Conceptual Designs for Antiproton Space Propulsion Systems

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Conceptual designs for antimatter propulsion systems are reviewed, including 1) solid core liquid propellant rockets, 2) magnetically confined gaseous core rockets using both liquid and solid propellants, 3) plasma rockets, 4) pion rockets, which are driven directly by the mass annihilation products, and 5) ram-augmented rockets. Generally it is found that as the specific impulse of the propulsion system increases, the thrust decreases. Solid core rockets can have a specific impulse as high as 1000 s and thrust-to-engine mass ratios of 100 *g*. The performance here is limited by the temperature of the solid core. In a gas core rocket, a propellant gas is heated by the charged particles resulting from the annihilation. The charged annihilation products are contained by a magnetic bottle. The primary limitation here is heating of the chamber wall and nozzle. For this system, somewhat higher specific impulses can be achieved. Lining the chamber with a solid propellant or ablative material can increase the specific impulse somewhat, but the range of application is narrow. The chamber walls and nozzle can be removed by heating the propellant to ionization temperatures and then using magnetic, or electric, fields to contain and direct the plasma. With plasma rockets, specific impulses of 100,000 s or more could be achieved. Pion rockets can have a specific impulse of 20 × 10⁶ s but thrust-to-engine mass ratios of only 0.01 *g*. If the propulsion system can collect its propellant as it travels through a planetary atmosphere, or through the residual hydrogen in space, then extremely high specific impulses could be achieved.

Introduction

DURING the last decade, several designs for antiproton annihilation rockets have been proposed. Some of the first investigations were performed by Morgan,[1,2] who considered the annihilation process in detail and more recently has shown that the annihilations occur in a very narrow region.[3,4] Morgan has considered two conceptual designs[5]: 1) a rocket which directly exhausts the annihilation products and 2) a rocket which uses the annihilation products to heat a plasma. Recently LaPointe has completed a detailed analysis of pulsed plasma heated engines.[6] Early investigations were also performed by Forward,[7,8] who considered technical solutions to the problems of antiproton generation and storage and who developed a cost analysis[9] for high energy missions that shows where antiproton annihilation propulsion systems are competitive.

Vulpetti et al.[10-12] and Howe and Metzger[13] have examined in detail solid core rockets that use the annihilation products to heat a solid. The propellant is then heated by being pumped through passages in the solid and exhausted through a nozzle. The maximum temperature of the solid core limits the performance of this rocket to specific impulses of about 1000 s. A gas core rocket,[14] where a gaseous propellant is heated directly by the annihilation products, can attain specific impulses as high as 1500 s.[13] Vulpetti[15] has examined the use of pellets in antimatter propulsion and has shown that it may be possible to attain specific impulses as high as 20×10^6 s. Metal clad pellets have been examined for fusion propulsion by Kamash and Galbraith[16,17] and may have applications to antiproton annihilation propulsion. Takahashi[18] has proposed that antiproton annihilations could provide a source for muons in muon-catalyzed fusion. Finally, Hora and Löb[19] have recently proposed a pion drive for intersteller rockets, with a specific impulse of approximately 10×10^6 s.

Single stage to orbit vehicles have been proposed by Vulpetti[11] and Froning,[20] but such rockets will require extensive radiation protection.[6,21] Other general discussions on antiproton annihilation propulsion have been presented by Nordley,[22] Borowoski,[23] Garrison,[24] Cassenti,[25,26] and Sowell.[27]

Annihilation Reaction

Antimatter propulsion makes use of the annihilation of antiprotons with ordinary matter. For example, when an antiproton $\bar{p}$ and proton p annihilate,[6,7,25] the products of the annihilation are generally pions π or

$$\bar{p} + p \rightarrow m\pi^0 + n\pi^+ + n\pi^- \tag{1}$$

Pions, to a first approximation, can be taken to be the particles that transmit the strong force. The strong force is responsible for binding the protons and neutrons together in an atomic nucleus. The number of neutral π^0 and charged pions $\pi^\pm$ created are approximately equal with

$$m \approx 2, \qquad n \approx 1.5 \tag{2}$$

The pions are unstable with the neutral pions decaying almost immediately (a mean life of 0.84×10^{-16} s) into high energy gamma rays γ

$$\pi^0 \rightarrow \gamma + \gamma \tag{3}$$

The charged pions decay into muons μ and an associated neutrino ν_u

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \tag{4}$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}\mu \tag{5}$$

Muons are heavy electrons (about 200 times the electron mass), and neutrinos are generally believed to be massless. Neutrinos are quite penetrating and readily pass through matter without interacting. The muons are unstable and decay into electrons e and the appropriate neutrinos, according to

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \tag{6}$$

$$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \tag{7}$$

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The final products of the reaction will be gamma rays, neutrinos, electrons and positrons (i.e., antielectrons). If the electrons and positrons combine they will annihilate according to

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{8}$$

Hence if complete annihilation occurs, the final products will be gamma rays and neutrinos. A summary of characteristics of the reaction products is presented in Table 1.

The charged products produced readily interact with matter, depositing some fraction of their kinetic energy during collisions with the electrons and nuclei. The charged particles can also be directed or trapped by magnetic or electric fields. Neutral reaction products can be considered a loss, although the energy from the gamma rays could be absorbed by using large quantities of matter.[21]

Performance Measures

A comparison of various antiproton propulsion systems requires a set of measures. These measures, though, must extend the common low speed measures[28] to relativistic speeds. The common definition for the specific impulse for constant thrust is engine thrust F divided by the propellant weight flow rate (at one Earth gravity, g_0). Then

$$I_s = \frac{F}{\dot{m}_{p_i} g_0} \tag{9}$$

where $\dot{m}_{pi}$ is the onboard propellant rest mass flow into the engine. If $\dot{m}_{p_0}$ is the propellant rest mass flow rate out of the rocket, the thrust F can be written as

$$F = \dot{m}_p v_e = \frac{\dot{m}_{p0} v_e}{\sqrt{1-(v_e/c)^2}} \tag{10}$$

where v_e is the exhaust velocity, and c is the speed of light.

The definition of specific impulse follows from the ratio of total impulse to weight of propellant at one Earth gravity for a constant flow rate. The definition gives a conceptually correct infinite specific impulse for propellant mass with an exhaust velocity of the speed of light. Substituting Eq. (10) into Eq. (9)

$$I_s = \frac{(v_e/c)}{\sqrt{1-(v_e/c)^2}} \left(\frac{c}{g_0}\right) \left(\frac{\dot{m}_{p0}}{\dot{m}_{p_i}}\right) \tag{11}$$

The efficiency η will be defined as the kinetic exhaust power P_{out} divided by the input power P_{in} then

$$\eta = P_{\text{out}}/P_{\text{in}} \tag{12}$$

The exhaust power is

$$P_{\text{out}} = \dot{m}_p c^2 - \dot{m}_{p_0} c^2 = \dot{m}_{p_0} c^2 \left[\frac{1}{\sqrt{1-(v_e/c)^2}} - 1\right] \tag{13}$$

and the input power is

$$P_{\text{in}} = \dot{m}_a c^2 \tag{14}$$

where $\dot{m}_a$ is the total annihilated rest mass rate (i.e., twice the mass of antimatter annihilated). Combining Eqs. (12), (13), and (14)

$$\eta = \frac{\dot{m}_{p0}}{\dot{m}_a} \left[\frac{1}{\sqrt{1-(v_e/c)^2}} - 1\right] \tag{15}$$

The thrust-to-engine weight ratio $m_e g_0$ is the last measure

$$N = F/m_e g_0 \tag{16}$$

where m_e is the engine rest mass.

For small exhaust speeds relative to the speed of light, Eqs. (11) and (15) become

$$\left.\begin{aligned} I_s &\approx \frac{v_e}{g_0} \\ \eta &\approx \frac{\frac{1}{2}\dot{m}_p v_e^2}{\dot{m}_a c^2} \end{aligned}\right\} \frac{v_e}{c} << 1, \dot{m}_{p_0} \approx \dot{m}_{p_i} \approx \dot{m}_p \tag{17}$$

which produces the equivalent low speed definition for specific impulse.

Figure 1 illustrates the performance range for various propulsion systems. Note that as the specific impulse increases the thrust-to-mass decreases.

Solid Core Rockets

A simple, and reliable, antiproton annihilation rocket consists of a material, which is heated either directly or indirectly by the annihilation products, which in turn are used to heat a propellant. Figure 2 is a schematic of the system from Ref. 10. The antiprotons are annihilated in the central region, which contains a gas. The annihilation products heat a set of concentric cylinders. Propellant, typically hydrogen, is passed between concentric cylinders, heated, mixed, and expanded through a nozzle. Vulpetti[11,12] and Howe and Metzger[13] have performed detailed analyses, achieving thrust-to-mass ratios of between 1 and 10 g. Vulpetti's analysis[11,12] indicates an efficiency of approximately 70%. The performance of these rockets is limited to about 3000 K, which is the maximum temperature the solid core can maintain.

Gaseous Core Rockets

If the propellant, usually hydrogen since its low molecular weight provides a high specific impulse, is heated directly, the the heat transfer will be reduced to the containment chamber walls. Transpiration cooling[13] can then be used to keep the

Table 1 Summary of elementary particle properties

Particle	Antiparticle	Change	Mass, MeV	Mean life, s	Principle decay made
Proton, p	$\bar{p}$	+1	938.3	stable	—
Electron, e^-	e^+	−1	0.511	stable	—
Muon, μ^-	μ^+	−1	105.7	2.2×10^{-6}	$e^- + \nu_e + \bar{\nu}_e$
Electron neutrino, ν_e	$\bar{\nu}_e$	0	0	stable	—
Muon neutrino, ν_μ	$\bar{\nu}_\mu$	0	0	stable	—
Photon, γ	same	0	0	stable	—
Positive Pion, π^+	π^-	+1	139.6	2.6×10^{-8}	$\mu^+ + \nu_\mu$
Neutral Pion, π^0	same	0	135.0	8.4×10^{-16}	$\gamma + \gamma$
Negative Pion, π^-	π^+	−1	139.6	2.6×10^{-8}	$\mu^- + \bar{\nu}_\mu$

Table 2 Liner properties

Liner	ρ, g/cm³	T_v, K	T_m, K	H_v/R_uT_u	H_m/R_uT	C_S/R_u	C_L/R_u
H_2[29]	0.070	20	14	2.724	0.504	0	0
LiH[29,30]	0.820	1316	953	0.753	0.466	0.604	0
R154[31]	1.205	813	588	0.126	0	0.185	0.185
Plexiglas[32]	1.140	530	0	0.645	0	0.200	0

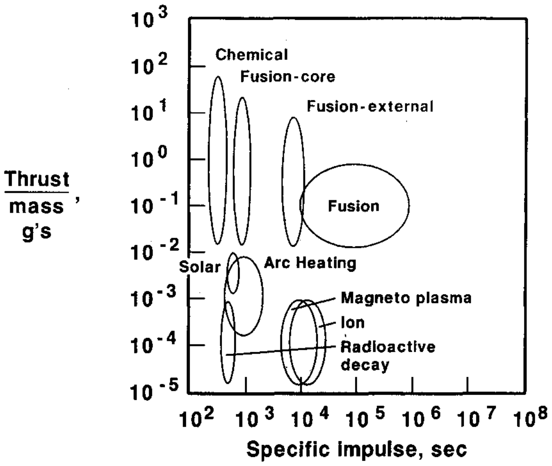


Fig. 1 Rocket performance map.

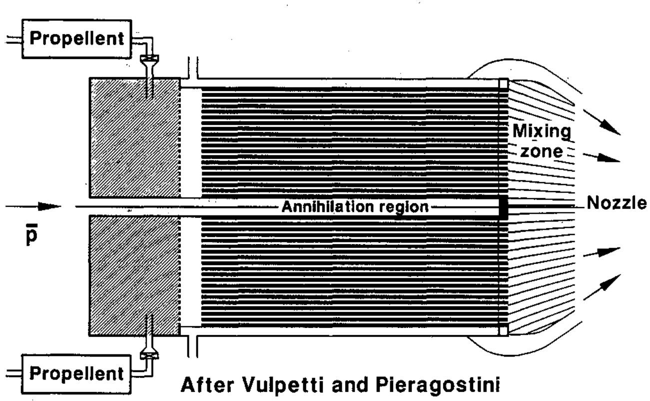


Fig. 2 Solid core rocket conceptual design.

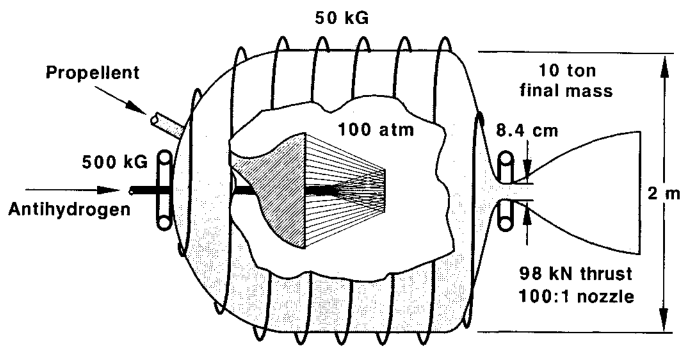


Fig. 3 Gaseous plasma antimatter rocket.

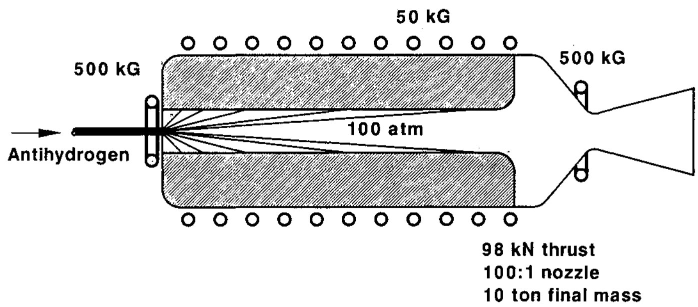


Fig. 4 Solid propellant antimatter rockets.

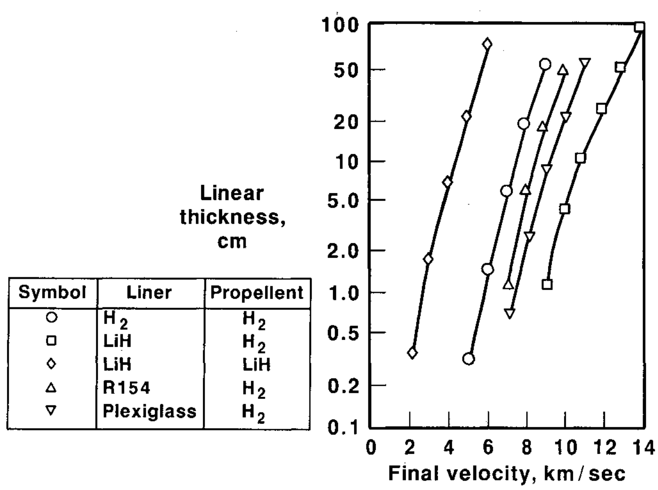


Fig. 5 Ablation in solid propellant rocket.

chamber walls cool. Figure 3 is a schematic of the concept. The annihilations occur directly in the propellant. The charged annihilation products (i.e., pions, muons, and electrons) are trapped by a magnetic field of approximately 50 kG in the center. The particles are trapped axially by using at least 200 kG coils on the ends. Howe[13] and Cassenti[14] have shown that the specific impulse is typically 1000 s and with transpiration cooling could be as high as 1800 s.[13] The thrust-to-mass is about 1 g. Efficiencies range between 25 and 35%.[14]

It may be possible to further increase the performance if the chamber wall and nozzle is lined with an ablative material. If a light molecular weight liner is used, it could add to the thrust. In fact the liner could contain the propellant and eliminate the need for propellant pumps as shown in Fig. 4. Assuming that the major heat transfer component to the liner is due to radiation, then the rate at which the liner recedes $\dot{r}_l$ is

$$\dot{r}_l = \sigma(T_c^4 - T_V^4)/[\rho C_L(T_v - T_m) + \rho C_S T_m + H_v + H_m] \quad (18)$$

where σ is the Stefan-Boltzman constant; T_c, the absolute chamber temperature; T_v, the temperature at which the liner vaporizes; H_v, the heat of vaporization; H_m, the heat of fusion; C_S, the average specific heat of the solid; C_L, the average specific heat of the liquid; and ρ, the density. The total thickness for the liner is then given by

$$r_l = \dot{r}_l t_f \quad (19)$$

where

$$t_f = \text{``burn'' time}$$

Equations (19) and (20) were incorporated in the analysis in Ref. 14. The properties for four liners are given in Table 2. The entry labeled R154 is a typical solid rocket motor insulator. The baseline engine parameters are given in Fig. 3, and Fig. 5 presents the liner thickness required if no cooling is provided. The case where the rocket is entirely solid propellant (LiH for the liner and propellant) is the poorest performer. This is because of the high temperature required to vaporize the LiH, which is more clearly illustrated in Fig. 6. It would appear that the liner can only provide a benefit if cooling is provided (e.g., transpiration cooling[13]). The fact that radiative heat transfer varies with the fourth power of the chamber temperature will clearly limit any improvements in the specific impulse.

Plasma Core Rockets

As the number of antiprotons annihilated increases in a given volume of propellant, higher propellant temperatures are achieved finally resulting in ionization. This provides a further increase in the specific impulses. Morgan[5] briefly examined this concept and estimated 1) a specific impulse of 10,000 s, 2) a thrust-to-mass ratio of more than 20 g, and 3) an efficiency of about 50%.

Recently, LaPointe[6] has analyzed antiproton annihilation heating of hydrogen plasmas. His results indicate that it should be possible to obtain significant thrusts at specific impulses of 50,000 s or more. Estimates indicate the thrust-to-mass ratio should be on the order of 10 g. The efficiencies though are low, about 1 to 2% including Bremstrahlung losses. If these losses are reduced, then the efficiencies could possibly be an order of magnitude more. Additionally an estimate of the mass of the radiation shield to protect the confining magnets, crew, and sensitive equipment may dominate the mass of the propulsion system, reducing the thrust-to-mass ratio by more than an order of magnitude.

It may be possible to decrease the external magnetic field requirements by heating propellant in the form of metal clad pellets. Such a system was first suggested by Vulpetti[15] but here a high specific impulse rocket (over 20×10^6 s) was proposed, while the metal cladding was not used to provide a confining magnetic field. Figure 7 illustrates the propulsion system concept. A pellet containing a hollow sphere of propellant is surrounded by a metal cladding. Antiprotons are injected into the pellet directly or through a hole. The annihilation products heat the remaining propellant and the ionized propellant is then directed by a magnetic nozzle. The metal cladding not only confines the propellant, while it is initially heated due to inertial effects, but a strong magnetic field is created due to the intense heating[16,17,33] as illustrated in Fig. 8. The field[33] is proportional to the plasma density gradient ∇n and the plasma temperature gradient ∇T. The temperatures are high enough to cause fusion to occur if deuterium and/or tritium are the constituents in the propellant. From Ref. 34, the magnetic fields are sufficient to confine the plasma, including pions and muons, producing fields on the order of 1–10 MG. The confinement times must also be calculated to determine the amount of energy transferred from the pions and muons to the propellant. The energy transferred to the fuel will be highly dependent on the plasma density. Higher densities will increase plasma Bremstrahlung losses but produce a better energy transfer. Both of these competing processes are important in determining the feasibility of this concept.

The confinement time can be found by considering a spherical shell of tungsten uniformly stressed to its yield point and subject to an internal pressure p from the heated plasma. The equation governing the expansion of the shell of tungsten is

$$\pi a^2 p - 2\pi h \sigma y = 4\pi a_0^2 h_0 \rho_0 \ddot{a} \tag{20}$$

where a is the radius of the spherical shell; h, the shell thickness; a_0, the initial shell radius; h_0, the initial shell thickness; σ_y, the shell yield stress; and ρ_0, the initial shell density. During the yielding the volume of the spherical shell is constant, or

$$a^2 h = a_0^2 h_0 \tag{21}$$

The magnetic field B will be taken as that required to contain the plasma at temperature[6] T or

$$B = K\sqrt{\sum_i n_i T_i} \tag{22}$$

Note that

$$\frac{p}{k} = \sum_i n_i T_i \tag{23}$$

where $K = 63.5$ kG for n in cm^{-3} and T in eV, k Boltzman's constant, and the sum is over all the plasma constituents. From Ref. 14, the field B_0, sufficient to trap most of the pions and muons in a radius R_0 is

$$B_0 R_0 = 50 \text{ kG} \times 100 \text{ cm} = A_0 \tag{24}$$

then Eq. (21) becomes

$$\left[K\frac{A_0}{a_0}\right]^2 a^2 - 2\left(\frac{a_0^2 h_0}{a}\right)\sigma_y = 4 a_0^2 h_0 \rho_0 \ddot{a} \tag{25}$$

Integrating Eq. (26) for tungsten, where $a_0 = 1$ cm, $\sigma_y = 5 \times 10^8$ dynes/cm^3, $\rho_0 = 20$ g/cm^3, and $h_0 = 10^{-3}$ cm re-

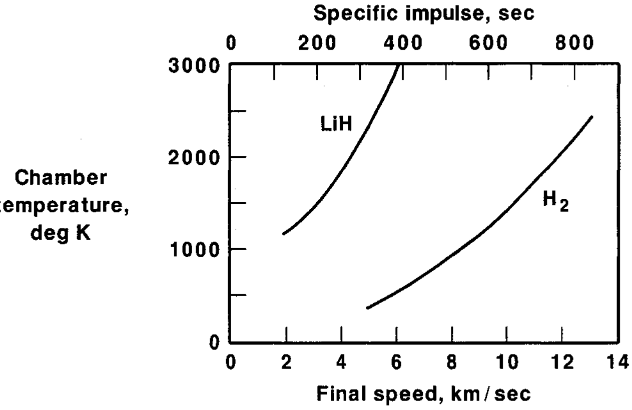


Fig. 6 LiH propellant rocket.

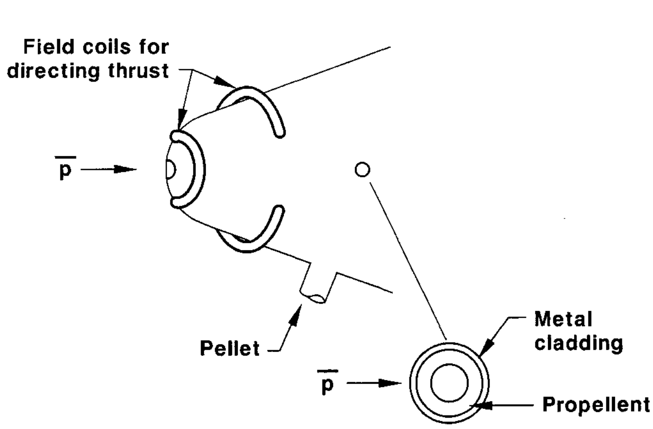


Fig. 7 Pellet rocket conceptual design.

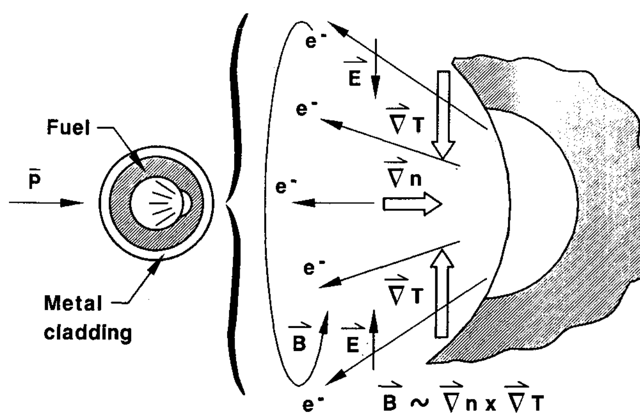
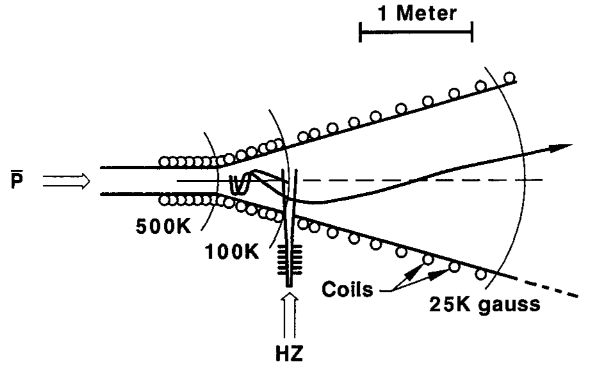
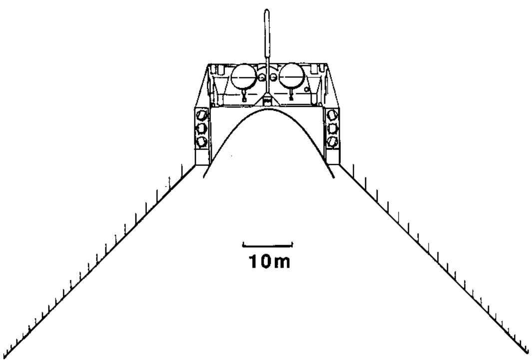


Fig. 8 Pellet containment.



After Morgan, 1982

Fig. 9 Pion rocket conceptual design.



After Hora & Lob, 1986

Fig. 10 Pion rocket system.

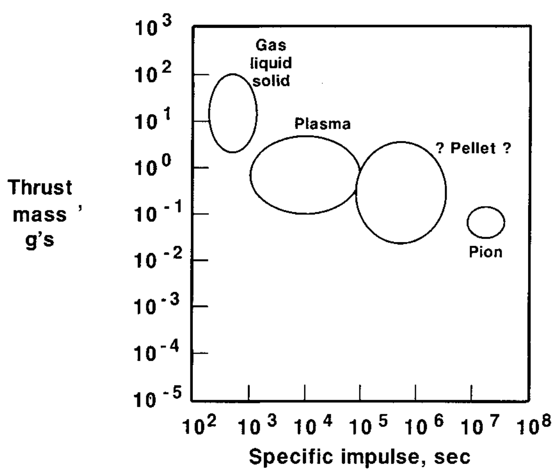


Fig. 11 Antimatter rocket performance map.

sult in the sphere doubling its radius in about 10 μs. For the conditions assumed by LaPointe, these confinement times do not appear to be sufficient to transfer the energy from the muons to plasma.[6] The magnetic nozzle may provide additional time for interactions to occur. A detailed analysis is required to determine if this mechanism will prove beneficial. If the confinement times are large enough, then it may be possible to achieve specific impulses of 1×10^6 s.

Pion Rockets

A relativistic exhaust velocity rocket can be attained by annihilating the antimatter with equal quantities of matter.[5,8] Magnetic fields would then be used to direct the pions produced in the annihilation products, as illustrated in Fig. 9. Morgan[5] has estimated such a rocket would have a specific impulse of 16 million s, thrust-to-mass ratio of 0.07 g and an efficiency of 40%. Hora and Löb,[19] see Fig. 10, obtained a specific impulse of 10×10^6 s, a thrust-to-mass ratio of 0.0085 g and an efficiency of almost 75%.

Interstellar Ramjet

Jackson[35] has proposed that antiproton annihilation can be used to heat hydrogen, in a manner similar to the plasma or gas core engines, collected in interstellar space (i.e., a modification of Bussard's interstellar ramjet concept[36]). His main conclusion was that at extreme relativistic velocities, the mass ratio would not exceed 2.56. This is a better performance than can ever be obtained by a pure mass annihilation rocket.

Conclusions

Figure 11 is a performance map for antiproton annihilation rockets. This should be compared with Fig. 1. The comparison shows that only fusion rockets have the capability to compete, in performance, with mass annihilation rockets. Ultimately for very high speed missions (i.e., interstellar missions) pion rockets will provide the best performance. Figure 11 also illustrates the tendency for the thrust-to-mass ratio to decrease as specific impulse increases. Also note that, except for pion engines, decreases in efficiency can be anticipated with increases in specific impulse.

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