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# Evaluation of Propulsion Options for Interstellar Missions

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## ABSTRACT

This paper describes an evaluation of various propulsion options for robotic interstellar rendezvous missions to stars ranging from 4.5 Light Years (L.Y.) with a 10-year trip time, to 40 L.Y. with a 100-year trip time. Concepts considered included advanced electric propulsion, nuclear (fission, fusion, antimatter) propulsion, beamed energy (e.g., light sails, MagSails) propulsion, electromagnetic catapults, in-situ propellant production concepts (e.g., the interstellar ramjet), and hybrid systems (e.g., antimatter-catalyzed fission/fusion).

The various candidate propulsion options were evaluated using three screening criteria. First, is it possible for the candidate system to achieve the required $\Delta V$, which can be as much as 0.6 c for a fast, 4.5-L.Y. mission. Second, does the propulsion systems require an extensive, mission-unique supporting infrastructure. Finally, the technology readiness levels of the various subsystem technologies of the propulsion concept are reviewed. This screening process resulted in the selection of beamed energy sail, matter-antimatter, and fusion ramjet concepts as the most promising candidates. Potential mission performance and near-term technology goals of these concepts were then evaluated.

## INTRODUCTION

On July 3, 1997, NASA Administrator Daniel S. Goldin asked JPL to evaluate technologies for a 10,000-AU, 50-year robotic interstellar precursor mission to be launched in 25 years. This activity has been expanded to include consideration of robotic interstellar rendezvous missions to the nearest 1,000 stars (e.g., from about 4.5 to 40 light years). This paper will focus on an evaluation of various propulsion options for interstellar rendezvous missions from 4.5 light years (L.Y.) with a 10-year trip time, to 40 L.Y. with a 100-year trip time.

Concepts to be considered include advanced electric propulsion, nuclear (fission, fusion, antimatter) propulsion, beamed energy (e.g., light sails, MagSails) propulsion, electromagnetic catapults, and in-situ propellant production concepts (e.g., the interstellar ramjet), and hybrid systems (e.g., antimatter-catalyzed fission/fusion). Interestingly, because of the high $\Delta V$ required for interstellar flyby and rendezvous missions (up to several tenths of the speed of light) and the large dry masses of the candidate propulsion systems, traditional non-propulsive enhancements like staging and gravity assist are of limited use, resulting in a need for specific impulses ($I_{sp}$) on the order of $10^4$ to $10^7$ $lb_f$-s/$lb_m$, depending on the mission overall $\Delta V$.

The various candidate propulsion options are evaluated using three screening criteria. First, is it possible for the candidate system to achieve the required $\Delta V$, which ranges from 100 km/s for a 1,000 AU mission to as much as two times 0.6 c (i.e., acceleration and deceleration) for a fast, 4.5-L.Y. rendezvous mission. Second, does the propulsion systems require an extensive, mission-unique supporting infrastructure. Finally, the technology readiness levels of the various subsystem technologies of the propulsion concept are reviewed. This screening process resulted in the selection of beamed energy sails, matter-antimatter, and fusion ramjet concepts as the most promising candidates. Potential mission performance and near-term technology goals of these concepts were then evaluated.

## IMPACT OF PRECURSOR AND INTERSTELLAR MISSIONS ON PROPULSION SYSTEM REQUIREMENTS

The long-range mission goal is the ability to rendezvous with scientifically interesting planets circling about other stars. Mission targets, such as planets capable of harboring life (and, ultimately, planets habitable by humans), would be identified by the NASA Origins Program, which will use progressively more sophisticated space-based observational techniques (e.g., telescopes, interferometers, etc.) to ultimately image Earth-like planets

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around the nearest 1,000 stars (i.e., from 4.5 to 40 L.Y.). In the near term, however, there are a number of interesting interstellar precursor scientific opportunities that could serve as intermediate, near-term technology demonstration missions on the way to developing propulsion systems capable of achieving the ultimate mission to the stars.

Some examples of these precursor opportunities are shown in Figure 1.[1] These include missions to the Heliopause (at ca. 100 Astronomical Units, A.U.), the sun's Gravitational Lens (550 A.U.), and the Oort cloud (ca. 10,000 A.U.). Order-of-magnitude $\Delta V$ and corresponding propulsion system $I_{sp}$ requirements (assuming $I_{sp} \sim \Delta V$) for these missions are given in Table 1. Figure 2 illustrates the range of $\Delta V$ values typically encountered as a function of the trip time desired.

Figure 2 also illustrates the difficulty of performing even near-term interstellar precursor missions; for example, advanced nuclear electric propulsion (NEP) requires roughly 50 years to reach the outer edge of the Kuiper Belt at 1,000 A.U. More ambitious missions require the use of fission, fusion, or antimatter reactions as the propellant exhaust, or of photons (beamed energy). Also, we need to stress that an interstellar mission will necessarily involve enormous energies. For example, accelerating a 1,000 metric ton mass to 10% of the speed of light would require all of the energy currently produced by humanity in one year (ca. $4 \times 10^{20}$ Joules per year, or an average power of 13 TW).

Table 1. Sample Mission, $\Delta V$, and $I_{sp}$ Requirements

| Mission | Typical $\Delta V$ | Typical Isp ($lb_f$-s/$lb_m$) |
|---|---|---|
| Planetary | 10 km/s | $10^3$ |
| 100-1,000 A.U.<br>• Heliopause (100 AU)<br>• Gravity Lens (550 AU) | 100 km/s | $10^4$ |
| 10,000 A.U.<br>• Oort Cloud | 1,000 km/s | $10^5$ |
| Slow Interstellar<br>• 4.5 L.Y. in 40 Years | 0.1 c | $3 \times 10^6$ |
| Fast Interstellar Rendezvous<br>• 4.5 L.Y. in 10 Years, 40 L.Y. in 100 Years | 0.4 c (Doubled) | $3 \times 10^7$ |

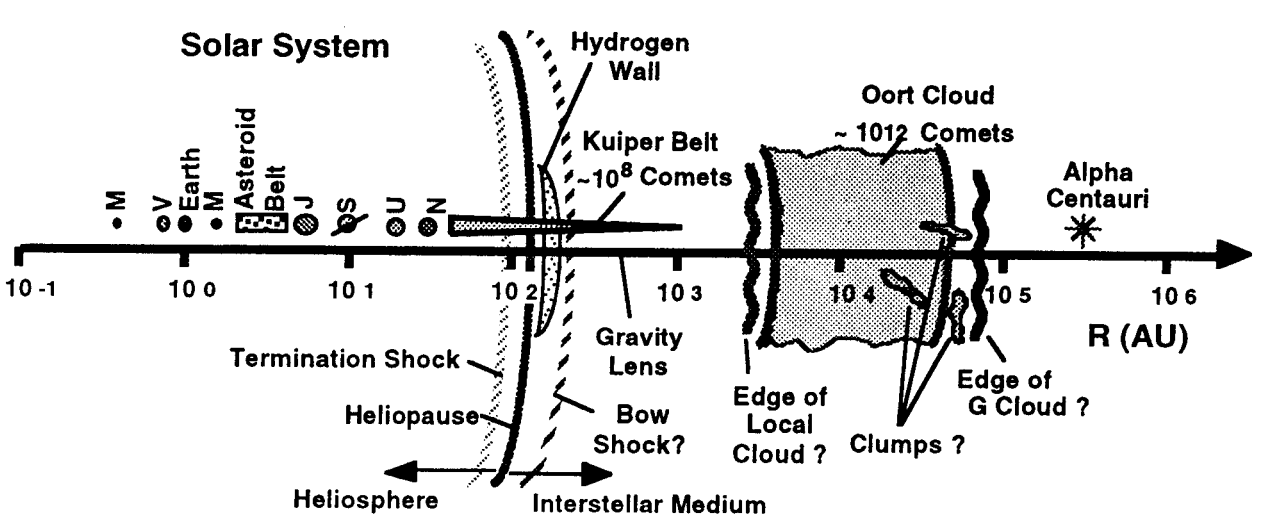


Figure 1. Scale of the Interstellar Medium (After Mewaldt, Ref. 1)

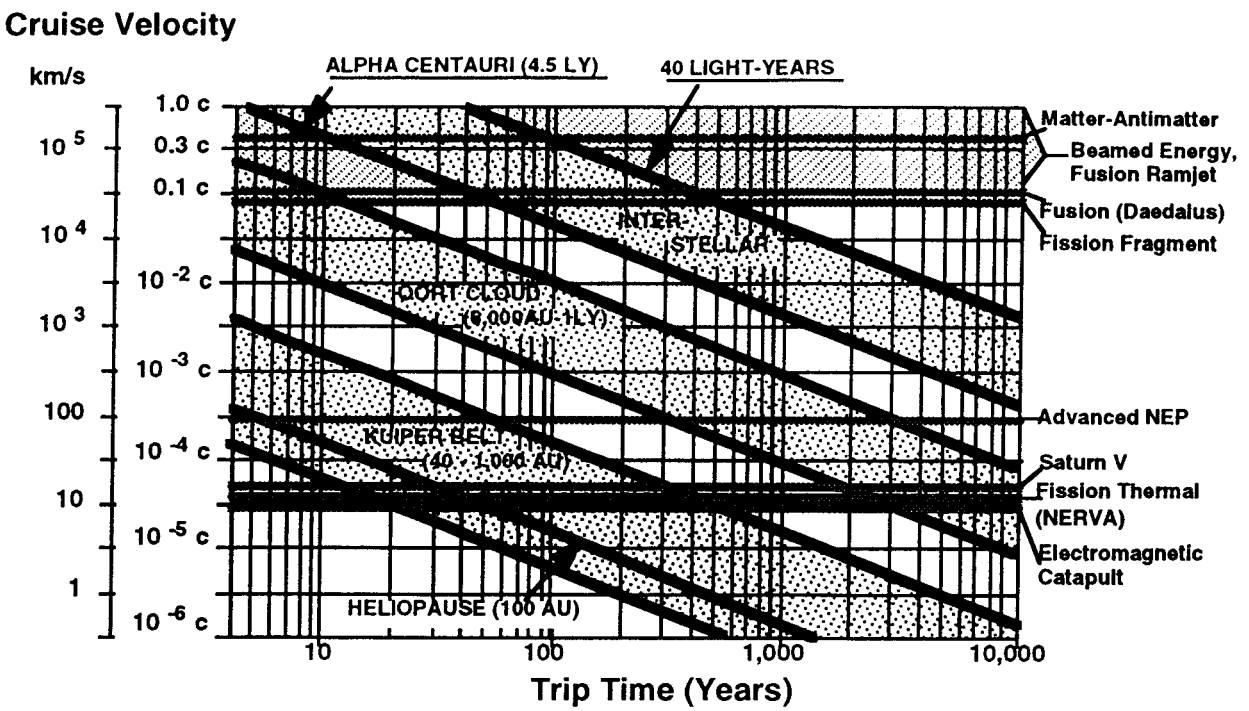


Figure 2. Mission Velocity and Trip Time

## CANDIDATE PROPULSION OPTIONS

Candidate propulsion systems are categorized by their energy source (e.g., fission, fusion, etc.) and are discussed in more detail below.

### Fission

**Fission Fragment Rocket.** Unlike a conventional fission-thermal propulsion system (e.g., NERVA, etc.), in which fission energy is used to heat a secondary working fluid (e.g., hydrogen), the Fission Fragment Rocket concept uses fragments of the fission process (e.g., $Sr^{90}$ and $Xe^{136}$ from $U^{235}$ fission) directly as the rocket exhaust gas (with an $I_{sp}$ of about $10^6$ $lb_f$-s/$lb_m$ or an exhaust velocity of 0.03 c).[2]

**Fission Fragment "Sail".** This concept is similar to the Fission Fragment Rocket approach, but uses a thin sheet (sail) doped with a fissionable material. This system can be used as a regular solar sail near a star.[3]

### Fusion

In Inertial Confinement Fusion (ICF) and Magnetic Confinement Fusion (MCF), fusion energy is used to heat a secondary propellant working fluid (such as hydrogen) to an $I_{sp}$ of about $10^4$ to $10^5$ $lb_f$-s/$lb_m$, or the fusion products are directly exhausted with a maximum $I_{sp}$ of about $10^6$ $lb_f$-s/$lb_m$ or an exhaust velocity of 0.03 c. (The illustrated example is the Daedalus 2-stage ICF vehicle.[4])

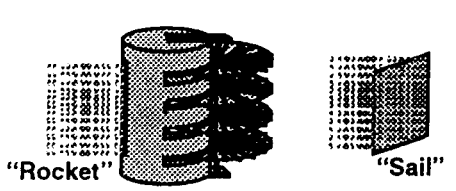


Figure 3. Fission Fragment Propulsion Concepts

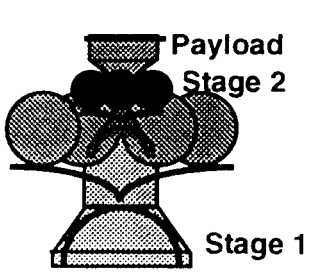


Figure 4. Daedalus Two-Stage Inertial Confinement Fusion (ICF) Propulsion Concept

## Matter-Antimatter Annihilation

In the "Beam-Core" Antimatter Rocket concept, equal amounts of matter and antimatter (in the form of protons and antiprotons) are combined and annihilate each other to produce high-speed annihilation products (charged pions and muons) as the rocket exhaust gas (with an $I_{sp}$ of about $10^7$ $lb_f$-s/$lb_m$ or an exhaust velocity of 0.3 c). A magnetic nozzle is used to direct the charged pions out the nozzle.[5]

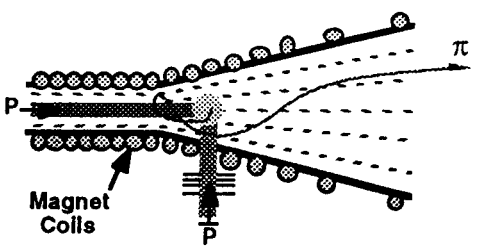


Figure 5. Beam-Core Matter-Antimatter Rocket Concept

## Fission / Fusion / Antimatter Combinations

**Antiproton Catalyzed Fission / Fusion.** Fusion reactions can be "catalyzed" by addition of small amounts of antimatter (antiprotons). One approach, under development at Pennsylvania State University (PSU), uses antiprotons to trigger a sub-critical micro-fission explosion, which then ignites fusion fuel in an ICF system.[6] A second approach, muon catalyzed fusion, uses negative muons produced by antiproton annihilation. The muons replace electrons in hydrogen (or deuterium, tritium, etc.) atoms, allowing the nuclei to approach more closely to enhance the rate of fusion.[7]

**Bussard Interstellar Ramjet.** In this concept, first proposed by Bussard, hydrogen from interstellar space is collected ("scooped") for use in a fusion reactor and as propellant in a fusion propulsion system. This alleviates the relatively low $I_{sp}$ of a fusion propulsion system by providing essentially unlimited propellant.[8]

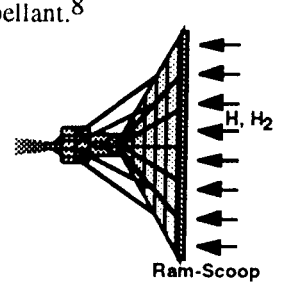


Figure 6. Bussard Interstellar Fusion Ramjet Concept

## Beamed Energy Sails

**Laser LightSails.** In this concept, a laser beam is used to "push" a solar sail. (Particles of light, photons, have momentum that is transferred to sail). This concept requires very large transmitter lens and receiver (sail) optics (e.g., 1,000-km diameters) and very high powers for rendezvous missions (e.g., 1,000-TW power levels). A multi-stage LightSail can be used to stop the vehicle at the target star system for rendezvous missions. In this case, a large outer sail ("1st stage") reflects the laser beam back at a smaller inner sail ("2nd stage") to stop the inner sail; the larger outer sail then accelerates out of the star system.)[9]

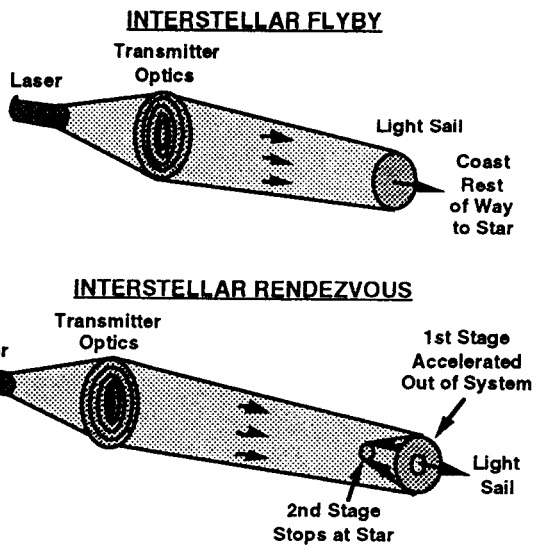


Figure 7. Beamed Energy Laser LightSail

**Microwave Sails.** This concept is the microwave analog to the laser LightSail. This approach has the advantage that the vehicle can be made ultra-lightweight for robotic mission flybys; in this case, the "sail" consists of wire mesh with holes in the mesh less than 1/2 the wavelength of the microwaves. The low mass of the vehicle reduces the power requirements to the tens of GW level. However, the microwave sail concept is generally not practical for rendezvous missions because of the longer wavelength of microwaves as compared to laser light (i.e., the longer wavelengths require much larger optics, as discussed below).[10]

**Particle Beam / MagSail.** This concept uses a linear accelerator to fire out high-speed particles (e.g., a relativistic particle beam) that push against the vehicle.[11] The particles can either hit a physical "pusher plate", or charged particles can push against

(and be reflected by) electromagnetic fields in a variation of the Magnetic Sail (MagSail) concept.[12] Like the Laser LightSail, this concept could employ a "multi-stage" system for rendezvous missions.

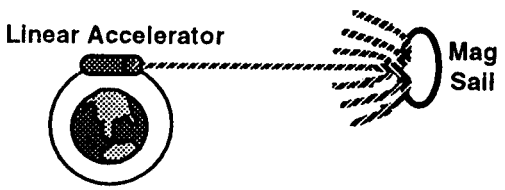


Figure 8. Relativistic Particle Beam / MagSail Concept

**Advanced Electric Propulsion**

Advanced nuclear electric propulsion (NEP) systems could be used for precursor missions, although they would have insufficient exhaust velocity (200 km/s) for interstellar missions.

**Electromagnetic Catapults**

Electromagnetic launchers (such as advanced versions of mass drivers or rail guns) could be used to launch small or micro-spacecraft. However, their demonstrated "muzzle" velocity (< 12 km/s) may limit them to solar system exploration missions.[13]

## EVALUATION METHODOLOGY

The large number of potential candidate propulsion systems makes it necessary to develop an evaluation methodology to eliminate those concepts that have insufficient performance or excessive supporting infrastructure requirements, or that require major technology advancements or breakthroughs.

One fairly straightforward figure of merit is the propulsion system's propellant exhaust velocity or specific impulse ($I_{sp}$). This is because of the impact of $I_{sp}$ on vehicle mass; as a general rule, it is desirable to have $\Delta V$ and $I_{sp}$ comparable in size to prevent excessive propellant requirements.

Some concepts, such as matter-antimatter annihilation propulsion or beamed-momentum propulsion may require a large supporting infrastructure to enable their use. For example, current antimatter production rates at facilities like CERN and FermiLab are in the range of a few nanograms ($10^{-9}$ g) per year; for matter-antimatter annihilation propulsion, where all of the propulsive energy comes from the annihilation reaction, many tons of antimatter will be required for interstellar missions. However, as discussed above, <u>any</u> interstellar propulsion system will necessarily have large energy requirements.

The final evaluation criterion deals with the technological readiness of the various concepts. Many of these systems (and their sub-systems) are at a relatively low Technology Readiness Level (TRL). Furthermore, in some cases, there remain major feasibility issues that have had only limited analysis. Finally, some concepts require major technology breakthroughs to make them practical.

**$\Delta V$ Capability**

The first and most important figure of merit is the propulsion system's propellant exhaust velocity or specific impulse ($I_{sp}$). This is because of the impact of $I_{sp}$ on vehicle mass as derived from the "Rocket Equation":

$$M_o / M_b = \exp ( \Delta V / g_c I_{sp} ) \qquad \text{(Eq. 1)}$$
$$M_p = M_o - M_b$$

where

$M_o$ = Vehicle wet mass
$M_b$ = Vehicle dry mass
$M_p$ = Propellant mass
$\Delta V$ = Velocity change
$I_{sp}$ = Specific impulse
$g_c$ = Unit conversion between $\Delta V$ and $I_{sp}$
= 9.8 for $\Delta V$ in m/s and $I_{sp}$ in $lb_f$-s/$lb_m$

As a general rule, it is desirable to have $\Delta V$ and $I_{sp}$ comparable in size to prevent excessive propellant requirements. Thus, all of the systems can meet the $\Delta V$ requirements of typical planetary missions (ca. 10 km/s, corresponding to an $I_{sp}$ of 1,000 $lb_f$-s/$lb_m$). Progressively more demanding missions, such as those to 100-1,000 A.U. (e.g., Kuiper Belt, gravitation lens of the sun at 550 A.U., etc.), 10,000 A.U. (interstellar precursor), and interstellar missions require corresponding increases in $\Delta V$ and $I_{sp}$. (Interestingly, a $\Delta V$ of 100 km/s is also needed for fast, 4 month round trip Mars missions.)

This evaluation criterion quickly eliminates advanced electric propulsion from consideration; even advanced ion engines (using xenon propellant) or Lorentz-force accelerator (LFA) engines (using hydrogen propellant) operating at an $I_{sp}$ of 20,000 $lb_f$-s/$lb_m$ simply do not have sufficient $I_{sp}$ for interstellar missions. Similarly, electromagnetic catapult launchers, with a demonstrated launch velocities of 12 km/s (corresponding to an $I_{sp}$ of 1,200 $lb_f$-s/$lb_m$) are inadequate.

Finally, ultra-light solar sails with very low areal densities (factors of 10-100 times better than existing sail technologies) could fly very near the sun (where sunlight pressure is higher) for an added boost for near-term interstellar precursor missions such as to the heliopause.

Thus, Advanced Electric Propulsion, Electromagnetic Catapults, and Ultra-Light Solar Sails fail the first test because they possess insufficient ΔV capability for interstellar missions.

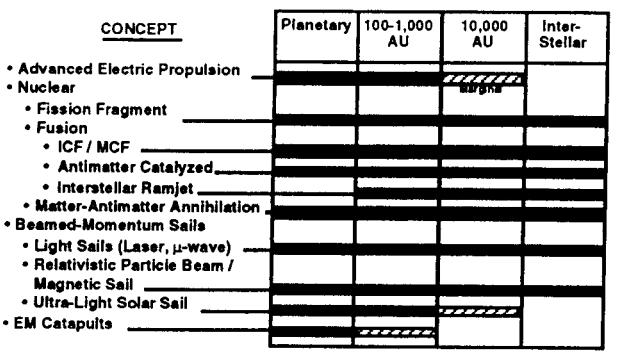


Figure 9. ΔV Capability of the Candidate Concepts

## Requirement for a Large, Mission-Unique Infrastructure

The second evaluation criteria deals with the potential need for a large, possibly space-based supporting infrastructure that is unique for the propulsion concept. The assumption here is that this infrastructure would represent a significant up-front cost that typically would have limited application beyond the interstellar mission.

For example, the fission fragment propulsion concept would require the construction of a unique facility (ground- or space-based) to produce large amounts (20 kg of fission fragment propellant per kg of vehicle dry mass to reach 0.1c) of short-lived, high-energy, highly-fissionable nuclear fuels such as americium (Am) or curium (Cm). These fuels are currently produced from reprocessed spent nuclear fuel (a costly process). Similarly, the relativistic particle beam concept would require a space-based particle beam facility that would have limited applicability beyond in-space transportation.

Fusion systems using aneutronic (i.e., neutron-free) fuels like $He^3$ would also require a significant infrastructure on the Moon or Jupiter to extract $He^3$ from the lunar regolith (by baking the soil) or jovian atmosphere (using aerostat-based facilities). Interestingly, the antimatter-catalyzed fusion concepts would not require major investments in antiproton production capability because the amount of antimatter required is relatively small. For example, planned improvements (approved and funded) at CERN over the next several years will increase its antiproton production rate by a factor of 10-100 over current capabilities; additional proposed improvements (not yet approved or funded) would increase the rate an additional factor of 10-100.[14]

By contrast, "pure" matter-antimatter annihilation propulsion, where all of the propulsive energy comes from the annihilation reaction, will require major new antiproton production facilities to supply the tons of antimatter required for interstellar missions. However, it must be noted that there are a number of dual-use spin-offs of antiproton research, such as medical applications (e.g., imaging and destruction of cancer tumors in the 1 mm size range), that could justify the infrastructure investment.[14]

Finally, laser or microwave light sails will require a major space-based infrastructure consisting of the beam source and the associated optics. However, this should represent only a scale-up of existing or near-term technologies (albeit to very large scales). Lastly, the beamed-energy infrastructure has the unique capability of multiple use as a time-shared power and propulsion source; for example, previous Horizon Mission Methodology studies (developed by Dr. John Anderson, NASA HQ) have identified the vision of a "Public Utilities in Space" concept, with a grid of laser/microwave beams supplying power in space analogous to the electric power and natural gas utilities on Earth.

Thus, the Fission Fragment and Particle Beam/ MagSail concepts strongly fail the infrastructure test. "Pure" Matter-Antimatter and Beamed Energy LightSail propulsion concepts only weakly fail this test, either because of the potential for multiple in-space or spin-off applications, or because they require only extrapolation of existing technologies. Therefore, only fusion, matter-antimatter annihilation, and LightSail propulsion will be carried on to the third evaluation criterion, technology requirements.

## Technology Requirements

Technology requirements for the three leading candidates is discussed next in detail. Note that all of the concepts have numerous uncertainties and major unresolved feasibility issues; there is no clear winner. Rather, the challenge is to identify the approach that has the fewest number of developmental and operational "miracles" required for its implementation. For convenience, Table 2 presents the Technology Readiness Level (TRL) definitions.

Table 2. Technology Readiness Level (TRL) Definitions

| TRL | Definition |
|---|---|
| 1 | Basic principals observed and reported. |
| 2 | Technology concept and/or application formulated. |
| 3 | Analytical and experimental critical function and/or characteristic proof-of-concept. |
| 4 | Component and/or breadboard validation in laboratory environment. |
| 5 | Component and/or breadboard validation in relevant environment. |
| 6 | System / subsystem model or prototype demonstration in a relevant environment (ground or space). |
| 7 | System prototype demonstration in a space environment. |

**Laser Sails.** When discussing laser light sails, it is important to note that an extensive body of technology and analysis exists for solar sails. Much of this work was done by JPL in the late 1970s to evaluate the feasibility of using a solar sail for the Haley Comet rendezvous mission. At that time, detailed analyses were made of solar sail fabrication techniques (thin silvered sheets and light-weight booms), control and dynamics, and trajectory analyses. The study found that solar sails were eminently feasible from a technology and mission performance point of view, but the development risk was considered too high for the short time available before launch. Since that time, a number of organizations have continued to analyze solar sails and further their technological development. For example, the private World Space Foundation has built a "boilerplate" Engineering Demonstration Model (EDM) square solar sail 30 meters on a side. Thus, interest in solar sails for a variety of lunar and Mars cargo missions, as well as planetary missions, has continued at a low level because solar sails represent the most fuel efficient possible inter-orbital "supertanker" in space.[15]

Interstellar light sails introduce additional technological issues primarily because of their large size and the need for high-intensity laser beams to propel them. For example, one important issue is the need for a very low sail areal density (mass per unit area); the lower the areal density, the lower the sail mass and corresponding beam power required. A number of concepts have been proposed for ultra-light sails; for example, one approach involves in-space production of a sail "substrate" film upon which is sprayed a highly-reflective coating material (e.g., aluminum). The substrate is selected to be a material that sublimes or decomposes in space (e.g., due to solar UV radiation), leaving behind only the reflective material. Also, very highly reflective thin-film coatings are needed, although there is an open issue as to the reflectivity of ultra-thin (few hundred atom thick layer) films that needs to be resolved. (Very high reflectivity is needed because of the potential for high laser beam intensities; for example, a laser with an intensity of 100 "suns" [i.e., a power per unit area 100 times that of sunlight at 1 A.U.] must have a reflectivity of 99.95% to maintain the same temperature as a solar sail [at 1 A.U.] with a reflectivity of 95%.) Finally, laser light sails will have potentially unique structures and dynamics issues due to their large size, and because the laser beam typically has a Gaussian power (i.e., light pressure) distribution (rather than the flat one of sunlight). Interestingly, spinning sails may be a solution to this problem; they have inherent stability due to their rotational momentum, although they are slower than 3-axis stabilized sails to re-orient themselves during planetocentric orbital "pumping" maneuvers. There have been no operational solar sail tests of yet, but a spinning sail structure was deployed by the Russians from a Progress tanker after its resupply mission was completed.[16]

**Beamed Energy Systems.** A variety of visible and near-visible infra-red (VIS/IR) lasers and microwave sources have been developed. Ground-based systems can be used for initial technology demonstration efforts, but space-based systems will be required for long-range power/momentum beaming so as to eliminate any distortions due to the Earth's atmosphere. For space-based systems, lasers that derive their excitation energy directly from the sun (e.g., "solar-pumped", where solar photons excite the lasant material) or from electricity (e.g., through solar cells or a nuclear-electric power system) are preferred over chemical lasers due to the mass of lasant chemicals that would need to be imported from Earth.

A number of candidate systems exist for laser or microwave sails. For example, laser options include the electric-power Free Electron Laser (FEL), the solar-pumped gas-phase $CH_3I$ laser (developed by LaRC in the 1980s)[17] and, more recently, solid-phase solar-pumped lasers.[18] Various very high power pulsed microwave systems (with duty cycles approaching "continuous wave", or CW output) have been developed for military applications. In this case, the issue is not so much one of technological feasibility as it is of scaling to the high powers required for laser or microwave sails.

Similarly, a great deal of the work done by SDIO and BMDO (and its continuing spin-off research for ground-based astronomy) in controlling beam pointing, tracking, spread, and jitter through the use of adaptive optics and "guide star" technology (for countering atmospheric distortion) is available. Also, large optics are required for interstellar distances; however, this requirement can me met with gossamer-structures Fresnel lenses (essentially concentric rings of thin-film plastic and vacuum), or by space-filling conjugate-locked phased-arrays of laser "tubes" or microwave transmitters.

For the purposes of sizing beamed energy optics, we make the assumption of diffraction-limited optics. With this assumption, the variation of transmitter (e.g., laser or microwave) and receiver (sail) areas for the limit of diffraction-limited optics is given by:[17]

$$A_t \cdot A_r = \lambda^2 \cdot L^2 \cdot \ln\{ 1 / (1-\eta) \} \qquad \text{(Eq. 2)}$$

where:

$A_t$ = Transmitter optics area
$A_r$ = Receiver optics area
$\lambda$ = Wavelength
$L$ = Distance between transmitter and receiver
$\eta$ = Spot size efficiency

The "spot" size efficiency term ($\eta$) is illustrated in Figure 10; it relates as to how much of the centrally-peaked Gaussian power distribution is intercepted by the receiver. For most power-beaming applications, $\eta$ is typically on the order of 0.9.

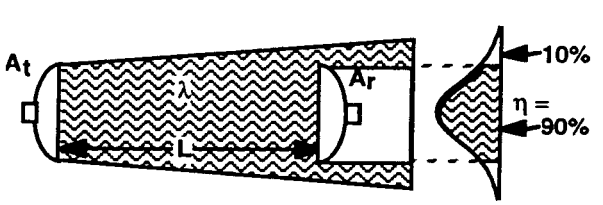


Figure 10. Transmitter and Receiver Spot Size

The variation of transmitter and receiver diameter with transmission distance is shown graphically in Figure 11. Because of the requirement for power beaming over interstellar distances for rendezvous missions, only laser LightSails will be considered in the mission analyses. Finally, note that the beaming requirements for initial robotic flyby missions will be much easier than for rendezvous missions, because the beam need only track the spacecraft over fractions of a light-year (instead of the full interstellar beaming distances required to stop the spacecraft at the target star for the rendezvous mission).

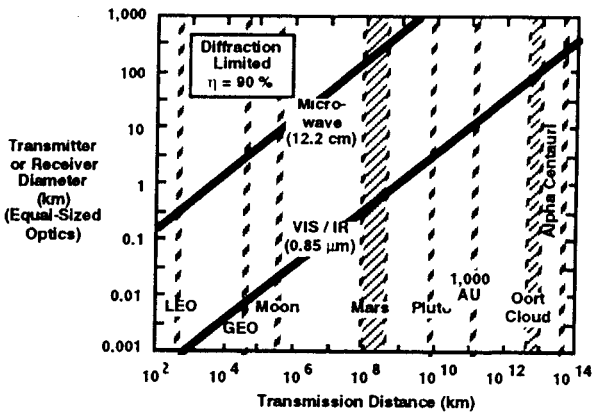


Figure 11. Variation of Transmitter and Receiver Diameter with Transmission Distance

The final issue for any beamed power and propulsion system is the high beam powers required. Although initial demonstrations can be accomplished with existing lasers in the 0.1 to 10 MW class, eventually GW and TW class systems will be needed. Again, this is more an infrastructure issue than a technology feasibility issue; furthermore, the potential for multi-user, time-shared availability of copious amounts of beamed power in space (analogous to the Public Utilities grid on Earth) could revolutionize human exploration and development of space.

**Matter-Antimatter Annihilation Propulsion.** Matter-antimatter annihilation propulsion has been recognized for decades as the "ultimate" propulsion capability; however, a major antiproton production infrastructure is required for its implementation. Although currently conceptual, a number of improvements have been proposed that could enable many order-of-magnitude improvements over current and near-term state-of-the-art (SOA) production capabilities. Additionally, there is a potential for significant dual-use of antiprotons for non-propulsive uses (e.g., medical) that might "amortize" and justify construction of an antiproton "factory".

However, there are a number of major feasibility issues associated with the production and storage of high-density forms of antimatter (e.g., solid anti-$H_2$). (A high-density storage form is needed because the current storage medium of an antiproton plasma is space-charge limited to around $10^{10}$ to $10^{11}$ antiprotons/cm$^3$.) Formation of solid anti-$H_2$ "ice" involves a number of steps and corresponding technologies. The first involves laser "cooling" of the antiproton to very low temperatures (i.e., velocities); this has been demonstrated for normal-matter atoms but

Table 3. Technology Advancements Required for Beamed Energy Laser / Microwave LightSails

| TECHNOLOGY | WHY | TRL | COMMENTS |
|---|---|---|---|
| • Sail areal density | • Total mass (and thus beam power required) | 3-4 | • Major impact on beam power |
| • Sail ultra-high reflectivity | • Minimize waste heat rejection needs, allows greater acceleration | 2-3 | • High reflectivity needed at high beam intensities |
| • Sail dynamics | • Large-structures dynamics | 3-4 | • Modeled for solar sails |
| • Laser/μ-wave source | • Space-based solar-pumped or electric preferred (not chemical for space-based) | 4-5 | • Various VIS/IR laser and microwave options available |
| • Beam pointing accuracy, spread, jitter | • Near diffraction-limited required for interstellar distances | 5-6 | • Major feasibility issue<br>• Spin-off from SDIO/BMDO |
| • Large optics | • Maintain focus at interstellar distances | 3-4 | • Use gossamer structures or space-filling optics |
| • High powers | • Depends on vehicle mass (10's of GW to 1,000's of TW) | 3-4 | • Major infrastructure with extensive dual-use potential |

not "bare" protons or antiprotons. The next step requires formation of an anti-atom from antiprotons and anti-electrons (positrons); this has been recently demonstrated at CERN with the formation of 11 anti-H atoms. Next, it is necessary to form an anti-$H_2$ molecule from anti-H atoms; this would be accomplished for antimatter by using positrons as the "third body" in the atom-atom recombination collision to take away the energy of recombination. Finally, the anti-molecules would be laser cooled to form clusters and eventually ice crystals. The solid crystals would then be magnetically levitated and their position controlled for use in a pellet storage and feed system; this has been demonstrated at Brown University for normal-matter solid $H_2$.[19]

Various matter-antimatter (proton-antiproton) engines have been numerically modeled;[5] the most attractive for interstellar missions is the "Beam-Core" concept that uses equal amounts of protons and antiprotons. The charged annihilation products (pions, $\pi^{\pm}$) are directed by a magnetic nozzle to produce thrust. Although the Beam-Core engine has a low efficiency of converting annihilation energy into propulsive energy (around 20%), the "propellant" exhaust velocity (0.3c) is ideal for interstellar missions. Figure 12 shows the distribution of energy and matter from the proton-antiproton annihilation process.[5]

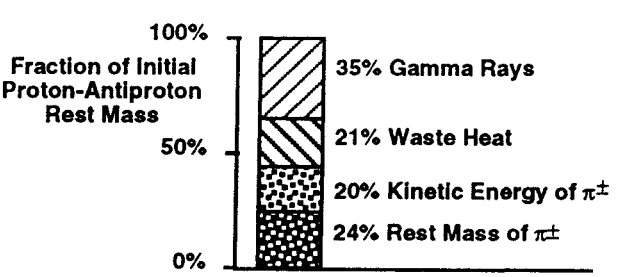


Figure 12. Distribution of Energy and Matter from the Proton-Antiproton Annihilation Process in the Beam-Core Matter-Antimatter Rocket Engine

One interesting consequence of the "loss" of roughly 76% of the initial propellant mass (by conversion into energy) is that the classical Rocket Equation (Eq. 1) no longer holds. The Appendix presents a derivation of a relativistic Rocket Equation that takes into account both the Relativistic effects of both vehicle and propellant exhaust (charged pions) moving near the speed of light, and the unavailability of a majority of the original propellant mass for producing thrust.

Table 4. Technology Advancements Required for Matter-Antimatter Annihilation Propulsion

| TECHNOLOGY | WHY | TRL | COMMENTS |
|---|---|---|---|
| • Major increase in antimatter production | • Require ~$10^{12}$ increase over near-term (5 yr) SOA (nano-g -> kilo-g) | 2-3 (New concepts) | • Major feasibility issue, but major dual-use potential |
| • High-density solid anti-$H_2$ formation/ storage | • Too large a mass to store as low-density plasma in Penning Traps | 2-3 | • Major feasibility issue |
| • Laser cooling | | 3-4 | • For normal atoms |
| • Anti-atom formation | | 4-5 | • 11 anti-H atoms |
| • Anti-molecule formation | | 2-3 | • For normal molec. |
| • Magnetically levitate solid anti-$H_2$ | | 4-5 | • For normal $H_2$ |
| • Engine physics | • Engine Isp, efficiency | 3 | • Various engines modeled |
| • Feed System | • Magnetically levitate solid anti-$H_2$ | 4-5 | • For normal $H_2$ |
| • Magnetic nozzle | • Magnetically capture and re-direct annihilation products to produce thrust | 2 | • Synergisms with fusion magnetic nozzle research |

**Fusion Propulsion.** Many technological issues need to be solved before ICF and MCF propulsion are possible. Fundamental scientific issues still to be resolved include the demonstration of a sustained, controllable, high-density fusion reaction. Another issue involves overall fusion energy gain, which is the energy generated in the fusion plasma divided by the input energy; current MCF systems are about a factor of 2 short of "scientific" breakeven (where energy in equals fusion energy out), whereas propulsion systems will need a gain on the order of 1000. One critical aspect affecting the required gain is the type of fusion driver employed; these are typically low-efficiency systems requiring large amounts of electric power (which is ultimately derived from the fusion reaction).

Fusion fuels like deuterium-tritium (D-T) produce neutrons as a by-product of the fusion reaction. Thus, significant radiation shielding is required for these systems. An alternative approach is to use fuels that produce little or no neutrons. The disadvantage to this approach is that these aneutronic ("no neutron") fuels are harder to "ignite". Examples of aneutronic fuels include deuterium-helium$^3$ (D-He$^3$) (which produces a small amount of neutrons through a side reaction of D-D), or a true aneutronic fuel of protons and boron$^{11}$ (p-B$^{11}$).

Fusion fuel availability is also an issue, given the large amounts of energy required for interstellar missions. Deuterium can be extracted from seawater at a cost of about $1K/kg (in 1988). Tritium can be obtained from the lithium-neutron (Li-n) breeder reaction; it is available from the Mound Laboratory at a cost of $7.5M/kg (in 1988). Note however that tritium has a half-life of 12.3 years; thus, a D-T fusion system must make provisions for removal of decay heat from the tritium storage system. The He$^3$ isotope is the rarest fusion fuel with a cost of $0.7M/kg (in 1988) from the Mound Laboratory; it is produced by tritium decay and can be extracted from the helium in natural gas (5 ppm of the He, 1.3 kg/year) or from weapons (15 kg/year). Because of the difficulty of obtaining He$^3$ from terrestrial sources, extraterrestrial sources, such as the Moon (1 gram He$^3$ per 100 metric tons of lunar regolith) or Jupiter's atmosphere, have been considered.

For both ICF and MCF propulsion, one of the necessary development requirements is to gain a fundamental scientific understanding of the plasma/nozzle interactions. For ICF systems, large, robust, high-power laser or particle-beam drivers will be needed. Fundamental scientific understanding of basic

components of an MCF propulsion system (i.e., the plasma divertor and the fuel mixture area) must be achieved through further research.

Finally, the thermal-to-electric power conversion systems will have a significant impact on the vehicle's overall mass, although this element of the system is not a major technology driver.

**Antimatter Catalyzed Fusion Propulsion.** Because of the difficulty of "igniting" fusion reactions, several schemes have been proposed to simplify or reduce the energy requirements of the "drivers" of the fusion ignition process. For example, fusion reactions can be "catalyzed" by addition of small amounts of antimatter (antiprotons). One approach uses antiprotons to trigger a sub-critical micro-fission explosion, which then ignites fusion fuel in an ICF system.[6] A second approach, muon catalyzed fusion, uses negative muons ($\mu^-$) produced by antiproton annihilation.[7] The muon is often considered to be a "heavy electron," with a mass 207 times that of the electron. In this concept, the muon replaces the electron in a hydrogen atom (or molecule). The resulting "atom" has a classical Bohr radius 207 times smaller than its electron counterpart; thus, the nuclei are able to approach each other more closely. This in turn enhances the probability of overlap between the wave functions of the nuclei of colliding atoms, and thus increases the probability of fusion. The fusion energy "ionizes" (ejects) the muon, which goes on to attach itself to another nucleus, and the process repeats for the lifetime of the muon (2 $\mu$s).

It is important to note here that these antiproton "catalyzed" fusion concepts require relatively modest amounts of antimatter that can be supplied with the existing infrastructure (e.g., CERN, FermiLab). By contrast, "pure" matter-antimatter annihilation propulsion, where all of the propulsive energy comes from the annihilation reaction, requires copious amounts of antimatter and would thus require an extensive, new infrastructure.

**Interstellar Fusion Ramjet.** The interstellar ramjet seeks to circumvent the Rocket Equation by collecting propellant (from interstellar hydrogen clouds) during the mission.[8] This system is somewhat conceptual; however, it has the potential advantage of providing unlimited range and mission flexibility. One of the major feasibility issues is the need to use hydrogen in a fusion reaction; the H-H reaction is very difficult to ignite. For comparison, the Lawson criterion $n\tau$ (where n is the number of nuclei per unit volume and $\tau$ is the confinement time) is $\sim 10^{14}$ cm$^{-3}$ s for D-D or D-T fusion; by contrast, $n\tau$ $\sim 10^{34}$ cm$^{-3}$ s for H-H fusion. Interestingly, the ram scoop is not a physical structure, but a magnetic field; however, it is more complex than a magnetic nozzle "run backwards". (A magnetic nozzle run this way would "choke" and exclude hydrogen at the throat of the scoop.[20]) Another unique requirement of the scoop magnetic field is tits immense size (e.g., dimensions of thousands of kilometers), implying powerful magnetic fields (e.g., $10^7$ Tesla).[21] Also, a laser capable of ionizing hydrogen is required because the magnetic scoop cannot collect neutral atoms. Finally, a major feasibility issue associated with the interstellar ramjet is the same one encountered in supersonic ramjet (scramjet) systems, where the engine thrust must be greater than the ram inlet drag. Bussard has proposed conceptual schemes where the scooped interstellar hydrogen would be accelerated to produce thrust without introducing significant "drag" on the vehicle.

## Summary of the Evaluation Process

Based on the results of the evaluation screening, as shown in Figure 13, advanced electric propulsion, ultra-light solar sails, and electromagnetic catapults have insufficient $\Delta V$ capability for interstellar missions. However, they are potentially very attractive for a variety of solar system exploration missions.

Of the remaining concepts capable of performing interstellar missions, fission fragment and relativistic particle beam / MagSail concepts are the least desirable due to a combination of a need for a unique, large infrastructure, and the presence of a low overall TRL and unresolved major feasibility issues.

The most likely remaining candidates, fusion (ICF/MCF, antimatter-catalyzed, and interstellar ramjet), matter-antimatter annihilation, and beamed laser/microwave sails, also suffer from either a need for a large infrastructure or a host of major feasibility issues. Thus, there is no single concept that is without potentially significant shortcomings.

For the purposes of mission analyses of these concepts for relatively fast (i.e., velocities on the order of 0.4 c) rendezvous missions, we have selected beamed energy, matter-antimatter annihilation, and the fusion ramjet as the "best" candidates. (Fusion concepts that carry only on-board propellants are only capable of reaching speeds on the order of 0.1 c.) These systems are evaluated for their mission performance below.

Table 5. Technology Advancements Required for Fusion Propulsion

| TECHNOLOGY | WHY | TRL | COMMENTS |
|---|---|---|---|
| • Controlled fusion and overall high gain | • Gains of 1000 typically required<br>• ICF generally lighter than MCF, but MCF more developed | 3-4 | • Major feasibility issue; currently gain ~ 0.5<br>• Spin-off from DoE terrestrial fusion program |
| • Fusion drivers | • Impacts mass, power | 4-5<br>4-5 | • ICF: lasers, particle beams<br>• MCF: magnets, RF heating |
| • Fusion fuels | • Aneutronic fuels harder to ignite, $He^3$ rare | 3-4 | • Extract $He^3$ from lunar soil or Jupiter (large infrastructure ?) |
| • Propellant/plasma mixing/extraction, mag. nozzles | • Minimize plasma instabilities, maximize transfer of plasma energy to propellant "working fluid", direct plasma to produce thrust | 2-3 | • Major feasibility issue (not addressed by DoE)<br>• Directly impacts achievable Isp and thruster efficiency |
| • Power conversion & radiators | • Electric power required for drivers, magnets, etc.<br>• Use dynamic power conversion, advanced radiators | 4-5 | • Major impact on overall mass (typically radiator mass ~1/2 system dry mass) |
| • Antimatter Catalyzed | • Micro-fission catalyzed<br>• Muon catalyzed ($p^- \rightarrow \mu^-$) | 3-4<br>2-3 | • Under development at PSU<br>• Conceptual |
| • Easier drivers | • Reduced ignition temp. | 3 | • Reduces vehicle size/mass |
| • Requires only small amounts of antimatter | • Use mods to CERN or FermiLab facilities, store as plasma in Penning Traps | 4-5 | • Does not require major antimatter production infrastructure |
| • Interstellar Ramjet | • Minimizes propellant requirements | 2-3 | • Ram onset ~1-6%c (depends on interstellar H density) |
| • H-H fusion | • H-H harder to ignite | 2 | • Major feasibility issue |
| • Magnetic ram-scoop physics | • Scoop collects ionized interstellar H | 2-3 | • Ram scoop similar to magnetic nozzle |
| • Hydrogen ionization laser | • Need to ionize H to interact with scoop magnetic field | 3-4 | • Laser power, efficiency of ionizing interstellar H |
| • Engine thrust > ram drag | • Similar to scramjet problem | 1-2 | • Major feasibility issue (directly impacts Isp, thrust, efficiency) |

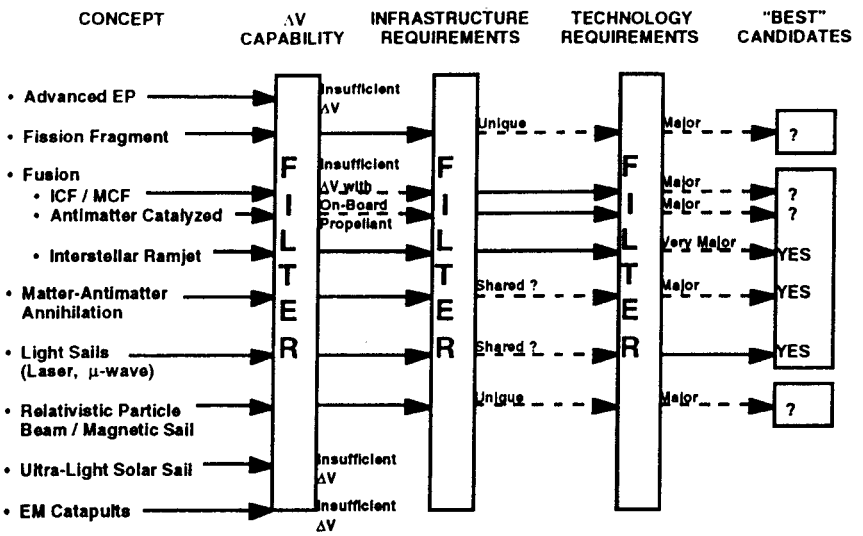


Figure 13. Results of the Screening Process

## EVALUATION OF BEAMED ENERGY, MATTER-ANTIMATTER, AND FUSION RAMJET CONCEPTS FOR INTERSTELLAR RENDEZVOUS MISSIONS

In this section, we evaluate the selected propulsion options for their potential performance for a robotic interstellar rendezvous mission. A payload mass of 1 metric ton (MT) is assumed in all cases; however, the actual payload mass assumed has little impact on the overall mission performance due to the large vehicle "dry" masses required for these missions (e.g., tens to thousands of metric tons).

As described previously, the mission requirement is for a rendezvous with stars from 4.5 L.Y. (with a trip time of 10 years), to 40 L.Y. (with a trip time of 100 years), resulting in an average coast velocity on the order of 0.40 to 0.45 c. In fact, the closer interstellar mission (4.5 L.Y. in 10 years) is actually more demanding because of the slightly higher average velocity (i.e., 0.45 c), but especially because the time available for coast is dramatically shortened by the acceleration and deceleration time required by the propulsion system. Figure 14 illustrates the case for the 4.5 L.Y. rendezvous mission with a total trip time of 10 years for the situation of equal acceleration and deceleration; for an acceleration (and deceleration) of 0.18 gees, there is no coast period and the peak velocity is 0.9 c.

This raises the interesting issue of the vehicle's thrust-to-weight (T/W) ratio or acceleration. For example, as discussed below, beamed energy sails have a thermally-limited acceleration that is a function of the sail's material; even for a very advanced aluminum-sheet sail, the acceleration may only be 0.2 gees. Similarly, the acceleration of the matter-antimatter and fusion ramjet concepts may be very low because they employ electromagnetic forces (e.g., a magnetic nozzle) to direct the rocket exhaust; thus, these systems may have a T/W more like that of an electric propulsion system (e.g., milli-gees), rather than that of a chemical or nuclear-thermal rocket (e.g., typically >0.1 gee).

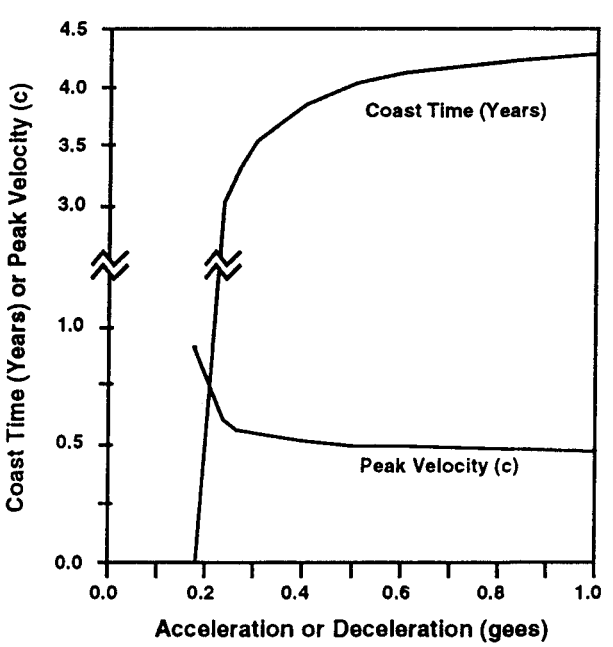


Figure 14. Effect of Acceleration and Deceleration on Coast Time and Peak Velocity for the 4.5 L.Y. Interstellar Rendezvous Mission with a 10 Year Total Trip Time

**Beamed Energy**

The beamed energy LightSail concept for interstellar missions has previously been investigated by Forward[9] and others. We will follow Forward's analysis with the difference that we will assume the use of a filled array of laser transmitters rather than a Fresnel lens. Like Forward, we will assume 1-μm wavelength transmitter "optics" with a diameter of 1,000 km; this allows transmission of laser power over a distance of 40 L.Y. with a LightSail "spot" size of less than 1,000 km, as determined by the assumption of diffractionless optics as discussed above.

**Mission Analyses.** One very important result of Forward's analyses is the identification of an optimum sail thickness to yield a thermally-limited maximum acceleration that is a function of the total sail areal density (including payload), reflectance, transmittance, absorbance, emissivity, and allowed operating temperature. In his analyses, Forward found an optimum sail thickness for aluminum of 16 nm, corresponding to a total sail areal density of 0.1 g/m$^2$, which yielded a thermally-limited acceleration of 0.036 gees. A 3.6-km diameter sail based on these assumptions enabled flybys of the nearer stars with trip times on the order of 40 years at a modest laser power of 65 GW; the laser beaming distance during the 3-year acceleration phase was only 0.17 L.Y. Using similar assumptions, a 96-km diameter sail could perform a 4.5 L.Y flyby with a minimum trip time of 16 years by accelerating all the way to the target (hence the larger sail diameter) at a laser power of 46 TW. Similarly, the minimum flyby trip time to 40 L.Y. is 46 years with an 857-km diameter sail with a laser power of 3,719 TW. Interestingly, McKay[22] and Landis[23] have considered other sail materials (e.g., gold and beryllium, respectively) that permit a higher thermally-limited acceleration, although at the potential cost of a higher areal density (e.g., 3.2 gees and 5.1 g/m$^2$, and 0.42 gees and 0.066 g/m$^2$, respectively); these types of materials can enable shorter trip times, although at the cost of increased laser power.

However, in order to perform a rendezvous mission, a significantly higher acceleration is required. Forward assumed the use of an advanced high-emissivity coating to allow an increase in the thermally-limited sail acceleration to 0.2 gees. With this assumption, the minimum trip times and laser powers required for the 4.5 and 40 L.Y. rendezvous missions (assuming acceleration at 0.02 gees to the target) are 20 years and 51 TW, and 60 years and 3,693 TW, respectively. Note that in Forward's analyses, the outbound acceleration was limited to 0.02 gees so that the same laser power would decelerate the inner sail (with one-tenth the mass of the outer sail) at the thermally-limited maximum of 0.2 gees. A shorter trip time could be achieved, with ten times the laser power, by accelerating the sail at 0.2 gees, and then reducing the laser power ten-fold to accommodate deceleration of the inner sail at 0.2 gees (and continued acceleration of the outer sail at 0.02 gees). Also, as discussed above, alternate-material sails could also allow shorter trip times, but again at the cost of increased laser power.

One interesting issue raised by these analyses is the problem of retro-reflecting the laser beam from the outer to the inner sail during the deceleration step. This is due to the large separation distances between the sails; for example, this separation distance is 0.8 L.Y. for the 4.5 L.Y., 20-year rendezvous mission, and 4.9 L.Y. for the 40 L.Y., 60-year rendezvous mission. In effect, the outer sail needs to perform like a high-quality, diffraction-limited optical system comparable to the phased-array laser system. Furthermore, for the 4.5 L.Y. mission using a 122-km diameter sail, the "spot" size projected back onto the 39-km diameter inner sail is actually larger (149-km diameter) than the inner sail. This results in only 22% of the beam being intercepted, necessitating a corresponding power increase to 233 TW during the deceleration phase. (Note that the beam has a Gaussian power distribution that peaks in the center; thus, the power intercepted is determined by Eq. 2 rather than the simple ratio of spot size to sail area.)

**Matter-Antimatter Annihilation Propulsion**

Matter-antimatter annihilation yields the highest possible energy density ($6.8 \times 10^{16}$ J/kg for proton-antiproton annihilation). We selected the Beam-Core proton-antiproton engine concept for these analyses because of its high $I_{sp}$, and moderate efficiency of converting annihilation energy into directed thrust (20%).[5] Figure 15 illustrates a conceptual matter-antimatter propulsion system. It consists of a beam-core engine (with magnetic nozzle fields of 100 to 200 Tesla), a normal-matter liquid hydrogen ($LH_2$) storage and feed system (essentially that of a conventional chemical or nuclear-thermal rocket system), and a solid anti-hydrogen magnetic storage and feed system (and associated sub-systems like sub-Kelvin refrigeration to prevent sublimation of the solid anti-$H_2$), and other sub-systems (e.g., radiation shielding, power conversion, etc.).

Finally, as discussed previously, because only 24% of the initial matter-antimatter reactants mass remains after annihilation, we must use the relativistic rocket equation modified for "loss" of 76% of the initial propellant mass. This results in a mass ratio ($M_0/M_b$)

for a given $\Delta V$ and $I_{sp}$ that is much higher for a relativistic beam-core matter-antimatter rocket than for either a classical or relativistic "conventional" rocket (where only a small amount of propellant mass converted into energy).

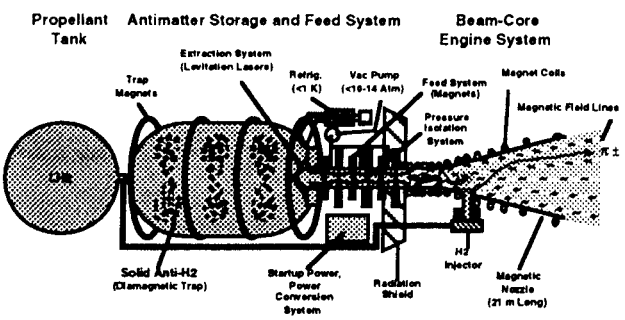


Figure 15. Conceptual Matter-Antimatter Propulsion System

**Mission Analyses.** Thus, for a rendezvous mission, it is necessary to use a four-stage rocket, with the first two stages used for acceleration to ca. 0.4 c, and the remaining two stages used to decelerate at the target stellar system. The fourth stage (with a small amount of additional antimatter) is then used to explore the system. One of the major unknowns at this time is the propulsion system dry mass scaling relationships as a function of propellant mass (for "conventional" storage of $LH_2$ and magnetic levitation/storage of solid anti-H2), engine power, and so on. For the purposes of obtaining a first-order estimate of the vehicle mass, we will assume an overall "tankage factor" for the propulsion system's dry mass ($M_{dry}$) of 10 % of the total propellant mass ($M_p$), or $M_{dry} = 0.10 \cdot M_p$.

For this assumption, the 4-stage vehicle is used for the rendezvous missions. The vehicle for the 4.5 L.Y., 10-year rendezvous mission (with a 1-year acceleration and deceleration period for a peak velocity of 0.50 c) has an initial (wet) mass of 6,571 MT, requires 2,986 MT of solid anti-$H_2$, and has a maximum (first-stage) engine jet power of 396 TW; the corresponding vehicle for the 40 L.Y., 100-year rendezvous mission (with a 2-year acceleration and deceleration period for a peak velocity of 0.41 c) has an initial (wet) mass of 1,657 MT, requires 753 MT of solid anti-$H_2$, and has a first-stage jet power of 47 TW.

These are very large amounts of antimatter; production and storage of these quantities represents a major challenge to use of matter-antimatter propulsion for interstellar missions. Nevertheless, it is interesting to note the historical growth rate of antiproton production shown in Figure 16. Extrapolating this trend indicates an annual production of the required magnitude by 2030. Finally, 1998 is the 100th anniversary of the first production of liquid hydrogen by Dewar; today, we use 100 MT of $LH_2$ per Space Shuttle launch, or roughly 1,000 MT per year.

## Interstellar Fusion Ramjet

The interstellar fusion ramjet was originally conceived by Bussard.[8] Its primary benefit for interstellar rendezvous missions is its ability to overcome the inherent $I_{sp}$ limitation ($10^6$ $lb_f$-s/$lb_m$) of fusion propulsion by collecting interstellar hydrogen. Without this capability, fusion propulsion, like fission fragment propulsion (with a similar $I_{sp}$), is limited to relatively slow (i.e., 0.1 c) interstellar flybys.

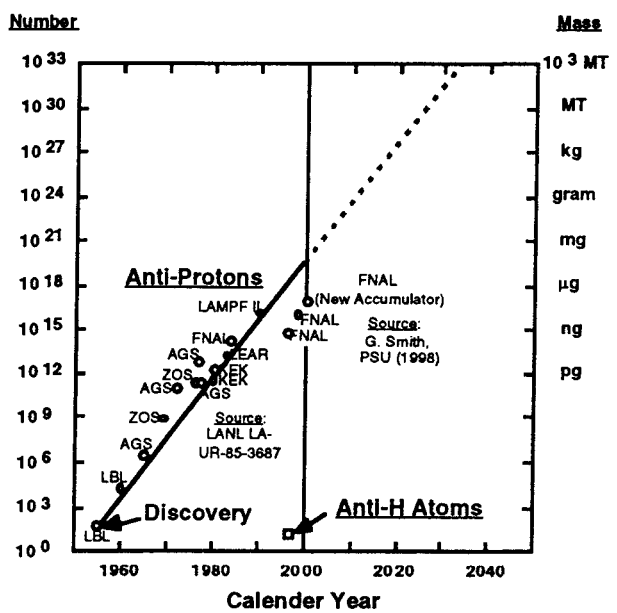


Figure 16. Annual Antiproton Production Rate

This option represents the highest risk, because of the need to overcome major technological obstacles, but also the highest payoff, because the fusion ramjet is capable of essentially unlimited range (and thus mission flexibility), and high relativistic speeds (>> 0.5 c).[20]

However, this concept has three major feasibility issues that must be resolved. First is the need for H-H fusion. Second is the need for an extremely large electromagnetic scoop to collect the interstellar hydrogen with dimensions of thousands of kilometers and field strengths on the order of $10^7$ Tesla.[21] This also includes the need for a unique field shape that does not "choke" the hydrogen flow at the throat of the nozzle. Finally, it is necessary to develop a "drag free" fusion reactor configuration that does not significantly

reduce the axial velocity of the interstellar hydrogen (in the frame of the vehicle); otherwise the vehicle will slow down.

**Mission Analyses.** For mission analysis purposes, a fusion ramjet with a dry mass of 3,000 MT is assumed.[24] It operates at an $I_{sp}$ of $10^6$ $lb_f$-s/$lb_m$ (0.03 c) and a total jet power of 40 TW. For an interstellar hydrogen density of 1 atom per cubic centimeter and a scoop diameter of 6,000 km, the speed required for the onset of ram-scoop operation (i.e., the speed at which the forward motion of the vehicle sweeps out a mass of hydrogen equal to the engine's propellant mass flow rate of 0.83 kg/s or $5 \times 10^{26}$ atoms/s) is 5.91% c. The on-board hydrogen propellant required to reach this speed is 15,354 MT; thus, the vehicle has a total (wet) mass of 18,346 MT on departure.

If we assume a length-to diameter (L/D) of 5, such that the inward radial velocity of the collected hydrogen is one-tenth that of the vehicle's forward velocity), then the ram-scoop is 30,000-km long and 6,000-km in diameter.

The mission scenario for these assumptions would consist of the following steps. First, on-board hydrogen is used to accelerate the vehicle to a speed of 0.06 c over a period of 0.6 years, at which point ram-scoop operation begins. The vehicle continues to accelerate to a speed of 0.61 c for the 4.5 L.Y. rendezvous mission (0.41 c for the 40 L.Y. case), and then coasts. The ram-scoop is then turned on and the hydrogen flow choked (to bring it to rest relative to the vehicle) to produce drag. (A small amount of the scooped hydrogen is collected to replenish the on-board propellant tanks.) Finally, the vehicle is turned around and on-board hydrogen is used in the fusion rocket to bring the vehicle into orbit about the target star. A smaller, auxiliary vehicle could then be used to explore the system.

As an example of the potential versatility of the fusion ramjet concept, if the on-board hydrogen tanks are refilled, either from local resources or a second set of propellant tanks filled during the deceleration phase, the fusion ramjet could then continue on to another stellar system.

### Critical Non-Propulsion Technologies

Although the focus of this paper has been on propulsion technology, there are several additional critical technologies that will require major advancements. For example, because of the finite limit of the speed of light, round-trip communication times will be measured in decades. Thus, the vehicle will require extremely advanced autonomy (e.g., software) and avionics (e.g., hardware), which are separate functions in today's spacecraft, that will grow to become a single function. Similarly, structures technology requires major advancements due to the very large size of the various concepts (e.g., dimensions on the order of thousands of kilometers). In fact, there are two major technology paths in structures; the first involves large, thin-film structures for the LightSails; the second involves large, heavy structures for systems like the beamed-energy laser array, the matter-antimatter rocket, and the fusion ramjet.

Other critical technologies which will require significant (but not major) advancement include communications, power systems, and navigation. Interestingly, Lesh[25] has already shown that optical communication over interstellar distances is feasible given modest extrapolations of the technology. On-board spacecraft power at kilowatt levels could be met by advanced nuclear power systems like RTGs. However, a large propulsion-system related power system may be required for the matter-antimatter and fusion ramjet systems. This includes energy storage systems for startup power, thermal-to-electric power conversion during engine operation, and housekeeping power during coast (for cryogenic refrigeration systems, electromagnetic storage of antimatter, etc.). Finally, navigation will require advancements in position knowledge (e.g., advanced optical navigation), timing (e.g., advanced highly-accurate and stable clocks), and acceleration (changes in position and time).

## TECHNOLOGY DEVELOPMENT INITIAL STEPS

There are major challenges to implementing propulsion technologies for interstellar flights. We can identify some of the current state-of-the-art and ultimate technology metrics for these missions. The difficulty is in identifying near-term activities that could be performed over the next five years that could begin to address some of the major feasibility issues, and to aid in a down-select among the three candidate propulsion options.

Tables 6 to 8 list the current state-of-the art, near-term (five-year) feasibility assessment goals, and ultimate interstellar rendezvous mission technology capability for the beamed energy, matter-antimatter, and fusion ramjet concepts.

Table 6. State-of-the Art, Near-Term (Five-Year) Feasibility Assessment Goals, and Interstellar Mission Capability for the Beamed Energy Concept

| State-of-the-Art | Five Year Goal | Interstellar Capability |
|---|---|---|
| Solar Sail<br>• Solar sail 10-20 g/m$^2$ areal density<br>• Solar sail dimensions ~30 m<br><br>Solar/Laser Thermal/Electric Propulsion<br>• Solar Thermal LEO-GEO OTV thruster $I_{sp}$ ~ 800 $lb_f$-s/$lb_m$<br>• ETO Laser Thermal launch 1 kg to 100 ft<br>• "Laser" PV cell electric power output ~10X for solar PV cells<br><br>Laser<br>• Solar-pumped semiconductor laser, 0.35-0.4, 0.7-0.8, 1 μm wavelengths, 30% sunlight-to-beam efficiency<br>• Total laser CW power ~1 MW<br>• Pointing $10^{-8}$ radians (unclassified)<br>• $10,000/kg ETO | Solar Sail<br>• Fly GEO-Storm Solar Sail<br>Laser Sail<br>• Measure ultra-thin (<< 1 μm) film optical, mechanical, and thermal properties<br>• Develop and model ultra-lightweight structure concepts (for ultra-thin film sails)<br>• Fly μ-wave Levitated Mesosphere Explorer<br><br>Solar/Laser Thermal/Electric Propulsion<br>• Solar Thermal LEO-GEO OTV thruster $I_{sp}$ ~ 1,000 $lb_f$-s/$lb_m$<br>• Demo laser-thermal LEO-GEO OTV thruster $I_{sp}$ ~ 2,000 $lb_f$-s/$lb_m$<br>• ETO Laser Thermal launch 1 kg to LEO altitude<br>• Use laser to illuminate solar PV cells in LEO<br><br>Laser<br>• Upgrade WSTF lasers to 1-10 MW<br>• Demo Orbital Debris Removal | Laser Sail<br>• Laser sail 0.1 g/m$^2$ areal density including supporting structure and controls<br>• Laser sail diameter to 1,000 km<br>• Laser sail shape control capable of retro-reflecting beam to 5 LY<br>• Laser sail control<br>• Beam-following controls<br>• Sail properties yielding >0.2 gee acceleration<br><br>Laser<br>• Solar-pumped laser, ~0.5 to 1.0 μm wavelength, >30% sunlight-to-beam efficiency<br>• Total laser CW power $10^{13}$ to $10^{15}$ W<br>• Precise pointing $10^{-11}$ radians<br>• Low-cost ETO transportation $100/kg LEO |

Table 7. State-of-the Art, Near-Term (Five-Year) Feasibility Assessment Goals, and Interstellar Mission Capability for the Matter-Antimatter Concept

| State-of-the-Art | Five Year Goal | Interstellar Capability |
|---|---|---|
| • 15 ng/Year anti-protons<br>• 11 anti-H atoms/Year<br>• Store $10^{10}$ anti-protons<br>• Magnetic levitation, storage, and movement of normal-matter solid & liquid $H_2$ drops<br>• 100 °K superconductor magnets at ~ 1-10 Tesla<br>• $10,000/kg ETO | • 150 ng/Year anti-protons<br>• Demo (with normal matter) conversion of P+e -> H atoms -> $H_2$ -> solid $H_2$ (to simulate solid anti-$H_2$ production steps)<br>• 10-100 anti-H2 /Year<br>• Store $10^{12}$ anti-protons<br>• 100 °K superconductor magnets at ~ 10-100 Tesla | • Solid anti-hydrogen ($H_2$)<br>  • Manufacture $10^3$ MT/Mission<br>  • Storage<br>  • Manipulation and control<br>• Thermalization of annihilation reaction<br>  • Magnetic nozzle 100-200 Tesla<br>• High temperature, radiation (gamma-ray) hard superconductors<br>• Low-cost ETO transportation $100/kg LEO |

Table 8. State-of-the Art, Near-Term (Five-Year) Feasibility Assessment Goals, and Interstellar Mission Capability for the Fusion Ramjet Concept

| State-of-the-Art | Five Year Goal | Interstellar Capability |
|---|---|---|
| • D-D fusion<br>• $n\tau \sim 10^{14}$ cm$^{-3}$ s<br>• Gain ~ 0.5)<br>• 100 °K superconductor magnets at ~ 1-10 Tesla<br>• $10,000/kg ETO | • Model H-H fusion<br>• Develop and model physics of ram scoop concept<br>• Develop and model physics of "drag-free" ram scoop / fusion reactor concept<br>• 100 °K superconductor magnets at ~ 10-100 Tesla | • Controlled H-H Fusion<br>• $n\tau \sim 10^{34}$ cm$^{-3}$ s<br>• Gain ~ 1,000<br>• Physics of ram scoop concept<br>• Magnetic fields at $10^7$ Tesla<br>• Physics of "drag-free" ram scoop / fusion reactor concept<br>• Materials to permit $I_{sp}$ of $10^6$ sec<br>• Thermalization of reaction products<br>• Magnetic nozzle<br>• High temperature, radiation (neutron) hard superconductors<br>• Low-cost ETO transportation $100/kg LEO |

## CONCLUSIONS AND RECOMMENDATIONS

Based on the results of the evaluation screening, advanced electric propulsion, ultra-light solar sails, and electromagnetic catapults have insufficient $\Delta V$ capability for interstellar missions. However, they are potentially very attractive for a variety of solar system exploration missions.

Of the remaining concepts capable of performing at least slow (i.e., ca. 0.1 c) interstellar flyby missions, fission fragment and relativistic particle beam / MagSail concepts are the least desirable due to a combination of a need for a unique, large infrastructure, and the presence of a low overall TRL and unresolved major feasibility issues.

The most likely candidates for fast (i.e., ca. 0.4 c) interstellar rendezvous missions, beamed energy sails, matter-antimatter annihilation, and the fusion ramjet, also suffer from either a need for a large infrastructure or a host of major feasibility issues. Thus, there is no single concept that is without potentially significant shortcomings.

For example, although fusion propulsion does not require a unique infrastructure (even an $He^3$ production infrastructure might be shared with terrestrial fusion users), there remain major feasibility issues associated with all of the fusion concepts at the performance levels required for interstellar missions.

Similarly, although matter-antimatter annihilation propulsion has been recognized for decades as the "ultimate" propulsion capability, a major antiproton production infrastructure is required for its implementation. There is however a potential for significant dual-use of antiprotons for non-propulsive uses that might "amortize" and justify construction of an antiproton "factory". Also, there are a number of major feasibility issues associated with the production and storage of high-density forms of antimatter (e.g., solid anti-$H_2$).

Beamed energy sail systems also require a large space-based infrastructure of beam source and optics systems. However, this infrastructure can lead to a major in-space capability for beamed power to a variety of users, resulting in a "Public Utility" for power in space. Finally, much of the required technology for a beamed energy sail system has been demonstrated; the major issue is scaling to the large sizes and high powers required for interstellar missions.

Thus, there is no single clear winner; beamed energy sails, matter-antimatter annihilation, and fusion are the "best" choices based on our current level of understanding. Interestingly, a beamed energy sail system may be the most near-term option. However, a beamed energy sail system gives the least mission flexibility; every maneuver at interstellar distances must be planned years in advance because of the speed-of-light time lag. Therefore, matter-antimatter annihilation and

fusion systems should also be pursued because these systems will provide the highest degree of mission flexibility.

Near-term (5-year) technology development goals should seek to resolve the major feasibility issues associated with each concept. For example, the mechanical, thermal, and optical properties of ultra-thin film materials is largely unknown and represents a major question that must be answered in order to asses beamed energy sails. For matter-antimatter propulsion, experiments with normal matter should seek to duplicate, in a manner appropriate for antimatter, the steps required to go from protons and electrons to atoms, then to molecules, and finally to solid molecular ice. For the fusion ramjet, the H-H fusion reaction, magnetic scoop, and "drag free" reactor concepts should be computationally modeled. Finally, cross-cutting technologies, such as high-field, radiation-resistant superconducting magnets, should be pursued.

In conclusion, we would echo the words of Robert Forward:[26]

> "It is difficult to go to the stars. But it is not impossible. There are not one, but many future technologies, all under intensive development for other purposes, that, if suitably modified and redirected, can give the human race a magic starship that will take us to the stars.
>
> And go we will."

## ACKNOWLEDGMENT

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# APPENDIX

## DERIVATION OF THE CLASSICAL AND RELATIVISTIC ROCKET EQUATIONS WITHOUT AND WITH "LOSS" OF PROPELLANT MASS

### INTRODUCTION

One of the issues associated with the use of a beam-core matter-antimatter rocket is the conversion of 76% of the initial (stored) propellant mass into energy, thus leaving only 24% of the initial propellant mass for producing thrust or, more formally, for producing a change in the velocity ($\Delta V$) of the vehicle. In this Appendix, we derive the "classical", non-relativistic Rocket Equation, and then the relativistic Rocket Equation for the normal case where a negligible fraction of the initial propellant is converted into energy. This situation corresponds to that normally encountered in chemical, fission, and fusion rockets. It also applies to matter-antimatter rocket concepts which use a small amount of matter-antimatter annihilation energy to heat a larger mass of normal-matter "working fluid", such as hydrogen. Next, we will derive the classical and relativistic rocket equations for the situation where only a small fraction, "a", remains of the initial propellant mass to produce thrust.

We will follow closely the derivation developed by Forward.[20] For example, for the relativistic cases, we make use of the standard formulas for relativistic mass increase:

$$m = m_0 / (1-v^2/c^2)^{1/2} \qquad \text{(Eq. A-1)}$$

where

$m$ = Relativistic mass
$m_0$ = Rest mass
$v$ = Velocity
$c$ = Speed of light

and for addition of velocities:

$$u = ( v + w ) / ( 1 + vw/c^2 ) \qquad \text{(Eq. A-2)}$$

where

$u$ = Total velocity seen by a stationary observer
$v,w$ = Additive velocities

### CLASSICAL ROCKET EQUATION

In the classical Rocket Equation derivation, a rocket with initial mass M ejects a mass of reaction mass (propellant) dm at a constant exhaust velocity (i.e., $I_{sp}$) relative to the rocket of w, as shown in Figure A-1. In the center of mass of the system, the resultant rocket velocity is U (i.e., $\Delta V$), and the reaction mass velocity is u.

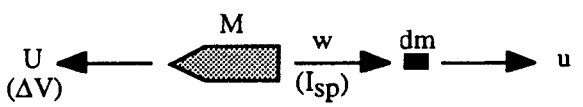


Figure A-1. Classical Rocket

First, we start with the conservation of energy:

$$dM = -dm \qquad \text{(Eq. A-3)}$$

(The minus sign indicates the decreasing mass of the rocket.)

Next, we conserve momentum:

$$d(M \cdot U) = u \cdot dm \qquad \text{(Eq. A-4)}$$

Finally, we use the classical addition of velocities:

$$u = w - U \qquad \text{(Eq. A-5)}$$

Expanding the derivatives, combining the above equations, and rearranging gives:

$$M\,dU + U\,dM = u\,dm = -(w - U)\,dM$$
$$U\,dM + (w - u)\,dM = -M\,dU$$
$$(U + w - U)\,dM = -M\,dU$$

$$dM / M = -dU / w \qquad \text{(Eq. A-6)}$$

Integrating Eq. (A-6) gives:

$$\ln (M) = -U/w \qquad \text{(Eq. A-7)}$$

which, when evaluated for the rocket mass limits of $M_0$ (initial wet mass) and $M_b$ (final "burnout" dry mass) and initial and final velocities ($V_i = 0$ and $V_f = \Delta V$), with $w = I_{sp}$, yields the classical Rocket Equation:

$$\ln ( M_0 / M_b ) = \Delta V / I_{sp} \qquad \text{(Eq. A-8a)}$$

$$M_0 / M_b = \exp ( \Delta V / I_{sp} ) \qquad \text{(Eq. A-8b)}$$

## RELATIVISTIC ROCKET EQUATION

We follow essentially the same steps for the relativistic Rocket Equation, with the difference being the use of relativistic equations for mass and velocity, and conservation of mass-energy content of the system (as opposed to conservation of mass only in the classical case).

First, we start with the conservation of mass-energy:

$$d\{M_0/(1-U^2/c^2)^{1/2}\}c^2 = -d\{m_0/(1-u^2/c^2)^{1/2}\}c^2 \qquad \text{(Eq. A-9)}$$

(Note that mass-energy, or $mc^2$, is conserved.)

Next, we conserve momentum:

$$d\{M_0/(1-U^2/c^2)^{1/2} \bullet U\} = u \bullet d\{m_0/(1-u^2/c^2)^{1/2}\} \qquad \text{(Eq. A-10)}$$

Finally, we use the relativistic addition of velocities:

$$u = ( w - U ) / ( 1 - wU/c^2 ) \qquad \text{(Eq. A-11)}$$

Expanding the derivatives, combining the above equations, and rearranging gives:

$$\begin{aligned} M_0\, d\{U/(1-U^2/c^2)^{1/2}\} &+ U/(1-U^2/c^2)^{1/2}\, dM_0 \\ &= u / (1-u^2/c^2)^{1/2}\, dm_0 \\ &= -(w-U) / (1-wU/c^2) / (1-U^2/c^2)^{1/2}\, dM_0 \end{aligned}$$

$$\begin{aligned} M_0 \{dU/(1-U^2/c^2)^{1/2} &+ U(1-U^2/c^2)^{-3/2}(U/c^2)dU\} \\ &+ U/(1-U^2/c^2)^{1/2}\, dM_0 \\ &= -(w-U) / (1-wU/c^2) / (1-U^2/c^2)^{1/2}\, dM_0 \end{aligned}$$

$$\begin{aligned} \{U + (w-U) / (1-wU/c^2)\} &/ (1-U^2/c^2)^{1/2}\, dM_0 \\ &= -M_0\{1/(1-U^2/c^2)^{1/2}+U^2/c^2(1-U^2/c^2)^{-3/2}\}dU \end{aligned}$$

$$dM_0 / M_0 = -dU\{1+U^2/c^2/(1-U^2/c^2)\}/\{U+(w-U)/(1-wU/c^2)\}$$

$$dM_0 / M_0 = -dU(1-wU/c^2)/\{(1-U^2/c^2)(w(1-U^2/c^2)\} \qquad \text{(Eq. A-12)}$$

Unfortunately, Eq. (A-12) cannot be integrated analytically. However, if we assume that $U \sim w$, such that $(1-wU/c^2) \sim (1-U^2/c^2)$, then we obtain an equation:

$$dM_0 / M_0 = -c^2/w\, dU / (c^2-U^2) \qquad \text{(Eq. A-13)}$$

which can be analytically integrated to give:

$$\ln (M) = -c^2/w \bullet 1/(2c) \bullet \ln \{(c+U)/(c-U)\} \qquad \text{(Eq. A-14)}$$

which, when evaluated for the rocket mass limits of $M_0$ (initial wet mass) and $M_b$ (final "burnout" dry mass) and initial and final velocities ($V_i = 0$ and $V_f = \Delta V$), with $w = I_{sp}$, yields the relativistic Rocket Equation:

$$\begin{aligned} \ln ( M_0 / M_b ) &= c/(2I_{sp}) \ln \{(c+\Delta V)/(c-\Delta V)\} \\ &= c/(2I_{sp}) \ln \{(1+\Delta V/c)/(1-\Delta V/c)\} \end{aligned} \qquad \text{(Eq. A-15a)}$$

$$\begin{aligned} M_0 / M_b &= \{(c+\Delta V)/c-\Delta V)\}^{c/(2Isp)} \\ &= \{(1+\Delta V/c)/(1-\Delta V/c)\}^{c/(2Isp)} \end{aligned} \qquad \text{(Eq. A-15b)}$$

## CLASSICAL ROCKET EQUATION WITH LOSS OF PROPELLANT

The derivations presented above were obtained previously by Forward;[20] we present them here for completeness. We now consider the case for the matter-antimatter rocket, where a significant portion of the on-board propellant mass "disappears" and is not available to produce thrust; this impacts the conservation of momentum condition.

We define a parameter, a, which represents the fraction of propellant mass remaining for thrust production (i.e., a = 0.24 for a beam-core matter-antimatter rocket). Thus, of the total initial propellant reacted ($M_p$), a mass $M_r$ is available to produce thrust (i.e., impart momentum to the rocket), and a mass $M_x$ is "lost" (converted to energy in this case) and unavailable to impart momentum to the rocket.

$$\begin{aligned} M_p &= M_r + M_x \\ M_r &= a\, M_p \\ M_x &= (1 - a)\, M_p \end{aligned} \qquad \text{(Eq. A-16)}$$

(Note that the mass $M_x$ need not be converted into energy; it could, for example, simply be ejected uniformly in a direction perpendicular to the rocket's motion so as to cancel out any net momentum.)

We now begin the derivation of the classical Rocket Equation with "loss" of propellant mass. Following the steps outlined above, we start with the conservation of energy:

$$dM = -dm \qquad \text{(Eq. A-17)}$$

Next, we conserve momentum, and explicitly include the parameter "a" for the (net) mass of propellant ejected by the rocket:

$$d(M \bullet U) = u \bullet a \bullet dm \qquad \text{(Eq. A-18)}$$

Finally, we use the classical addition of velocities:

$$u = w - U \qquad \text{(Eq. A-19)}$$

Expanding the derivatives, combining the above equations, and rearranging gives:

$$M\,dU + U\,dM = u\,a\,dm = -a\,(w - U)\,dM$$
$$U\,dM + a\,(w - u)\,dM = -M\,dU$$
$$(U + aw - aU)\,dM = -M\,dU$$
$$\{\,U\,(1-a) + aw\,\}\,dM = -M\,dU$$

$$dM / M = -dU / \{\,U\,(1-a) + aw\,\} \qquad \text{(Eq. A-20)}$$

As expected, Eq. (A-20) reduces to Eq. (A-6) when a=1.

Integrating Eq. (A-20) gives:

$$\ln (M) = -1/(1-a) \ln \{aw + (1-a)U\} \qquad \text{(Eq. A-21)}$$

which, when evaluated for the rocket mass limits of $M_o$ (initial wet mass) and $M_b$ (final "burnout" dry mass) and initial and final velocities ($V_i = 0$ and $V_f = \Delta V$), with $w = I_{sp}$, yields the classical Rocket Equation including loss of propellant:

$$\ln (M_o / M_b)$$
$$= -1/(1-a) \ln \{\,(aI_{sp} + (1-a)\Delta V) / aI_{sp}\,\}$$
$$= -1/(1-a) \ln \{\,1 + (1/a-1)\,\Delta V / I_{sp}\,\} \qquad \text{(Eq. A-22a)}$$

$$M_o / M_b$$
$$= \{\,(aI_{sp} + (1-a)\Delta V) / aI_{sp}\,\}^{-1/(1-a)}$$
$$= \{\,1 + (1/a-1)\,\Delta V / I_{sp}\,\}^{-1/(1-a)} \qquad \text{(Eq. A-22b)}$$

## RELATIVISTIC ROCKET EQUATION WITH LOSS OF PROPELLANT

We now repeat the relativistic Rocket Equation derivation, with the difference being the use of the parameter "a"

Again, we start with the conservation of mass-energy:

$$d\{M_o/(1-U^2/c^2)^{1/2}\}c^2 = -d\{m_o/(1-u^2/c^2)^{1/2}\}c^2 \qquad \text{(Eq. A-23)}$$

Next, we conserve momentum, and explicitly include the parameter "a" for the (net) mass of propellant ejected by the rocket:

$$d\{M_o/(1-U^2/c^2)^{1/2} \bullet U\} = u \bullet a \bullet d\{m_o/(1-u^2/c^2)^{1/2}\} \qquad \text{(Eq. A-24}$$

Finally, we use the relativistic addition of velocities:

$$u = (\,w - U\,) / (\,1 - wU/c^2\,) \qquad \text{(Eq. A-25)}$$

Expanding the derivatives, combining the above equations, and rearranging gives:

$$M_o\,d\{U/(1-U^2/c^2)^{1/2}\} + U/(1-U^2/c^2)^{1/2}\,dM_o$$
$$= u \bullet a / (1-u^2/c^2)^{1/2}\,dm_o$$
$$= -a\,(w-U) / (1-wU/c^2) / (1-U^2/c^2)^{1/2}\,dM_o$$

$$M_o\,\{dU/(1-U^2/c^2)^{1/2} + U(1-U^2/c^2)^{-3/2}(U/c^2)dU\}$$
$$+ U/(1-U^2/c^2)^{1/2}\,dM_o$$
$$= -a\,(w-U) / (1-wU/c^2) / (1-U^2/c^2)^{1/2}\,dM_o$$

$$\{U + a\,(w-U) / (1-wU/c^2)\} / (1-U^2/c^2)^{1/2}\,dM_o$$
$$= -M_o\{1/(1-U^2/c^2)^{1/2} + U^2/c^2(1-U^2/c^2)^{-3/2}\}dU$$

$$dM_o / M_o =$$
$$-dU\{1+U^2/c^2/(1-U^2/c^2)\}/\{U+a(w-U)/(1-wU/c^2)\}$$

$$dM_o / M_o$$
$$= -dU(1-wU/c^2)/\{(1-U^2/c^2)((1-a)U+w(a-U^2/c^2)\}$$

which reduces to Eq. (A-12) for a=1. Finally, we have:

$$dM_o / M_o$$
$$= -dU(1-wU/c^2)/\{(1-U^2/c^2)(-w/c^2U^2+(1-a)U+aw)\} \qquad \text{(Eq. A-26)}$$

Unfortunately, Eq. (A-26) cannot be integrated analytically. However, if we assume that $U \sim w$, such that $(1-wU/c^2) \sim (1-U^2/c^2)$, then we obtain an equation:

$$dM_o / M_o = -dU / \{-w/c^2U^2+(1-a)U+aw\} \qquad \text{(Eq. A-27)}$$

which can be analytically integrated to give (after considerable algebraic manipulation):

$$\ln(M) = 1/[(1-a)^2+4aw^2/c^2]^{1/2} \cdot \ln\{(-2wU/c^2+(1-a)-[(1-a)^2+4aw^2/c^2]^{1/2}) / (-2wU/c^2+(1-a)+[(1-a)^2+4aw^2/c^2]^{1/2})\} \quad \text{(Eq. A-28)}$$

which, when evaluated for the rocket mass limits of $M_o$ (initial wet mass) and $M_b$ (final "burnout" dry mass) and initial and final velocities ($V_i = 0$ and $V_f = \Delta V$), with $w = I_{sp}$, yields the relativistic Rocket Equation with loss of propellant:

$$\ln(M_o / M_b) = 1 / [(1-a)^2+4aI_{sp}^2/c^2]^{1/2} \cdot \ln\{ [(-2I_{sp}\Delta V/c^2+(1-a)-[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})(1-a+[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})] / [(-2I_{sp}\Delta V/c^2+(1-a)+[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})(1-a-[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})]\} \quad \text{(Eq. A-29a)}$$

$$M_o / M_b = \{ [(-2I_{sp}\Delta V/c^2+(1-a)-[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})(1-a+[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})] / [(-2I_{sp}\Delta V/c^2+(1-a)+[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})(1-a-[(1-a)^2+4aI_{sp}^2/c^2]^{1/2})]\}\{1 / [(1-a)^2+4aI_{sp}^2/c^2]^{1/2}\} \quad \text{(Eq. A-29b)}$$

## COMPARISON OF THE ROCKET EQUATIONS

Figure A-2 illustrates the values of $M_o/M_b$ calculated by the four versions of the Rocket Equation for an $I_{sp}$ (0.33 c) and "a" parameter (0.24) characteristic of a matter-antimatter rocket. In each case, as $\Delta V$ becomes large, the relativistic Rocket Equation is larger than its classical counterpart.

However, a larger divergence is seen in the effect of loss of propellant mass for thrust (i.e., momentum) production. Thus, the mass ratio $M_o/M_b$ for a relativistic rocket with an $I_{sp}$ of 0.33 c requiring a $\Delta V$ of 0.5 c is around 5 if the loss of propellant is ignored; however, if a value of a=0.24 (rather than a=1) is included, the mass ratio roughly doubles to about 10.

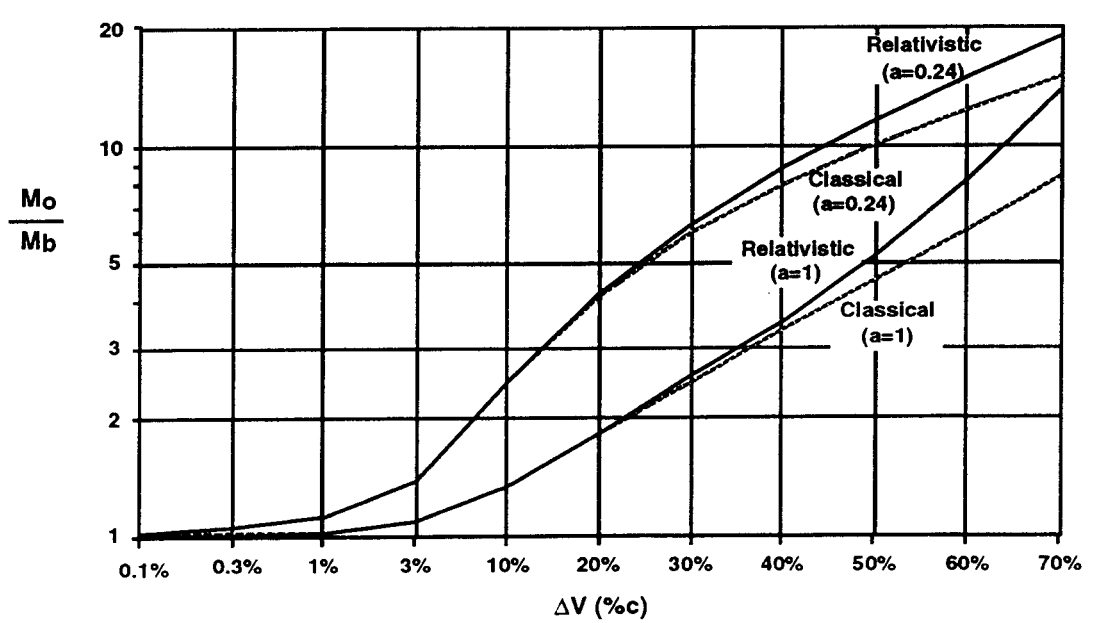


Figure A-2. Comparison of the Four Versions of the Rocket Equation