Antimatter Production for Near-term Propulsion Applications

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Abstract

The superior energy density of antimatter annihilation has often been pointed to as the ultimate source of energy for propulsion. Unfortunately, the limited capacity and very low efficiency of present-day antiproton production methods suggest that antimatter may be too costly to consider for near-term propulsion applications. We address this issue by assessing the antimatter requirements for six different types of propulsion systems, including two concepts in which antiprotons are used as a “catalyst” for fusion-based thrust production. These requirements are compared against the capacity of current antimatter production facilities and then assessed assuming the improved capabilities which could exist within the early part of next century. Results show that although it may be impractical to consider systems which rely on antimatter as the sole source of propulsive energy, the requirements of the antimatter-initiated, fusion-based concepts do fall within projected near-term production capabilities. In fact, such systems could feasibly support interstellar precursor missions and omniplanetary spaceflight with antimatter costs ranging up to $60 million per mission.

Introduction

The annihilation of subatomic particles with their antimatter counterparts has the highest energy per unit mass of any reaction known in physics. The energy released from proton-antiproton annihilation (4.3×10^{13} cal per gram of antiprotons) is 10^{10} times greater than oxygen-hydrogen combustion and 100 times more energetic than fission or fusion. That is, one gram of antihydrogen (i.e., a “mirror” atom composed of an antiproton and positron (antielectron)) reacted with the same amount of normal hydrogen produces a total energy equivalent to that delivered by 23 Shuttle External Tanks (ET).

Ever since 1953 when Eugene Sanger first proposed use of electron-positron annihilation to produce thrust,[1] there have been many serious[2-6] and not-so-serious attempts to identify ways of exploiting antimatter for propulsion. Practically all of these concepts involve applying the products from proton-antiproton annihilation either (1) to create thrust directly or (2) to energize a propellant through interparticle collisions or heating of an intermediate solid core. In addition, the scientific community, which until several decades ago had exhibited only casual curiosity about the subject, is now devoting more attention and resources to uses of antimatter. The best examples of this are the accelerators at Fermi National Accelerator Laboratory (FNAL) and The European Laboratory for Particle Physics (CERN), which routinely produce antiprotons to extend the energy range of particle collision experiments.

Although the worldwide production capacity has been growing at a nearly geometric rate since the discovery of the antiproton in 1955, the current output rate of 1 to 10 nanograms (ng) per year is minuscule compared to that of other exotic materials. For this reason, some people have questioned the practicality of using antimatter for propulsion, at least within the next century or so. They feel that the energy costs would be exorbitantly high and would never allow antimatter to be competitive with other propulsion technologies.

This skepticism stems from two misconceptions. First, it clearly ignores the established historical precedents of dramatic capacity growth and cost reduction for the production of other exotic materials, such as liquid hydrogen and enriched Uranium-235 (U-235). These materials and others were extremely expensive at first, but once the production infrastructure was in place, improvements could be implemented and costs dropped dramatically. The second misconception is that all the concepts which utilize antimatter rely on the annihilation reaction as the sole source of propulsive energy. Although it is true that “conventional” antimatter systems, which derive all their energy from annihilation, offer the highest specific impulse ($I_{sp} \sim 10^5$ to 10^7 sec) of any propellant-based propulsion concept, there are several antiproton-catalyzed hybrid fission/fusion concepts that require far less antimatter, while still coming close to the performance of conventional antimatter rockets ($I_{sp} \sim 10^4$ to 10^6 sec).[7-9] In fact, these quantities could be well within the range of existing production facilities at FNAL and CERN, once several promising upgrades are incorporated.

It appears that the prospects of exploiting antimatter for space propulsion are not so bleak after all and may indeed be quite favorable. We have confirmed this by conducting a study in which we calculated the antimatter quantities required to accomplish a broad range of missions, and compared these values against the production costs of the current infrastructure. Using these numbers as a reference, we examined the incorporation of upgrades and improvements which could further increase production capacity and ultimately lower energy costs. The results suggest a roadmap for evolution of production infrastructure, starting with quantities to support antimatter-catalyzed fusion for interstellar precursor missions and omniplanetary spaceflight, and then evolving to conventional antimatter rockets for true interstellar exploration.[10]

Fundamental Energy Cost Constraints

The creation of antimatter is an inherently energy-intensive process. Not only must the entire rest mass of the antiparticles be provided as energy into the production process, but the application of this energy is ordinarily quite inefficient. The conversion of input energy E_{in} into the rest mass energy of the collected antiprotons E_{out} can be expressed in terms of an efficiency $h = E_{out}/E_{in}$. Noting the equivalence between E_{out} and antiproton mass M_a (i.e., $E_{out} = M_a c^2$), we rearrange terms to yield the energy required to create a unit mass of antiprotons:

$$E_{in}/M_a = \frac{c^2}{h} \quad . \tag{1}$$

This specific energy is inversely proportional to the conversion efficiency, since the speed of light c is constant. Conservation of baryon number requires that formation of an antiparticle is always accompanied by creation of its standard particle counterpart. Thus, the antiproton can at most be 1/2 of the total rest mass produced in a perfectly efficient conversion process. This sets a theoretical limit on the conversion efficiency h of 1/2.[11]

The total energy cost K is obtained by multiplying Eq. (1) with power utility costs k_{grid} (= $ per unit energy) and M_a:

$$K = \frac{k_{grid} M_a c^2}{h} \quad . \tag{2}$$

Equation 2 clearly shows that conversion efficiency h is a major factor in dictating energy costs. Unfortunately, the values of h associated with present-day facilities are extremely low. A good example of this is FNAL which creates antiprotons by means of colliding beams of relativistic protons with high-atomic number (high-Z) material targets. The protons, which are accelerated to an energy of 120 GeV (120 x 10^9 electron volts), yield a spray of photons, proton-antiproton pairs and other particles at the collision site. Only a small portion of these antiprotons leave the target at the proper momentum and small enough exit angle to be magnetically focused and retarded for subsequent storage.

The performance of the overall collection process is quite low and yields about 1 antiproton per 10^5 proton collisions. Multiplying acceleration energy (120 GeV/proton) by collection ratio (10^5 proton/antiproton) yields an energy requirement E_{in}/M_a of 1.2 x 10^{16} eV/antiproton or, in terms of mass, 1.16 x 10^{21} J/g. Applying a "wall-plug" power efficiency of 50% and substituting into Eq. (1) results in an h of 4 x 10^{-8}. Substituting this value of h and a k_{grid} of \$0.10 per kilowatt-hour (kW-hr) into Eq. (2) yields an energy cost of \$62.5 trillion per gram (g) of antiprotons.

The cost of producing large quantities of antimatter (i.e., gram-scale or above) with current facilities is exceedingly high. However, studies have shown that the efficiency of production based on proton/high-Z material collisions can be improved substantially by optimizing proton acceleration energy and incorporating improved collection methods. Assuming an optimized energy of 200 GeV and a collection ratio of 1 antiproton per 20 collisions[12] yields an h of 2 x 10^{-4} (or 10^{-4} if a 50% wall-plug efficiency is again assumed). This 3 to 4 order of magnitude improvement over current capability yields a cost of \$25 billion per gram, which is roughly 1,000 times the cost of an equivalent energy load of Shuttle ET propellants. As we will explain later, such improvements would require a substantial investment of 3 to 10 billion dollars for a dedicated production facility.[13]

Equation 2 suggests that as long as commercial power rates remain near current levels of \$0.01 to \$0.1 per kW-hr, the cost of producing large quantities of antimatter will be high, regardless of the extent to which efficiency can be improved. Even at the maximum theoretical h of 1/2, antiprotons will cost \$5 million per gram. Although this is comparable in terms of energy content to the cost of Shuttle ET propellants, no one has conceived of a technology that could come close to this level of performance. Therefore in order for large-scale production to become even remotely practical (especially at the kilogram (kg) to metric ton (mT) quantities required for interstellar missions using “pure” antimatter rockets), power utility costs will have to drop dramatically below current levels (k_{grid} << \$0.1/kW-hr). This is unlikely to occur until abundant power based on a conceivably “free” resource, such as Deuterium-Deuterium (D-D) fusion, becomes available.

The prospects for applications involving small amounts of antimatter (M_a ~ 1 microgram (μg)) however look much more promising. Several potential near-term technologies which are being pursued in the areas of commercial radioisotope medicine production, diagnostic tomography and cancer therapy require antimatter quantities ranging from only 0.1 to 100 nanograms (ng). With today’s production infrastructure, the energy costs for these applications lie within the affordable range of \$0.006 to \$6 million. What is more important, especially for high-energy applications such as propulsion, is the significant reduction in antimatter energy costs that could be achieved by incorporating several upgrades into FNAL and other existing facilities. As the following discussion shows, a 2 to 3-order of magnitude reduction in energy costs appears feasible and could be implemented within the next decade. With such upgrades, the 1 to 100 μg quantities required for omniplanetary spaceflight and interstellar precursor missions based on antimatter-catalyzed fusion would cost \$0.6 to \$60 million.

Antimatter Requirements

We consider six different antimatter propulsion concepts. These include four “conventional” systems driven solely by annihilation energy and two “catalyzed” systems powered by antimatter-initiated fusion.

The “simplest” conventional system is the solid core concept[5,14] which uses antiprotons to heat a solid, high-atomic number (Z), refractory metal core. As with a nuclear thermal rocket, propellant is pumped into the hot core and expanded through a nozzle to generate thrust. A slightly more sophisticated variant of this is the gas core concept[5,6,14] which substitutes the low-melting point solid with a high temperature gas, thus permitting greater operational temperatures and performance. The third conventional concept is the plasma core.[6,14] Here the gas is allowed to ionize and operate at even higher effective temperatures. The “ultimate” conventional system is the beamed core[3,6,10] which avoids the problems of heating a secondary fluid altogether by expelling the charged annihilation products directly from the vehicle at velocities approaching the speed of light.

The antimatter-catalyzed concepts differ from the conventional systems in that antiprotons are used as a driver to initiate a combined fission/fusion process in a compressed plasma or condensed material target. Practically all of the propulsive energy is derived from fusion reactions. The first of these concepts is Antimatter-Catalyzed Micro-Fission/Fusion (ACMF).[7] Here a pellet of Deuterium-Tritium (D-T) and Uranium-238 (U-238) is compressed with particle beams and irradiated with a low-intensity beam of antiprotons. The antiprotons are readily absorbed by the U-238 and initiate a hyper-neutronic fission process that rapidly heats and ignites the D-T core which expands to produce pulsed thrust. The second concept is Antimatter-Initiated Microfusion (AIM).[8] Here an antiproton plasma is repetitively compressed via combined electric and magnetic fields while droplets containing D-T or Deuterium-Helium-3 (D-He3) are synchronously injected into the plasma. The antiprotons annihilate with a fissile seed which together heat the plasma to ignition conditions. The products are directed out a magnetic nozzle to produce thrust.

The performance of each concept is represented in terms of four parameters: rocket exhaust velocity $V_e (= g \cdot \mathrm{Isp})$, fusion power gain b, energy utilization efficiency h_e, and the vehicle structure to propellant mass ratio l, which reflects the penalties of massive containment and driver systems. A more detailed description of the concepts and parameter values[2-8] is given in Appendix A.

Antimatter requirements are calculated using an expression derived by equating the applied annihilation energy to the kinetic energy of the exhaust,[11] while accounting for the contribution of fusion energy gain as outlined in Appendix B. Relativistic equations for rocket performance and kinetic energy are applied to obtain an expression for antimatter mass M_a, as a function of payload mass M_{pay}, mission velocity $D\mathrm{V}$, and propulsion system performance:

$$M_a = \frac{1}{2(1+b)}\left(\frac{g-1}{g+(h_e-1)}\right)\left(\frac{R-1}{1+l-Rl}\right)M_{pay} \quad , \qquad (3)$$

where

$$R = \left(\frac{1 + \frac{Dv}{c}}{1 - \frac{Dv}{c}} \right)^{\frac{c}{2v_e}} \qquad \text{(Relativistic mass fraction } (= M_{\text{initial}} / M_{\text{final}})) \ , \qquad (4)$$

and

$$g = \frac{1}{\sqrt{1 - (v_e/c)^2}} \qquad \text{(Lorentz-Fitzgerald contraction factor)} \ . \qquad (5)$$

We use Eq. (3) to illustrate in Fig. 1 the dependence of antimatter mass on payload and mission velocity[10] for the ACMF, AIM, plasma core and beamed core concepts. Plots for the solid and gas core concepts are not shown, because the *Isp*'s are lower than either of the antimatter-catalyzed concepts, and the antimatter requirements are only marginally less than that of the plasma core. Appendix B provides a more detailed discussion of comparative performance.

In the lower range of mission velocities (10 km/sec DV 10^3 km/sec), the ACMF and AIM concepts are clearly superior in terms of minimizing antimatter requirements. For planetary, early interstellar precursor and simple omniplanetary applications, ACMF exhibits the best performance. The reference case of a 1-year human round-trip mission to Jupiter with a 10 to 100 metric ton (mT) payload requires an antimatter quantity of 1 to 10 micrograms (μg). It appears as though this requirement could drop into the 1 to 10 ng range for payloads consistent with unmanned, planetary missions. However, ACMF was originally conceived for crewed omniplanetary flight and is probably not scaleable to smaller sizes due to the large mass of its ion driver system. Therefore, ACMF is restricted to missions which would require 1 to 10 μg and DV 's less than or equal to 100 km/sec.

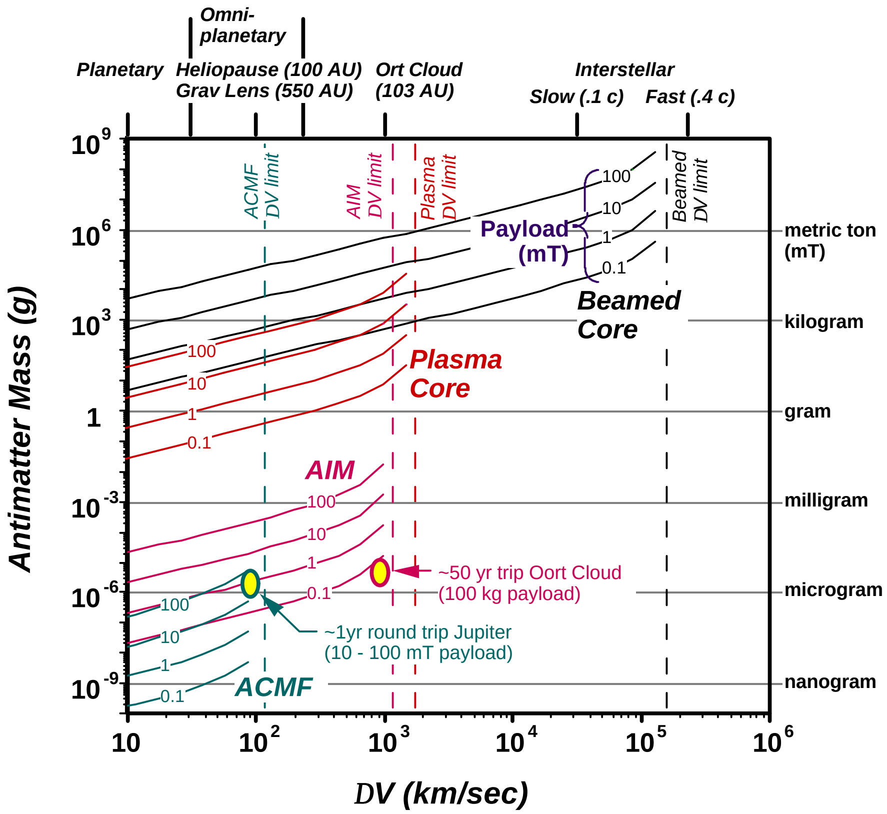

Figure 1: Antimatter requirements for different propulsion concepts

The AIM concept, which does not need a driver and benefits from a higher Isp, can accomplish more ambitious missions, such as interstellar precursor trips to the Oort cloud. However, the antimatter requirement is roughly 1 to 2 orders of magnitude greater than ACMF. For that reason, this concept is better suited for unmanned missions with smaller payloads. The design point in Fig. 1 represents a 50-year trip to the Oort cloud with a 100 kg payload. Even with the higher rate of antiproton usage, the total requirement is still relatively low, within the 10 to 100 µg range. The structural ratio and Isp limit the maximum DV to 10^3 km/sec.

The only antimatter concept that can achieve velocities above 2 x 10^3 km/sec and accomplish missions well beyond solar influence is the beamed core. Although a structural ratio consistent with the AIM and plasma core concepts is assumed, the much higher exhaust velocity of the annihilation products permits vehicle accelerations to velocities approaching 0.4 c, which would enable "fast" missions to Alpha Centauri in 10 years.[10] At first this appears quite attractive until one notes that the antimatter requirement is many orders of magnitude greater than either the ACMF or AIM reference case. For a payload of 1 metric ton (mT), the antimatter requirement is about 40 mT, depending on the mission. The beamed core requires tremendous amounts of antimatter, but it is the only concept that can travel to the nearest stars (i.e., 4 to 40 light years) within a “reasonable” time (i.e., 10 to 100 years).

Although the inordinately high antimatter requirements of the conventional systems may be impractical to consider in the near-term, the more modest quantities associated with ACMF and AIM may be quite attainable. The catalyzed systems could not be used for trips to the stars, due to their limited DV’s of only 10^2 to 10^3 km/sec. However, ACMF and AIM do have sufficient performance to propel interstellar precursor probes and support human exploration of the entire solar system.

Antimatter Production Capability

Almost all of the controlled antimatter in the world is produced at either CERN or FNAL. This unique capability was added from the late-70’s to the late-90’s to increase the energies of particle collision experiments. A brief history of the development of antimatter production capability at these two facilities is given in Appendix C.

During a year-long period between 1997 and 1998, FNAL produced 1 ng of antiprotons. This was done in the midst of a very large experimental program which did not have sufficient funds to run 24 hours per day, 365 days per year. The instantaneous production rates were around 10^{11} antiprotons/hour, so a full year of operation would have produced 8.8×10^{14} antiprotons. This equates to an annual yield of approximately 1.5 ng, which is 3 to 4 orders of magnitude less than the quantities required for missions using ACMF and AIM.

It is important to remember that neither of the facilities at FNAL or CERN was designed for the purpose of producing antiprotons. This capability, which was added after the facilities had been operating for some time, was only intended to generate enough antiprotons for collision experiments. The collection ratio r_p, which can be viewed as the effective antiproton yield (i.e., antiprotons collected) per proton on target, was never a major concern. Although the current ratio is extremely poor ($r_p \quad 10^{-5}$), there are many ways in which it can be improved.

We consider the case of FNAL, which is the largest, most convenient source of antiprotons in the U.S. This year, FNAL’s accelerator is down for commissioning of a new Main Injector. We expect that when the new injector comes on-line in 1999, production yields will increase by another order of magnitude. This will eventually boost the production rate to about

10^{12} antiprotons/hour. We therefore expect that by the early part of next decade, the total annual production capacity should approach 15 ng. At the same time, FNAL could start incorporating even better collection devices and techniques. Development of more efficient collection equipment, such as improved focusing horns and multiple large-aperture receivers, has been considered, and could culminate in substantial production gains. It is quite reasonable to expect perhaps an additional 50-fold increase in efficiency with these upgrades, thus yielding a 500-fold improvement over current capability.

The impact of incorporating such improvements is shown in Fig. 2. The final result is a nearly 3-order of magnitude increase of production capacity into the microgram-range. This is significant because at this level one can seriously begin to consider use of antimatter-catalyzed fusion propulsion devices for space applications.

These production enhancements are obviously aimed at expanding support of scientific research at FNAL. However, customers who are planning to use the facility for replenishment of portable antiproton devices, such as NASA and commercial users, would require an additional feature beyond those planned to support scientific activities.

In the current production process, high-energy antiprotons from the original proton collision site can be stored temporarily in the Main Injector at a relatively low kinetic energy of 433 MeV. They are subsequently extracted and accelerated to much higher energies for collision experiments. To transfer these antiprotons into a small-volume, portable device, such as a Penning trap, an additional deceleration process, which would reduce antiproton energies from 433 MeV to no more than 20 keV, is required between the Main Injector and storage device.[15]

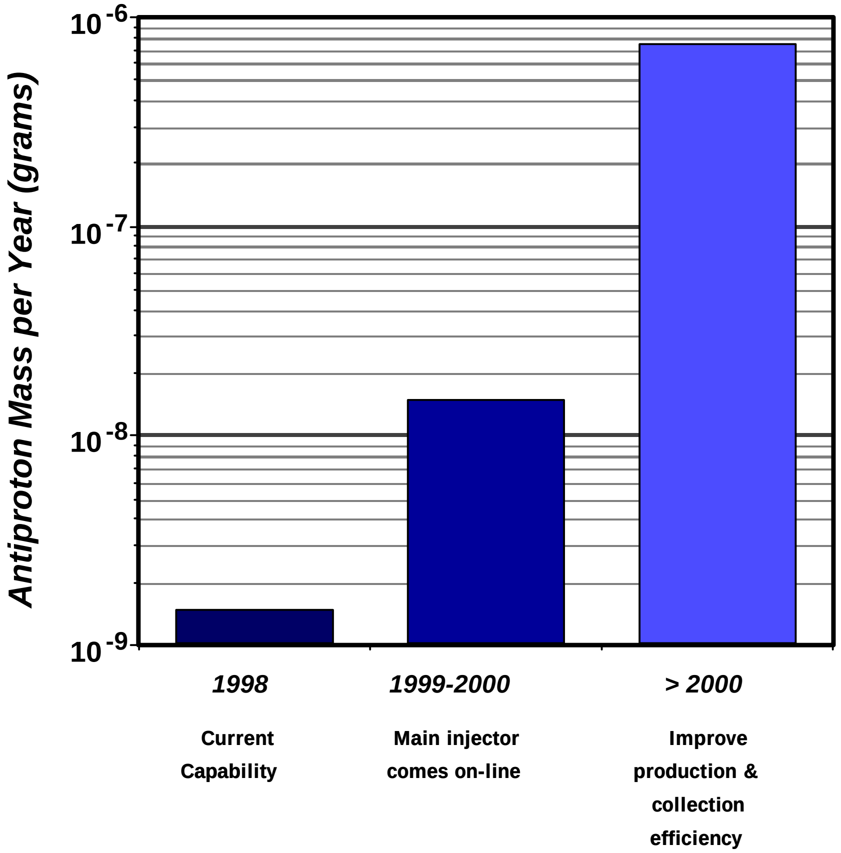

Figure 2: Impact of near-term improvements at FNAL

The development of antiproton Penning traps has progressed extremely well over the last 10 years. The PS200 experiment[16] trapped over 10^6 antiprotons for periods of hours. This is seen as a means of soon being able to confine up to 10^{12} antiprotons with transfer to a remote site for periods of many days.[17] Synergistic Technologies of Los Alamos, NM is currently developing a magnetic degrading spectrometer which will simply and inexpensively decelerate antiprotons into such portable traps. This approach is adequate for some important commercial applications and demonstrating fundamental propulsion concepts, such as generation of subcritical microfission reactions and plasma formation as a precursor to fusion reactions. However, it will not be capable of providing the much larger quantities needed for direct propulsion applications. In this case, a more efficient decelerator section will be required to achieve production rates equivalent to ~1 μg per year. Antiproton decelerators which accomplish this do exist (e.g., at CERN), and in the case of FNAL would cost about $10 million to construct.

Long-Term Improvements

If the anticipated demand from the scientific community, NASA and the commercial sector continues to grow, then investment in a completely new production-oriented facility would probably be warranted.[18] In the 1980's, the RAND Corporation studied development of such a capability and concluded that a capacity of 0.1 to 1 gram per year could be achieved with a new machine costing $3 to $10 billion.[13]

It is important to note that these costs are consistent with those of some previous major national science projects, and the design of such a facility falls well within the realm of known technology. In fact, the basic production process would be very similar to the current method of creating antiprotons from collisions of protons with high-Z targets. However, improvements, such as higher-Z accelerated particles and more efficient collection/focusing devices, would enhance efficiency considerably.

For capacities above 1 gram, which would support a highly-evolved transportation infrastructure within the solar system and trips into interstellar space, a completely new production technology is necessary. Several methods look promising, but all are at the very early stages of technological maturity.

Other issues are how to store groups of antiprotons of this scale and containment of the stored energy on this scale. Again, the energy stored within 1 gram of antimatter is roughly equivalent to the energy delivered by 23 Shuttle ET’s. A systematic approach to safe storage of such quantities is required, as has been done with other highly energetic and reactive materials. Studies of high-density storage of antimatter are underway and are an important step along this critical pathway.

Antimatter Production Costs

The costs of producing batches of antimatter on demand are not well characterized, since the facilities do not yet provide this function as an actual service. FNAL is beginning to recognize the existence of an incipient demand outside the high-energy physics community. Although less experienced than FNAL, Brookhaven National Laboratory has recently expressed interest in “going into the antimatter business,” however Brookhaven’s facilities are much less developed than those at FNAL.

From our previous analysis, the cost of producing 1 μg of antimatter is $62.5 million. Assuming current production levels, the antimatter needed to support highly ambitious ACMF or AIM missions (~ 100 μg) would cost ~$6 billion, much too high for practical considerations. In addition, the extremely low production rate would require an unreasonably long fill time on the order of 100's of years. The situation looks discouraging until we account for the anticipated improvements to the current production capacity. In this case the costs would go down by at least 2 orders of magnitude to ~$0.6 million per μg or $60 million for a 100 μg mission. This is expensive, but within the range of customer costs for a Shuttle launch and certainly a single large deep space mission.

For antimatter requirements in the 1 milligram range and above, costs would have to be based on the capabilities of a new facility. In the previous section, the initial cost for such a capability was estimated to be $3 to $10 billion.[13] Production efficiencies would be much greater. Assuming an h of 10^{-4} and the power costs and wall-plug efficiencies from before, the costs could come down by 1 to 2 more orders of magnitude to ~$25,000 per μg. In this case the antimatter cost for a 100 μg mission would be $2.5 million. At such values, antimatter becomes affordable enough to support a highly-evolved space transportation infrastructure based on some form of antimatter-catalyzed fusion.

Conclusions

We have completed a study which (1) evaluated the antimatter requirements for various propulsion concepts over a range of missions and velocity requirements, (2) compared these requirements against the capabilities of the existing antimatter production infrastructure, (3) compared these again assuming the improved capability expected over the next several years, and (4) estimated antimatter costs in $/microgram for both the current and improved infrastructure.

Results show that the antimatter costs associated with conventional antimatter rockets, that is systems which rely on antimatter as the sole source of propulsive energy, are too high to be seriously considered for anything other than missions to nearby stars. Even missions within the solar system and into near-interstellar space would require production rates 6 to 9 orders of magnitude greater than the existing infrastructure.

Antimatter-catalyzed fusion, however, holds considerable promise for near-term applications. Although this form of propulsion could not be used for trips to the stars, it does provide excellent performance for missions within the solar system and near-interstellar space. The requirements for antimatter are on the scale of 1 to 100 micrograms per mission, which with the current infrastructure equates to an antiproton cost of $60 million to $6 billion. However, with several upgrades that could be incorporated in the near-term, the cost per mission could drop by at least 2 orders of magnitude to $60 million per mission, and possibly less. These costs are certainly within the range of economic feasibility, and suggest that antimatter-catalyzed fusion may be a viable “first step” in applying antimatter for space propulsion.

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Appendix A: Antimatter Propulsion Requirements

Fundamentals of Antiproton Annihilation

It was clear early on that proton-antiproton annihilation offered the best promise for propulsion simply because of its enormous energy density and immediate production of charged particle products. When a proton p and antiproton $\bar{\mathrm{p}}$ annihilate, an assortment of charged and uncharged pions π are produced according to the reaction:

$$\bar{\mathrm{p}} + \mathrm{p} \rightarrow \mathrm{m}\pi^{o} + \mathrm{n}\pi^{+} + \mathrm{n}\pi^{-} \quad . \tag{A1}$$

To a first approximation, pions are the particles that transmit the strong force, which is responsible for binding protons and neutrons together in an atomic nucleus. The number of neutral pions π^{o} and charged pions $\pi^{\pm}$ created are approximately equal with m 2 and n 1.5. The neutral pions are extremely unstable and decay almost immediately with a mean life, τ_{m}, of 84 x 10^{-18} sec into two high-energy gamma rays, γ, of 200 MeV each. The charged pions decay more slowly (τ_{m} = 70 x 10^{-9} sec) into muons μ and associated neutrinos ν_{μ}:

$$\pi^{o} \rightarrow \gamma + \gamma \quad , \tag{A2}$$

$$\pi^{+} \rightarrow \mu^{+} + \nu_{\mu} \quad , \tag{A3}$$

$$\pi^{-} \rightarrow \mu^{-} + \bar{\nu}_{\mu} \quad . \tag{A4}$$

Muons are essentially heavy electrons (~ 200 times the electron mass), and neutrinos are generally believed to be massless. Neutrinos are quite penetrating and readily pass through matter without interacting. Consequently their energy is considered to be entirely lost. The muons are unstable and decay at a slower rate than their parent pions (τ_{m} = 6.2 x 10^{-6} sec) into electrons e and neutrinos, according to:

$$\mu^{+} \rightarrow \mathrm{e}^{+} + \nu_{\mathrm{e}} + \bar{\nu}_{\mu} \quad , \tag{A5}$$

$$\mu^{-} \rightarrow \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}} + \nu_{\mu} \quad . \tag{A6}$$

In most cases, the timescales for confinement or heating interactions will be shorter than the decay time of the muons. Hence, the final products of the reaction will be the gamma rays in Eq. (A2), and the charged pions or muons in Eqs. (A3) and (A4). However if the process is allowed to proceed through muon decay, then the electrons and positrons in Eqs. (A5) and (A6) combine and annihilate to form two 0.5 MeV gamma rays according to:

$$e^{+} + e^{-} \rightarrow g + g \quad . \tag{A7}$$

The ultimate products of the $\bar{p}p$ reaction are actually quite undesirable. The neutrinos cannot be contained with any known field or material and carry away approximately 50% of the total reaction energy. Furthermore, the gamma rays, which radiate isotropically, are ineffectual in producing directed thrust. The most that can be done is to absorb them in a high-atomic weight material and use their energy for heat.

Antimatter Propulsion Concepts

Because of the losses discussed earlier, an important aspect of all antimatter-powered propulsion concepts is to utilize the products as soon as possible after the original $\bar{p}p$ reaction, when most of the product energy is tied up in a charged state. This entails either (1) using the products to heat a reaction fluid through fluid/product collisions or an intermediate material, or (2) directing the highly energetic charged pions or muons out a magnetic nozzle to produce thrust. The propulsion concepts that employ these mechanisms generally fall into four categories: (1) solid core, (2) gaseous core, (3) plasma core, and (4) beamed core configurations.

The solid core concept[5,14] uses antiprotons to heat a solid, high-atomic weight (Z), refractory metal core. Propellant is pumped into the hot core and expanded through a nozzle to generate thrust. The performance of this concept is roughly equivalent to that of the nuclear thermal rocket ($Isp \sim 10^3$ sec) due to temperature limitations of the solid. However, the antimatter energy conversion and heating efficiencies are typically high due to the short mean path between collisions with core atoms ($h_e \sim 85\%$).

The gaseous core system[5,6,14] substitutes the low-melting point solid with a high temperature gas, thus permitting higher operational temperatures and performance ($Isp \sim 2 \times 10^3$

sec). However, the longer mean free path for thermalization and absorption results in much lower energy conversion efficiencies (h_e 35%).

One step beyond this concept is the plasma core,[6,14] where the gas is allowed to ionize and operate at even higher effective temperatures. Heat loss is suppressed by magnetic confinement in the reaction chamber and nozzle. Although performance is extremely high (I_{sp} ~ 10^4 - 10^5 sec), the long mean free path results in very low energy utilization (h_e 10%).

The “ultimate” system is the beamed core concept[3,6,10] which avoids the problems of heating a secondary fluid altogether. Here, the charged products of the proton-antiproton annihilation are directly expelled out of the vehicle along an axial magnetic field. The exhaust velocities of these products are exceptionally high (I_{sp} ~ 10^7 sec), approaching the speed of light. Although energy utilization efficiencies are also high (h_e ~ 60%), the flowrate and thrusts are typically very low.

In addition to these pure-antimatter systems, there are several concepts which utilize antiprotons as a driver to catalyze and initiate a hybrid fission/fusion process in a compressed plasma or condensed material target. Practically all of the propulsive energy in these cases is derived from fusion reactions. Consequently, antimatter requirements are much lower than the pure-antimatter systems.

The first of such processes is Antimatter-Catalyzed Micro-Fission/Fusion (ACMF).[7] Here a pellet of D-T and U-238 is compressed with particle beams and irradiated with a low-intensity beam of antiprotons. The antiprotons are readily absorbed by the U-238 and initiate a hyper-neutronic fission process that rapidly heats and ignites the D-T core. The heated fission and fusion products expand to produce thrust, but the inherent isotropy of the flow results in a lower effective energy utilization and jet efficiency. Although additional thrust is obtained from an ablating surface that absorbs neutrons and electromagnetic radiation from the ignited pellet, the performance of this concept is lower than the plasma and beamed core rockets (I_{sp} 13,500 sec). Gaidos et al[6] have shown that the interaction between the antiproton beam and target exhibits extremely high-gain yielding a ratio of fusion energy to antimatter rest mass energy, b , of 1.6×10^7. However, energy utilization is also lower due to the isotropic expansion process (h_e ~ 15%). Assuming a 3-order of magnitude improvement in the efficiency of producing antiprotons over current values, the net energy gain is 640.

Another concept is Antimatter-Initiated Microfusion (AIM).[8] Here a non-neutral plasma of antiprotons within a special Penning trap is repetitively compressed via combined electric and magnetic fields. Droplets containing D-T or D-He3 mixed with a small concentration of a metal, such as Pb-208 or U-238, are synchronously injected into the plasma. The main mechanism for heating the liquid droplet is antimatter-induced fission fragments which have a range of 45 microns (μm) in the droplet. The power density released by the fission fragments into the D-T or D-He3 is about 5 x 10^{13} W/cm^3, which is enough to completely ionize and heat the fuel atoms to fusion ignition. The heated products are directed out magnetic field lines to produce thrust. The Isp and energy efficiency for this concept are higher than ACMF (Isp 67,000 sec and h_e ~ 84% with D-He3, and Isp 61,000 sec and h_e ~ 69% with D-T). The gains b are 10^5 for D-He3 and 2.2 x 10^4 for D-T. Again assuming a 3-order of magnitude improvement in antiproton production efficiency, these gains are near breakeven in terms of net energy flow.

Although net energy gain is a fundamental consideration in the development of terrestrial power sources, it should not be the case for in-space power sources designed for exploration. Equally important to energy gain are the mass and portability of the source. This is where antiproton-initiated nuclear power sources offer a distinct advantage over conventional nuclear power sources.

Appendix B: Propulsion Performance Comparison

Reference Mission Requirements

The values of the propulsion parameters in Appendix A make it possible to evaluate mission performance and antimatter requirements for the various concepts. In this analysis, we consider six reference missions which reflect ambitious robotic and manned exploration of the solar system, precursor interstellar study of phenomena outside the solar system, and missions to our closest stellar neighbors. These reflect the data used in a recent evaluation of propulsion options for interstellar missions.[10] The missions and their associated *D*v ’s are shown in Table B1.

Table B1: Reference Missions

Mission	Description	Typical ΔV (km/s)
Planetary	Deep space robotic missions throughout solar system	10
Omniplanetary	Ambitious human exploration throughout solar system	30 - 200
100 - 1000 AU	Interstellar precursor missions to • Heliopause (100 AU) • Gravity Lens focus (550 AU)	100
10,000 AU	Interstellar precursor mission to Oort Cloud (10,000 AU)	1,000
Slow Interstellar	4.5 light-years in 40 years	30,000 (= 0.1 c)
Fast Interstellar	4.5 light-years in 10 years or 40 light-years in 100 years	120,000 (= 0.4 c)

Analysis

We first estimate total propellant quantities for each of the propulsion concepts defined in Appendix A and determine how they compare with the various missions in Table B1. We begin with the relativistic rocket equation, which is usually expressed as:

$$\frac{\Delta V}{c} = \frac{R^{\frac{2V_e}{c}} - 1}{R^{\frac{2V_e}{c}} + 1} \ . \tag{B1}$$

Here R is the ratio of wet mass to dry mass, or $R = \left(M_p + M_o\right) / M_o$, where M_p is propellant mass and M_o is the dry mass (including vehicle structure, systems and payload). V_e is the exhaust velocity of the propulsion system, and is proportional to specific impulse Isp or $V_e = g\,Isp$. Equation B1 can be modified and expressed in terms of the ratio of propellant mass to vehicle dry mass, that is:

$$\frac{M_p}{M_o} = R - 1 \ , \tag{B2}$$

where

$$R = \left(\frac{1 + \frac{\Delta V}{c}}{1 - \frac{\Delta V}{c}} \right)^{\frac{c}{2V_e}} \ . \tag{B3}$$

A graph illustrating the variation of propellant requirement with mission ΔV for each of the propulsion concepts is shown in Fig. B1. These parametrics clearly illustrate the performance superiority of the high-Isp systems. The best performer is the beamed core concept. Next comes the plasma core, followed by the antimatter-initiated fusion concepts.

Figure B1 can be misleading because it treats antimatter and reaction propellant on an equal basis. For example, the beamed core concept's propellant requirements are roughly 2 orders of magnitude less than the plasma core, and it is able to accomplish interstellar missions with propellant loadings comparable to today's launch systems. However, half of the propellant is antimatter, which is much harder to produce than typical propellants. The assumption that better performance is always desirable does not apply when utilizing an expendable that is much more costly than the reaction propellant.

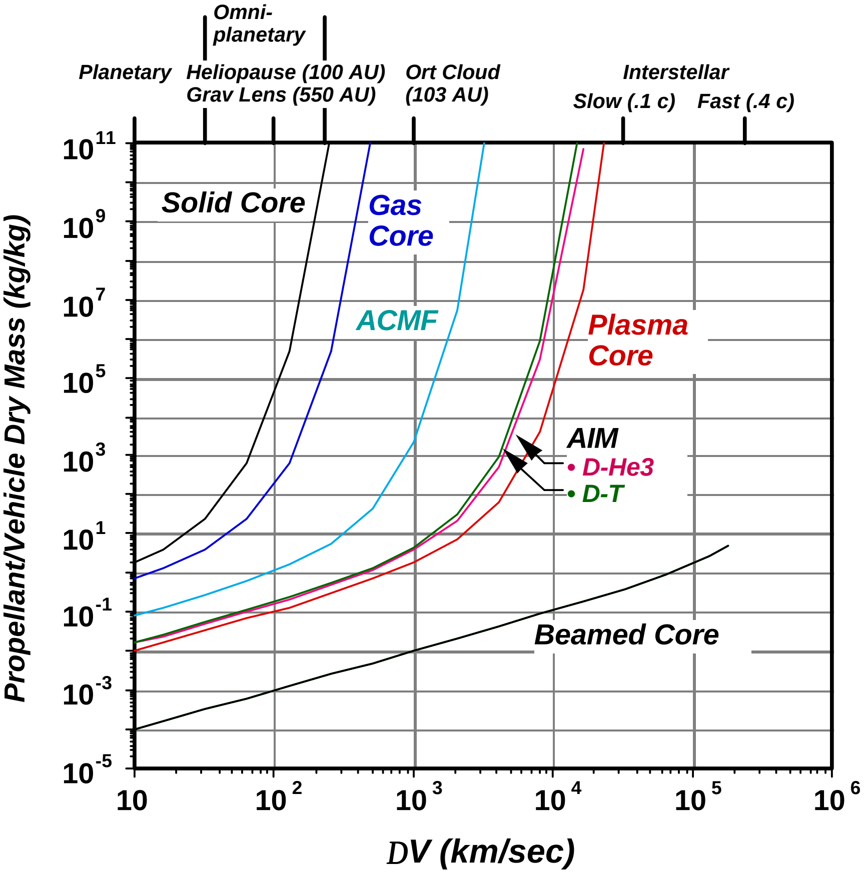

Figure B1: Propellant requirements for various antimatter propulsion concepts
Isp values: Solid Core (1,000 secs), Gas Core (2,000 secs),
Plasma Core (10^5 secs), Beamed Core (10^7 secs),
ACMF (13,500 secs), AIM (61,000 - 67,000 secs)

Our ultimate goal is to evaluate antimatter requirements against the production capacity at current facilities. Therefore, we must look beyond mere propellant and estimate the antimatter requirements for each of these concepts. This is particularly important with the catalyzed-antimatter concepts since most of the energy is coming from fusion. We determine antimatter mass requirements by first equating the actual energy introduced into the propellant with the jet energy of the exhaust, that is:

$$\left(E_{\bar{p}p} + E_{\text{fusion}}\right) h_e = \left[M_p - \frac{E_{\bar{p}p} + E_{\text{fusion}}}{c^2} \right] c^2 (g - 1) \quad . \tag{B4}$$

The left-hand side of Eq. (B4) represents the combined annihilation and fusion energy applied to the exhaust where h_e is the energy utilization efficiency. The right-hand side of Eq. (B4) represents kinetic energy of the exhaust products, where g represents the Lorenz-Fitzgerald factor, $g = \left(1 - (V_e/c)^2\right)^{-1/2}$. Note that the rest mass of the annihilation and fusion energy is subtracted from the total reaction mass.

$E_{\bar{p}p}$ is the rest mass energy of the annihilation reaction and accounts for both proton and antiproton reactants, $E_{\bar{p}p} = 2m_A c^2$. The fusion energy E_{fusion} is expressed in terms of annihilation energy with $E_{\text{fusion}} = bE_{\bar{p}p}$. The fusion energy gain b varies substantially for the two catalyzed concepts. For the ACMF process, analyses yield b = 1.6 x 10^7. The AIM process yields generally lower values, b = 10^5 for D-He3 and b = 2.2 x 10^4 for D-T. We expect these values to change as the concepts become more refined.

Substituting these variables into Eq. (B4) and rearranging yields the following expression for the antimatter to propellant mass ratio:

$$\frac{M_a}{M_p} = \frac{1}{2(1+b)} \left[\frac{g - 1}{h_e + g - 1} \right] \tag{B5}$$

Equations B5 and B2 can be combined to yield an expression for antimatter to inert mass ratio as a function of mission requirements, fusion gain and energy efficiency:

$$\frac{M_a}{M_o} = \frac{1}{2(1+b)} \left[\frac{g - 1}{h_e + g - 1} \right] (R - 1) \tag{B6}$$

Figure B2 shows the ratio of antimatter mass to vehicle dry mass for each concept over the DV range. For missions within the solar system and into near interstellar space, antimatter requirements for the catalyzed concepts are many orders of magnitude lower than their pure antimatter counterparts. At a point well beyond the solar system and when considering missions to interstellar space, beamed core becomes superior.

ACMF is clearly superior to all other concepts in terms of antimatter efficiency. This continues until we consider trips to the Oort cloud and beyond. At this point the better performance with AIM overtakes ACMF and results in lower antimatter usage. ACMF’s requirement is generally 2 orders of magnitude less for missions within the solar system.

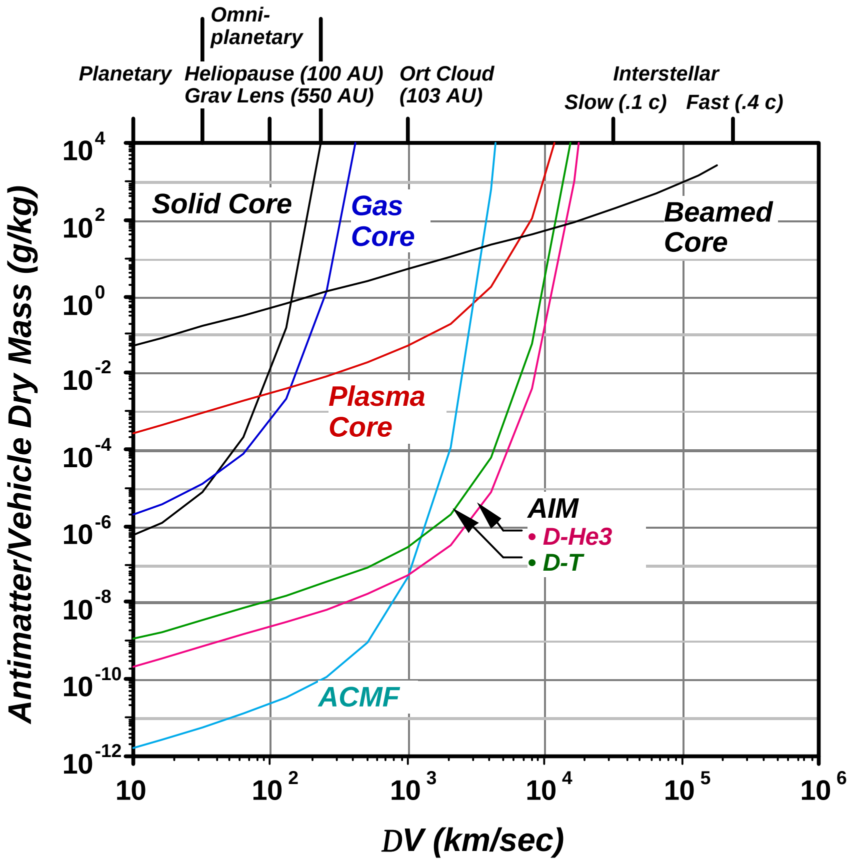

Figure B2: Antiproton mass requirements for various antimatter propulsion concepts

Inert mass can be expressed in terms of payload mass by using the definition for structure to propellant ratio, $l = M_{struct} / M_{prop}$.

$$M_o = \left(\frac{1}{1 + l - lR} \right) M_{pay} \quad . \qquad \text{(B7)}$$

Substituting Eq. (B7) into Eq. (B6) yields Eq. (3) in the main body of the paper.

Appendix C: Background

About 20 years ago, physicists at CERN began to seriously study ways to extend the capability of their existing accelerator in order to increase the proton collision energies of their high-energy particle experiments. They succeeded in doing this by incorporating an antiproton production capability into their main accelerator and by adding the Antiproton Collector (ACOL) for temporary storage. These upgrades enabled them to perform direct proton-antiproton collisions and effectively doubled the collision energies of their experiments. Soon thereafter, FNAL built the Antiproton Accumulator (AA), a copy of CERN's ACOL. Today, the AA is at the center of FNAL's program involving 1 TeV x 1 TeV (1 TeV = 10^{12} electron volts) collisions between antiprotons and protons.

In the early 1980's, CERN constructed the Low Energy Antiproton Ring (LEAR), an electromagnetic storage device which decelerates and cools antiprotons from the ACOL down to an energy of 5.9 MeV. Using LEAR as a supply, high intensity antiproton beams of extremely low emittance and energy resolution could be produced and made available for research in low-energy nuclear, particle and atomic physics. To free up funds for the Large Hadron Collider (LHC), CERN closed down LEAR at the end of 1996. However, many physicists successfully persuaded CERN to keep the ACOL running in a modified form called the Antiproton Decelerator (AD). The AD has all the beam characteristics of LEAR. However, instead of a continuous beam, it delivers 250 nanosecond bunches of 10^7 antiprotons every minute, which are ideal for collection and storage experiments using Penning traps and even more advanced devices.

The AD will start operation in early-1999, and it will be used primarily to support research aimed at studying the formation and spectroscopy of atomic antihydrogen. The long-term significance of this work is potentially enormous, since the ultimate, most efficient way of transporting antimatter to space could be in the form of electrically neutral atomic antihydrogen stored in miniature magnetic bottles. In the meantime, there will be many opportunities to carry out research with Penning-type traps filled with antiprotons at the AD. Assuming continuous operation, this device will be capable of producing 10^{12} to 10^{13} antiprotons per year which translates to 1.5 to 15 picograms (1.5 x 10^{-12} to 15 x 10^{-12} grams).

In summary, antiprotons are currently produced in relatively small quantities, i.e., roughly 1 nanogram per year. Systems for deceleration and storage are available at CERN for important experiments in formation of antihydrogen atoms, and similar devices could become available at FNAL within the next few years.