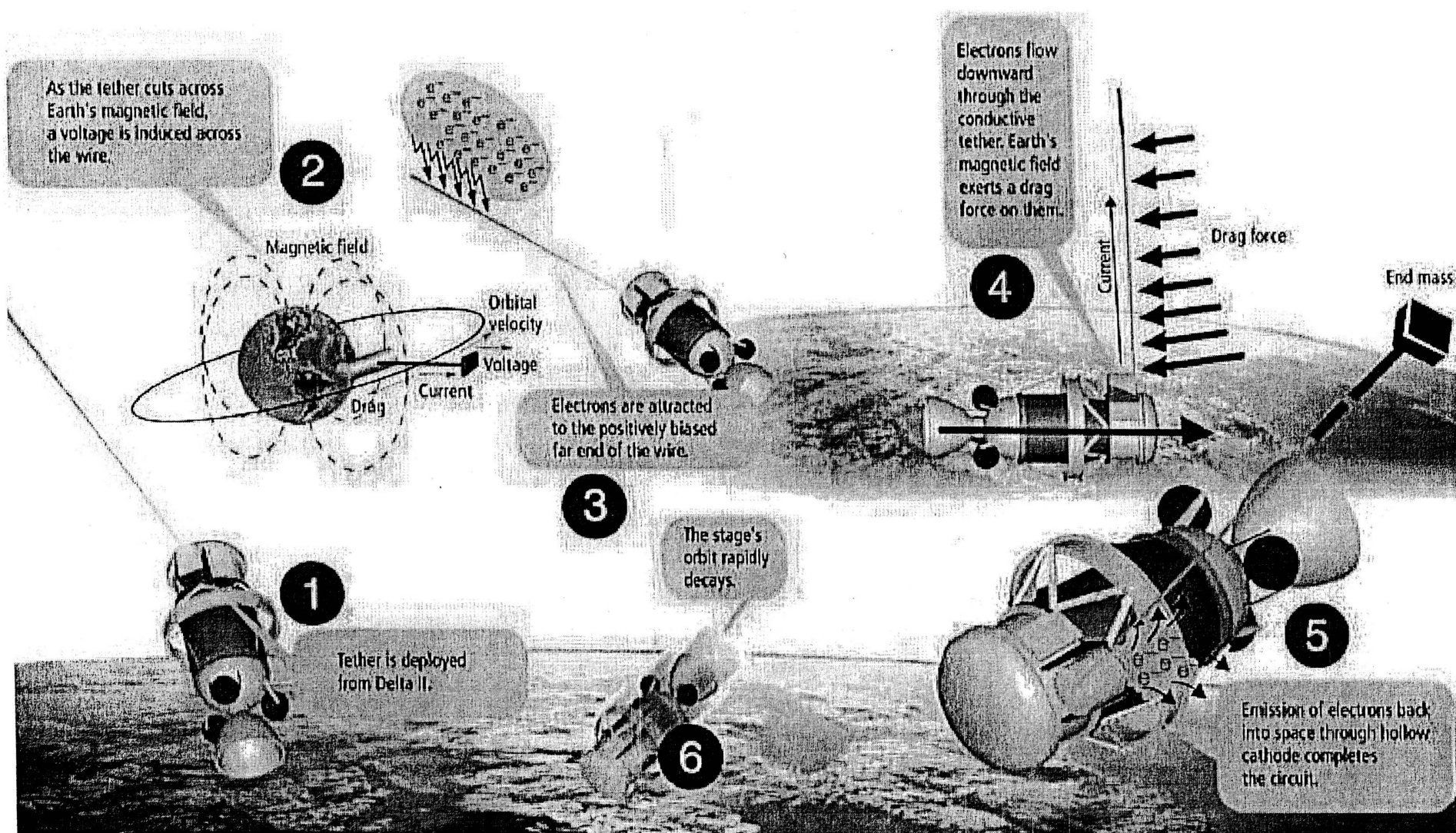


Propulsive Small Expendable Deployer System (ProSEDS) Experiment

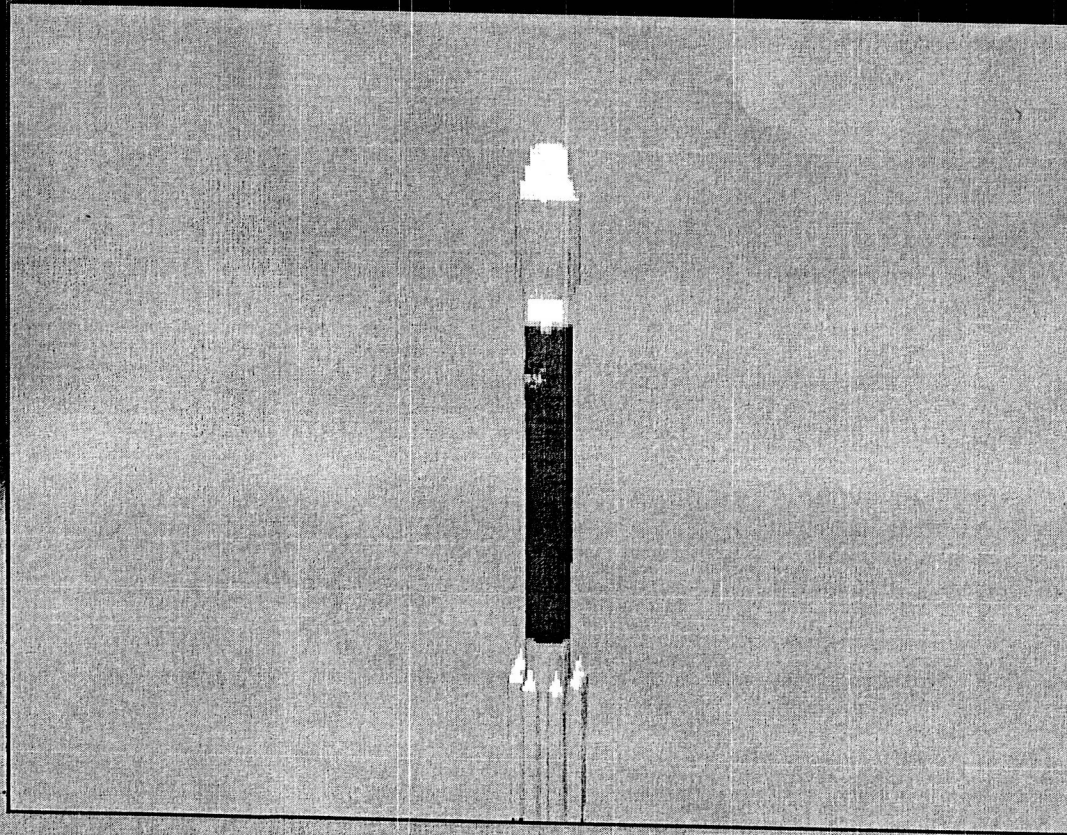


What is ProSEDS?

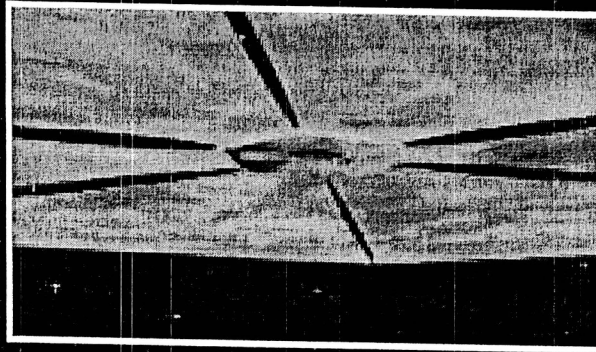
ProSEDS is a secondary payload on a Delta-II GPS Mission. A 5 kilometer conducting wire (tether) will be deployed to generate electrodynamic thrust without propellant. The Delta stage then rapidly descends. Current flowing through the tether experiences a drag force because of interaction with Earth's magnetic field. This drag force is coupled mechanically to the stage via the tether, thus lowering the stage's orbital Altitude. ProSEDS is scheduled for launch this year.



ProSEDS

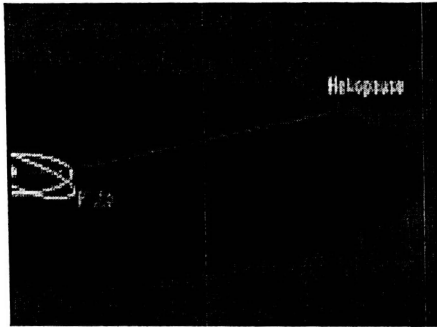


Ultra-lightweight Solar Sails

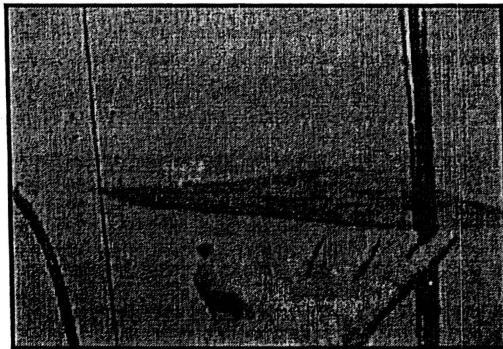




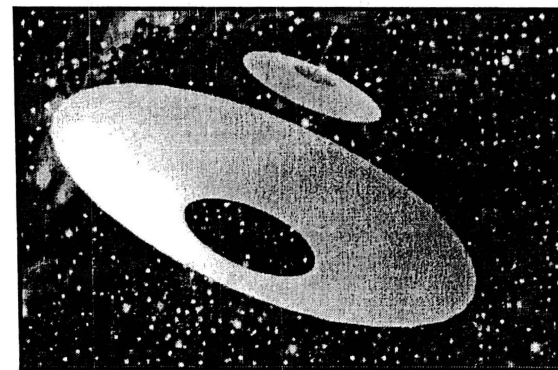
Solar Sail Propulsion for Interstellar Exploration



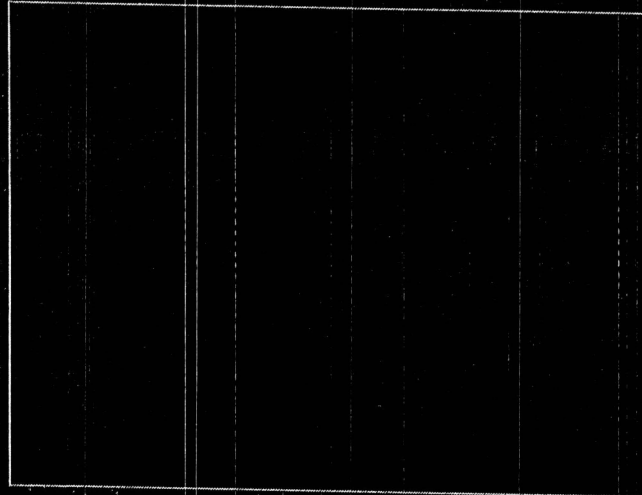
The Heliopause is a barrier where charged particles from the sun cannot go beyond because cosmic rays from deep space force them back.



**Carbon fiber μ -truss fabric
(1 gm/m², 2 mm thick)**



Ultra-lightweight Solar Sails

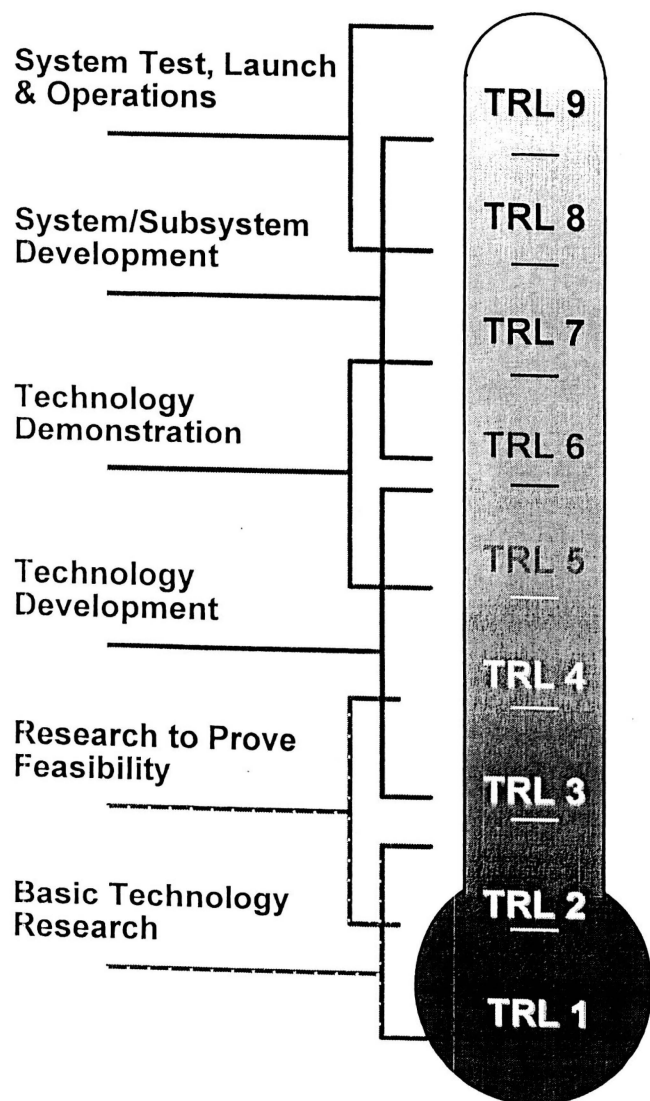
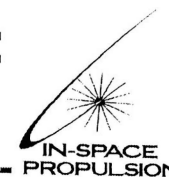




BACKUPS



In-Space Propulsion Program Mid-TRL Technologies: Definitions of Technology Readiness Levels



TRL 6

Definition: System / subsystem model or prototype demonstration in a relevant environment (Ground or Space).

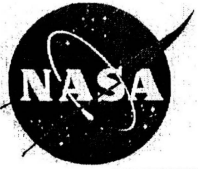
TRL 4 & 5

Definition(4): Component and / or breadboard validation in laboratory environment.

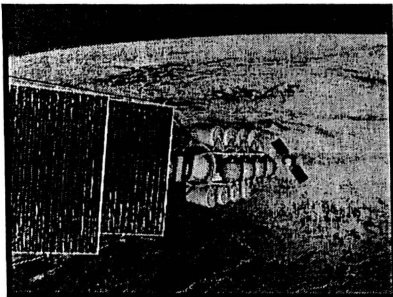
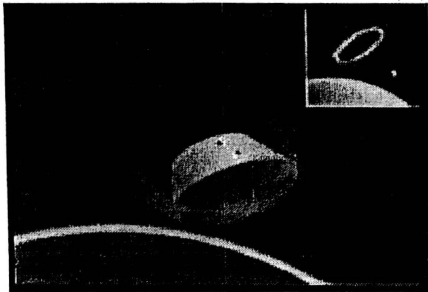
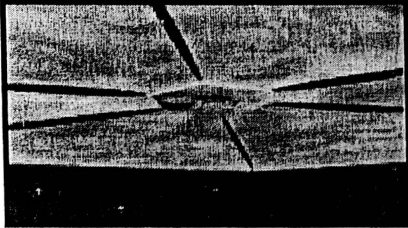
Definition(5): Component and / or breadboard validation in relevant environment

TRL 3

Definition: Analytical and experimental critical function and / or characteristic proof-of-concept.



In-Space Propulsion Program Overview



♦ Objective

- Develop in-space propulsion technologies that can enable and/or benefit near and mid-term NASA science missions by significantly reducing cost, mass, and/or travel times.

Technology areas include:

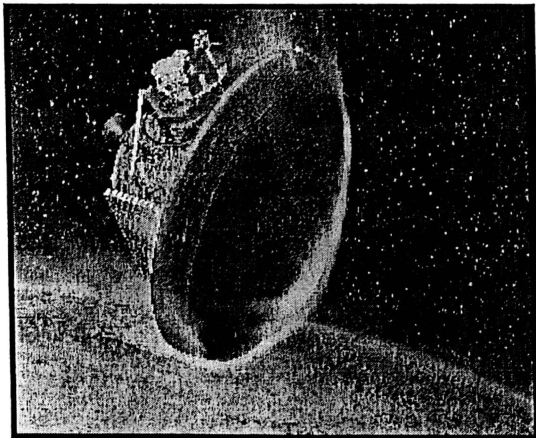
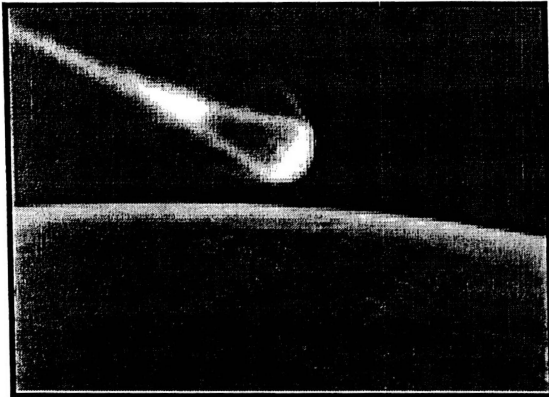
- Solar Electric Propulsion (nuclear electric is now part of Nuclear Systems Initiative)
- Propellantless Propulsion (aerocapture, solar sails, tethers, etc.)
- Advanced Chemical Propulsion

♦ Approach:

- Identify and prioritize the most promising technologies using systems analysis and peer review.
- Develop mid-TRL technologies to TRL 6 for incorporation into mission planning within 3-5 years of initiation.
 - Maximize use of open competition to seek best solutions



Aeroassist / Aerocapture

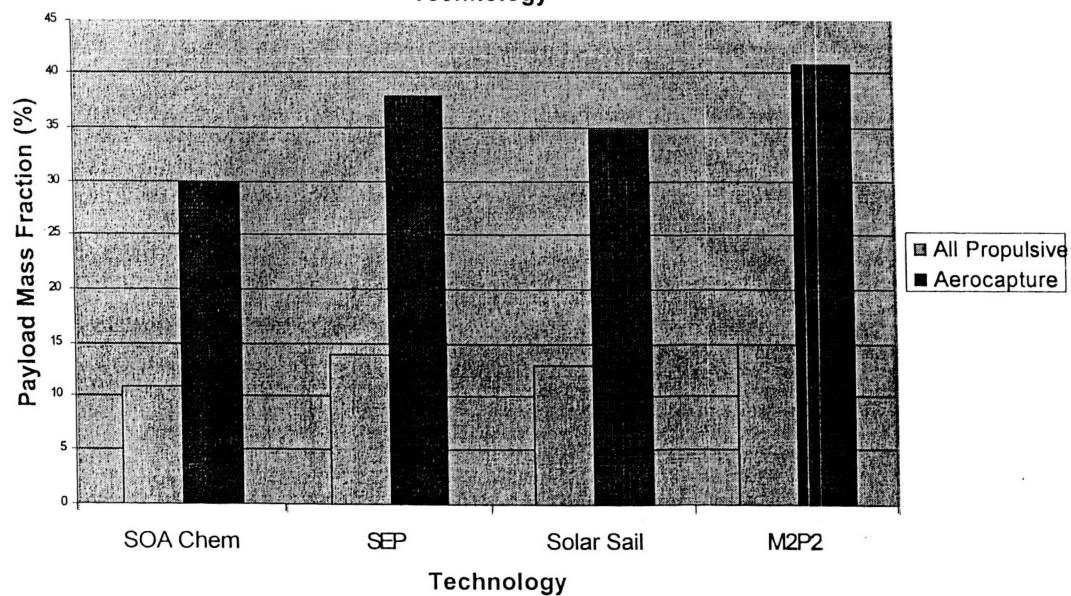
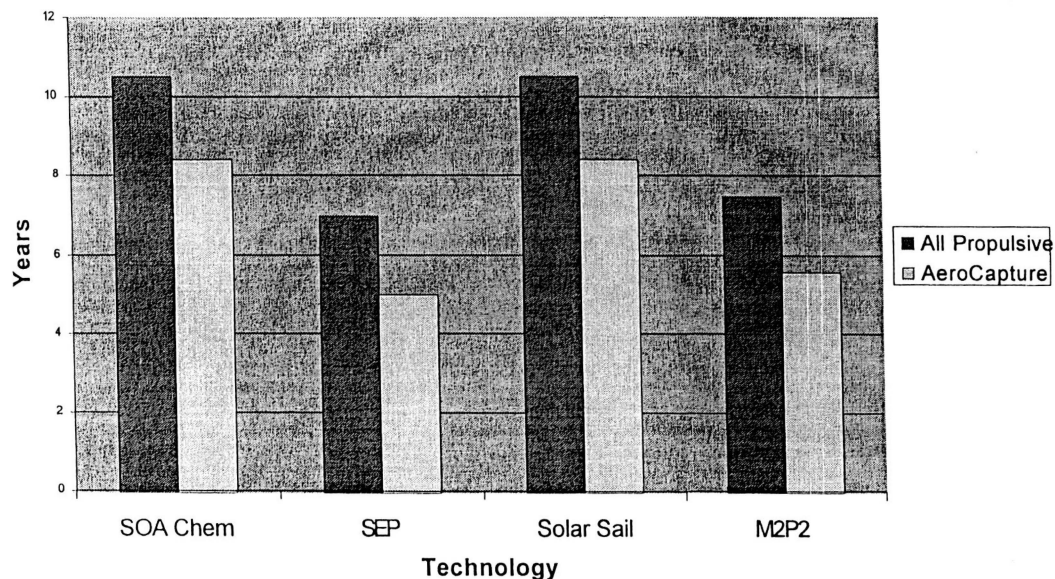


◆ Benefits:

- Very little propellant required for orbit insertion/entry
- Capable of high delta V impulsively at target arrival (multi-g deceleration)
- No environmental issues
- Lower transportation system mass
- Enhance science return and reduce risk
- Shortens trip times to outer planets (by using aerogravity assist or allowing higher Earth departure energies)
- Enables precision landing
- Improves reliability and science return



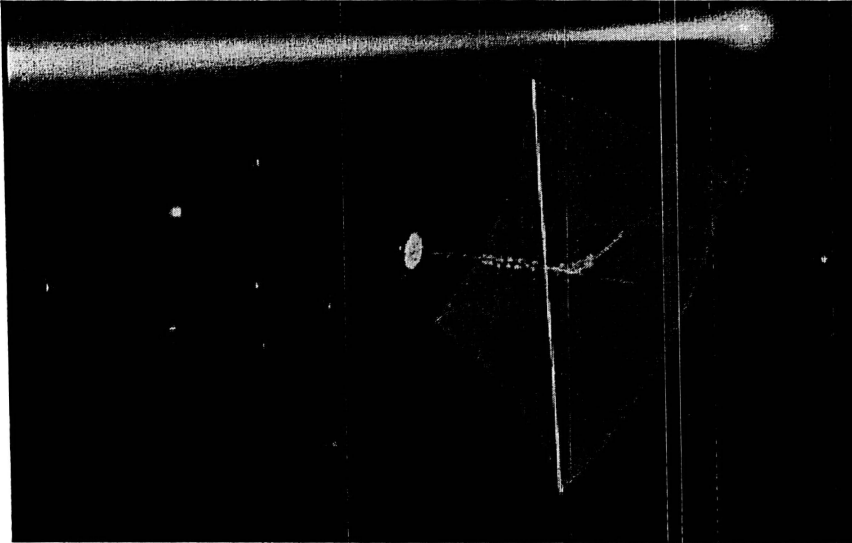
Benefits of Aerocapture Example: Titan Explorer



**Aerocapture
provides significant
benefits in Trip Times
&
Payload Mass Fraction
to all mission designs**



Solar Sails



◆ Benefits:

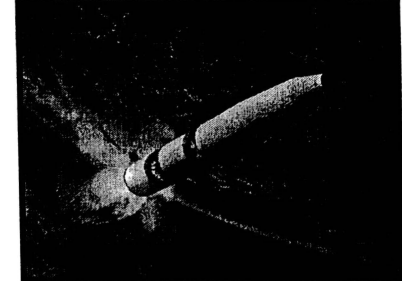
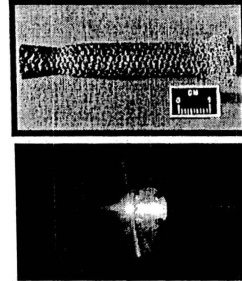
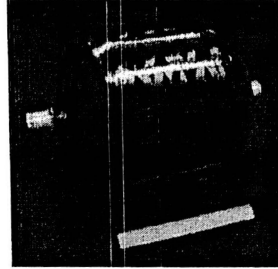
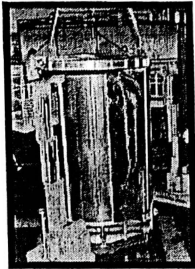
- No propellants required
- As technology advances (lighter sail material) more ambitious missions are possible – missions closer to the sun and reduced trip time for outer planets
- Very simple design (engineering challenge is large area and low mass)
- No environmental issues
- Sails can open up new regions of the solar system to accessibility for important science missions

◆ General Description:

Solar sails use photon “pressure” or force on thin, lightweight reflective sheet to produce thrust;



Advanced Chemical Propulsion



Cryogenic Fluid Management

Enabling long-term storage of cryogens in low g, especially important to outer-planet missions. These concepts also provide benefits to other In-Space Propulsion Technologies such as which also make use of cryogenic storage for fuels. . .

Lightweight Components

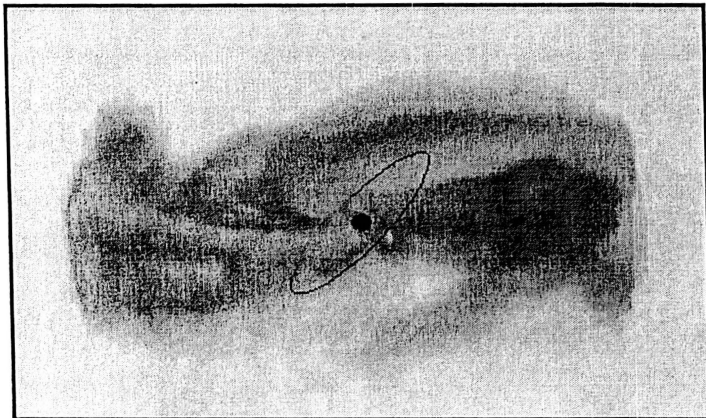
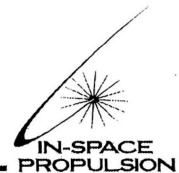
Optimizing component, material and manufacturing technology to reduce mass. Benefits are cross-cutting: applying to feed system components, tanks, etc., new lightweight components also provide advantages in over-all mass savings to propulsion technologies beyond Advanced Chemical Propulsion, including kw SEP,

Advanced Fuels

These storable chemical propulsion concepts offer performance improvements over state-of-the-art Chemical Propulsion, through attributes such as higher density or increased Isp or operating temperature.



Solar Polar Imager



♦ Measurement Strategy

- ♦ Surface Velocity for Helioseismology Investigations
- ♦ High Latitude Magnetic Fields and Coronal Holes
- ♦ Image Corona and Inner Heliosphere from Over Poles
- ♦ Image Coronal Mass Ejections in the Ecliptic Plane
- ♦ In-situ Particles and Fields Measurements
- ♦ Solar Irradiance in Polar Regions

♦ Science Objectives

- ♦ Measure near-surface meridional circulation
- ♦ Measure sub-surface jets and azimuthal and meridional circulation
- ♦ Measure the Sun's polar magnetic field and refine solar dynamo models
- ♦ Measure global oscillations on the far side of the Sun
- ♦ Image global effects of CMEs and evolution on the full 3-D corona
- ♦ Track the complete life cycle of active regions and coronal holes
- ♦ Link variations in the high-latitude heliosphere to surface conditions
- ♦ Measure angular momentum loss in the solar wind

♦ Mission Description

♦ Example Mission Design

- Launch: Delta II 2425, 769 kg @ $C_3 = 0.25 \text{ km}^2/\text{s}^2$
- Solar Sail Trajectory
 - 4 - 5 Year Flight Time, 2 year OPS
- Final Orbit: 0.48 AU Circular Solar Orbit with 60° Inclination
 - 3:1 Resonance with Earth

♦ Flight System Concept

- 3-Axis Stabilized
- Solar Array Implementation
- Payload: 34 kg, 24.5 W, 15.6 kbps