ADVANCED PROPULSION FOR THE XXIst CENTURY

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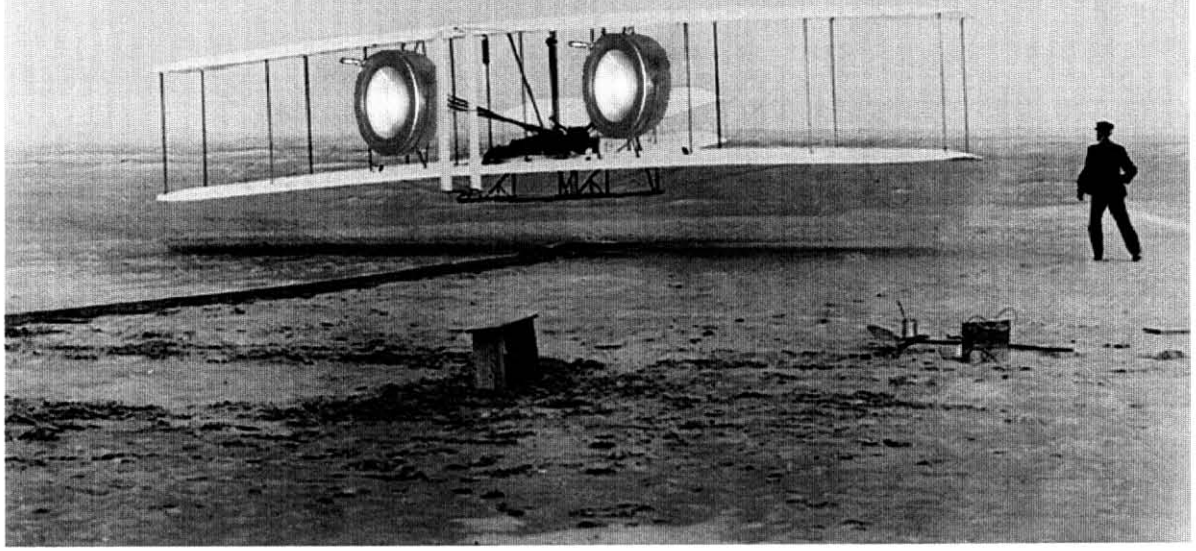
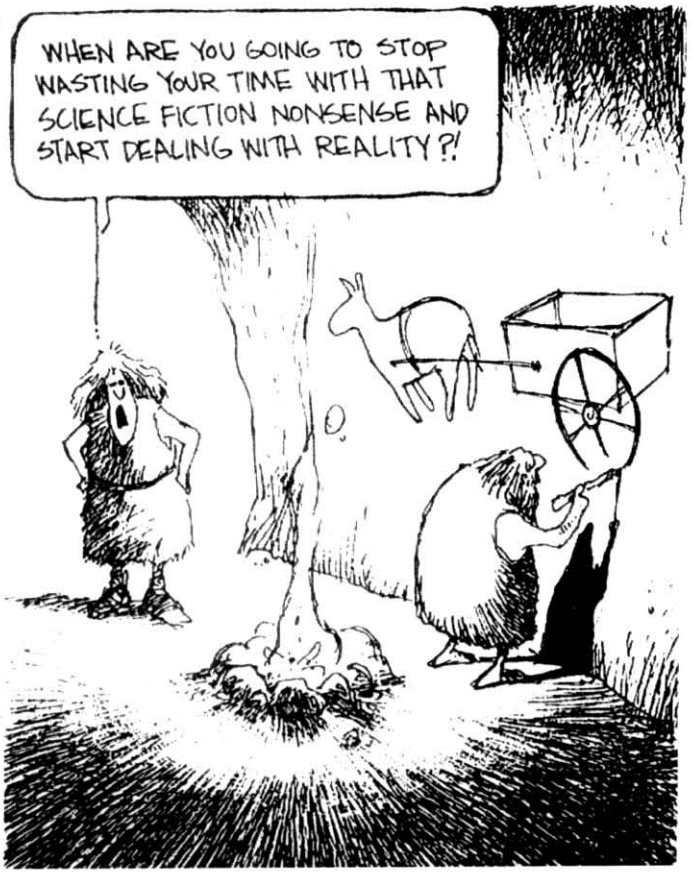


OUTLINE

- Introduction
  - The need for Advanced Space Propulsion:
    - Reduce costs
    - Enable bold, new missions
- Categories and Applications of Advanced Space Propulsion
  - What are the Options
  - Where do they fit in different Mission Applications
- Looking to the Future
  - Limitations and Possibilities



NON SEQUITUR By Wiley

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THE OTHER CENTENNIAL OF (SPACE) FLIGHT

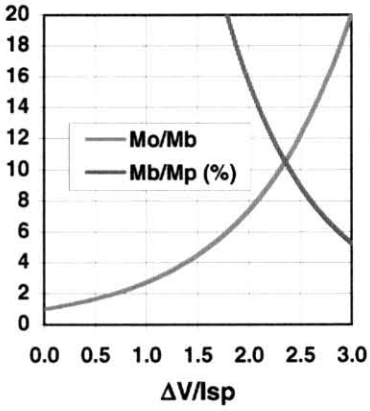
1903: Konstantin E. Tsiolkovsky derives the fundamental equation describing rocket performance:

The Rocket Equation

$$M_o / M_b = EXP(\Delta V / g_c \bullet I_{sp})$$

$$M_p = M_o - M_b$$

- M_o = Initial ("wet") mass
- M_b = Final burnout ("dry") mass
- ΔV = Velocity change
- I_{sp} = Specific Impulse = Thrust / M-Dot
- g_c = Unit conversion between ΔV and I_{sp}
- M_p = Propellant mass



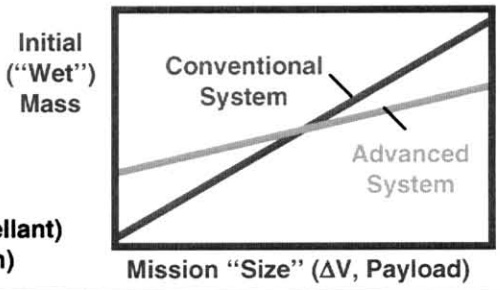
As ΔV/Isp increases

- Wet Mass grows exponentially
- Eventually can't build tanks light enough to hold required propellant ("impossible mission")

- **BUT - Isp ISN'T THE WHOLE STORY!**

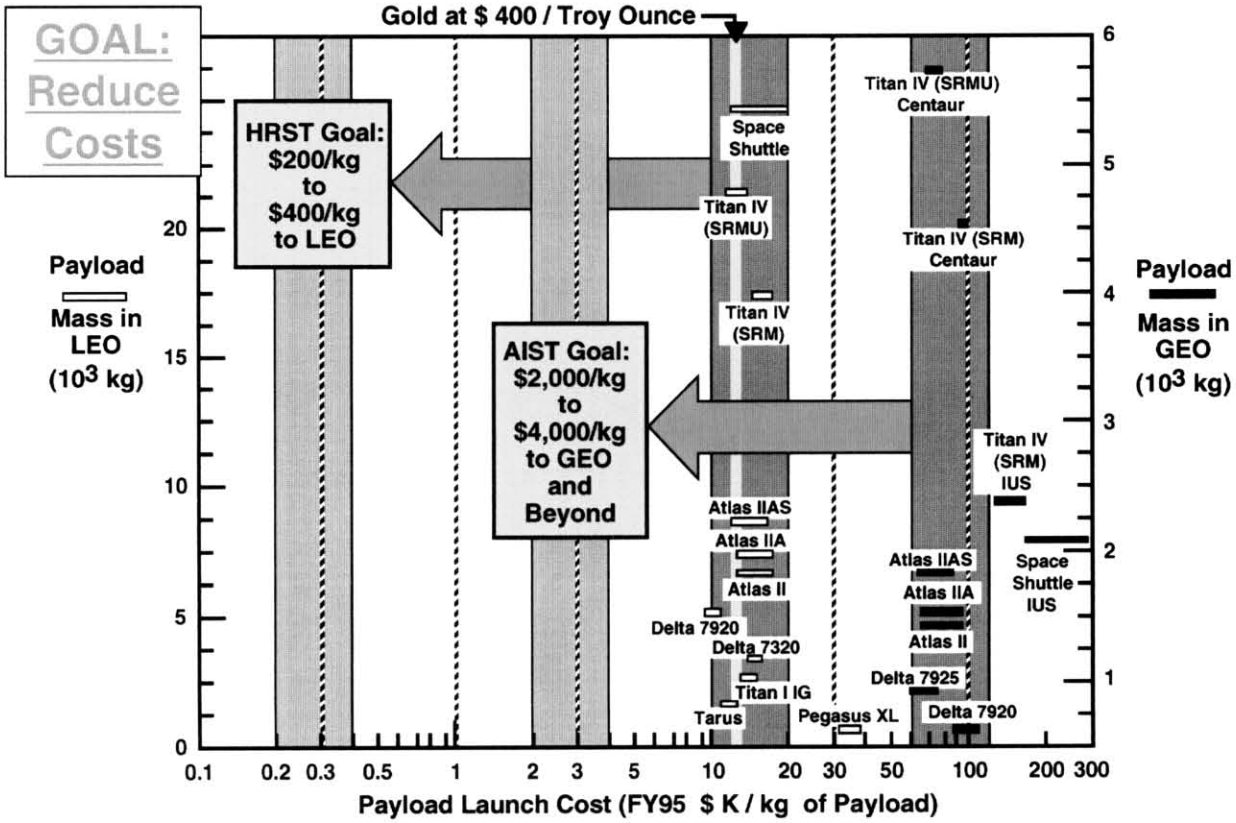
$$M_b = M_{Dry} + M_{PL}$$

- M_b = Final burnout ("dry") mass
- M_{Dry} = Propulsion system "dry" mass (without propellant)
- M_{PL} = Payload mass (Everything that isn't propulsion)



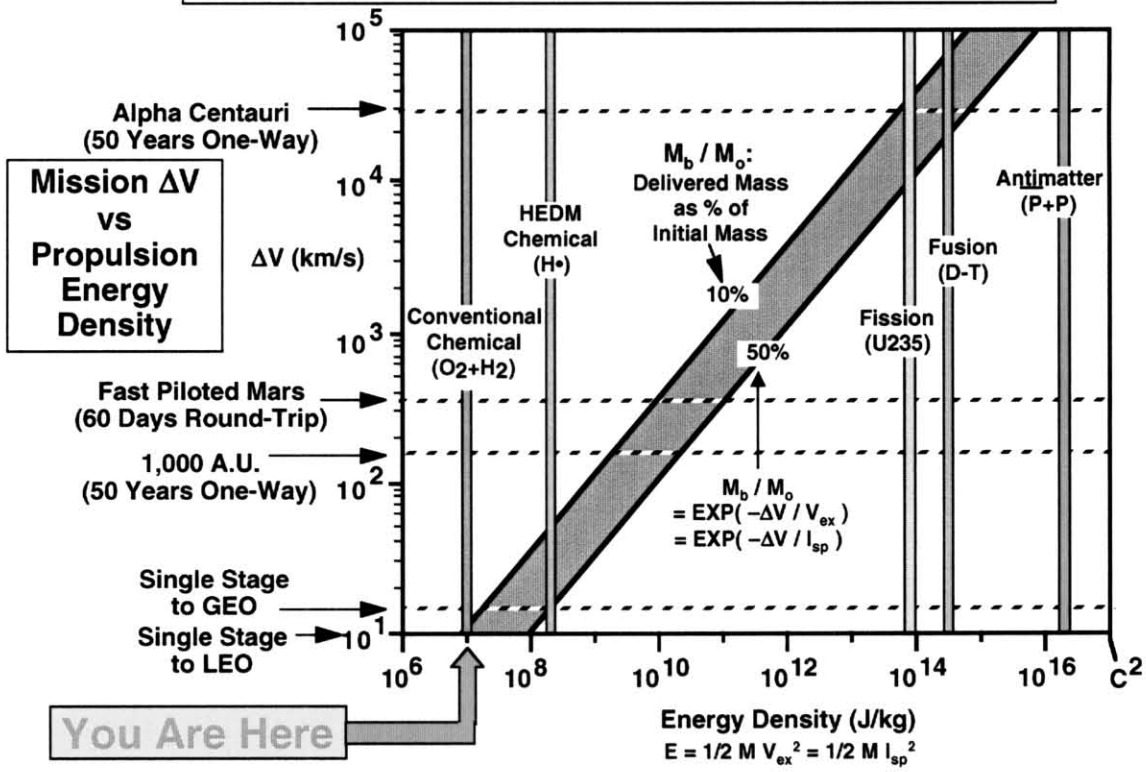
Improve cost/performance by attacking:
- Isp
- Dry Mass
- ΔV
- Circumvent the limits inherent in the Rocket Eq.

THE PROBLEM: HIGH LAUNCH COSTS WITH EXISTING LAUNCH VEHICLES



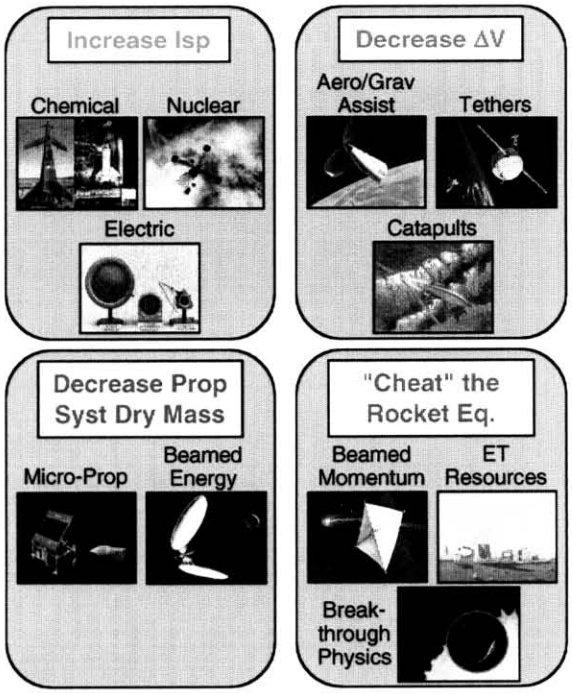
THE PROBLEM: MISSION CAPABILITY

GOAL: Enable New / Impossible Missions



ADVANCED PROPULSION IN PERSPECTIVE

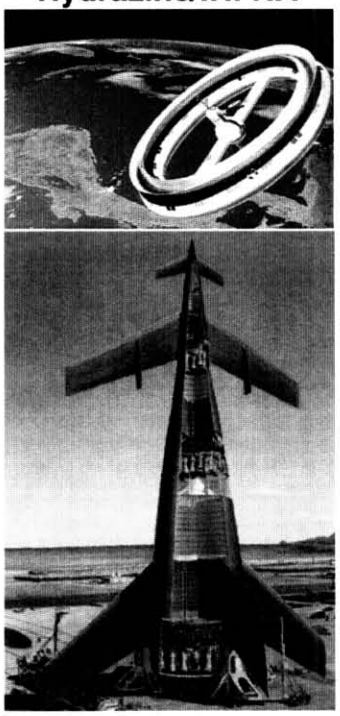
- **Overriding goal of advanced space propulsion is to <u>reduce cost</u> and <u>enable new missions</u>**
- **Ultimate performance limit is determined by Rocket Equation: $M_{final}/M_{initial}$ = exp(ΔV/Isp)**
  = f (Isp, Prop System Dry Mass, ΔV)
- **How do we improve performance ?**
  - Increase Isp
    - **Historical Emphasis: Chemical -> Electric -> Nuclear -> · · · · ·**
  - Decrease Prop System Dry Mass
    - **Inflatable Structures, On-Orbit Assembly**
    - **Micro-Propulsion**
    - **Beamed-Energy (Take the Engine Energy Source Off of the Vehicle)**
  - Decrease ΔV that Must Be Supplied by the Propulsion System
    - **Gravity Assist**
    - **Aeroassist, Aero-Gravity Assist**
    - **Catapults**
    - **Tethers**
  - Circumvent the Intrinsic Physics of the Rocket Equation
    - **Don't Carry All the Propellant You'll Need With You - Live Off the Land: Beamed-Momentum Sails, Extraterrestrial Resources**
    - **Invent Totally New, Breakthrough Physics**



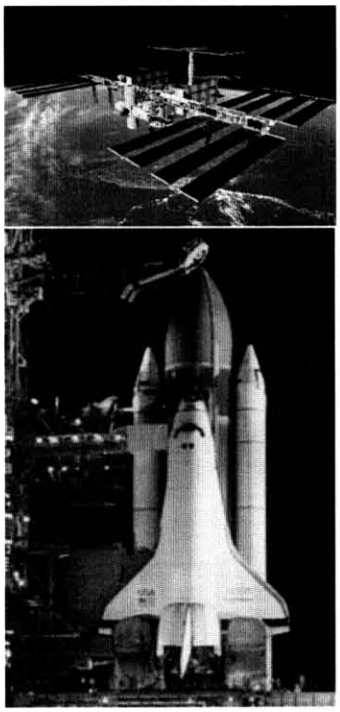
ADVANCED CHEMICAL PROPULSION - THEN AND NOW -

1950 -> Increased Isp -> **2000** -> Increased Isp -> **20xx ?**

- **Hydrazine/IRFNA**



- **LH_2/LO_2**



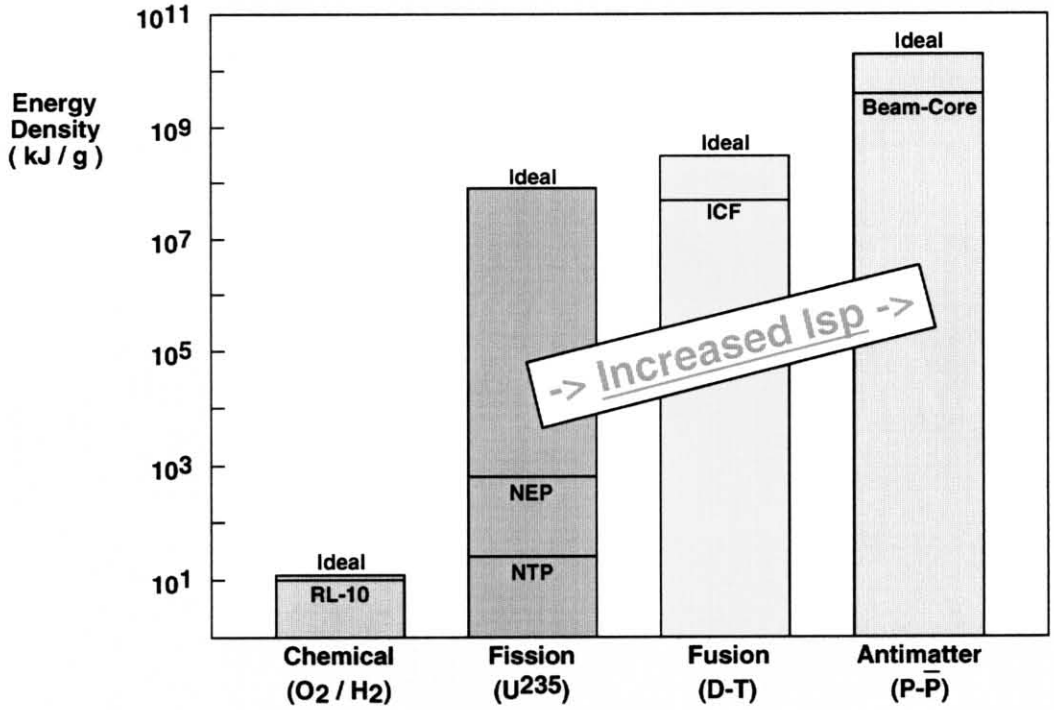
"Green" Propellants
- H_2O_2, O_3, HAN

Advanced Chemical
- F_2, ClF_5, OF_2, N_2F_4, B_2H_6

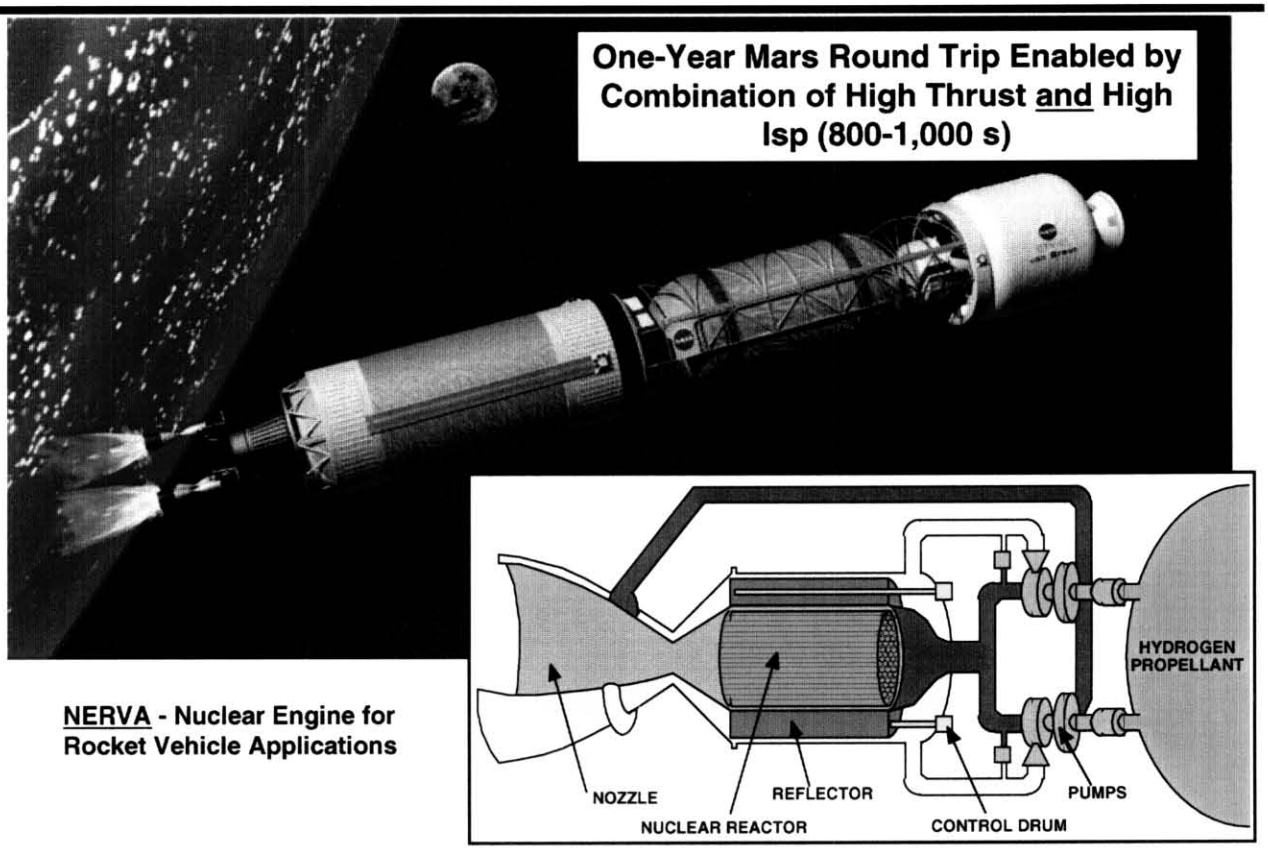
High-Energy Density Materials (HEDM)
- Gel Propellants
- Strained-Ring Fuels
- Atoms in Solid Molecular Matrix
  - H in C->CH_4, H in H_2
- Excited/Metastable Species
  - Metastable He*
- Metallic H

NUCLEAR ENERGY ENABLES HIGHER Isp

Comparison of Chemical and Nuclear Energy Densities

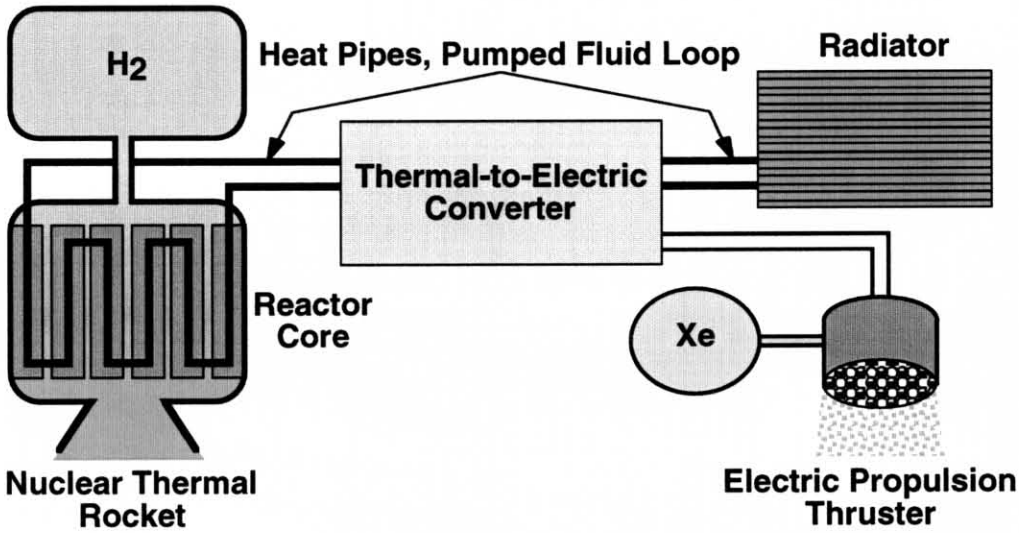


SOLID CORE NUCLEAR THERMAL ROCKET FOR PILOTED MARS MISSIONS



NERVA - Nuclear Engine for Rocket Vehicle Applications

"BI-MODAL" HYBRID NUCLEAR-THERMAL / NUCLEAR-ELECTRIC PROPULSION

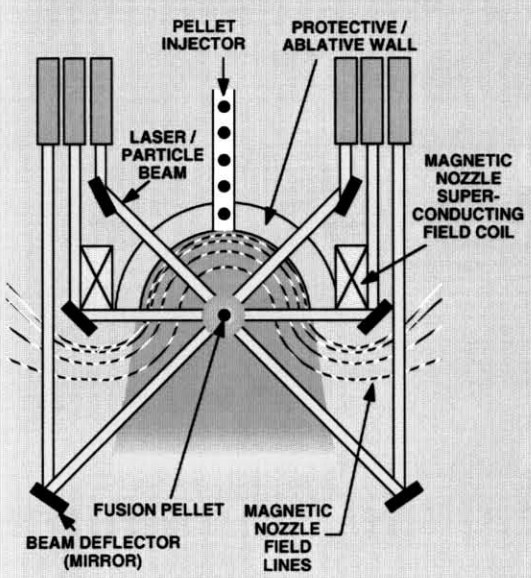


Features

- High Thrust for Planetary Escape / Capture
- High Isp for Interplanetary Cruise
- Power for Spacecraft Ops, Propellant Refrigeration

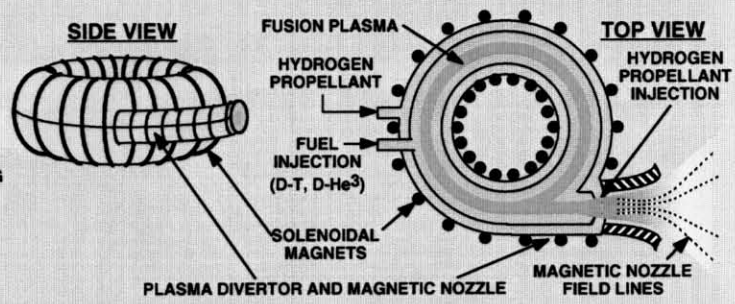
INERTIAL AND MAGNETIC CONFINEMENT FUSION (ICF/MCF) PROPULSION

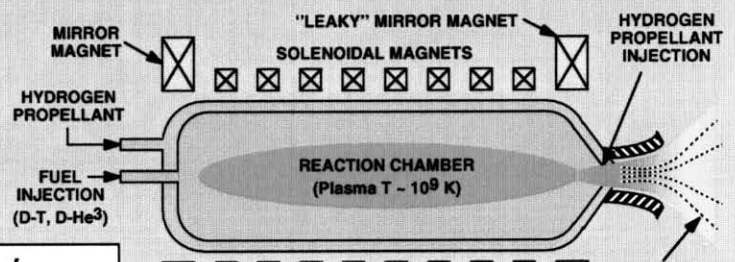
Inertial Confinement Fusion (ICF)



Magnetic Confinement Fusion (MCF)

- Tokamak ("Doughnut"-Shaped Geometry)

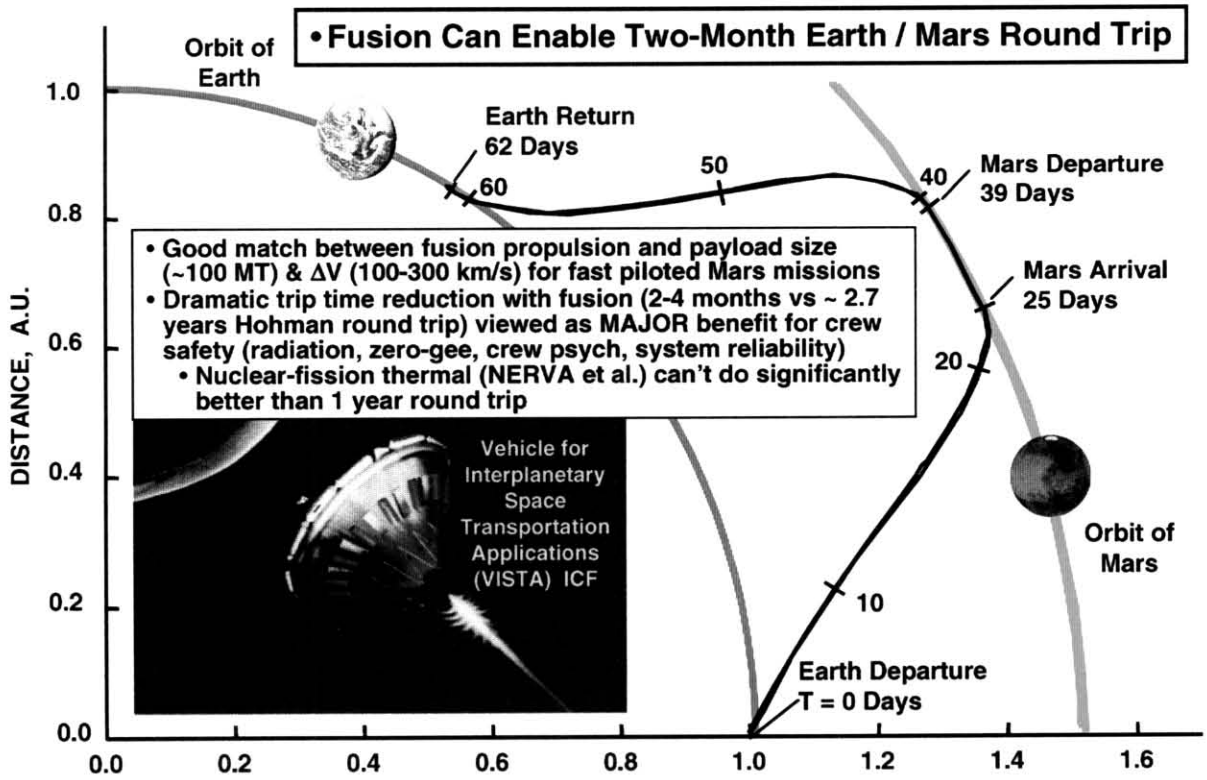




- Tandem Mirror MCF (Cylindrical Geometry)

- Many possible Fusion systems/ configurations under consideration
- DoE goals ($/kW$_e$-hr) not same as NASA goals (Isp, kg/kW$_{jet}$)

FUSION PROPULSION CAN ENABLE RAPID HUMAN EXPLORATION OF THE SOLAR SYSTEM

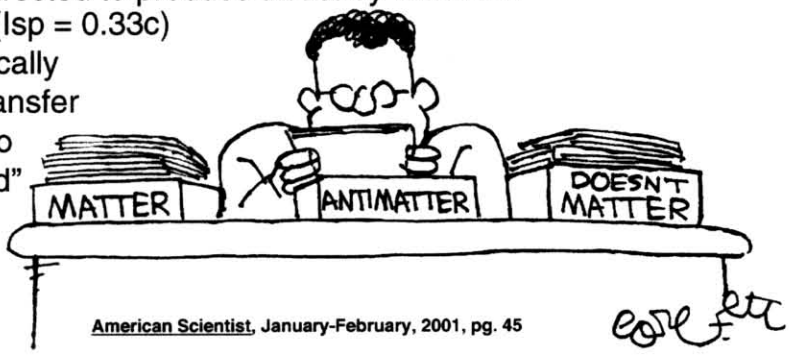


Based on Joint JPL, LLNL, ETEC, JSC Study of the VISTA Inertial Confinement Fusion (ICF) Concept

MATTER-ANTIMATTER ANNIHILATION FOR PROPULSION REQUIRES ANTIPROTONS

- **Electron (e^-) - Positron (e^+) Annihilation (E/M ~ 3.0×10^{16} J/kg)**
  $e^- + e^+ \rightarrow 2\gamma$ (511 MeV each)
  - Not practical for propulsion because reaction products (gamma rays):
    1. Can't be directed to produce thrust (fly off in all directions)
    2. Do not efficiently transfer annihilation energy to propellant "working fluid" (e.g., normal-matter H_2)

- **Proton (P^+) - Anti-Proton (P^-) Annihilation (E/M ~ 1.8×10^{16} J/kg)**
  $P^- + P^+ \rightarrow 3.0\ \pi^+, \pi^- + 2.0\ \pi^0$ ($\pi^0 \rightarrow 2\gamma$)
  $\pi^+, \pi^- \rightarrow \mu^+, \mu^-$ + neutrinos and then **$\mu^+, \mu^- \rightarrow e^+, e^-$ + neutrinos**
  - Preferred for propulsion because charged reaction products (pions) and decay products (muons):
    1. Can be confined and directed to produce thrust by means of electromagnetic fields (Isp = 0.33c)
    2. Can be electromagnetically confined to enhance transfer of annihilation energy to propellant "working fluid" (for higher thrust at expense of lower Isp)

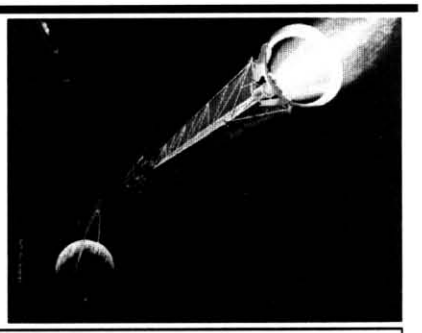


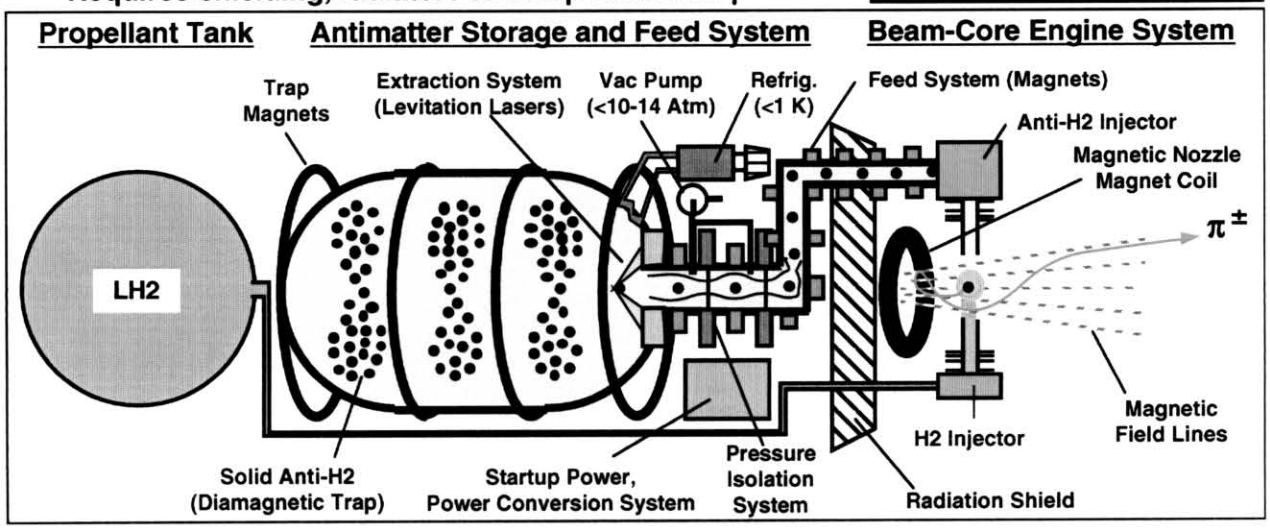
American Scientist, January-February, 2001, pg. 45

BEAM-CORE MATTER-ANTIMATTER PROPULSION SYSTEM CONCEPT

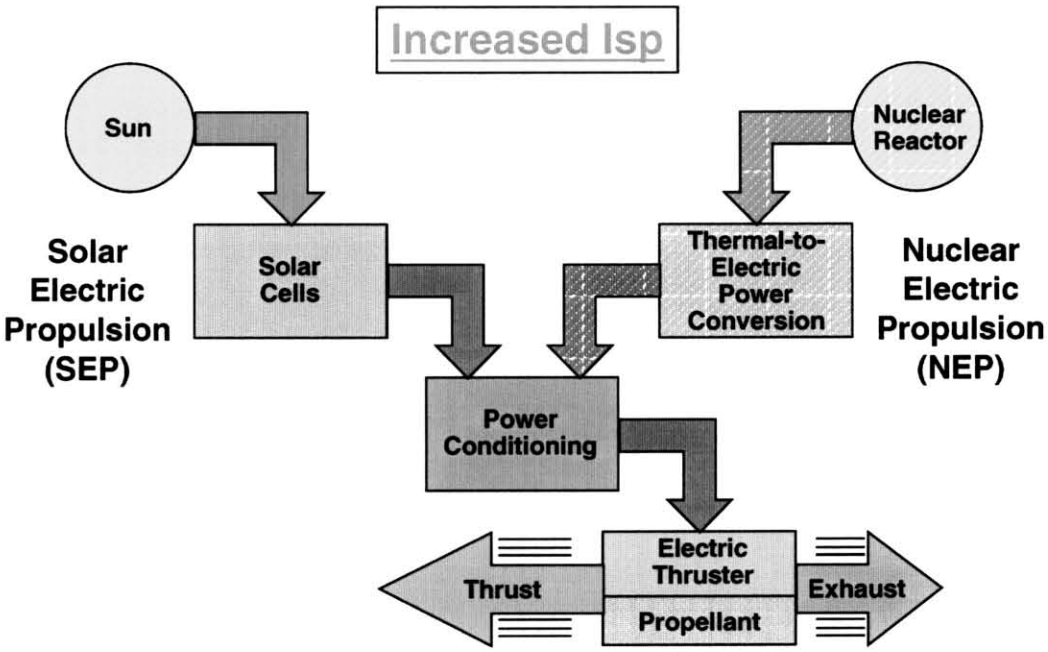
React equal amounts of protons (p+) & anti-protons (p-) to produce charged pions ($\pi\pm$) and neutral pions (π°)

- **Charged pions deflected by magnetic fields ("magnetic nozzle") and used as rocket exhaust to produce thrust**
  - **Highest possible Isp ~ 0.33 c, but low MC^2 efficiency**
    - **22% of p+/p- rest mass as $\pi\pm$, 20% as $\pi\pm$ kinetic energy**
    - **Need lots of antimatter (Currently ~ 10 ng/year)**
- **Neutral pions decay into ~200 MeV gamma rays (γ)**
  - **Requires shielding, radiators to dump absorbed γ**





SOLAR / NUCLEAR ELECTRIC PROPULSION SUBSYSTEMS



ELECTRIC PROPULSION THRUSTER TYPES

ELECTROTHERMAL

- Resistojets

- Arcjets

- Microwave Electro-thermal Thrusters (MET)

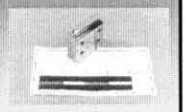
- Pulsed Electro-thermal Thrusters (PET)

ELECTROSTATIC

- Ion Engines

- Hall Thrusters

- Field Emission Thrusters



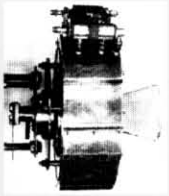
- Colloid Thrusters

In Use
R&D

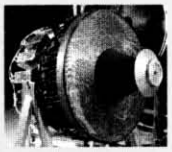
ELECTROMAGNETIC

- Pulsed Plasma Thrusters (PPT)

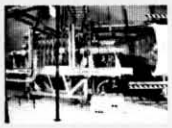
- Magneto-Plasma-Dynamic (MPD) Thrusters



- Pulsed Inductive Thrusters (PIT)

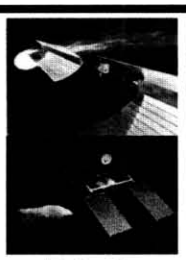


- Variable I_{sp} Plasma Rocket (VASIMR)



SEP AND NEP VEHICLE CONCEPTS OVERVIEW

DS-1

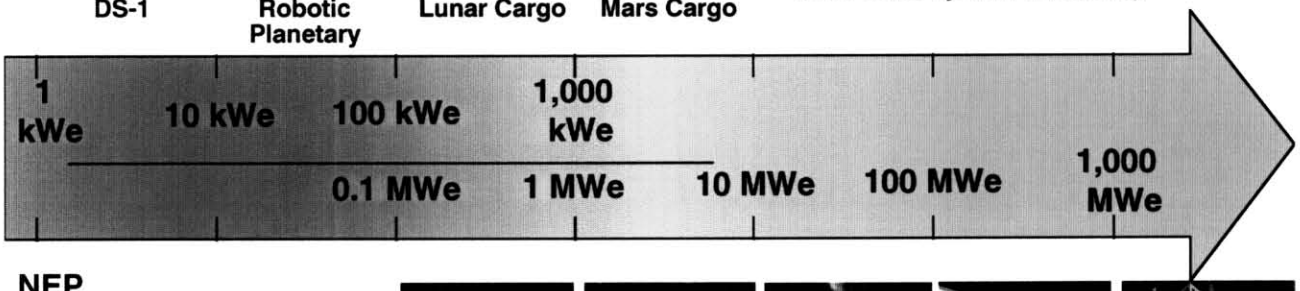

Robotic Planetary

Lunar Cargo

Mars Cargo

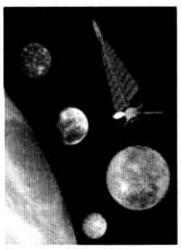
SEP

- Well-suited for small, first-generation robotic EP missions (low electric power, Pe)
- $1/R^2$ solar power decrease limits rendezvous range to ~ Asteroid Belt (but can be used as "kick stage" for outer solar system missions)



NEP

- Well-suited for outer solar system exploration (constant power)
- Potential for many kWe for science at destination
- Significant economy-of-scale at high power (MMW Pe) can enable piloted missions


Robotic Outer Planet

Mars Cargo

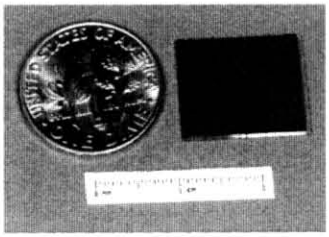
Interstellar Precursor

Piloted Mars

. . . and Beyond

MICROPROPULSION

Subliming Solid Micro-Thruster



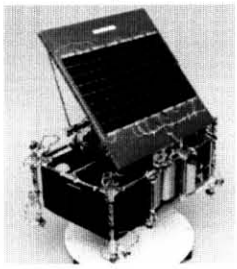
Reduce Prop System Dry Mass

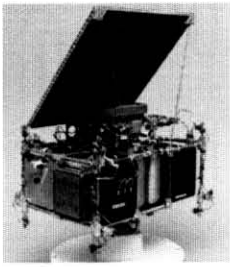
MICROPROPULSION APPLICATIONS

- Primary (ΔV) Propulsion or Attitude Control / Stationkeeping Propulsion for Microspacecraft
- Ultra-High Precision Attitude Control / Stationkeeping Propulsion for Conventional-Sized Spacecraft (e.g., Space-Based Interferometers)

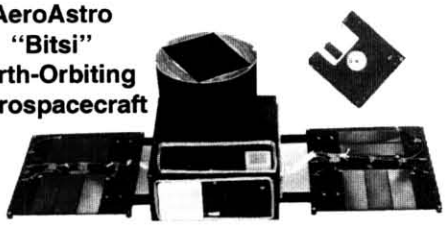
The Microspacecraft Vision:
Instead of one, $1B "Flagship" Spacecraft, send hundreds-thousands of $1M Microspacecraft

JPL MTD II Deep-Space Microspacecraft Functional Model





AeroAstro "Bitsi" Earth-Orbiting Microspacecraft



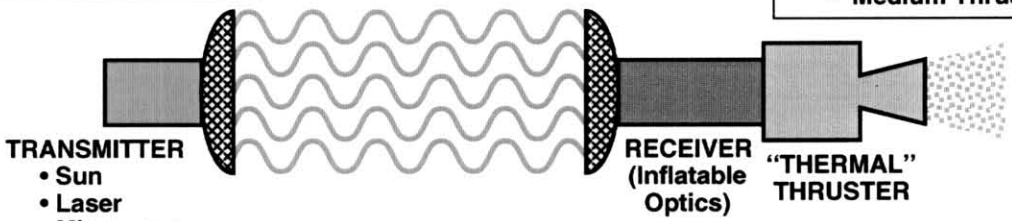
BEAMED ENERGY PROPULSION (SOLAR / LASER / MICROWAVE)

Reduce Prop System Dry Mass
Take the Engine (Energy Source) Off of the Vehicle

DIRECT UTILIZATION

- Solar Thermal Propulsion (STP)
- Laser Thermal Propulsion (LTP)
- Microwave Thermal Propulsion (MTP)

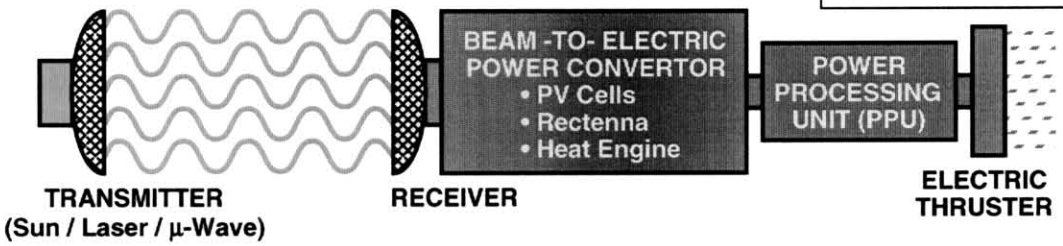
- Fills a niche for Earth orbit raising between Chemical (fast, heavy) and SEP (slow, light)
  - Potentially >2-5X the Isp of Chem
  - Medium Thrust



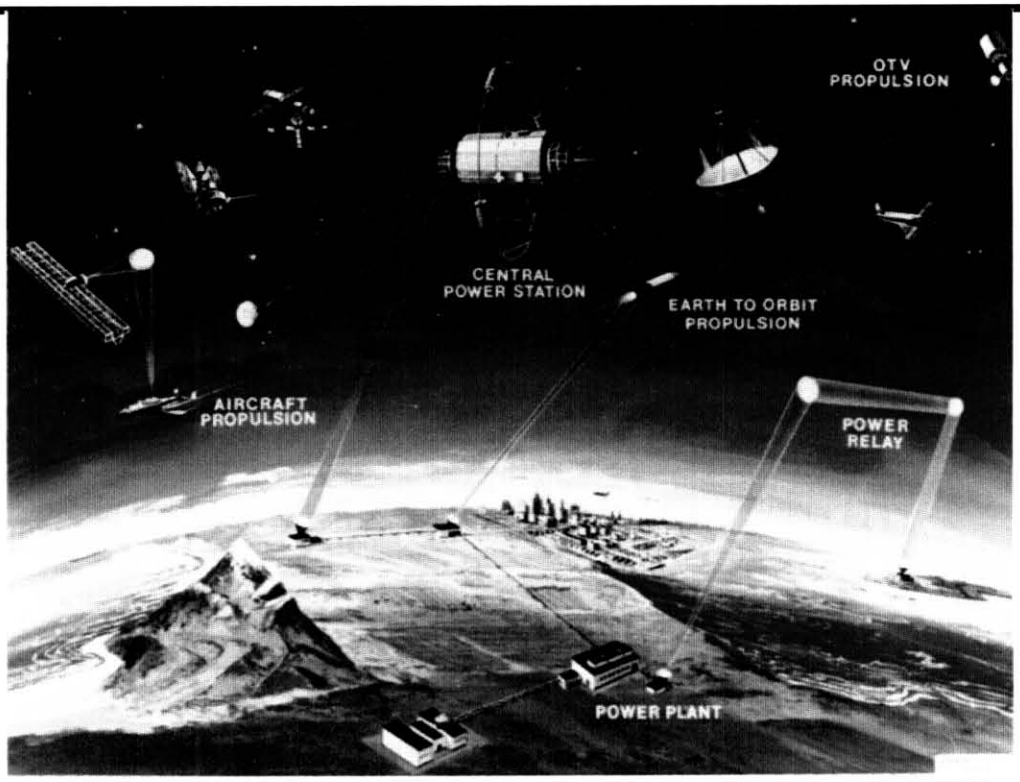
INDIRECT UTILIZATION

- Solar Electric Propulsion (SEP)
- Laser Electric Propulsion (LEP)
- Microwave Electric Propulsion (MEP)

- "Laser" PV cells can be twice as efficient as solar cells
- Microwave rectenna can be >80% efficient



THE VISION OF BEAMED ENERGY AS A SPACE POWER GRID

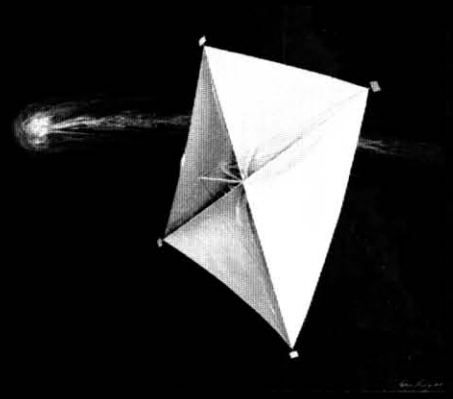


- **MAJOR** Issue: Who pays for large, up-front infrastructure ?

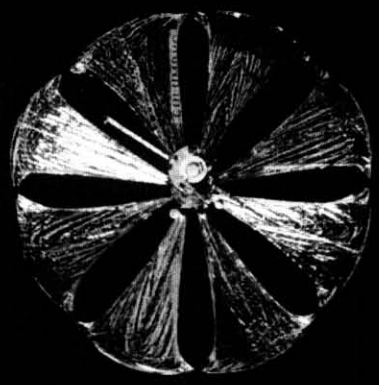
BEAMED MOMENTUM PROPULSION: SOLAR/LASER/MICROWAVE SAILS

Circumvent the Rocket Equation

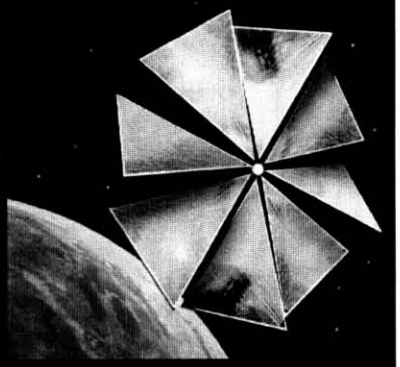
"Propellantless" Propulsion



JPL Haley Comet Rendezvous
3-Axis Square Sail



Russian Znamya
Spinning Circular Sail

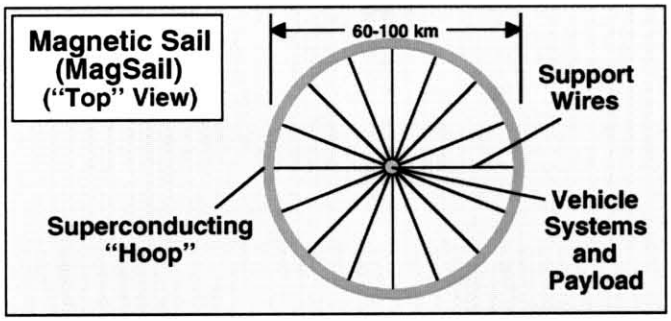


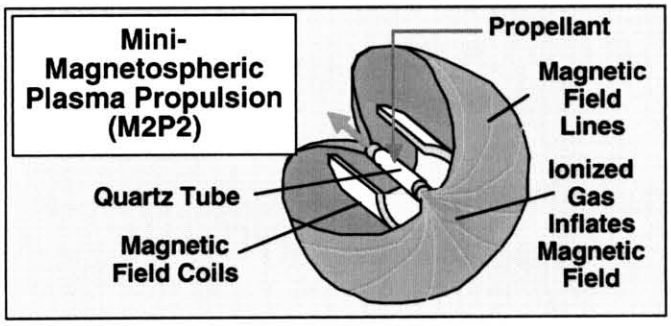
Planetary Society
Cosmos Sail

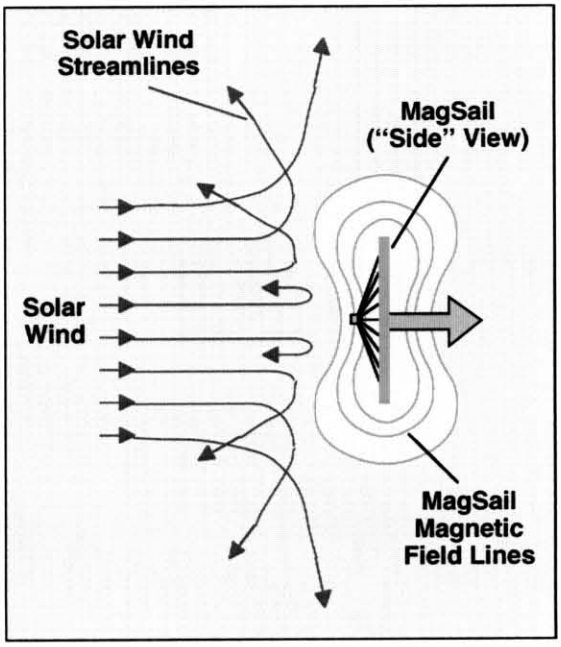
Sunlight Pressure on Ideal Sail = 9 N/km^2 (5 lb/mile^2) at 1 AU

ELECTROMAGNETIC SAILS: SOLAR WIND PARTICLE ANALOGS TO SOLAR SAILS

- **Electromagnetic Sails use solar wind ion force on a magnetic "wall" to produce thrust**
  - **Magnetic Sail (MagSail) - Zubrin and Andrews**
    - **Generates mag. (10^{-5} Tesla) barrier by superconductor ("Wall" dia >> loop dia.)**
  - **Mini-Magnetospheric Plasma Propulsion (M2P2) - Winglee**
    - **Uses ionized gas to "inflate" magnetic field to large sizes**







AEROASSIST: AEROBRAKING / AEROCAPTURE / AEROMANEUVERING

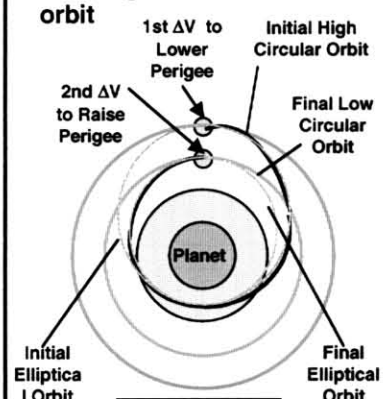
Reduce Propulsive ΔV

Use Aerodynamic Drag and Lift to Reduce Propulsive ΔV

AEROASSIST

AEROBRAKING

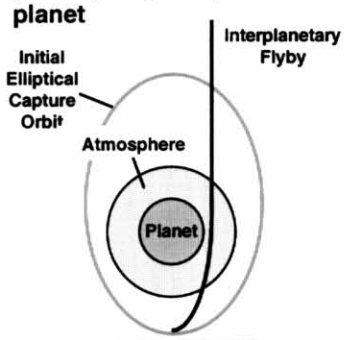
- Use aerodynamic drag to go from higher orbit to lower orbit



Balluet

AEROCAPTURE

- Use aerodynamic drag to go from interplanetary flyby trajectory into capture orbit (initially elliptical) about planet

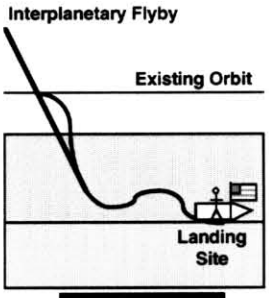


INCREASING L/D

Raked Cone

AEROMANEUVER

- Use aerodynamic drag and lift to land at a specific landing site
- Example: Space Shuttle



Biconic

CHEMICAL AND ELECTROMAGNETIC CATAPULTS

- What are Chemical and Electromagnetic Catapults ?
  - Chemical: Cannon, Light Gas Gun, Pneumatic Catapult, and Ram Accelerator
  - Electromagnetic: Rail Gun, Mass Driver (Coil Gun), and MagLifter
- Why are Chemical and Electromagnetic Catapults Interesting ?
  - Alternative "Launch Vehicle" (from Earth, Moon, Orbit and Elsewhere)

Use Catapult to Reduce Propulsive ΔV

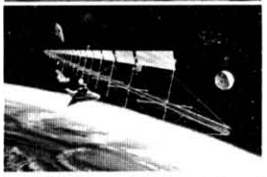
  - Possible Cost Reduction per kg Launched
  - Possible Increase in Launch Frequency & Safety
  - May Enable SSTO by Providing Initial Boost ("0th" Stage) During Most Difficult Portion of Launch
  - Reaction Engine (Electric Propulsion "Thruster")

Increase Isp, Live Off the Land

  - Omnivorous
  - Efficient

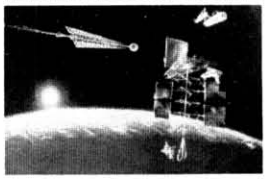
- MAJOR Issue: Who pays for large, up-front infrastructure ?

MagLifter Earth Launch Assist System



Electro-magnetic Catapult in Earth Orbit

Lunar Mass Driver and Oxygen Production Facility



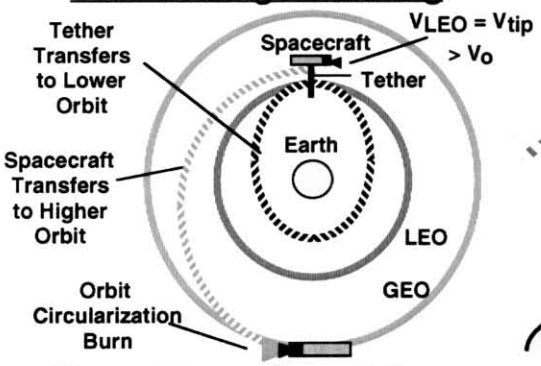
Mass Driver Returning Asteroid to Earth Orbit

TETHERS, TRAWLERS, AND TOWERS

Use Orbital Mechanics to Reduce Propulsive ΔV

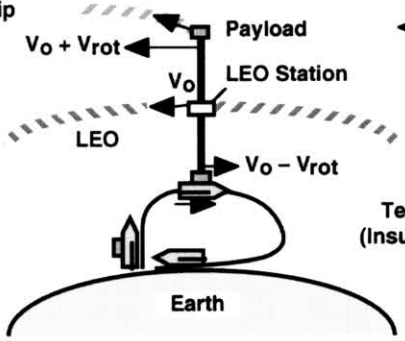
• **BUT** - Who pays for Infrastructure ?

Orbit Raising / Lowering



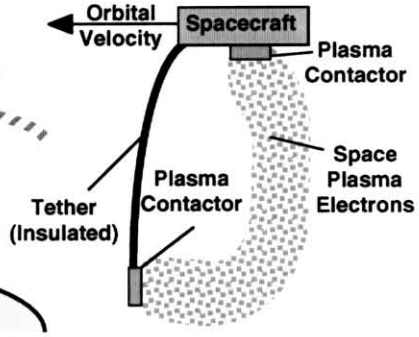
Rotating Tether

Enable Suborbital-SSTO

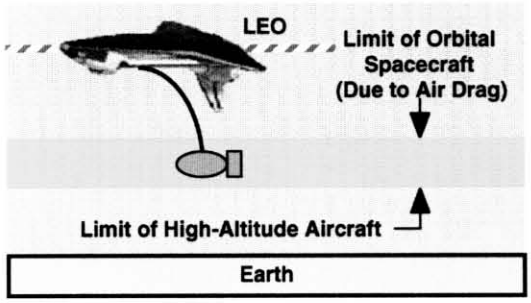


Electrodynamic Tether

Power -or- Propulsion

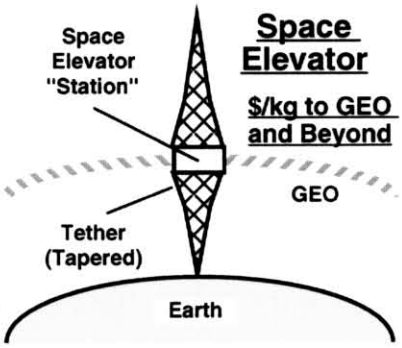


Upper Atmosphere Science



Space Elevator

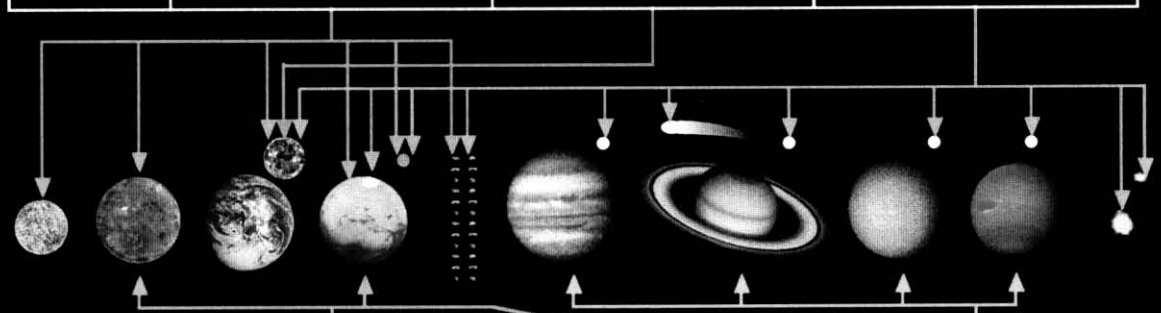
$/kg to GEO and Beyond



EXTRATERRESTRIAL RESOURCE UTILIZATION (ETRU)

Circumvent the Rocket Equation - "Live Off the Land"

Feedstock	Regolith (Soil)	Surface Regolith	Water (Water-Ice)
Process	Chemical Reduction of Regolith	Bake Regolith	Water Electrolysis
Output	O_2, Metals ("Slag")	Trace Gases (H_2, N_2, He_3, etc.)	H_2, O_2



Feedstock	CO_2 (Atmosphere)	CO_2, H_2 (H_2O) (H_2 from Earth ?)	Outer-Planet Atmosphere
Process	Zirconia "Electrolysis"	Sabatier + Water Electrolysis	"Scoop" from Atmosphere
Output	O_2, CO	O_2, CH_4	H_2, CH_4, He_3

ANOMALIES IN PHYSICS
- THEN AND NOW -

	OLD PARADIGMS	ANOMALIES - 1900 -	NEW PARADIGMS	ANOMALIES - 2000 -
Macroscopic	• Newton's Gravitation	• Sun's Energy Output Over Time; Radioactivity • Mercury's Orbit	• Relativity	• Missing Mass • "New" Cosmological Const. • Naked Singularities • Time Machines Not Forbidden
Microscopic	• Maxwell's Field Eq.	• Photoelectric Effect • Blackbody UV Emission • Line Spectra	• Quantum Mechanics	• Missing Solar Neutrinos • Imaginary Mass Neutrinos • FTL Quantum States Communication Observed

NASA BREAKTHROUGH PHYSICS PROPULSION (BPP) PROGRAM

Circumvent the Rocket Equation
Totally New, Breakthrough Physics

PROGRAM LEAD: **Marc Millis, NASA GRC (http://www.grc.nasa.gov/WWW/bpp/)**

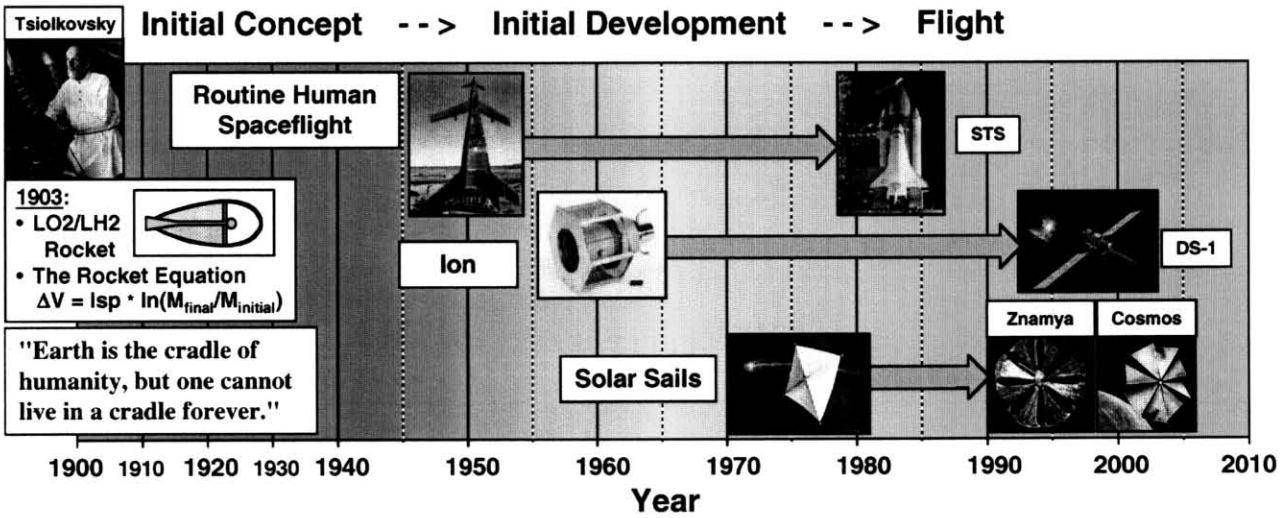
OBJECTIVE:
- **Advance science to provide new foundations for breakthrough propulsion technology.**
- **Produce incremental, credible, and measurable progress toward conquering the ultimate breakthroughs needed to revolutionize space travel and enable interstellar voyages.**

TECHNICAL GOALS:
- **Mass: Discover new propulsion methods that eliminate or dramatically reduce the need for propellant.**
  - **"Inertialess" space drives, gravity shielding/antigravity, thrusting against the zero-point vacuum field**
- **Speed: Discover how to circumvent existing limits to dramatically reduce transit times.**
  - **Wormholes, Warp Drives**
- **Energy: Discover new energy methods to power these propulsion devices.**
  - **Zero-point energy (Casimir Effect), deep Dirac energy levels**

PROGRESS:
- **Identified issues, potential for research programs**
- **Solicited Proposals, convened Advisory Counsel to review proposals, funded tasks**
- **Results being published in peer-reviewed journals**
- **Funding for all Revolutionary Propulsion (including BPP) cut in 2003**

DEVELOPMENT OF ADVANCED PROP TECHNOLOGIES TAKES TIME AND $$$

- Typically takes <u>decades</u> to go from concept to flight
  - Basic research often tied to grad student life cycle (e.g., 4+ years)
- Costs dramatically increase over development life
  - $100K for "paper" studies, basic research -> $100M for space flight demo
- Flight demos (e.g., New Millennium DS-1 SEP) critical for acceptance
  - Project Managers <u>very</u> risk adverse
  - Nothing succeeds like success - Many proposals now being funded for SEP missions; Project Prometheus JIMO NEP



CONCLUSIONS

- Some predictions for the future (any of which could be altered by changes in National policy; e.g., Apollo)
- Near-Term (5-15 years) - Robotic exploration of the Solar System
  - Pretty much limited to what's already in development (as opposed to research)
  - SEP, NEP (e.g., Project Prometheus JIMO) with Advanced Ion and/or Hall thrusters
  - Aeroassist (Medium-high L/D aero-brake/capture) at target, with Chemical or SEP used for injection
  - Others: Solar Sails, Solar Thermal, Momentum Exchange Tethers
- Mid-Term (15-30 years) - Human exploration of the Moon and Mars
  - Extraterrestrial Resource Utilization to produce propellants
  - Nuclear Thermal (NERVA/LANTR, Bi-Modal)
  - MW_e-class SEP, NEP for cargo missions
  - 100-MW_e class (MMW_e) NEP for piloted missions
  - Robotic micro-technologies, first interstellar precursors (Solar Sails, NEP)
- Far-Term (30+ years) - Routine, low-cost, fast access to anywhere in the Solar System
  - Characterized by BIG systems (today's sci-fi and basic research)
    - Very demanding technologies
      - Fusion, Antimatter Catalyzed Fission/Fusion
    - Big Infrastructures (Who builds the Interstate Highway System?)
      - Launch Assist Catapults, Laser Propulsion ETO, Space Elevator
- Very Far Term (22nd Century ?) - Interstellar missions
      - Advanced Fission, Fusion, Antimatter, Laser Sails

"Earth is the cradle of humanity, but one cannot live in a cradle forever."