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Abstract

Antiprotons provide an extremely high energy density storage mechanism. Recently more than 10^5 antiprotons have been stored for one month at 4K and in the near future there are plans for combining antiprotons with positrons to create antihydrogen resulting in an even higher energy density, Antiprotons, when they annihilate with ordinary matter, provide enough energy: 1) to trigger fusion reactions, 2) to fission heavy nuclei. or 3) to provide muons for driving muon catalyzed fusion reactions. In this paper a combination of fission and magnetically insulated inertial confinement fusion is proposed for pellets on the order of one centimeter in radius. It appears that the pellets will be safe from premature ignition, non–toxic, and well below radiation standards. Since the design can be scaled, significant variations in size are possible. Rough calculations indicate that the pellets will produce a specific impulse exceeding 100,000 seconds.

Introduction

During the last decade antiproton annihilation propulsion has been the subject of research[1–5]. The use of antiprotons to directly heat a propellent requires at least milligrams of antimatter to perform useful mission&. Milligram quantities of antiprotons are well beyond current capabilities and will require substantial technological improvements before becoming a reality[7,8]. Concepts for using antiprotons to catalyze fusion reactions that would require far fewer antiprotons have recently been proposed[9–13]. The approaches are based on: I) antiproton fissioning of heavy nuclei[10–12], 2) direct antiproton heating for igniting a fusion reaction[9,13], and 3) muon production using antiprotons for muon catalyzed fusion[14].

Smith, et al proposal to use antiprotons to fission heavy nuclei has been the subject of considerable research[10–12]. When an antiproton annihilates in a heavy nucleus such as uranium or plutonium, the nucleus fissions almost 100 percent of the time[15,16]. About 20 percent of the fission energy is present in the fission fragments, and about 13 or 14 neutrons are emitted. Some of these neutrons initially released will produce additional fissions with a considerably lower yield of neutrons. The energy present in the fission fragments is readily absorbed by the fusion fuel, It is more difficult to absorb the neutron kinetic energy, while the absorption of the gamma ray energy is very difficult, Nevertheless antiproton annihilation provides a means for sustaining fission reactions without a critical mass of fissionable material. The fission energy then provides a means for initiating fusion reactions.

Shamatov[13], Cassenti[5,17] and Kammash and Galbraith[9], have proposed using the annihilation of antiprotons (or antihydrogen) to initiate fusion reactions directly, When an antiproton annihilates in matter it produces mostly pions and about five percent kaons. About 60 percent of the pions are charged. The pions are moving at relativistic velocities (about 95 percent of the speed of light), and the absorption of the kinetic energy requires on the order of meters of path length for significant energy absorption,. Of course the energy must be absorbed before the pions decay (i.e., in about 20 nanoseconds) into a muon and an associated neutrino. The muons are charged and will travel on the order of kilometers before decaying. The muon has a mean life about 100 times the life of a pion. Since muons are charged they can also deposit energy in the plasma. The muon decays into an electron, or a positron, and two associated neutrinos. The electrons, or positrons, can also deposit energy in a plasma. In order to increase the path length in the plasma a magnetic field could be applied but the relativistic speeds require extremely large fields. For example, about 100 kG are required for one meter diameter containment and 10 MG for a one centimeter diameter pellet. Magnetic fields are difficult to generate in a steady state, but can be generated in transient situations. Hasegawa[18], and Kammash and Galbraith[19,20] have proposed using magnetic fields developed at the surface of laser heated materials. At the heated surface the material is ionized, with the ion cores and the electrons sharing the absorbed energy. The **ions** and electrons stream away from the surface with the electrons moving faster than the ion cores. The ions and electrons moving into the surface are readily stopped. Hence there is a net negative current flow away from the surface. The net current *flow* **creates** a magnetic field which readily contains the plasma. Measurements and mode l ~ indicate that the fields are large enough to contain the annihilation products resulting when an antiproton annihilates on a nucleus, and the field is large enough to isolate the plasma from a surrounding heavy metal shell. The shell will contain the plasma due to its strength and inertia, in a manner similar to inertial confinement fusion, The antiprotons provide a lightweight mechanism for heating the plasma to fusion ignition temperatures, **and,** hence, are well suited ***for*** **use** in propulsion systems.

,,The last method proposed for using antiprotons as a catalyst to initiate fusion reactions, uses the muons, resulting from antiproton–nucleon annihilations, to sustain muon catalyzed fusion **of** a deutrium–tritium **mixture**[14]. The antiprotons provide a compact source for the muons when compared to the accelerators that have been proposed[24], and, hence, are ideal for use in propulsion systems.

Each of the above methods for using antiprotons to catalyze fusion reactions present disadvantages for use in propulsion. Pellet designs for antiproton catalyzed fission reactions require an initial compression using ion beams[11,12]. The ion accelerators are heavy and there would be a distinct advantage in eliminating them. Direct heating of the plasma to initiate a fusion reaction uses very little of the annihilation energy – about two percent[8]. While muon catalyzed fusion is effective in **a** narrow temperature range at about 1200K to support a resonance between the tritium and deuterium atoms in a molecule. **These** low temperatures will be difficult to sustain.

This paper will concentrate on a combination of antiproton induced fission and magnetically insulated inertial confinement fusion, Muon catalyzed fission could be utilized by injecting muons, from an antiproton annihilation, at appropriately heated points in the fusion fuel, at the correct time.

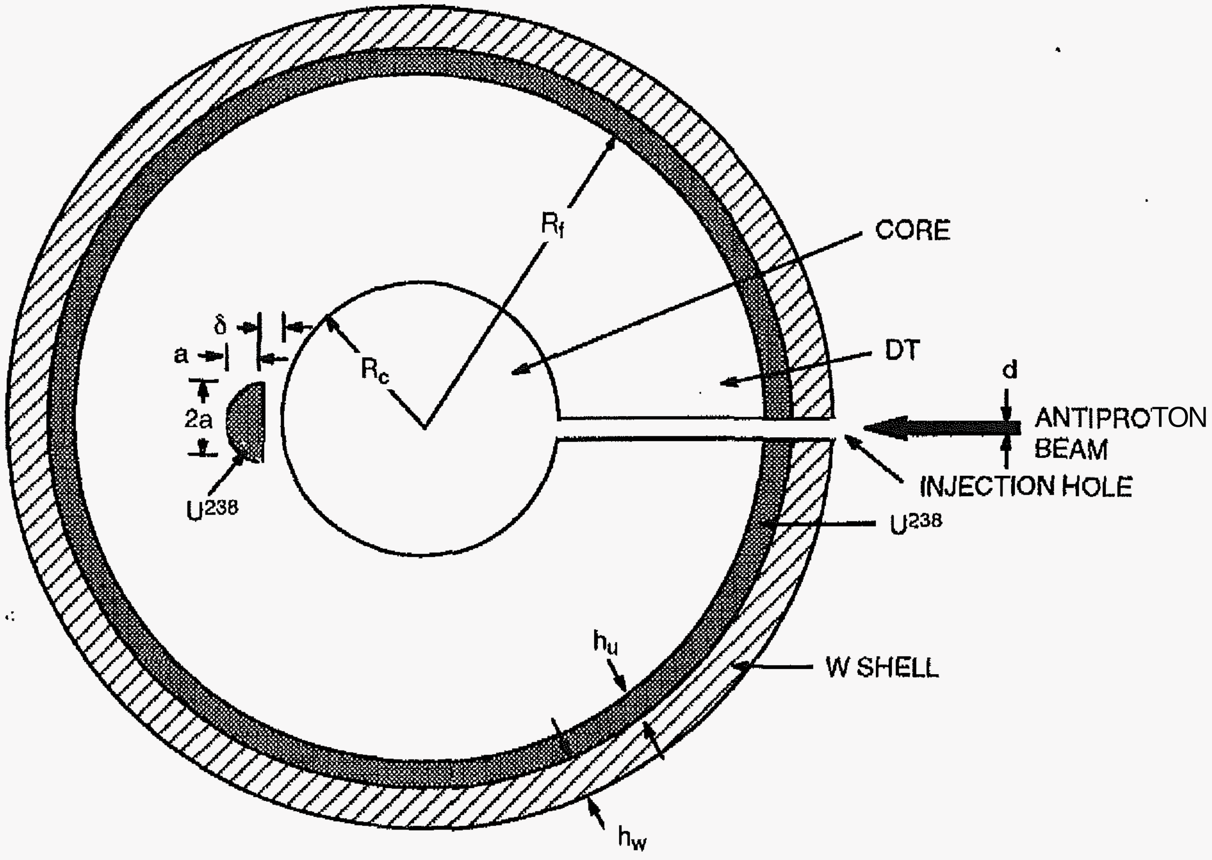
Basic Design

The pellet to be ignited consists of several materials. The fusion fuel can be deuterium–tritium, or lithium deuteride[25]. The fuel has an outer radius, R_f and an inner radius, R_c (see Figure 1). The fuel contains a hemisphere of fissionable material such as U^{235}, U^{238}, Pu^{239}. The fusion fuel is surrounded by a shell consisting of a heavy metal. The outer layer of the shell should be a dense high melting temperature material such as tungsten. The inside shell layer can be a neutron generating, or reflecting material such **as** uranium. The shell and fuel has a hole which is perpendicular to the flat surface **of** the hemisphere of fission material. The flat surface of the hemisphere is assumed to be a small distance, δ, below the surface.

A pulse of antiprotons and positrons[13], ***is*** injected through the hole in the shell. The energy of the antiprotons is chosen so that the annihilation occurs at the surface **of the** hemisphere. The annihilation of the antiprotons ionizes the fuel above the hemisphere. Fuel ions fill the empty core of the pellet with a plasma. The electrons created by the annihilation create a current flow developing **a** transient magnetic field. The field is contained within the shell and traps charged particles (fission fragments, ion cores, electrons, muons, and pions). The charged particles heat the core of the pellet to fusion temperatures. The uranium on the inside layer of the shell generates and/or reflects **some** neutrons back into the fuel, while the tungsten shell contains the fusion fuel hopefully long enough for the fusion reaction to go to completion.

Analytical Model

The pulse of antimatter should consist of equal quantities of antiprotons and positrons to preserve neutrality[13]. The pulse *can* be antihydrogen or it can be partially or completely ionized. If the pulse has a length,



,Figure 1. Pellet Construction and Geometry.

$l_{\bar{p}}$, and a kinetic energy, $T_{\bar{p}}$ then the heating time, $\tau_{\bar{p}}$ is given by:

$$\tau_{\bar{p}} = \sqrt{\frac{m_p}{2T_{\bar{p}}}}\,\ell_{\bar{p}} \tag{1}$$

for nonrelativistic velocities. If the pulse is forced through a solid shell (i.e., a shell without a hole), then the beam energy will have to be about 100 MeV, Otherwise the beam energy only needs to be high enough to traverse the plasma and fuel without significant scattering to maintain a small spot size.

The annihilation of the antiprotons will ionize material in the immediate neighborhood and release relativistic particles. The *nonuniform, heating* will *create* magnetic fields that can be roughly estimated as[22]

$$\frac{1}{1\ \mathrm{mG}}\dot{B} = \frac{1}{10\ \mathrm{ps}}\left(\frac{T}{1\ \mathrm{keV}}\right)\left(\frac{10\ \mu\mathrm{m}}{d}\right)^2 \sin\alpha, \tag{2}$$

and

$$\frac{1}{1\mathrm{mG}}\bar{B} = 3.6\left(\frac{T}{1\ \mathrm{keV}}\right)^{1/2}\left(\frac{10\ \mu\mathrm{m}}{d}\right)\left[\frac{A^{1/2}(Z+1)^{-1/2}}{1.1}\right]\sin\alpha. \tag{3}$$

where

$\dot{B}$ is the rate of change of the magnetic field with respect to time,
$\bar{B}$ is the steady magnetic field,
A is the atomic weight of the plasma (taken to be 2.5 for deuterium–tritium fuel),
Z is the atomic number of the plasma (taken to be 1.0 for deuterium–tritium fuel),
d is the heated spot size, and
α is the angular position from the beam axis,

Assuming the angular position is uniformly distributed between zero and π/2 the probability, $p_\alpha d\alpha$ for the angle to be between *a* and $\alpha+d\alpha$ is

$$p_\alpha\, d\alpha = \sin\alpha\ d\alpha. \tag{4}$$

The average angle is then

$$\bar{\alpha} = \int_0^{t/2} \alpha \sin a \, da = 1. \tag{5}$$

Then

$$\sin \bar{\alpha} = 0.8 - 1,$$

which is well within the approximations in equations (2) and (3). In order to transition between the transient growth, equation (2), and the steady field, equation (3), we can take the transient field, B(t) to be

$$B(t) = \bar{B}\,(1 - e^{\nu t}) \tag{6}$$

From equation (6), the rate of growth of the field is

$$\dot{B} = \nu \bar{B} e^{-\nu t}. \tag{7}$$

Then from equations (2) and (3)

$$\nu = \frac{\dot{B}}{\bar{B}} = \frac{1}{36\ \mathrm{ps}}\left(\frac{T}{1\ \mathrm{keV}}\right)^{1/2}\left(\frac{10\ \mu\mathrm{m}}{d}\right)\left[\frac{1.1}{A^{1/2}(Z+1)^{-1/2}}\right] \tag{8}$$

Equations (2),(6),(8) are used to describe the transient magnetic field.

The pions developed in an annihilation will deposit a small portion of their energy in the plasma, before they leave the pellet. The energy deposition, dE/dx, will be on the order of

$$\frac{dE}{dx} \approx 0.5 \frac{\mathrm{MeV}}{\mathrm{cm}}\left(\frac{\varrho_{\mathrm{plasma}}}{\varrho_{\mathrm{LH}_2}}\right), \tag{9}$$

where $\varrho_{\mathrm{plasma}}/\varrho_{\mathrm{LH}_2}$ is the ratio of the plasma density to the density of liquid hydrogen. There will also be a recoil energy for annihilations in the plasma, ε, of about 20 MeV[9].

The pions will not travel in a straight line due to the magnetic field but will spiral about the magnetic field lines. The path, in rectangular coordinates (x,y,z), is given by

$$x = r\cos\theta,\quad y = r\sin\theta \quad\text{and}\quad z = k\left(\frac{\theta}{2\pi}\right), \tag{10}$$

where, for relativistic energies,

$$r = \frac{\sqrt{E^2 - E_0^2}}{ecB} \tag{11a}$$

$$\frac{2\pi r}{k} = \tan\phi, \tag{11b}$$

θ is the total angle travelled about the initial velocity direction, and

ϕ is the angle between the particles velocity vector and the antiproton beam (see Figure 1).

The parameters in equations (11) are: E, the energy of the particle (i.e., the pion), Eo, the rest mass energy (139.6 MeV for pions), c, the speed of light, and e, the charge on an electron.

The total path length, s, followed is given by

$$ds^2 = dx^2 + dy^2 + dz^2, \tag{12}$$

which can be integrated, using equations (10) to yield

$$s = \sqrt{1 + \left(\frac{2\pi r}{k}\right)^2}\; z. \tag{13}$$

Without **the magnetic** field the **path** length, s_0, will be taken to be the average distance across the core, which can be shown to be

$$s = s_0 = R_c \tag{14}$$

Hence the path length increases by a factor, f_L given by

$$f_L = \sqrt{1 + \left(\frac{2\pi r}{k}\right)^2} \tag{15}$$

Using the average angle, $\bar{\phi}$, calculated as in equations (4) and (5), the path length is

$$s \approx 2\,R_c \tag{16}$$

The energy deposited by the pions and the recoil, E_π, is

$$E_\pi = \frac{1}{2}\,\nu_\pi \frac{dE}{dx}\left(\frac{\varrho_{\mathrm{plasma}}}{\varrho_{\mathrm{LH}_2}}\right) s + \varepsilon \tag{17}$$

where ν_π is the number of charged pions created at the annihilation site (about 3.6).

One half of the pions move into pellet core with the plasma, and the other half move into the fission hemisphere.

When the antiproton annihilates on the flat of the hemisphere, the material will fission releasing the kinetic energy of fission fragments, E_f and a number of neutrons, and pions, which can cause additional fissions. From Reference [12], for U^{238},

$$\nu_f \approx 13.7 \tag{18}$$

and

$$E_f \approx 170 \text{ MeV}. \tag{19}$$

Half of the released neutrons will enter the fission hemisphere, and can cause additional fissions, The fission cross section, σ_f for U^{235}, varies as a function of the neutron kinetic energy, T, of the neutrons approximately as[25]

$$\sigma_f = CT^a, \tag{20}$$

where the constants C and a can be found from[25]

$$\sigma_f = 1000 \text{ b @ } T = 10^{-2} \text{ eV, and} \tag{21}$$

$$\sigma_f = 1 \text{ b @ } T = 10^6 \text{ eV}. \tag{22}$$

The kinetic energy of the fission neutrons can be approximated by[25]

$$p_T \, dT = A \, e^{-T} \sinh \sqrt{2T} \, dT \tag{23}$$

where $p_T dT$ is the probability of the kinetic energy of the fission neutrons being between T and T+dT.

The average kinetic energy is then

$$T = \frac{\int_a^\infty T e^{-T} \sinh \sqrt{2T} \; dt}{\int_0^\infty e^{-T} \sinh \sqrt{2T} \; dT} = 2.0 \text{ MeV}. \tag{24}$$

This results in a cross section, $\bar{\sigma}_f$, at the average energy of

$$\bar{\sigma}_f \approx 0.8 \text{b}. \tag{25}$$

If the annihilation occurs at the center of the hemisphere, the neutrons will travel a distance, a (i.e., the hemisphere diameter), then the fraction of neutrons causing additional fissions, r_f, is

$$\sigma_f = \frac{1}{2}\left[1 - \exp\left(-\frac{\varrho_f \, \sigma_f \, a}{A_f \, m_{amu}}\right)\right], \tag{26}$$

where

ϱ_f is the density of the fissionable material,
A_f is the atomic weight of fissionable material,
m_{amu} is the. atomic mass unit $(1.66\text{x}10^{-24}$ g).

The quantity

$$\ell_f = \frac{A_f \, m_{amu}}{\varrho_f \, \sigma_f} \approx 27 \text{ cm} \tag{27}$$

for uranium. This second *fission* will *emit* ν_s –2.4 secondary neutrons, which we will also take to travel a distance a. These can cause additional fissions resulting in a geometric series for the additional fissions. The series can be summed to yield the total number of additional fissions, $dN_f/d_{\bar{p}}$, per antiproton annihilation as

$$\frac{dN_f}{d\bar{p}} = \frac{\frac{1}{2}\,\nu_f\,(1 - e^{-a/\ell_f})}{1 - \nu_s\,(1 - e^{-a/\ell_f})} \tag{28}$$

We can use equation (28) to calculate the radius of a critical mass, a_{crit}, by setting the denominator to zero, or

$$1 - \nu_s\left(1 - e^{-a_{crit}/\ell_f}\right) = 0, \tag{29}$$

or

$$a_{crit} = \ell_f \, \ell n\left[\frac{1}{1 - \frac{1}{\nu_s}}\right] \approx 15 \text{ cm}. \tag{30}$$

which is larger by a factor of about two than the value for plutonium, or a factor of 10 in the mass. Sources for the error include: 1) scattering of the neutrons was neglected, which will increase the path length, 2) the average secondary neutron energy was used but lower energy neutrons are much more likely to cause fissions than higher energy neutrons, and 3) scattering reduces the neutron energy.

During the antiproton heating and the subsequent fission reactions the inertia of the inner and outer shells must contain the plasma. The generated magnetic fields will insulate the shell from the hot plasma. Equilibrium **of** an infinitesimal **element of** the **shell** results in

$$\varrho h \frac{d^2r}{dt^2} = p - \frac{2\sigma h}{r}, \tag{31}$$

where

- ϱ is the shell density (taken to be the density of tungsten 19.3 g/cm3),
- h is the shell thickness (taken to be the tungsten thickness),
- r is the **radius** of the shell at half the shell thickness,
- p is the pressure, and
- σ is the tensile yield stress of the shell (taken to be 5x108 dynes/cm3 **for** tungsten).

The pressure has two components: **1)** the **plasma pressure, p_p, and, 2)** the magnetic pressure, p_B. The pressure **due** to **the** magnetic **field is** negative (i.e., **com**pressive) and can be **evaluated** from[5]

$$p_B = -k\frac{B^2}{\mathcal{X}}, \tag{32}$$

where

- k is Boltzmann's constant, and
- $\mathcal{X} = 63.5\ \mathrm{kG\ cm^{3/2}/{}^\circ K^{1/2}}$.

The plasma pressure can be determined from the perfect gas law as

$$p_p = \frac{NkT}{V}, \tag{33}$$

where

- N is the number of particles, and
- $V = 4\pi r^3/4$ is the volume the particles occupy inside **the shell.**

From the kinetic theory of **gases**, the total energy in the plasma is

$$E, = \frac{3}{2} NkT. \tag{34}$$

Substituting for NkT in equation (33) using equation (34), and substituting for the volume

$$p_p = \frac{E_p}{2\pi r^3}. \tag{35}$$

The energy deposited in the plasma core is the sum of the energy deposited by the pions and the energy deposited by the fission fragments. Equations (17), (19) and (28) can be used to find an **upper** unit for *E,,,* where

$$E,\ (t) = \left[E,\ + E_f\left(1 + \frac{dN_f}{dt}\right)\right]\begin{cases} N_p\left(\frac{t}{\tau_p}\right) & 0 \le t \le \tau_p \\ N_p, & t > \tau_p \end{cases} \tag{36}$$

Using equation (36) for the energy of the plasma, equation (35), **will** give an upper limit for the plasma pressure on the shell. Equation (31) then becomes

$$\ddot{R}_f = \frac{E_p\ (\tau_p)}{2\pi\ \varrho_w\ h_w\ R_f^3} - \frac{kB^2}{\varrho_w\ h_w\ \mathcal{X}^2} - \frac{2\sigma}{\varrho_w\ R_f}, \tag{37}$$

where the density, ϱ_w, and thickness, h_w, of the tungsten shell have been used, and the radius has been set to the outer radius of the fuel (R_f).

The inertial confinement time, t_i, must be greater than the time it would take a p–wave to traverse the thickness of the tungsten shell[18]. The **p–wave** speed in **a** solid is given by

$$C_p = \sqrt{\frac{(1-\nu)E}{(1+(1)(1\ \nu)E/\nu)P_w}} \tag{38}$$

where E is the Young's modulus (about **4.1x** 10^{12} dy/cm^2 for room temperature Tungsten), and **v** is the Poisson ratio (about 0.23 for room temperature Tungsten). The inertial confinement time is bounded by

$$t_i > \frac{h_w}{C_p} \tag{39}$$

A rough calculation **indicates** that heating of the Tungsten shell (e.g., due to fission **gamma** ray emission) **will** not raise the shell temperature by more than 100 C. Hence room temperature properties can be used. Recall that the magnetic fields will insulate the shell from the plasma.

The inertial confinement time must be greater than the time for the plasma to fuse[18], t_f, where

$$t_f = \frac{\sigma T}{E_\alpha\ n_{plasma} < \sigma v >} \tag{40}$$

where

- T is the plasma temperature,
- E, is the energy of the alpha particle emitted,
- n_{plasma} is the plasma number density, and
- $<\sigma v>$ is the reaction rate.

An upper unit on the plasma temperature and the core energy are related by

$$\frac{3}{2} NkT = E_c = \frac{1}{2} NE, \tag{41}$$

The ideal specific impulse of the system can now be determined by assuming all of the fusion alpha particle energy, from all of the fuel, is emitted with the total mass of the pellet. The exhaust velocity, v_e, can then be determined from

$$\frac{1}{2} m_T v_e^2 = \frac{m_f E_\alpha}{2A\, m_{amu}}, \tag{42}$$

where

m_T is the total pellet mass,

m_f is the total fuel mass, and recall

A is the atomic weight of the plasma (Equations 2 and 3).

The specific impulse, I, can then be approximated as

$$I_{sp} = \frac{v_e}{g}. \tag{43}$$

where g is the acceleration of gravity at the surface of the earth.

The model can now be used to examine specific pellet designs.

Results

The model was used to predict the response of a typical pellet. A deuterium–tritium fuel was taken for simplicity. The alpha particle energy produced in a fission reaction was taken to be 3.5 MeV[18]. This was the energy assumed to be present in the exhaust, since the alpha particle can be directed by magnetic fields. The reaction rate, <σv>, was taken to be 10^{-15} cm^3/s which occurs at a plasma temperature of 80 keV.

The pellet geometry is summarized in Table 1. The pellet has a shell of tungsten 0.01 cm thick and there is no uranium on the inside of the shell. The shell has an outer radius of about 1 cm. The hemisphere of uranium is so small that it only supports secondary fissions about one percent of the time. The antimatter pulse contains 3x109 antiprotons and lasts 3 ns. The core density is about 1.25x10^{21} / cm^3, if only the hemisphere of material above the flat uranium surface enters the core. The core temperature is 83 keV. The magnetic field reaches about 2 MG at end of the pulse. The tungsten shell does not move during the heating by the antimatter pulse. The characteristic inertial confinement time is at least 20 ns and the time for the fusion reaction is about 10 ns. The total mass of the pellet is about 3.5 mg, and absorbs about 7.3x10^{17} erg producing a specific impulse of about 600,000s for complete (100 percent) fusion burning. If ten percent of the fuel fuses, the ideal specific impulse is about 200,000s; while five percent yields about 150,000s for an ideal specific impulse.

Table 1

Typical Pellet Geometry

Description	Symbol	Dimension - cm
Core radius	R_f	0.01
Fuel radius	R_c	1.0
Uranium shell thickness	hu	0.0
Tungsten shell thickness	h_u	0.01
Antiproton beam radius	d	0.0003
Uranium hemisphere radius	a	0.03
Hemisphere distance from core surface	δ	0.0075

The above calculations are quite rough, but do indicate that the design may be feasible. Of course, if the pellet is scaled to the size of a thermonuclear warhead, then, with minor variations in design, a single antiproton (or neutron) will trigger the critical mass fission device resulting in complete fusion. The resulting blast can be contained as shown by Metgzer[26] and used for propulsion. Thermonuclear warheads can also be used externally as in the Orion rocket. Hence, if the pellet is scaled up in size, (and designed as in a thermonuclear warhead) then the pellet will ignite and fuse. The design problem is how to shrink the pellet to sizes on the order of one centimeter. If the pellets do not contain a critical mass *of* uranium or plutonium, then the propulsion system will not violate the spade nuclear weapon ban.

Other variations in the design are also possible. The hole in the shell and the fuel can be removed (i.e., filled) with the antiproton energy tuned tu pass through the shell and fuel and then annihilate at the fissionable hemisphere[27]. The tritium can be replaced with Li^6 (the lithium will make the tritium upon absorbing a neutron), which will eliminate the radioactive hazard of tritium. Finally a plastic foam can be used to absorb **gamma** rays **as** in a thermonuclear warhead[28].

Conclusions

An antiproton catalyzed fusion method has been proposed that combines magnetically insulated inertial confinement fusion and annihilation induced microfission. The model proposed contains **many** assumptions (some of the assumptions are not conservative). Yet the proposal will almost certainly work in some form since the size can be scaled to the level **of a** thermonuclear weapon which was demonstrated **40** years **ago,** It may be possible using this proposal to develop fusion pellets that are safe from premature ignition, non– toxic, and ***with*** radiation levels well below background. Such pellets would be competitive for propulsion but may not be competitive for power generation. Rough estimates indicate a specific impulse of over one hundred thousand seconds.

Future work should include detailed Monte–Carlo simulations of the annihilation, fission reactions, plasma ignition, electromagnetic fields, and the fusion of the fuel. A complete simulation of the thermal and mechanical response of the outer shell is also required. Such simulations would accurately determine the pellet size range and the theoretical specific impulse.

References

1. Forward, R.L.,"Antiproton Annihilation Propulsion", Journal of Propulsion and Power, Vol. **1, pp. 370–374,1985.**

2. Morgan, D.L.,"Investigation of Matter-Antimatter Interactions for Possible Propulsion Applications". NASA **CR–141356,1975.**

3. Vulpetti, G.,"Antimatter Propulsion for Space Exploration". 36th Congress of the International Astronautical Federation, **IAA–85–491,** New York, **1985.**

4. Howe, S.D., and J.D. Metgzer, **"Survey** of Antiproton–Based Propulsion Concepts, and Potential Impact on a Manned Mars Mission". Los Alamos Preprint LA–WR–87–2191, Los Alamos National Laboratory, Los Alamos, NM, **1987.**

5. Cassenti, B.N.,"Conceptual Designs for Antiproton Space Propulsion Systems.". Journal of Propulsion and Power, Vol. 7, pp. **368–373,1991.**

6. Cassenti, B.N.,"Antimatter Propulsion for OTV Applications". Journal of Propulsion and Power, **Vol. 1,pp.143–149, 1985.**

7. Cassenti, B., P. Mannheim, and P. Gould, "Concepts for the Efficient Production and Storage of Antimatter". **AIAA 93–2031,1993,**

8. Cassenti, B.N., "Concepts €or the Efficient Production of Antimatter". Eleventh Symposium on Space Nuclear Power and Propulsion, Alburquerque, NM, January, 1994.

9. Kammash, T. and D.L Galbraith,"Antimatter–Driven–Fusion Propulsion for Solar System Exploration", Journal of Propulsion and Power, Vol. 8, pp. **644–** ,1992.

10. Lewis, **R.A.,** et al,"Antiproton Based Microfusion". Fusion Technology, **Vol.** 20, pp. **1046–1050,1991.**

11. Lewis, R.A., et al "An Antiproton Driver for Internal Confinement Fusion Propulsion". **AIAA91–3618,** September, 2991.

12. **Lewis, R.A., et** al, "An Antiproton Catalyst for Internal Confinement Fusion Propulsion". **AIAA** 90–2760, July, 1990.

13. Shmatov, M.L.,"Ignition **of** Thermonuclear Microexplosions with Antimatter". Preprint **1621,** A.F.IOFFE Physical Technical Institute, Academy of Sciences of Russia, **St.** Petersburg, **1993.**

14. Takahashi, H.,"Thoughts on the Muon Catalyzed Fusion Process for Antimatter Propulsion and for the Production of High Mass Number Nuclei". Antiproton Science and Technology edited By B.W. Augenstein, et al, World Scientific, Singapore, **1988.**

15. Morgan, D.L., "Annihilation of Antiprotons in Heavy Nuclei", AFRPL TR 86–011, Air Force Rocket Propulsion Laboratory, Edwards ***Air*** Force Base, **1986.**

16. **PS 177** Collaboration at **LEAR,** "Antiproton Induced Fission in 238U and 209Bi. In Physics at LEAR with Low Energy Antiprotons, Proceedings of the Fourth LEAR Workshop, Villars–sur–Ollon, Switzerland, **1988,** pp. 793–796.

17. Cassenti, B.N.,"High Specific Impulse Antimatter Rockets". AIAA 91–2548, June, 1991.

18. Hasegawa, A. "MagneticallyInsulated Inertial Confinement Fusion: A New Approach to Controlled Thermonuclear Fusion". Physical Review Letters, Vol.56, pp.139–142, 1986.

19. Karmmash, T. and D.L Galbraith,"A High Gain Fusion Reactor Based on the Magnetically Insulated Inertial Confinement Fusion (MICF) Concept". Nuclear Fusion, Vol 29, pp. 1079–1099, 1989.

20. Kammash, T. and D.L Galbraith, "Reaction Physics and Mission Capabilities of the MICF Reactor", Journal of Propulsion and Power, Vol. 6, pp. 412– , 1990.

21. Sakagani, Y., "Two Dimensional Distribution of Self-Generated Magnetic Fields Near the Laser Plasma Resonant Interaction Region". Physical Review Letters, Vol.42, pp. 839–842, 1979.

22. Max, C.E., W.M. Manheimer, and J.J. Thomson, "Enhanced Transport Across Laser Generated Magnetic Fields". Phys. Fluids, Vol. 21, pp. 128–139,1978.

23. Raven, A., O. Willi and P.T. Rumsby, "Megagauss Magnetic Field Profiles in Lasp Produced Plasmas". Physical Review Letters, Vol. 41, pp. 554–557, 1978.

24. Subotowicz, M.,"Propulsion Concepts for Nuclear Matter Compression Energy and 'Cold' Fusion EnergySources in Interstellar Flight". Acta Astronautics, Vol. 17,pp. 937–942, 1988.

25. Muhkin, K.N., Experimental Nuclear Physics – Vol. I. Mir Publishers, Moscow, 1987.

26. Metzger, J.D. and P. Venetoklis,"Contained Pulsed Nuclear Propulsion System for Space Mass–Mover Missions". CONF940101, American Institute of Physics, pp. 653– 658,1994.

27. Morgan, D.L., Jr., "Annihilation Localization in Gas–Core and Plasma Core Annihilation Rocket Engines". 39th Congress of the International Astronautical Federation, Paper No. IAA–88–554, AIAA, Washington, DC, October, 1988

28. Rhodes, R., The Making of the Atomic Bomb, Simon & Schuster, Inc. New York, 1986.