Antimatter Propulsion for OTV Applications

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Recent investigations have indicated that it may be possible to generate and store antiprotons in quantities sufficient to propel rockets to the nearer stars. Annihilating these antiprotons with matter would yield energy in the form of relativistic particles. These particles could then be used to heat a propellent and provide thrust. Building a rocket capable of propelling vehicles to the stars is well beyond the current technology. Nevertheless, it is possible to devise annihilation rockets with considerably less performance, requiring only minor extrapolations of current technology. As an orbital transfer vehicle such a rocket could use a standard DeLaval nozzle with a 100:1 area ratio. The combustion chamber would be 2 m in diameter, operating at 100 atm and a temperature slightly above the boiling point of water. The relativistic particles, created during the annihilation, would be trapped in a 50-500 kG magnetic field and would be used to heat liquid hydrogen. The high-magnetic fields required for confinement appear to be the major design concern. Once such a rocket is built it becomes a matter of engineering improvements to realize the ultimate potential performance of mass annihilation rockets.

Introduction

DURING the last few years, several investigators have proposed methods for acquiring and storing antiprotons in significant quantities.[1-4] When antiprotons are combined with an equal number of protons, both are completely annihilated. The annihilation products consists mainly of relativistic particles that can be used to provide thrust.[2,5] These particles theoretically can provide a specific impulse of more than 10^6 s.[5,6] Building a rocket capable of effectively using a propellent with a specific impulse of millions of seconds is well beyond current capability because of the large quantities of antimatter required. Fortunately, it is possible to combine small quantities of antiprotons with much larger quantities of matter to produce rockets with a specific impulse of a few hundred seconds.[5-8] Once a successful design for a low-specific impulse annihilation rocket is completed, higher performance annihilation rockets can be developed in an evolutionary manner.

The development of rockets based on the annihilation of matter will only be possible when it is possible to acquire and store antimatter in significant quantities. Physicists produce and store antiprotons everyday for use in elementary particle experiments. However, their objective is not to produce antiprotons in large quantities. Hence, new designs for production and storage will have to be developed. Antiprotons are produced by colliding high-energy proton beams with heavy-element targets. Some of the collision debris consists of antiprotons moving at various relativistic velocities. These antiprotons are separated, cooled, and placed in a storage ring.[2] For use in antimatter rockets, these antiprotons should be neutralized with antielectrons (positrons), trapped, and stored as solid antihydrogen. Forward[1,2] has discussed several approaches for making and storing antimatter. He estimates an efficiency of 0.017% should be achievable for the conversion of electrical energy into antimatter. Chapline[3] has suggested that using particle beams of heavy nuclei, instead of protons, could significantly increase the conversion efficiency. Once the antimatter is produced, it must be stored without contacting ordinary matter.[9,10] Even if solid antihydrogen is electrically or magnetically suspended in a container of matter, there would be vapor pressure present from both the antihydrogen (and to a much lesser extent the container) and hence annihilations would occur at any temperature above absolute zero. This annihilation rate would decrease exponentially as the temperature approaches absolute zero. Estimates[7] based on the kinetic theory of gases indicate that at 4.0 K a milligram of antihydrogen suspended electrically in a container of matter would last more than 10 years.

Details of the annihilation reaction are required for the efficient utilization of the energy released.[2,5] A simple annihilation reaction is the electron-positron annihilation. The annihilation products consist of two or more gamma rays, or

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{1}$$

Since the mass of the electron is 0.511 MeV, the gamma rays have a total energy content of more than 1.0 MeV. The annihilation of a proton (mass 938 MeV) and antiproton is considerably more complex. The reaction products, for proton-antiproton annihilation consists of two or more mesons. Most of these mesons are pions, but some kaons are also produced. Pions, to a first approximation, can be considered to be the particles that bind the nuclei of atoms together. These pions have a mass of approximately 140 MeV and carry 1) a unit positive or negative electron charge or 2) a neutral electric charge. The reaction usually proceeds by

$$p + \bar{p} \rightarrow m\pi^\circ + n\pi^+ + n\pi^- \tag{2}$$

where m and n are approximately 1.60. The charged pions are not stable and decay into muons (μ) and neutrinos (ν) or antineutrinos ($\bar{\nu}$), while the neutral pions decay into gamma rays

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

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

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

Muons (mass 106 MeV) can be considered to be heavy electrons, while neutrinos are neutral and massless (less than 10 eV). Electrons and muons each have their own corresponding

Presented as Paper 84-1485 at the AIAA/ASME/SAE 20th Joint Propulsion Conference, Cincinnati, Ohio, June 11-13 1984; received June 18, 1984, revision received Nov. 5, 1984.

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neutrino. The muons are also unstable and decay according to

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e \tag{6}$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \tag{7}$$

Charged pions have a mean life of 2.6×10^{-8} s while the neutral pions have a mean life considerably shorter at 0.84×10^{-16} s. Muons live about 100 times as long as charged pions with a mean life of 2.2×10^{-6} s. The charged pions, the muons, and the electrons readily interact (e.g., ionize atoms) with matter. The neutral pions react only with nuclei. Their extremely short life means that the interaction must occur at the annihilation site. Neutrinos have a negligible interaction with matter and the gamma rays are too energetic to readily interact with matter and, therefore, the energy is lost. Charged particles can be directed or trapped in magnetic fields. There are two possible methods for extracting thrust from the annihilation. The charged pions, muons, and electrons can be formed into a collimated exhaust or the charged particles can be used to heat propellent.[5-8] Only the second of these will be considered here.

The remainder of this paper will be divided into several sections. The next section will briefly outline the basic mission to be considered. An approach to constructing a rocket engine using the annihilation of matter is then presented, while an analysis of the engine efficiency in using antimatter is presented in the next section. The following section summarizes the results of a parametric study, and the last section lists some conclusions.

OTV Mission

Throughout this analysis the basic mission will consist of the transfer of a 10 metric ton spacecraft from low Earth orbit (LEO) to geosynchronous orbit (GEO) and back to LEO. No orbital plane changes will be considered in the basic mission. LEO will be taken to be an altitude of 200 km and GEO an altitude of approximately 36,000 km. Using Hohmann transfers,[11] the first leg of the mission increases the apogee of the 200 km circular orbit to 36,000 km and requires a change in speed of approximately 2.5 km/s. The orbit is circularized at GEO, requiring a change in speed of approximately 1.5 km/s. To return to LEO, a speed change of approximately 1.5 km/s will lower the perigee from GEO to 150 km. At the perigee, atmospheric drag can be used to lower the apogee to 200 km. At the new apogee of 200 km, a negligible speed change is then required to raise the perigee to 200 km. The total speed change for the entire mission is then approximately 5.5 km/s. Additionally, a plane change of 0.5 rad (approximately 28 deg) requires a change in speed of approximately 0.75 km/s at GEO. If the plane change is performed twice, the total mission change in speed would be 7.0 km/s. The base mission will consider only the 5.5 km/s requirement, an aeroassist can be used to reduce some of the additional 1.5 km/s speed change for plane changes.

This mission is among the simplest that any propulsion system will have to perform and therefore provides an ideal first step for developing antimatter rockets. Later missions requiring higher performance could then be developed by an engineering evolutionary approach. Hence, it is not necessary to show that an antimatter-powered orbital transfer vehicle (OTV) must be cost competitive with other OTV propulsion systems. The later evolutionary developments should more than return the initial costs for developing the antimatter manufacture and storage systems.

Design Approach

Several factors must be considered in the design of an OTV powered by proton-antiproton annihilation. The most important of these is the confinement or collimation of the exhaust products. Confining the annihilation products (i.e., the charged pions, muons, and eletrons) allows them to heat a propellent, such as hydrogen, significantly reducing the amount of antimatter required.[5,7,8] These charged particles can be confined by surrounding the combustion chamber with current-carrying coils. The resulting magnetic field will cause the charged particles to move along a helical path. The particles can be reflected at the ends of the combustion chamber by greatly increasing the magnetic field intensity at the ends.[12] For nonrelativistic speeds and collisionless processes[13] the fraction of particles trapped at the ends f_{TE} for particles initially emitted isotropically, is

$$f_{TE} = \sqrt{1 - (B_{min}/B_{max})} \tag{8}$$

where B_{min} is the magnetic field intensity at the center of the chamber and B_{max} the magnetic field intensity at the ends of the chamber.

Using the annihilation products to heat a propellent not only reduces the amount of antimatter, but also lessens the technical problems associated with the manufacture and storage of antimatter. This low-performance mission also allows the use of much current technology, thus minimizing the technical problems that would be associated with a rocket performing with a specific impulse of millions of seconds.

Radiation damage is one problem that should be investigated. The radiation damage will arise from the gamma rays generated from neutral pions and electron-positron annihilations. In addition, if nuclei heavier than unit atomic weight are used for the propellent, the possibility for neutron damage exists. The choice of engine materials can help to minimize the effects of radiation damage.

The rocket design can be considerd to contain a combustion chamber where the annihilation reaction and the propellent heating occurs. The combustion chamber is surrounded by

Table 1 OTV propellents used in parametric study

Propellent	No. of atoms, n_a	No. of degrees of freedom, f	Ratio of specific heats, γ	Molecular weight, M
H_2	2	5	7/5	2.02
H_2O	3	7	9/7	18.02
O_2	2	5	7/5	32.00
Air	2	5	7/5	28.80
He	1	3	5/3	4.03
Ne	1	3	5/3	20.18
Ar	1	3	5/3	39.95
Kr	1	3	5/3	83.80
Xe	1	3	5/3	131.30
Ra	1	3	5/3	222.00

current-carrying coils that produce a magnetic field which traps the charged annihilation products circumferentially. Additionally, the magnetic field intensity should increase at the ends to trap these particles axially. The heated propellent is exhausted through a conventional DeLaval nozzle.

The propellent is assumed to be an ideal gas. For a propellent with n_a atoms in each molecule, the number of degrees of freedom under ordinary conditions is

$$f=2n_a+1 \tag{9}$$

Then the ratio of the specific heats becomes

$$\gamma=(f+2)/f \tag{10}$$

and the specific heat at constant pressure is

$$c_p=\frac{f+2}{2}R \tag{11}$$

where

$R=R_u/M$, M is the molecular weight, and R_u the universal gas constant. Ten propellants were considered in the study, as listed in Table 1.

For the analysis of the nozzle, the chamber pressure P_c and the ratio of the exhaust to throat area exit A_e/A_t were input parameters. The ratio of the exit pressure to chamber pressure p_e/p_c was calculated iteratively by[14]

$$\eta_i^{\circ}=1 \tag{12}$$

$$\frac{P_e}{P_c}=1\Big/\left\{\sqrt{\eta_i^N}\left(\frac{A_e}{A_t}\right)\left(\frac{\gamma+1}{2}\right)^{1/(\gamma-1)}\sqrt{\frac{\gamma+1}{\gamma-1}}\right\}^{\gamma},\; N=0,1,2,... \tag{13}$$

$$\eta_i^{N+1}=1-p_e/p_c{}^{(\gamma-1)/\gamma} \tag{14}$$

Equations (13) and (14) are repeated until

$$|\eta_i^{N+1}-\eta_i^N|<10^{-4} \tag{15}$$

Given the final acceleration a_f and the final mass m_f as input parameters, the thrust F is

$$F=m_f a_f \tag{16}$$

For the analyses conducted, the final mass was chosen to be 10 metric tons and the acceleration was chosen as 9.81 m/s.[2] For the OTV mission, the change in speed Δv was set to 5.5 km/s; then, from Ref. 14, the exhaust velocity is

$$v_e=\Delta v/\Gamma \ell n(MR) \tag{17}$$

where

$$\Gamma=1+\frac{1-\eta_i}{(f+2)\sqrt{\eta_i}} \tag{18}$$

η_i is the last value of η_i^{N+1} in Eq. (14) and MR is the mass ratio that can be chosen as an input parameter. In the analysis MR was generally chosen to be 5.0.

Once the mass ratio and final mass are known, the propellent mass m_p is given by

$$m_p=(MR-1)m_f \tag{19}$$

while the propellant flow rate[14] is

$$\dot{m}_p=F/\Gamma v_e \tag{20}$$

The chamber temperature T_c can now be calculated from[14]

$$T_c=\frac{\frac{1}{2}v_e^2[(\gamma-1)/\gamma]}{\eta_i R}+T_{inj} \tag{21}$$

where T_{inj} is the propellent injection temperature, which was taken at 25K for all cases. Hydrogen is liquid at 25 K (of course, other propellents need not be liquid at 25 K). The density was taken to be given by

$$\rho_c=p_c/RTc \tag{22}$$

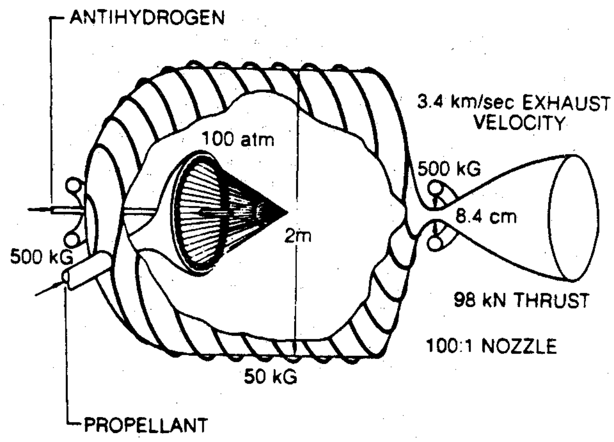

Fig. 1 Schematic of OTV antimatter rocket.

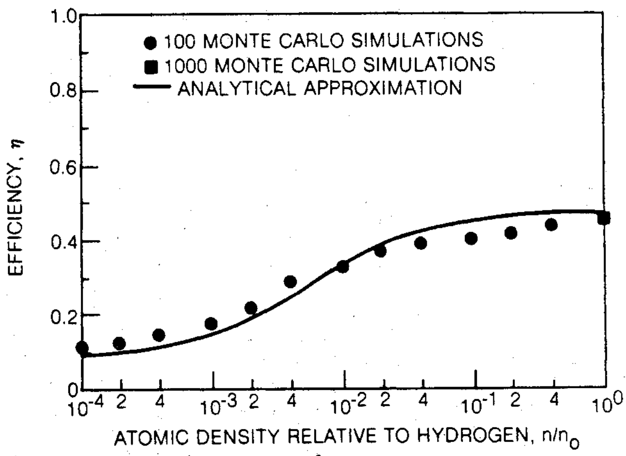

Fig. 2 Efficiency for annihilation energy transfer in an infinite combustion chamber.

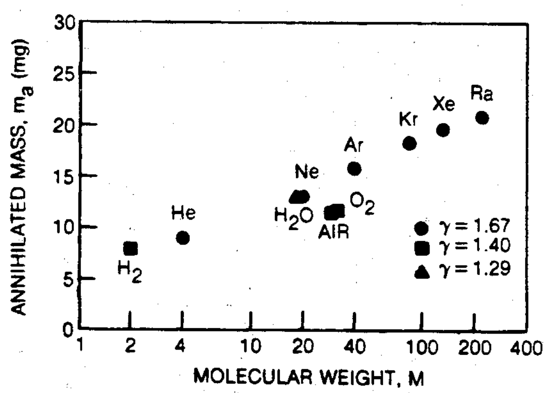

Fig. 3 Annihilated mass for various propellents.

The amount of matter to be annihilated, half of which is antimatter, can be calculated from

$$m_a = \frac{C_p (T_c - T_{\text{inj}})}{\eta c^2} m_p \tag{23}$$

where c is the speed of light and η the fraction of the annihilation energy transferred to the propellent. Generally, η will depend on the magnetic field strengths, the chamber density, and the atomic weight of the individual atoms. The quantity η for the OTV mission is about 0.35, which is shown in the next section.

The annihilated mass flow rate, from Eq. (24), is given by

$$\dot{m}_a = \frac{C_p (T_c - T_{\text{inj}})}{\eta c^2} \dot{m}_p \tag{24}$$

Finally, it should be noted that the throat area is[14]

$$A_t = F \Big/ \left\{ P_c \left[\gamma \sqrt{\frac{1}{(\gamma - 1)} \eta_i \left(\frac{2}{\gamma + 1} \right)^{(\gamma+1)/(\gamma-1)}} + \left(\frac{P_e}{P_c} \right) \left(\frac{A_e}{A_t} \right) \right] \right\} \tag{25}$$

To complete the analysis, the efficiency η in Eqs. (23) and (24) must be calculated, which is the subject of the next section.

Figure 1 is a schematic of the proposed mass annihilation rocket. The parameters chosen are shown in Table 2. For an efficiency η of 0.35, the amount of mass to be annihilated is approximately 8 mg, of which 4 mg is antihydrogen nuclei. The rocket would use a 50 kG field in the central region of the combustion chamber and a 500 kG at the ends. A field of 500 kG is not within current practice. The current necessary to maintain at least a 50 kG intensity is approximately 90 kA for a chamber length of 2 m and 400 turns. If the superconductor Nb_3Sn is used for the 50 kG coil a 50 kA/cm^2 current density could be supported.[15] Assuming a specific gravity of 8.5, the coil weight is approximately 3.75 metric tons.[16] Using high-strength aluminum (75 ksi) for the combustion chamber and assuming spherical ends, the combustion chamber mass is approximately 1.7 metric tons. Assuming the nozzle is 0.3 tons the total mass for the coils, nozzle, and combustion chamber is 5.75 tons. Assuming another 2.5 tons for support equipment (refrigeration, pumps, guidance and control systems, aeroassist system, etc.) leaves at least 1.5 tons for the payload out of the 10 ton final mass.

Efficiency Estimates

Three sources for the loss of annihilation energy were considered: 1) escape of charged particles through the ends of the magnetic fields, 2) loss of high-momentum particles that cannot be trapped by the central region of the magnetic field, and 3) loss of energy due to the decay of the particles into gamma rays, neutrinos, and positrons (antielectrons). The fraction of charged particles escaping through the ends, $1 - f_{TE}$, of the magnetic confinement field has been mentioned in the previous section and will be taken to be given by the nonrelativistic form in Eq. (8). Although Eq. (11), as derived in Ref. 12, is accurate only for nonrelative speeds, it should remain accurate as long as the transaction region from B_{min} to B_{max} is lengthened to account for the Lorentz contraction in the axial direction. Additionally, Eq. (8) is only approximately correct if the scattering occurs by collisions, and the relativistic products of the annihilation reaction do transfer their kinetic energy to the propellent by collisions with the propellent atoms. An estimate of the effects of scattering can be obtained from Ref. 13 where it is shown that the root mean square variation in the curvature is proportional to the density and inversely proportional to the speed of the annihilation product and the strength of the magnetic field. For example, in hydrogen at a density of 1% liquid hydrogen in a 50 kG field, the root mean square variation in the curvature is only 0.25% of the curvature without scattering when the particle is moving at one-tenth the speed of light. Hence, significant variations due to scattering will not occur until most of the kinetic energy is deposited in the propellent. At this point, the pions or the muons are likely to decay before they leave the chamber. Only the electrons (or positrons) are likely to leave the chamber by scattering and only after their kinetic energy is transferred to the fluid.

Table 2 Baseline OTV parameters

Quantity	Symbol	Value
Input parameters		
Propellent		H_2
Central magnetic field	B_{min}	50 kG
End magnetic field	B_{max}	500 kG
Combustion chamber radius	R_c	100 cm
Area ratio	A_e/A_t	100
Combustion chamber pressure	P_c	100 atm
Injection temperature	T_{inj}	25 K
Change in velocity	Δv	5.5 km/s
Mass ratio	MR	5
Final mass	m_f	10 tons
Final acceleration	a_f	981 cm/s^2
Calculated parameters		
Thrust	F	9.81×10^9 dynes
Exhaust velocity	v_e	3.37 km/s
Propellent mass	m_p	40 tons
Propellent flow rate	$\dot{m}_p$	28.7 kg/s
Chamber temperature	T_c	459 K
Throat radius	$\sqrt{A_t/\pi}$	4.2 cm
Exhaust radius	$\sqrt{A_e/\pi}$	42 cm
Efficiency	η	0.35
Annihilated mass	m_a	8.04 mg
Annihilated mass flow rate	$\dot{m}_a$	5.77×10^{-3} mg/s

Estimating the energy loss due to pions with a momentum too high to be confined by the central magnetic field is considerably more difficult. For the analysis, the energy distribution of the pions resulting from the annihilation must be known. From Ref. 5 this is

$$\frac{d^2N}{N_0}=\frac{2\sin\phi}{\bar{E}-E_0}\left(\frac{E-E_0}{\bar{E}-E_0}\right)\exp\left[-2\left(\frac{E-E_0}{\bar{E}-E_0}\right)\right]dE d\phi \quad (26)$$

where d^2N/N_0 is the fraction of pions between energies E and $E+dE$ and angles ϕ and $\phi+d\phi$, E the total pion energy, $\bar{E}$ the average pion energy (390 MeV), E_o the pion rest energy (140 MeV), and ϕ the angle between the pion velocity and the combustion chamber central axis. The quantity $E-E_0$ is then the pion kinetic energy. A pion of energy E will circle the magnetic lines of intensity B_{min} with a radius r given

$$r=\frac{\sin\phi\sqrt{E^2-E_0^2}}{qcB_{min}} \quad (27)$$

where q is the unit electron charge.

If the radius of the combustion chamber is r_c then particles with

$$E>\sqrt{1+\frac{qcB_{min}r_c^2}{2E_0\sin\phi}}\,E_0=E_{max} \quad (28)$$

will be lost. Not all angles ϕ between zero and π need to be included in this high-energy loss since pions with angle[12]

$$\phi<\cos^{-1}\sqrt{1-\frac{B_{min}}{B_{max}}}=\alpha \quad (29)$$

will escape through the ends. From Eqs. (26), (28), and (29), the fraction of the pions trapped in the central region is

$$f_{TC}=\frac{N}{N_0}=\int_\theta^{\pi-\alpha}\int_{E_0}^{E_{max}}\frac{2\sin\phi}{\bar{E}-E_0}\left(\frac{E-E_0}{\bar{E}-E_0}\right)$$

$$\exp\left[-2\left(\frac{E-E_0}{\bar{E}-E_0}\right)\right]dE d\phi \quad (30)$$

The integral in Eq. (30) can be evaluated approximately for large energy E, including the losses through the ends, the fraction of pions trapped $f_{T\pi}$ is, from Eqs. (8) and (30)

$$f_{T\pi}=\sqrt{1-\frac{B_{min}}{B_{max}}}-\beta_e{}^{-\beta}\,\ln\left[\sqrt{\frac{B_{max}}{B_{min}}}+\sqrt{\frac{B_{max}}{B_{min}}-1}\right] \quad (31)$$

where

$$\beta=\frac{qcB_{min}r_c}{\bar{E}-E_0}>>1 \quad (32)$$

Assuming that the fractional energy retained is equal to the fraction of particles trapped and assuming that the same fraction of muons and electrons is lost, the efficiency of the magnetic confinement is

$$\eta_m=f_{T\pi}{}^3 \quad (33)$$

where the cube is present because there are three possible particle losses (pions, muons, and electrons).

It should be noted that there are several critical assumptions present in Eqs. (31) and (33). These include: 1) that Eq. (8) holds for relativistic scattered particles, 2) that the fraction of muons and electrons lost is the same as the fraction of pions lost (a conservative assumption), 3) that the fraction of useful pion energy is equal to the fraction of pions trapped (a nonconservative assumption), and 4) that the quantity β in Eq. (32) is large.

Equation (33) does not contain all the losses. There are still losses through decay into particles that cannot be trapped. In Ref. 5 a Monte Carlo simulation was performed for the energy efficiency when antiprotons are annihilated in liquid hydrogen in an infinite chamber. The analysis from Ref. 5 can

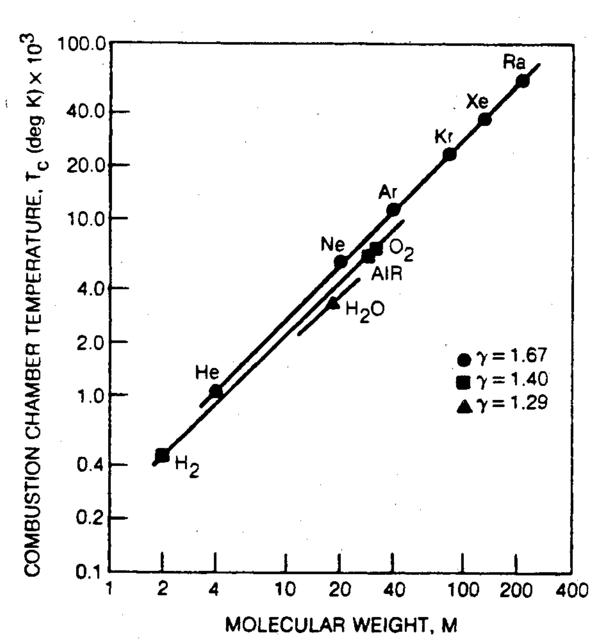

Fig. 4 Combustion chamber temperature for various propellents.

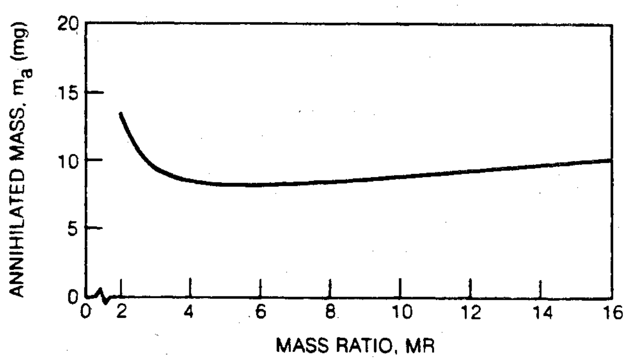

Fig. 5 Annihilated mass for various mass ratios.

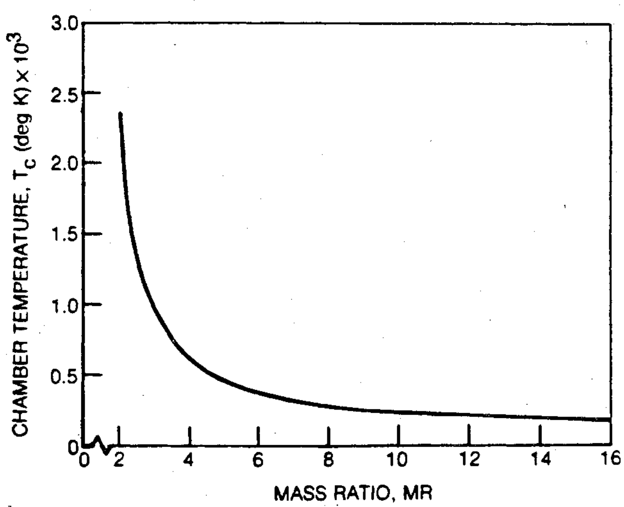

Fig. 6 Combustion chamber temperature for various mass ratios.

be extended to any density of hydrogen atoms by noting that probability for a collision is proportional to the atomic density. In Fig. 2 the results of simulations for other densities is presented. The efficiency for conversion in an infinite combustion chamber can be accurately approximated by

$$\eta_\infty = \ell n\left[\frac{1.592(n/n_0)+0.007414}{n/n_0+0.006776}\right] \tag{34}$$

as shown in Fig. 2.

These results apply only to a hydrogen propellent; for propellents with heavier nuclei, more neutral pions can be absorbed in the nucleus, producing an increase in efficiency. Assuming that 1) an infinite atomic weight nucleus would trap all of the neutral pions, 2) the gain in efficiency is exponential approaching the infinite atomic weight nucleus, and 3) the data in Ref. 7 where annihilations with carbon nuclei are about 7% more efficient in producing charged particles can be attributed to the absorption of neutral pions, then the gain g for heavier nuclei is approximately

$$g \approx 1.5 - 0.5e^{-0.013(\bar{Z}-1)} \tag{35}$$

where $\bar{Z}=M/n_a$ is the average atomic weight of the propellent per atom. The total efficiency η will be taken as the product of the factors in Eqs. (32), (34), and (35), or

$$\eta = f_{T\pi}{}^3 \ \eta_\infty g \tag{36}$$

Parametric Study

Variations in several of the parameters with respect to the baseline design in Fig. 1 and Table 2 were examined to determine the amount of annihilated mass required and the combustion chamber temperatures that would result.

In Figs. 3 and 4 the 10 propellents in Table 1 were considered and the results are shown. The amount of annihilated mass increased with molecular weight, approximately doubling at a molecular weight of 40 when compared to hydrogen. However, the combustion chamber temperature increased exponentially with the molecular weight, making hydrogen the most desirable propellent, in spite of the fact that there is only one proton in the nucleus. Note that at the higher temperatures, a significant amount of ionization (and dissociation) may occur, invalidating the perfect gas law used.

In Figs. 5 and 6 various mass ratios are presented and show a shallow minimum in the annihilated mass at a mass ratio of about 5. Note that even a mass ratio of 2 does not double the amount of mass that must be annihilated. On the other hand, at a mass ratio of 2 the combustion chamber temperature is rising rapidly, greatly increasing the technical problems related to cooling and structural reliability.

A significant technical challenge will be associated with the high magnetic field strengths. Figures 7 and 8 present the annihilated mass required for variations in the magnetic field configurations. Note that a decrease to a 25 kG central field will double the amount of mass to be annihilated and is rising steeply with decreasing strengths. The approximations made in developing the fraction of energy retained become inaccurate below a strength of about 50 kG (for a 2 m diam chamber). From Fig. 8, the end field strength can probably be halved without a significant increase in annihilated mass.

Figures 9 and 10 show that there are no significant changes in the annihilated mass with changes in the chamber pressure and area ratio.

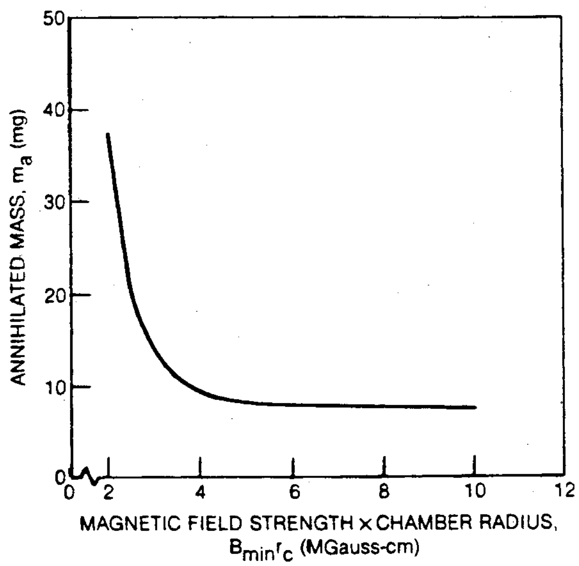

Fig. 7 Annihilated mass for various central magnetic field strengths.

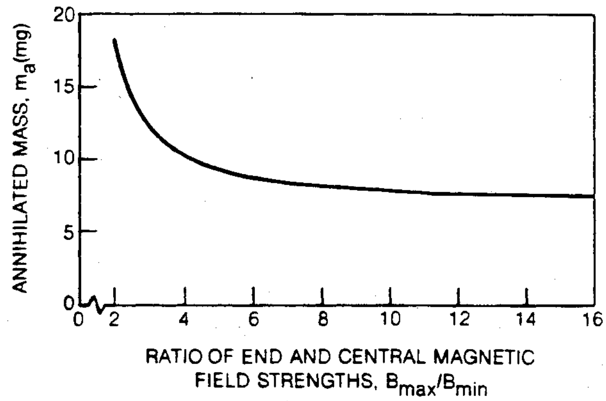

Fig. 8 Annihilated mass for various end magnetic field strengths.

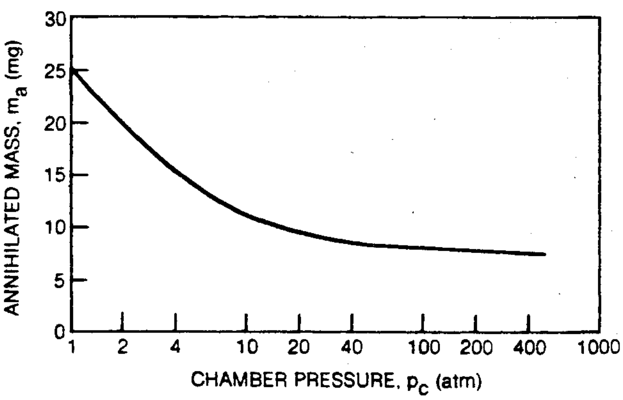

Fig. 9 Annihilated mass for various chamber pressures.

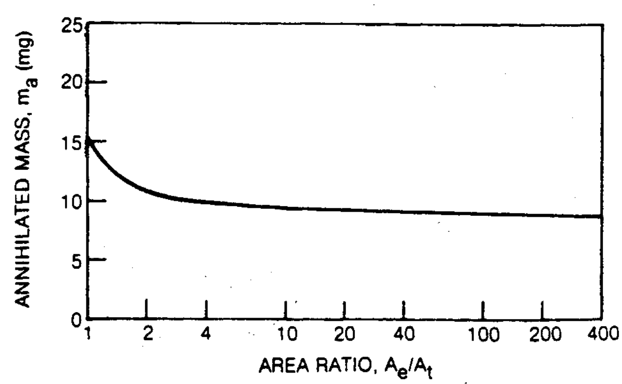

Fig. 10 Annihilated mass for various area ratios.

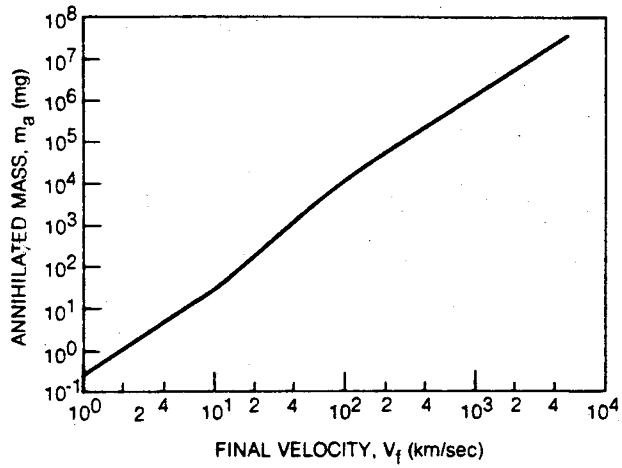

Fig. 11 Annihilated mass for various final velocities.

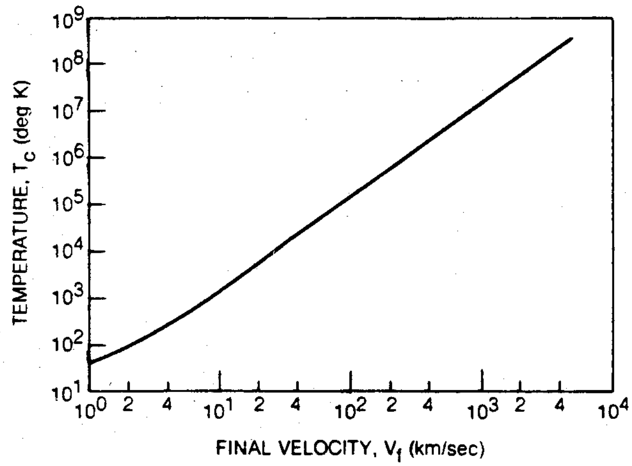

Fig. 12 Combustion chamber temperature for various final velocities.

Only the OTV 5.5 km/s change in velocity has been considered to this point, but higher velocity missions were also examined and the results are presented for various final velocities (i.e., total velocity change) in Figs. 11 and 12. Note that as in the previous figures only a single parameter, including propellent, is varied from the baseline mission in Table 2. In Fig. 11 there is a significant increase in the annihilated mass at about 400 km/s. This corresponds to the decrease in efficiency at relative atomic hydrogen densities of 10^{-2} in Fig. 2. From Fig. 12 at 400 km/s the hydrogen is beginning to dissociate and therefore the ideal gas laws used in the analysis are becoming more inaccurate.

Conclusions

An analytical model indicates that a rocket nozzle driven by the annihilation of matter can be constructed with only minor extrapolations of current technology. For the OTV mission examined (5.5 km/s velocity change) about 4.0 mg of antimatter would be required. The major technical challenge appears to be maintaining the high magnetic field strengths required for confining the annihilation products. A more accurate model for the confinements needs to be developed to determine if the magnetic field strengths can be decreased to strengths readily available with current technology. Two additional topics also need to be examined: the possibility of radiation damage and the use of spin polarization to produce the preferred directions for the annihilation products.

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