# THE NASA-JPL ADVANCED PROPULSION PROGRAM

Robert t I. Frisbee
Jet l'repulsion laboratory
California Institute of Technology
Pasadena, California

## ABSTRACT

The NASA Advanced Propulsion Technology program at the Jet Propulsion Laboratory (JPL) is aimed at assessing the feasibility of a range of mid-term to far-term advanced propulsion technologies that have the potential to significantly 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, feasibility research of ion engine technology using C60 (Buckminsterfullerene) propellant, and feasibility research of lithium-propellant Lorentz-force accelerator (LFA) engine technology. The directly-supported university/industry research includes modeling and proof-of-concept experiments in advanced, very high power, high-$I_{sp}$ electric propulsion, and in fusion propulsion.

## INTRODUCTION

I-here is a significant need for advanced space propulsion technologies with the potential for meeting the need of dramatic reductions in the cost of access to space, and the need for new propulsion capabilities to enable boid new space expiration (and, ultimately, space exploitation) missions of the 21st century. For example, as shown in Figure 1, current Earth-to-orbit (e.g., low Earth orbit, LEO) launch costs are extremely high (ea. $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).[1]

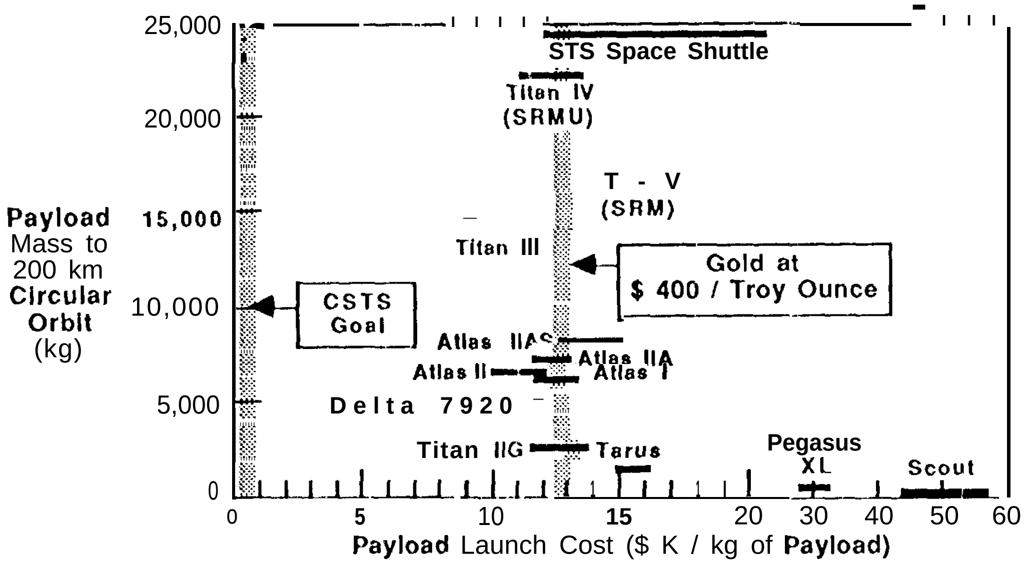


Figure 1. launch Costs versus Payload Mass

---

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 significantly enhance 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., lower initial "wet" mass due to a higher specific impulse, $I_{sp}$, and corresponding lower propellant requirement) and typically show the most benefit for relatively "difficult" 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.

This effect is illustrated in Figure 2, which contrasts the life-cycle total "crest" (e.g., system mass, initial development costs and operations costs, etc.) as a function of the mission "difficulty" (e.g., payload mass, mission AV, mission model size, etc.) for an advanced and SOTA system. The advanced system has a large intercept (high initial set-up "costs") but a low slope (low operating "costs" [e.g., high $I_{sp}$]). The SOTA system has a small intercept but high slope (e.g., low $I_{sp}$), resulting in a cross-over Point between the two lines. Thus, a SOTA system will have a lower life-cycle cost for an easy or "small" mission, but as the mission difficulty or "size" grows, the advanced system will be favored because the "larger" mission makes it possible to amortize the advanced system's initial investment.

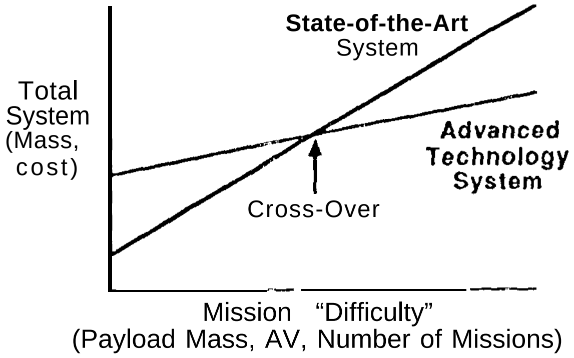


figure 2. Mission "Cost" versus "Difficulty" for Advanced and State-of-the-Ari (SOTA) Propulsion Systems

Table 1 lists some examples of missions enabled (either in cost or capability) by advanced propulsion. For example, long-life station-keeping or micro-spacecraft applications could be enabled by solar electric propulsion (SEP) with xenon-propellant ion or pulsed-plasma thrusters, or by BMDO-derived chemical micro-thrusters. Similarly, low-cost orbit raising (LEO to geosynchronous Earth orbit [GEO] or Lunar orbit) could be enabled with SEP or nuclear electric propulsion (NEP). In this case, the low-thrust SEP and NEP trajectories can be divided into "slow" (many-month trip time) missions using Xc-ion SEP, or "fast" (few-month trip time) missions using iOn engines operating on $C_{60}$ (Buckminsterfullerene) propellant, Russian Hall or TAL (Thruster with Anode Layer) thrusters, or lithium-propellant Lorentz-force accelerator (LFA) engines, Advanced robotic planetary missions could be enabled by technologies such as electric propulsion, micro propulsion systems, solar thermal propulsion (STP), or aerobraking. Low-cost, multi-year long piloted Mars missions could be enabled using various combinations of aerobraking, propellant production from Martian resources, near-term nuclear thermal propulsion (NTP) such as the NERVA nuclear rocket engine, and NEP systems using Li-LFA engines (to transport cargo to support the piloted portion of the mission). Very fast (100-day round-trip) piloted Mars missions could be enabled with advanced fission or fusion propulsion. Finally, robotic interstellar precursor missions could use NEP and piloted or robotic interstellar flyby or rendezvous missions could use fusion, antimatter, or beamed energy.

Table 1. Examples of Current Missions Using SOTA Propulsion Systems and Future Missions Enabled by the Use of Advanced Propulsion Technology

| Current Missions | Example Systems | Enabled Missions | Example Systems |
|---|---|---|---|
| Station-Keeping | $N_2H_4$, ResistoJet, Arcjet | Long-Life Station-Keeping, Micro-Spacecraft | Xe-Ion, Pulsed-Plasma |
| Orbit Raising (LEO->GEO/Moon) | Chemical (Solids, Liquids) | Low-Cost Orbit Raising: | |
| | | “slow” | SEP w/ Xe-Ion |
| | | “Fast” | SEP w/ C60-ion, Russian Hall or TAL; NEP w/ Li-LFA |
| Planetary (Slow Robotic) | Chemical (Solids, Liquids) | Planetary (Fast Robotic; Micro-S/C) | BMDO Micro-Chem, SEP, NEP, STP, Aerobraking |
| Piloted Mars (Slow, Massive) | Chemical | Low-Cost Piloted Mars: | |
| | | (slow) | Chemical w/ Aerobrake, ET Propellant Production; NTP (NERVA); NEP w/ Li-LFA |
| | | (Fast) | Gas-Core Fission, Fusion |
| | | Interstellar Precursor | MW-Class NEP |
| | | Interstellar | Fusion, Antimatter, Beamed Energy |

## THE NASA-JPL ADVANCED PROPULSION TECHNOLOGY PROGRAM

The NASA Advanced Propulsion Technology program at the Jet Propulsion Laboratory (JPL) addresses basic feasibility and proof-of-concept issues associated with a number of advanced concepts that have the potential for reducing the cost of space missions, and for enabling bold, new missions of the 21st century. These propulsion concepts were selected primarily to address a range of specific applications from near-term to far-term missions, Also, these concepts must satisfy at least minimal environmental constraints imposed on their development and eventual operation. (For example, mercury propellant ion engines are not considered because of the serious facility clean-up requirements associated with testing, and the launch failure issues of large-scale mercury dispersal into the environment.) Finally, whenever possible, funding from multiple sources (e.g., DoD, DoE, NSF, SBIR, etc.) has been sought to provide the “critical mass” of funding necessary to perform the required work.

The program consists of two main areas. The first involves cooperative modeling and research activities between JPL and various universities and industry; the second involves research at universities and industry that is directly supported by JPL. The cooperative research program consists of mission studies, feasibility research of iOn engine technology using $C_{60}$ (Buckminsterfullerene) propellant, and feasibility research of lithium-propellant Lorentz-force accelerator (LFA) engine technology. The directly-supported university / industry research program includes research (modeling and proof-of-concept experiments) in advanced, high-power, high-$I_{sp}$ electric propulsion for ambitious robotic planetary exploration missions; and in fusion propulsion for far-term, fast (< 100 day round trip) piloted Mars missions and, in the very far term, interstellar missions.

## MISSION STUDIES

The primary goal of the mission studies portion of the program is the identification and evaluation of new as well as existing advanced concepts in the context of changing technology and mission paradigms. This is done through a combination of mission benefit studies and annual workshops. The workshops also provide an important opportunity for cross-fertilization of ideas, techniques, and results for a wide variety of workers in the field of advanced space propulsion technology. For example, the 1995 annual workshop hosted -50 attendees with 29 presentations from NASA, DoD, DoE, industry, and academia.[2] Specialist "mini"-workshops have also been used to address specific topics ranging from advanced electric propulsion to potential breakthrough-physics concepts.[3]

As discussed above, one of the criteria used to select a candidate advanced propulsion concept is its applicability to a specific, well defined, ambitious mission or class of missions (e.g., cis-lunar [LEO/GEO/Lunar] orbit transfer missions). Thus, one important output of the mission studies portion of the program is the quantification of potential mission benefits (e.g., reduction in initial mass in LEO or trip time, increase in payload mass, etc.) provided by an advanced concept. Also, because the various performance characteristics of a given technology (e.g., $I_{sp}$, efficiency, specific mass, etc.) can be treated parametrically in a mission analysis study, it is often possible to identify major system parameters that drive mission performance, and, conversely, also identify those that have little impact on performance.

For example, based on experience gained in programs supported by the BMDO to evaluate and test a variety of Russian electric thrusters for orbit raising missions, JPL has begun preliminary evaluation of what benefits a high-$I_{sp}$ version of the Russian Central Research Institute of Machine Building (TsNIIMASH) thruster with anode layer (TAL) would have for planetary missions. This study assumes that this thruster operates at the same voltage as a solar array (e.g., ca. 700 VDC) in a "direct-drive" approach with a minimal power processing system. (By contrast, ion engines typically require significant power processing because they operate at kilovolt DC levels.) An example of the mission performance potential of direct-drive, high-$I_{sp}$ TAL SEP is shown in Figure 3. Additional examples of mission analysis studies are given below for several of the advanced propulsion systems investigated by this program.

## $C_{60}$-PROPELLANT ION ENGINE

The $C_{60}$-propellant ion engine has the potential for good efficiency in a relatively low specific impulse ($I_{sp}$) range (19,600 to 29,400 m/s, or 2,000 to 3,000 $lb_f$-s/$lb_m$) that is optimum for relatively fast (< 200 day) cis-lunar (LEO/GEO/Lunar) missions employing near-term, high specific-mass electric propulsion vehicles. This effect is illustrated in Figure 4, which compares the total initial mass in low Earth orbit (IMLEO) and trip times required for a low-thrust LEO-to-GEO orbit raising mission using either $C_{60}$-ion or Xc-ion engines in a SEP vehicle. Because of its higher efficiency at low $I_{sp}$s, the $C_{60}$-ion system can reduce the trip time by roughly 25 % as compared to the Xc-ion system. This example also illustrates the potential for significant cost savings possible with electric propulsion: an Atlas IIAS GEO-delivery payload (1895 kg) is launched on a Delta II 7920 with a SEP system into LEO and the SEP system is used to transport the payload to GEO. In this case, there is a roughly $60-80M savings in the use of the less expensive Delta launch vehicle, although this savings would be reduced by the cost of the SEP module.

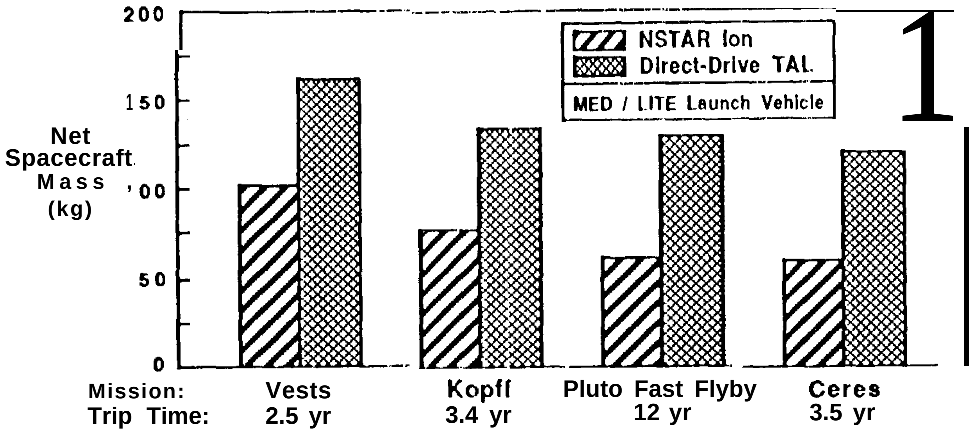


Figure 3. Comparison Between Direct-Drive Russian Thruster with Anode Layer (TAL) and NSTAR-Class Ion Engines for SEP Robotic Missions

Research and modeling on the $C_{60}$-ion engine is currently being performed by JPL (engine proof-of-concept demonstration),[4] Caltech ($C_{60}$ properties),[4] Colorado State University (cathode development), MIT (plume modeling), and USC (diagnostics). Previous work on this concept has demonstrated electrostatic acceleration of $C_{60}$ ions. However, an electron-bombardment ion engine configuration could not be used because the hot filament wire in the cathode caused unacceptably high rates of $C_{60}$ decomposition. A radio-frequency (RF) discharge ion engine was also found to be infeasible because the discharge was quenched due to the high electron affinity of $C_{60}$. Alternative approaches are currently under consideration. A “decision-gate” on further research in this area is planned for 1996.

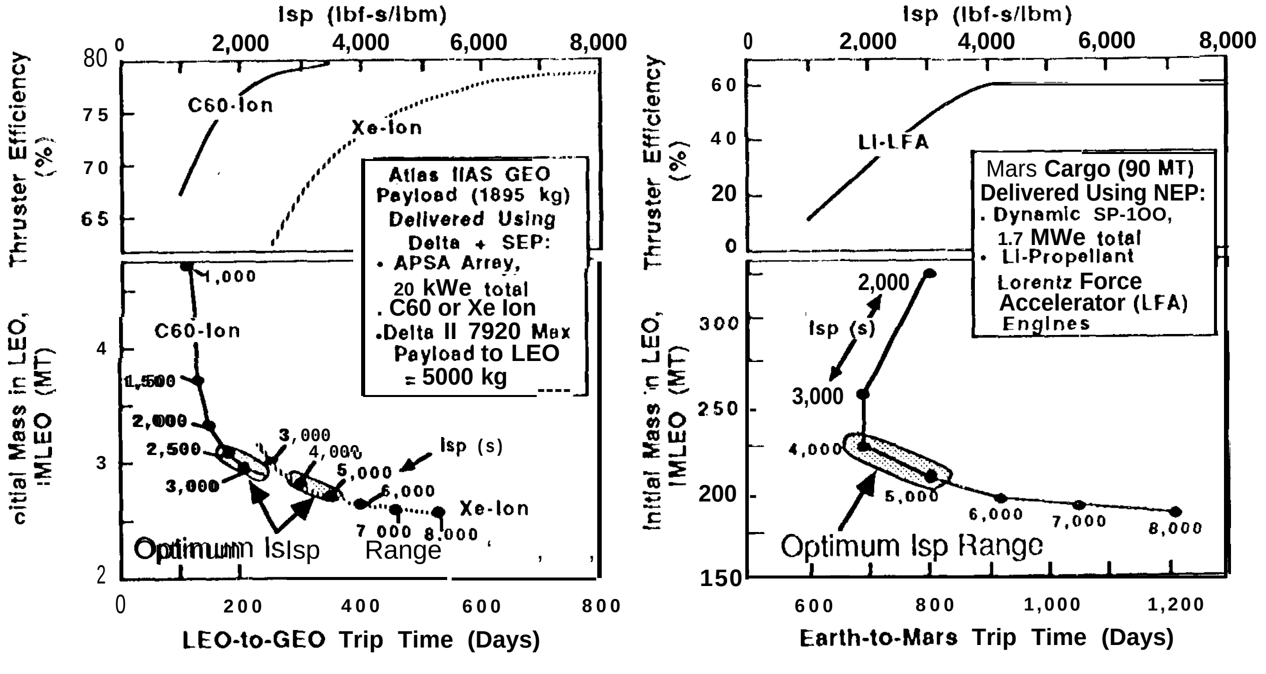


Figure 4. Impact of Electric Propulsion Thruster Efficiency on Mission IMLEO and Trip Time

## LITHIUM-PROPELLANT LORENTZ-FORCE ACCELERATOR (LFA) ENGINE

Numerous studies have identified the potential benefits of high-powered nuclear electric propulsion (NEP) for piloted Mars missions al power levels of tens of megawatts[5] to hundreds of megawatts.[6] These very high-power, piloted NEP systems are typically optimized for minimum trip time. More recently, there has been interest in slower, somewhat lower power (ea. 1 MW$_e$) NEP systems that could be used for supplying time-insensitive cargo in support of human exploration of Mars. (In this case, the crew would travel to Mars on an aerobraked chemical or nuclear-thermal propulsion vehicle.) These near-term NEP vehicles would make use of SP-100 reactor technology coupled with dynamic thermal-to-electric power conversion systems (e.g., Rankine) and either ion[7] or Lorentz Force Accelerator (LFA)[8] thrusters. For example, JPL and the Energy Technology Engineering Center (ETEC) evaluated the system shown in Figure 5 consisting of three SP-I 00 dynamic power modules, for a total "bus" electric power of 1.7 MW$_e$, and lithium-propellant LFA thrusters.[8] Figure 4 illustrates the potential performance of this vehicle as a function of $I_{sp}$; an optimum compromise between minimum trip time and total initial mass in low Earth orbit (IMLEO) occurs at an $I_{sp}$ around 39,200 m/s to 49,000 m/s (4,000 to 5,000 lbf-s/lbm). Finally, note that although the NEP system is typically lighter and requires fewer launches than a chemical or nuclear thermal propulsion (NTP) vehicle, this improvement in IMLEO is countered by the significantly longer trip time of the NEP vehicle (~ 260 days for the ballistic chemical or NTP vehicle versus ~ 800 days for the NEP vehicle).

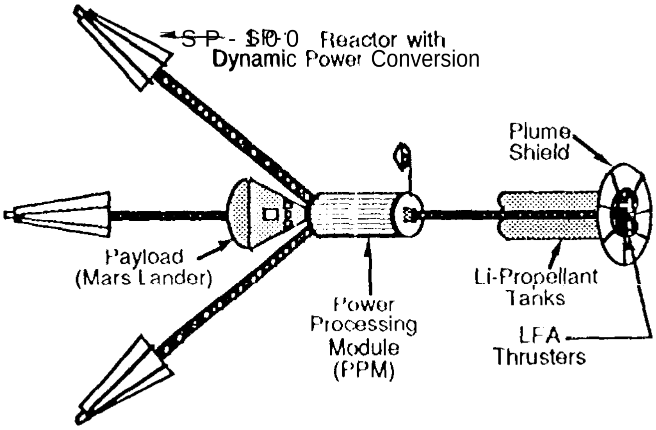


Figure 5. Megawatt-Class Nuclear Electric Propulsion (NEP) Vehicle With Li-Propellant LFA Thrusters

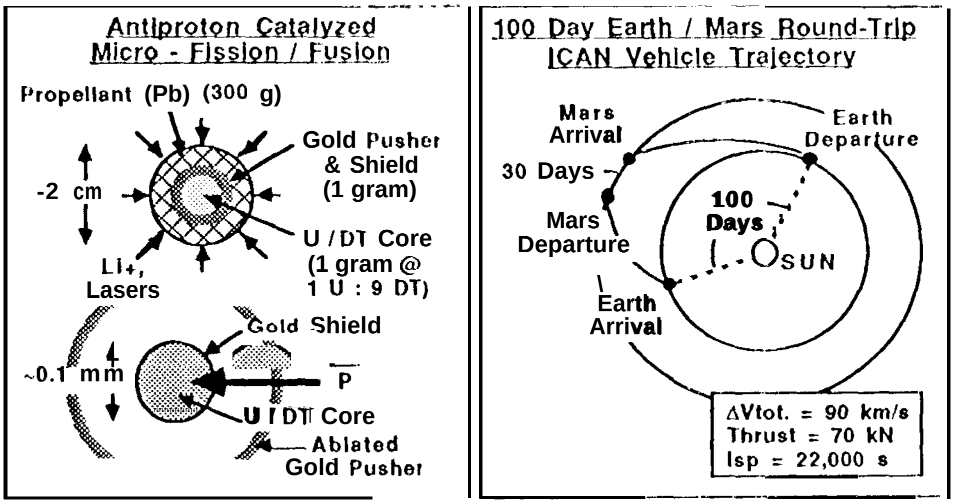
Interestingly, in terms of IMLEO and trip time, ion thrusters can give better mission performance than LFA thrusters for this type of NEP vehicle.[7, 8] However, there are serious system integration issues associated with the use of ion thrusters in megawatt-class electric propulsion systems due to their relatively low power-per-thruster. This introduces significant packaging and complexity issues for the use of ion thrusters that are not encountered for sub-megawatt (e.g., robotic mission) SEP or NEP systems.

Current LFA thruster research at JPL is centered on evaluating the feasibility of obtaining sufficient component life because of the significant impact that thruster lifetime has on vehicle performance. This work includes theoretical and experimental investigation of cathode erosion processes.[9] Additional cathode research and development is being supported at Thermacore Inc. through an SBIR. JPL is also supporting computational plume modeling at MIT because of the importance of understanding the effects of contamination from condensable propellants like lithium and $C_{60}$. Finally, JPL is supporting development of a 100- kW$_e$ class Li-propellant LFA thruster at the Moscow Aviation Institute (MAI) in order to make use of the expertise developed by the Russians during the past several decades. This use of MAI expertise will greatly accelerate the feasibility determination of LFA engine technology.

## ANTIPROTON-CATALYZED MICRO-FISSION / FUSION PROPULSION

Previous studies have identified fusion propulsion as an enabling technology for rapid human transportation within the solar system[10] and potentially for interstellar missions.[11] In particular, fusion propulsion is especially attractive for fast (100-day round trip) piloted Mars missions. For example, in the VISTA (Vehicle for Interplanetary Space Transportation Applications) study conducted by JPL, Lawrence Livermore National Laboratory (LLNL), Johnson Space Center (JSC), and ETEC, an inertial confinement fusion (ICF) propulsion system was found capable of performing a 60-day round-trip Mars mission with a 100-MT payload. This type of performance is typical of fusion rockets, although it requires large vehicles (~1600-MT dry without payload, 4100-MT of propellant), operating at high powers (30 GW) and high $I_{sp}$s (166,600 m/s or 17,000 $lb_f$-s/$lb_m$).[10]

An alternative approach to "conventional" VISTA-type fusion propulsion systems is the inertial-confinement antiproton-catalyzed micro-fission/fusion nuclear (ICAN) propulsion concept[12] under development at Pennsylvania State University (PSU), as shown in Figure 6.[13] In this approach to ICF propulsion, a pellet containing uranium (U) fission fuel and deuterium-tritium (D-T) fusion fuel is compressed by lasers, ion beams, etc. At the time of peak compression, the target is bombarded with a small number ($10^8$-$10^{11}$)[13] of antiprotons to catalyze the uranium fission process. (For comparison, ordinary U fission produces around 2 neutrons per fission; by contrast, antiproton-induced U fission produces 16-18 neutrons per fission.[12,14]) The fission energy release then triggers a high-efficiency fusion burn to heat the propellant, resulting in an expanding plasma used to produce thrust. Significantly, unlike "pure" antimatter propulsion concepts which use large amounts of antimatter (because all of the propulsive energy is supplied by matter-antimatter annihilation), this concept uses antimatter in amounts that we can produce today with existing technology and facilities. This technology could enable 100- to 130-day round trip (with 30-day stop-over) piloted Mars missions, as shown in Figure 6, 1.5-year round trip (with 30-day stop-over) piloted Jupiter missions, and 3-year one-way robotic Pluto orbiter mission (all with 100 MT payloads).[12]


Antiproton Catalyzed Micro - Fission / Fusion

100 Day Earth / Mars Round-Trip ICAN Vehicle Trajectory

Figure 6. Antiproton-Catalyzed Micro-Fission / Fusion Concept and Mission Performance of an ICAN Propulsion System for a Fast Piloted Mars Mission.

Also, because much of the fusion ignition energy comes from the initial fission reaction, it maybe possible to employ smaller or simpler pellet compression "drivers" (e.g., particle beams, lasers, etc.) than those considered for a "conventional" ICF system where all of the fusion ignition energy is derived from the compression process. Similarly, it may also be possible to use difficult-to-ignite aneutronic fuels like D-

He$^3$. For example, recent simulations of D-He$^3$ versus D-T antiproton-catalyzed micro-fission/fusion have shown that although neutron energy yields are reduced by a factor of 5 using D-He$^3$, the fusion energy yield is 12 times smaller than that with D-T due to the slow "burn" rate of the D-He$^3$ target (which allows time for disassembly of the target before it can be consumed).[14] However, neutron flux with D-He$^3$ may result in reductions in overall vehicle mass (due to decreased shielding, waste-heat control, etc. requirements) which may compensate for the reduced fusion energy yield.

Future plans for this activity, supported by JPL, the Air Force Office of Scientific Research (AFOSR), the National Science Foundation (NSF), the Pennsylvania State University Center for Space Propulsion Engineering, and the Rocketdyne Division of Rockwell International Corp., include completion of a portable antiproton Penning Trap in 1995. This trap will hold ~$10^9$ antiprotons.[13] The Penning Trap will be filled with antiprotons at CERN and transported to the Air Force Phillips Laboratory SHIVA-STAR facility at Kirtland AFB, where a demonstration of antiproton-catalyzed micro-fission (but not fusion) is planned for 1996. An improved Penning Trap (with higher capacity) will be assembled in 1997, and used for a demonstration of antiproton-catalyzed micro-fission and fusion in 1998. A schematic of the Penning Trap and the experimental facility at SHIVA-STAR are shown in Figure 7.[12,13]

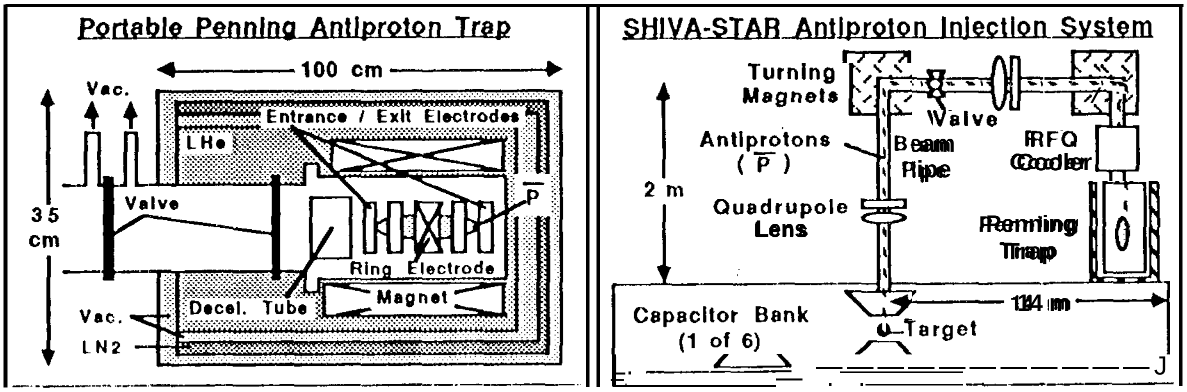


Figure 7. PSU Portable Antiproton Penning Trap and Experimental Facility at SHIVA-STAR.

## DENSE PLASMA FOCUS (DPF) THRUSTER

An alternative to the large ICF systems envisioned for systems such as the VISTA or ICAN concepts described above is the dense plasma focus (DPF) thruster under evaluation at Lawrenceville Plasma Physics (LPP) and the University of Illinois. The DPF thruster has the potential of being a compact (table-top sized) 'magnetic confinement fusion (MCF) device that operates in a magnetic "pinch" mode. This device could also operate on a number of fusion fuels including aneutronic fuels like p-B$^{11}$. However, unlike most ICF or MCF devices, it is not designed to operate at a high "gain", where gain is defined as the fusion energy output divided by the energy input to make the fusion reaction occur. In fact, the gain of the DPF thruster is estimated to be around one, corresponding to "break-even". Thus, from a spacecraft point of view, the DPF thruster has the potential of acting like an electric propulsion engine with an efficiency of 100 % and with the $I_{sp}$ of a fusion engine.

This concept, previously supported by the Air Force Phillips Laboratory (Edwards AFB) and now by JPL, is still in its early stages of development. To date, theoretical modeling and some limited testing have shown the preliminary feasibility of the concept. Plans for this year include detailed particle-in-cell (PIC) plasma modeling to be performed at LPP, and detailed experiments to be performed at the University of Illinois.[15]

## ADVANCED PROPULSION TECHNOLOGIES NOT ADDRESSED

The guiding paradigm of the advanced propulsion program has been the goal of identifying and evaluating the “feasibility” of a variety of advanced concepts in terms of their desirability (e.g., mission benefits) and technological feasibility (e.g., proof-of-concept experiments). This program has been able to pursue only a small fraction of the large number of advanced space propulsion technologies that have the potential for reducing costs and/or enabling ambitious space missions. In effect, this program has attempted to provide the “seed corn” required to assess basic feasibility issues; it is not our charter to provide for development or “product improvement.” Thus, in some cases, candidate propulsion technologies were not considered because it was felt that they were too mature. For example, resistojet, arcjet, and Xe-propellant ion engines, as well as NERVA-class solid-core nuclear rockets would fall in this category because their basic feasibility issues have already been resolved. Also, in several cases, advanced technologies are being addressed by other organizations; we coordinate our activities with the various centers to avoid duplication of effort. For example, the Air Force Phillips Laboratory (Edwards AFB, California) has a significant program in basic research and engineering of advanced, high-energy density materials (HEDM) chemical propellants and rocket engines to which we have provided some mission analysis support. (However, when appropriate, we do participate in activities, such as the work at Pennsylvania State University described above, involving multiple funding agencies, so as to assemble a “critical mass” of funding required for the task.)

Nevertheless, there are a number of potentially attractive advanced technologies that are worth pursuing but have not been due to budgetary constraints. For example, the area of extraterrestrial materials utilization, and in particular extraterrestrial propellant production, can provide major cost savings by reducing the IMLEO of a variety of robotic and piloted missions. Beamed-energy (e.g., laser or microwave) power and propulsion concepts have the potential for both reducing costs and enabling new missions. Various launch-assist catapult concepts[1] may also permit factor-of-twenty reductions in launch costs. Based on a variety of previous favorable mission analyses, we hope to be able to address some of the technological feasibility issues of these concepts in the near future.

## SUMMARY

As discussed earlier, these advanced propulsion concepts were selected to address representative types of mission applications ranging from mid-term to far-term missions. This is illustrated in Figure 8, which lists the advanced propulsion technologies being investigated under this program and some of the mission applications which benefit, in terms of cost reduction or mission enablement, from the use of these systems. For example, the $C_{60}$-ion and TAL systems can provide significant trip time savings and/or payload increases for low-power (kilowatts to several tens of kilowatts) SEP orbit-raising and robotic planetary missions. At megawatt power levels, the Li-LFA engine can reduce the costs of large cis-lunar or planetary cargo missions (in support of human exploration) by reducing the number of Earth launches. (However, as with any low-thrust system, there will be a trade-off between initial mass in LEO and trip time as compared to a high-thrust chemical or nuclear thermal system.) Finally, ambitious missions of the 21st century, such as fast piloted Mars’or interstellar missions, can be enabled by fusion or antimatter propulsion systems.

## ACKNOWLEDGMENTS

The work described in this paper was performed by the Jet Propulsion Laboratory (JPL), California Institute of Technology, under contract with the National Aeronautics and Space Administration.

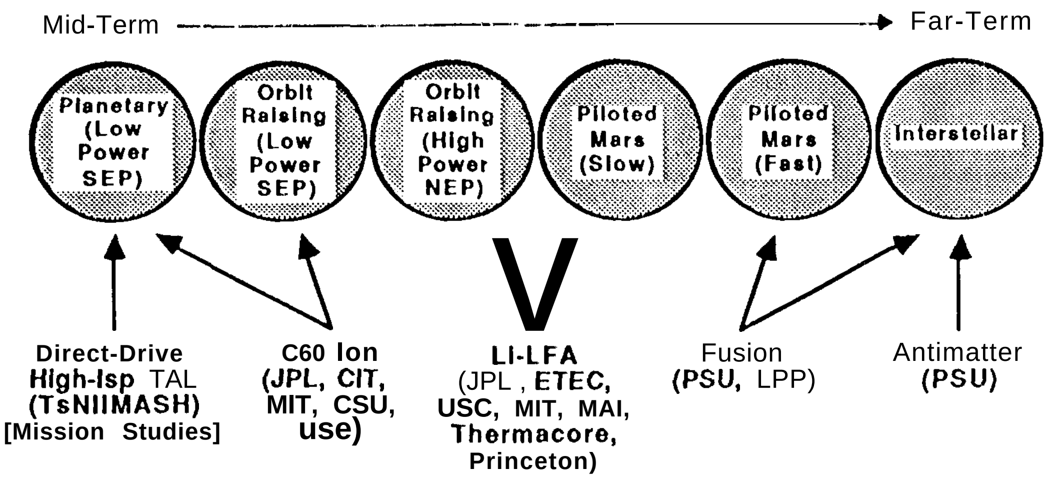


**Figure 8. Mission Applications and Advanced Propulsion Technologies Supported by the NASA-JPL** Advanced Propulsion Technology Program

## REFERENCES

1. Mankins, J. C., “Beyond the Next Generation: Advanced Concepts for Earth-to-Orbit Transportation," AIAA Paper AIAA 95-3138, presented at the AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

2. Bennett, G., and Frisbee, R., “Preparing for the Next Millennium: Report on the Sixth Advanced Space Propulsion Systems Workshop,” to be presented at the Space Technology and Applications international Forum (STAIF-96), Albuquerque NM, January 7-11, 1996.

3. Bennett, G., Forward, R., and Frisbee, R., “Report on the NASA/JPL Workshop on Advanced Quantum/Relativity Theory Propulsion,” AIAA Paper AIAA 95-2599, presented at the AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

4. Anderson, J., Fitzgerald, D., Leifer, S., and Mueller, J., “Design and Testing of a Fullerene RF Ion Engine,” AIAA Paper AIAA 95-2664, presented at the AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

5. Palaszewski, B. A., et al., “Nuclear Electric Propulsion: Manned Mars Mission Options,” presented at the Case for Mars III Conference, Boulder CO, July 22, 1987; Palaszewski, B. A., et al., “Electric Propulsion for Manned Mars Exploration,” presented at the JANNAF Propulsion Meeting, Cleveland OH, May 23, 1989; and Gilland, J., “Nuclear Propulsion Systems and Technologies for NASA Missions,” presented at the NASA OACT Third Annual Workshop on Advanced Propulsion Concepts, Pasadena CA, January 30-31, 1992, Proceedings published as JPL Internal Document JPL D-9416, R.H. Frisbee, Ed., January 30-31, 1992.

6. Frisbee, R.H., "Multimegawatt Electric Propulsion for Mars Missions,” AIAA Paper AIAA-91-3490, presented at the AIAA/NASA/OAI Conference on Advanced SEI Technologies, Cleveland OH, September 4-6, 1991.

7. Gilland, J., and George, J., "'Early Track' NEP System Options for SEI Missions,” AIAA Paper AIAA 92-3200, presented at the AIAA/SAE/ASME/ASEE 28th Joint Propulsion Conference, Nashville TN, July 6-8, 1992.

8. Frisbee, R.H., and Hoffman, N.J., "SP-100 Nuclear Electric Propulsion for Mars Cargo Missions," AIAA Paper AIAA 93-2092, presented at the AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference, Monterey CA, June 28- July 1, 1993

9. Goodfellow, K., and Polk, J., "Experimental Verification of a High-Current Cathode Thermal Model," AIAA Paper AIAA 95-3062, presented at the AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

10. Orth, C., Klein, G., Sercel, J., Hoffman, K., Murray, K., and Chang-Diaz, F., "Transport Vehicle for Manned Mars Missions Powered by Inertial Confinement Fusion," AIAA Paper AIAA 87-1904, presented at the AIAA/SAE/ASME/ASEE 23rd Joint Propulsion Conference, San Diego CA, June 29- July 2, 1987.

11. **Martin,** A., Ed., "Project Daedalus - The Final Report on the BIS Starship Study," *Journal of the British Interplanetary Society*, Supplement, 1978.

12. Smith, G. A., et al., "An Antiproton Driver for ICF Propulsion," AIAA Paper AIAA 94-2926, presented at the AIAA/ASME/SAE/ASEE 30th Joint Propulsion Conference, Indianapolis IN, June 27-29, 1994; and "Antiproton-Catalyzed Microfission/Fusion Propulsion," AIAA Paper AIAA 95-2900, presented at the AIAA/ASME/SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

13. Smith, G. A., et al., "Challenges to Computing Fusion Plasma Thruster Dynamics," AIAA Paper AIAA 94-3268, presented at the AIAA/ASME/SAE/ASEE 30th Joint Propulsion Conference, Indianapolis IN, June 27-29, 1994; and "Trapping Antimatter for Space Propulsion Applications," AIAA Paper AIAA 95-2891, presented at the AIAA/ASME /SAE/ASEE 31st Joint Propulsion Conference, San Diego CA, July 10-12, 1995.

14. Chwieroth, B., "Comparison of D-He(3) and D-T as Fuels for Antiproton-Catalyzed Microfission/Fusion Space Propulsion," Senior Honors Thesis, Department of Physics, Pennsylvania State University, Spring 1995.

15. Lerner, E. J., and Peratt, A. L., "Elaboration and Testing of a Theretical Model of Advanced Fuel Plasma Focus Performance for Space Propulsion," Final Report, JPL Contract 959962, Lawrenceville Plasma Physics, Lawrenceville NJ, March 20, 1995.