ADVANCED SPACE PROPULSION

[illegible]

39553

Robert H. Frisbee, Ph.D.

Jet Propulsion Laboratory
California Institute of Technology
Pasadena California

Transportation Beyond 2000:
Engineering Design for the Future

September 26-28, 1995

ABSTRACT

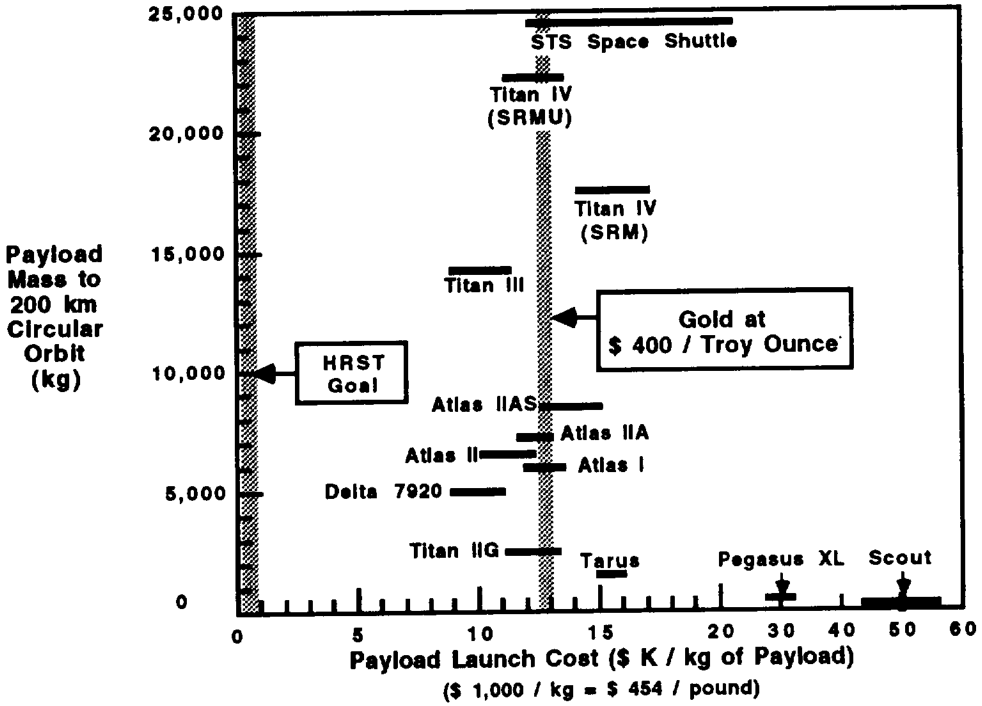
This presentation describes a number of advanced space propulsion technologies with the potential for meeting the need for dramatic reductions in the cost of access to space, and the need for new propulsion capabilities to enable bold new space exploration (and, ultimately, space exploitation) missions of the 21st century. For example, current Earth-to-orbit (e.g., low Earth orbit, LEO) launch costs are extremely high (ca. $10,000/kg); a factor 25 reduction (to ca. $400/kg) will be needed to produce the dramatic increases in space activities in both the civilian and government sectors identified in the Commercial Space Transportation Study (CSTS). Similarly, in the area of space exploration, all of the relatively "easy" missions (e.g., robotic flybys, inner solar system orbiters and landers; and piloted short-duration Lunar missions) have been done. Ambitious missions of the next century (e.g., robotic outer-planet orbiters/probes, landers, rovers, sample returns; and piloted long-duration Lunar and Mars missions) will require major improvements in propulsion capability. In some cases, advanced propulsion can enable a mission by making it faster or more affordable, and in some cases, by directly enabling the mission (e.g., interstellar missions).

As a general rule, advanced propulsion systems are attractive because of their low operating costs (e.g., higher specific impulse, I_{sp}) and typically show the most benefit for relatively "big" missions (i.e., missions with large payloads or ΔV, or a large overall mission model). In part, this is due to the intrinsic size of the advanced systems as compared to state-of-the-art (SOTA) chemical propulsion systems. Also, advanced systems often have a large "infrastructure" cost, either in the form of initial R&D costs or in facilities hardware costs (e.g., laser or microwave transmission ground stations for beamed energy propulsion). These costs must then be amortized over a large mission to be cost-competitive with a SOTA system with a low initial development and infrastructure cost and a high operating cost. Note however that this has resulted in a "Catch 22" standoff between the need for large initial investment that is amortized over many launches to reduce costs, and the limited number of launches possible at today's launch costs.

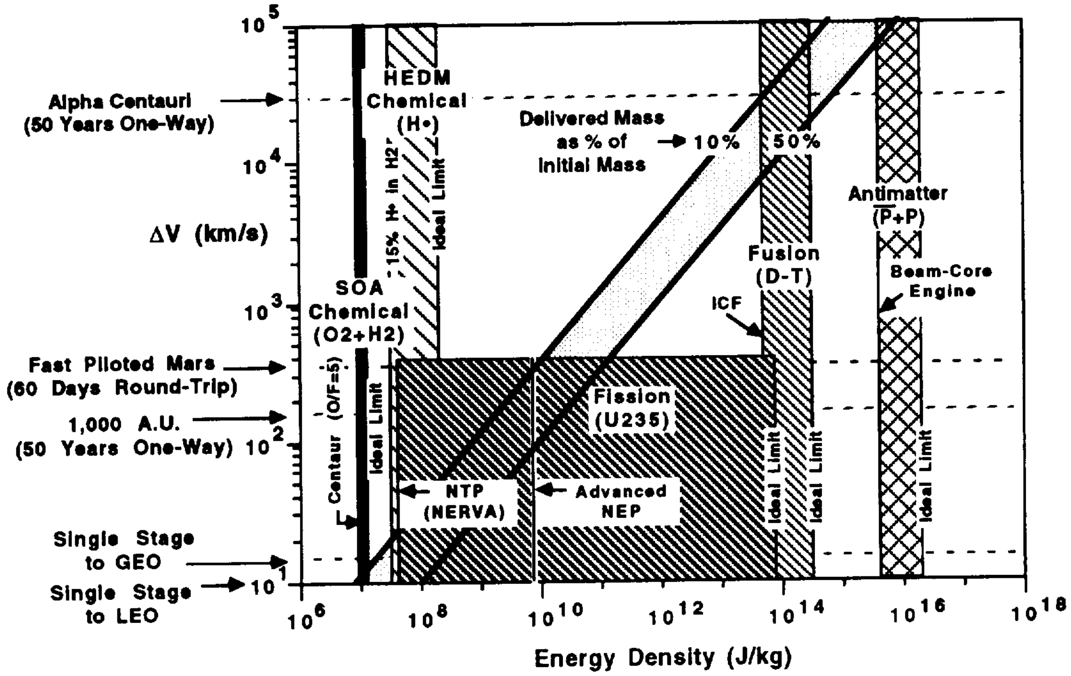
Some examples of missions enabled (either in cost or capability) by advanced propulsion include long-life station-keeping or micro-spacecraft applications using electric propulsion or BMDO-derived micro-thrusters, low-cost orbit raising (LEO to GEO or Lunar orbit) using electric propulsion, robotic planetary missions using aerobraking or electric propulsion, piloted Mars missions using aerobraking and/or propellant production from Martian resources, very fast (100-day round-trip) piloted Mars missions using fission or fusion propulsion, and, finally, interstellar missions using fusion, antimatter, or beamed energy.

The NASA Advanced Propulsion Technology program at the Jet Propulsion Laboratory (JPL) is aimed at assessing the feasibility of a range of near-term to far-term advanced propulsion technologies that have the potential to reduce costs and/or enable future space activities. The program includes cooperative modeling and research activities between JPL and various universities and industry; and directly-supported independent research at universities and industry. The cooperative program consists of mission studies, research and development of ion engine technology using C60 (Buckminsterfullerene) propellant, and research and development of lithium-propellant Lorentz-force accelerator (LFA) engine technology. The university/industry-supported research includes modeling and proof-of-concept experiments in advanced, high-I_{sp}, long-life electric propulsion, and in fusion propulsion.

LAUNCH COSTS > $10,000 / kg WITH EXISTING LAUNCH VEHICLES



MAJOR ADVANCES IN PROPULSION TECHNOLOGY REQUIRED FOR FUTURE SPACE MISSIONS

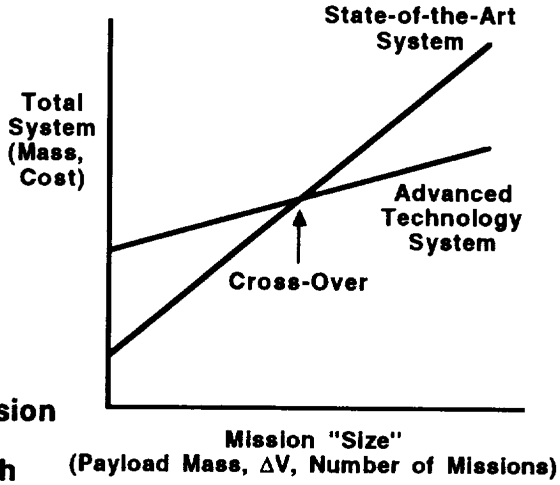


POTENTIAL TO REDUCE COST

JPL

ADVANCED PROPULSION CAN REDUCE COSTS

- Advanced propulsion shows most benefits for "big" missions
- Issue of Infrastructure "Rich" versus "Poor" systems
  - Beamed Energy, Maglifter, etc. systems minimize vehicle propulsion requirements at expense of large infrastructure
  - All-Rocket SSTO, HEDM, etc. systems put emphasis on improvements in vehicle propulsion (and minimize infrastructure) to yield more payload per launch



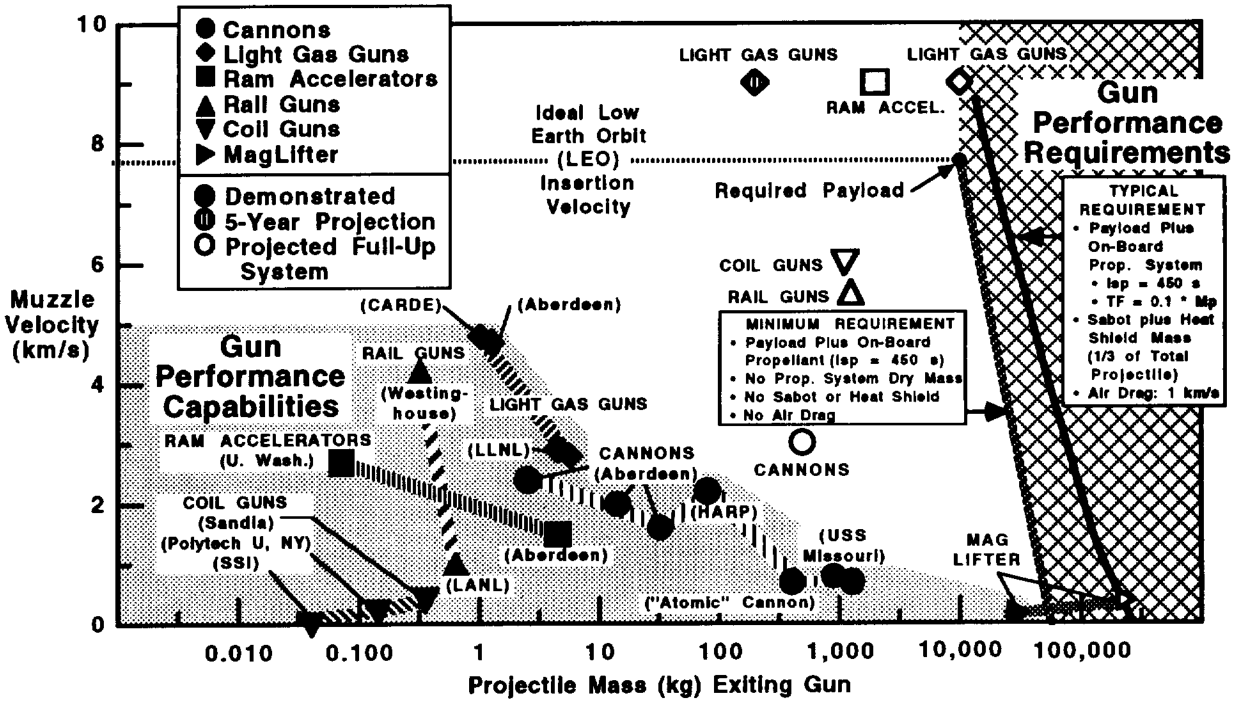
- Either approach results in a "Catch 22" standoff between need for large initial investment that is amortized over many launches to reduce costs, and the limited number of launches possible at today's launch costs

ADVANCED PROPULSION LAUNCH VEHICLE CONCEPTS

- Very Advanced (Exotic) Chemical - High Energy Density Matter (HEDM) Propulsion (Free Radicals, Excited States, Metastables)
  - Near-term "additives" to existing propellants and vehicles for incremental improvements in performance
  - Far-term, totally new propellant combinations and vehicles for quantum improvements in performance
- Nuclear Thermal (Fission, Antimatter)
  - Safety (public acceptance ?) as a launch vehicle
  - Infrastructure for development, test, operations
- Beamed Energy (Laser / Microwave) Earth-to-Orbit
  - Large infrastructure – high powers (~ 100 MW/MT) needed for launch
- Chemical / Electromagnetic Guns / Catapults
  - Cannon, Light Gas Gun, Ram Accelerator
  - Rail Gun, Mass Driver, MagLifter
- Tethers (Skyhooks, Launch Loops)

POTENTIAL TO REDUCE COST

JPL GUN LAUNCH CONCEPT COMPARISON



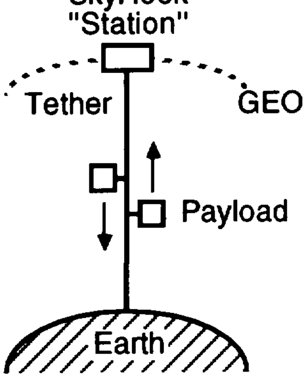
- Use Regime Appropriate Technology (RAT) to reduce overall costs
  - MagLifter (Vel. = 0 to Mach 0.9, Alt. = 0 to 1 mile)
  - Ramjet (Vel. = Mach 0.9 to ~5, Alt. = 1 to 20 miles)
  - Pure rocket (Vel. = Mach 5 to 25, Alt. = 20 to 200 miles)

TETHERS AS SKYHOOKS AND LAUNCH LOOPS

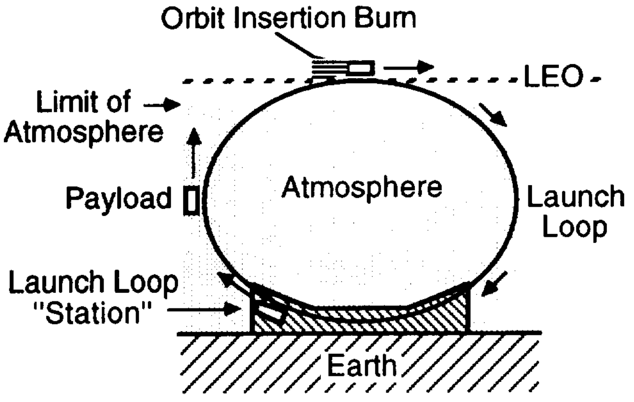
- Currently under development for orbit-to-orbit transfers
  - Use momentum instead of rockets

- Major paradigm shift in the concept of "launch vehicle"
  - Potential for large launch system infrastructure

SKYHOOK



LAUNCH LOOP



POTENTIAL TO ENABLE NEW MISSIONS

JPL ADVANCED PROPULSION CAN ENHANCE / ENABLE NEW CLASSES OF MISSIONS

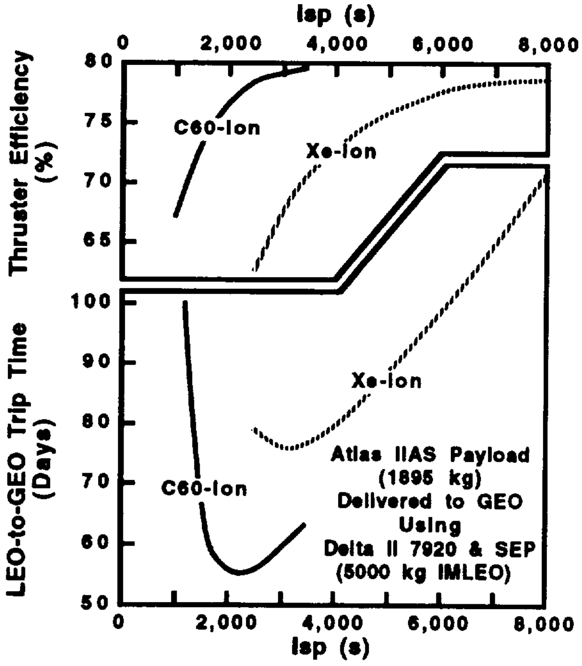
- **Advanced propulsion shows most benefits for "big" missions**
  - **Don't use 1000-MT fusion rocket to transport 1-MT Comsat to GEO**
- **Sample Missions:**

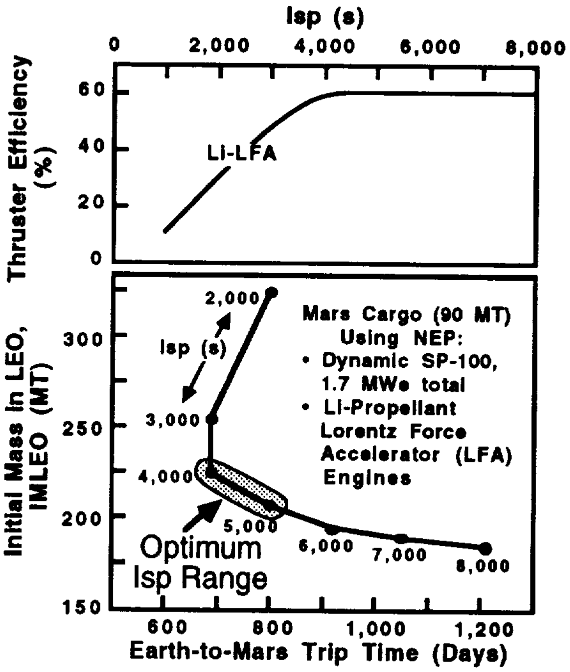
Current Missions	Example Systems	Enabled Mission	Example Systems
Station-Keeping	N2H4, ResistoJet, ArcJet	Long-Life Station-Keeping, Micro-Spacecraft	Ion, Pulsed Plasma
Orbit Raising (LEO->GEO/Moon)	Chemical (Solids, Liquids)	"Slow" Orbit Raising "Fast" Orbit Raising	SEP w/ Xe-Ion SEP w/ C60-Ion, Russian Hall or TAL; NEP w/ Li-LFA
Planetary (Robotic)	Chemical (Solids, Liquids)	Planetary (Robotic, Micro-S/C)	BMDO Micro-Chem, SEP, Aerobraking
Piloted Mars (Slow)	Chemical w/ Aerobrake, ET Propellant Production	Piloted Mars (Fast)	Fusion, Gas-Core Fission
Interstellar Precursor	MW-Class NEP	Interstellar	Fusion, Antimatter, Beamed Energy

ELECTRIC PROPULSION CAN ENABLE LOW-COST, NEAR-TERM ROBOTIC PLANETARY, CIS-LUNAR, AND MARS CARGO MISSIONS

- **Requires thrusters with high efficiency at low Isp**

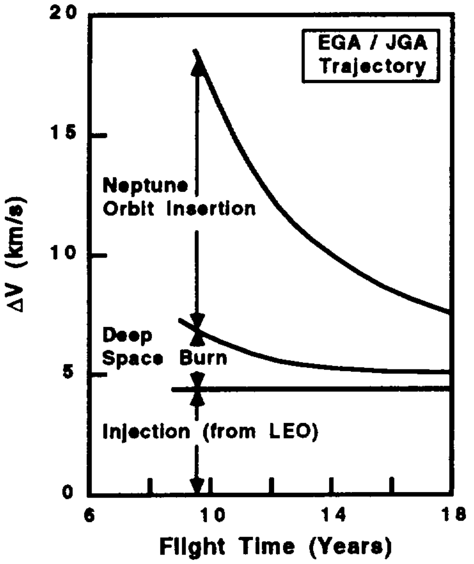
(Optimum Isp decreases as specific mass increases)

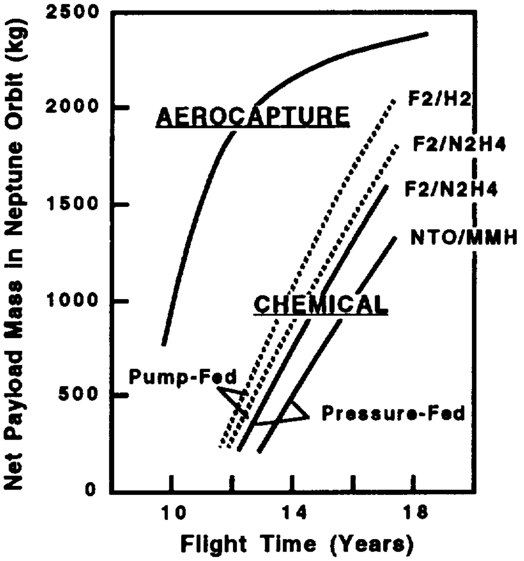




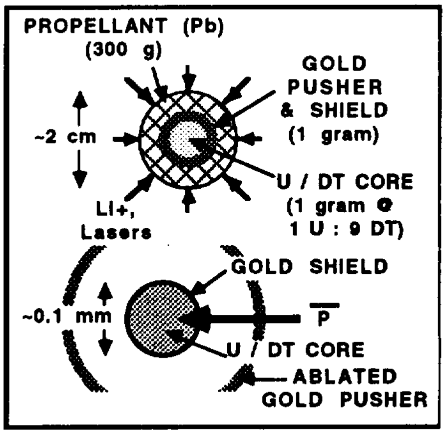
POTENTIAL TO ENABLE NEW MISSIONS

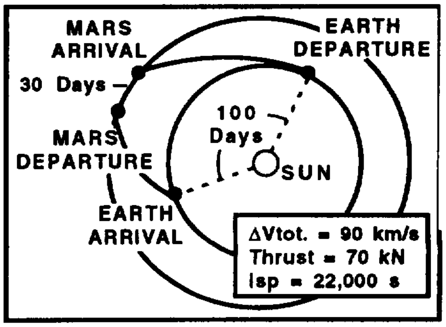
JPL BENEFITS OF AEROCAPTURE FOR A NEPTUNE ORBITER MISSION





ANTIMATTER-CATALYZED MICRO-FISSION/FUSION PROPULSION FOR FAST PILOTED MARS MISSIONS





ΔVtot. = 90 km/s
Thrust = 70 kN
Isp = 22,000 s

Concept

- Uranium (or Pu) enriched DT (or D-He3) pellet compressed (by ions, lasers, etc.)
- At the time of peak compression, the target is bombarded with a small number (~10^8) of antiprotons to catalyze fission
- The fission energy release triggers a high-efficiency fusion burn to heat the propellant
- Resulting expanding plasma used to produce thrust

Features

- Uses a small amount of antimatter - an amount that we can produce today with existing technology and facilities
- Mission benefits of 100-day Earth-Mars round trip
- Potential benefits of "easier" drivers / aneutronic fuels

Feasibility Issues

- Pellet implosion dynamics
- Fission burnup (number of antiprotons needed)
- Fusion ignition and burn (total gain)
- Transfer of fission/fusion energy to propellant
- Transfer of propellant energy to vehicle

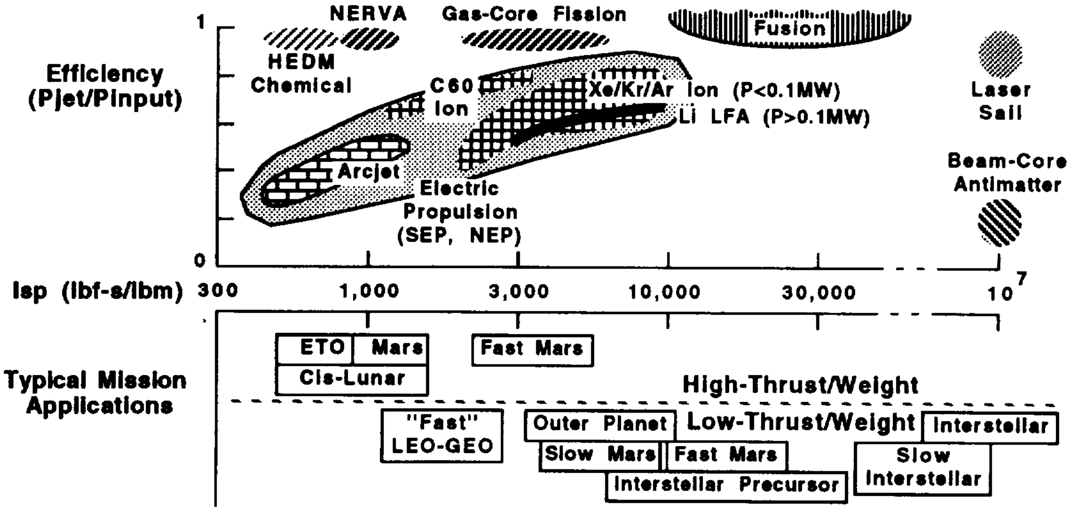
Research Partners

- Pennsylvania State University
- JPL, AFOSR, NSF
- Rocketdyne

JPL

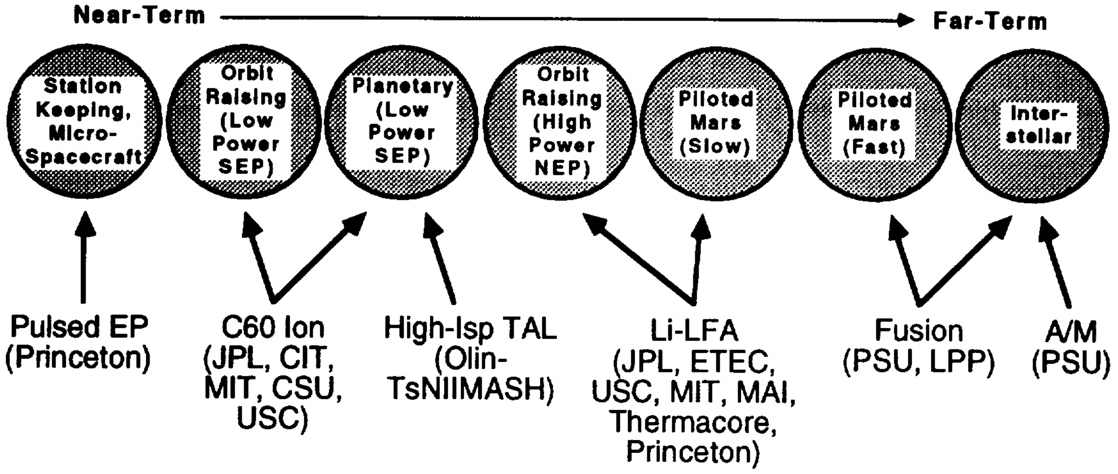
SELECTION CRITERIA REQUIRED TO DOWN-SELECT AMONG MANY COMPETING CONCEPTS

- Must have projected performance which offers unique capabilities for a well defined class of missions
- Must use an environmentally acceptable propellant (no Hg, etc.)
- Must be an area where small amounts of funding can have a large impact, especially with co-funding from other agencies



NASA-JPL ADVANCED PROPULSION TECHNOLOGY PROGRAM

- Current Advanced Propulsion Technology program contains a mix of near-term to far-term technologies in both cooperative and directly-supported university / industry tasks



Near-Term → Far-Term

Station Keeping, Micro-Spacecraft

Orbit Raising (Low Power SEP)

Planetary (Low Power SEP)

Orbit Raising (High Power NEP)

Piloted Mars (Slow)

Piloted Mars (Fast)

Inter-stellar

Pulsed EP (Princeton)

C60 Ion (JPL, CIT, MIT, CSU, USC)

High-Isp TAL (Olin-TsNIIMASH)

Li-LFA (JPL, ETEC, USC, MIT, MAI, Thermacore, Princeton)

Fusion (PSU, LPP)

A/M (PSU)

SUMMARY

JPL OPPORTUNITIES FOR LaRC

- Need to Reduce Cost, Enable New Classes of Missions

- Low-Cost Earth-to-Orbit (ETO)
  - NASP et al.
    - Propulsion / Aeroframe Integration Issues (Common to many advanced concepts)
  - Launch Assist (MagLifter, etc.)
    - Regime Appropriate Technologies (RAT)
  - Laser Power and Propulsion (Solar-Pumped, Diode Lasers)

- Mission Enabling
  - Detonation Propulsion (Venus Sample Return)
  - Aero-Capture/Brake/Maneuver
    - WaveRider Aero-Gravity Assist (Very high speed, high L/D)
  - High Altitude Aero. (e.g., low ambient pressure)
    - Mars Airplane (UAV), Balloon