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CONCEPTS FOR THE DESIGN OF AN ANTIMATTER ANNIHILATION ROCKET

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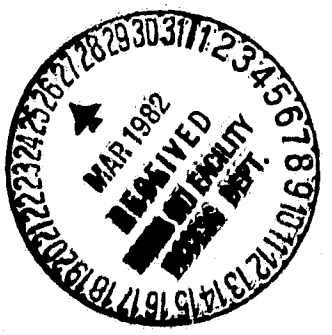

Abstract

Matter-antimatter annihilation is an attractive energy source to consider for the propulsion of future spacecraft. Annihilation produces considerably more energy per unit mass of propellant then any other known means of energy production.

Aside from the problem of the production of antimatter in the amounts required, an antimatter annihilation rocket requires several systems and components that are unique to its nature. Among these are an antimatter storage system, a means to extract the antimatter from storage, a system to transport the antimatter to the rocket engine, and the engine wherein annihilation occurs and thrust is produced.

Concepts upon which the design of these systems and components might be based are presented and discussed.

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1. Introduction

The annihilation of matter through contact with antimatter produces more energy per unit mass than any other means of energy production. This fact has led to numerous suggestions that matter-antimatter annihilation be considered as a means of propelling future spacecraft [1] [2] [3] [4].

It is the purpose of this paper to present the results of a particular line of work conducted over the last several years, in which some of the problems involved in the conceptual design of an antimatter annihilation rocket have been explained. Ideas are proposed upon which designs of some of the major components of such a rocket might be based. Included are rocket motors in which annihilation takes place and the annihilation energy is converted to thrust.

To achieve rocket propulsion through annihilation at least the following must be accomplished: (1) the production of substantive antimatter in at least milligram quantities, (2) storage of the antimatter in the rocket, (3) extraction on a continuing basis of the antimatter from storage, (4) transferral of the antimatter to the annihilation region, (5) annihilation, and (6) conversion of the annihilation energy to rocket thrust. In the following sections concepts in various degrees of detail are presented for achieving items (2) through (6) along with discussions of remaining problems. In addition elements of the underlying physics are discussed. Item (1) has been dealt with by others [5]; it will not be considered here.

A great amount of detailed research is required before the design of an antimatter annihilation rocket could actually be attempted. Such research would go well beyond the scope of the work presented here. In this article

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the intent is to set forth some ideas and concepts that may be relevant to the design of the major unique components of such a rocket. These ideas and concepts are discussed with varying levels of completeness and with reasoning that varies from qualitative to quantitative.

It is hoped that this work will be part of a basis for future research of a more detailed and a more complete nature.

2. Antimatter

Antimatter is composed of fundamental particles just as is matter. These "antiparticles" are the simplest form of antimatter. For nearly every type of fundamental particle there is a corresponding type of fundamental anti-particle. The only exceptions are certain particles, such as the photon and neutral pi meson (neutral pion). If antiparticles for these could be produced, they would be identical to the particles themselves, so there is no need for a distinction being made. An antiparticle is identical to its corresponding particle in regard to a number of properties, e.g. mass. It is the opposite counterpart to the corresponding particle in terms of a few properties. The most notable of these is electric charge. In fact, for every type of charged particle there is a type of antiparticle with opposite charge and identical mass.

The most important property of antiparticles for the present purposes is that they annihilate with particles. In the annihilation reaction a large fraction of the initial mass is converted to energy. The energy production follows Einstein's equation, $E = mc^2$, where E is the energy produced, m is the mass annihilated (initial minus final mass), and c is the velocity of light. Matter-antimatter annihilation produces much more energy for a given initial total mass than any other currently known process, including fusion and fission.

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Antiprotons, antineutrons, and antielectrons (positrons) can join together to form antinuclei, antiatoms, and antimolecules in exactly the same way that the corresponding particles can form nuclei, atoms, and molecules. A collection of very large numbers of antiatoms and/or antimolecules in the form of a gas, liquid, or solid can be termed substantive antimatter (or antisubstance). The simplest form of substantive antimatter is antihydrogen. This is composed of molecules which consist of two antihydrogen atoms each. Each of these antiatoms consists of an antiproton (itself an antinucleus in this case) with a positron (antielectron) bound to it.

Antiparticles and simple antinuclei have been produced in the laboratory by particle accelerators and are found in primary and secondary cosmic rays. Antiatoms have not been produced in the laboratory although they probably could be, in small numbers, with presently available means. Substantive antimatter might exist somewhere in the universe (antigalaxies perhaps), although this might be doubtful on some theoretical grounds. There is no current observational evidence for its cosmological existence.

3. Annihilation

Matter-antimatter annihilation occurs on the particle-antiparticle level. Annihilation occurs when the particle and corresponding antiparticle come sufficiently close so that the distance between them is about equal to their linear sizes or less. Annihilation can also occur between a particle and an antiparticle of an otherwise different nature, but the probability of annihilation is generally less for the same interparticle distance. Examples of annihilation reactions of particular concern here are

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$$p + \bar{p} \rightarrow \pi^+ + \pi^- + \pi^o \qquad (1)$$

and $$e^- + e^+ \rightarrow 2\gamma \qquad (2)$$

In (1) a positively charged proton (p) and a negatively charged antiproton ($\bar{p}$) annihilate to produce a positive, a negative, and a neutral pion. In (2) an electron (e^-) and a positron (e^+) annihilate to produce two gamma rays (γ). Products other than those shown for (1) and (2) are also possible. In (1) additional pions and/or other mesons heavier than the pion may be produced. The pions and other mesons eventually decay into other particles including muons (μ^+) and antimuons (μ^-), which also decay, and gamma rays. The final products of p-$\bar{p}$ annihilation are electrons, positrons, neutrinos, and gamma rays. Gamma rays may be produced directly, but such an occurence is relatively very unlikely. If the electrons and positrons from this process can be brought together to annihilate, then the only remaining products are neutrinos and gamma rays. In (2) higher numbers of gamma's may also be produced, although the likelihood of this is quite low.

Reaction (1) involves a total mass energy of 1877 Mev. About 60% of this initially goes into the kinetic energy of the charged mesons (nearly all pions). Later this number will be seen to be important in regard to how much of the p-$\bar{p}$ annihilation energy may be used for rocket thrust. The total mass energy in reaction (2) is about 1 Mev. This energy goes entirely into the energy of the gammas.

Particle-antiparticle reactions such as (1) and (2) form only a portion of the reactions that are important for matter-antimatter annihilation as it is likely to occur in a rocket. This is because the minimum useful amounts of

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antimatter, small in some applications, are large enough relative to the weight of the rocket so that the use of antimatter stored in the form of free antiparticles (e.g. antiparticles in a storage ring within the rocket) is probably not feasible. It will probably be necessary to use substantive antimatter, and for ease of handling this will probably be in solid form.

When substantive antimatter is involved in a controlled annihilation process, it is necessary for certain atomic scale reactions to take place in order that annihilation of the nucleus and antinucleus occur [6] [7]. It is the nucleus-antinucleus annihilation that produces, by far, the most energy in the annihilation of matter and antimatter. These reactions bring a nucleus (e.g., p) and an antinucleus (e.g., $\bar{p}$) close enough to one another for annihilation to take place. Examples of such reactions involving antiprotons and atoms of hydrogen (H) and antihydrogen ($\bar{H}$) are

$$\bar{p} + H \rightarrow Pn + e^- \tag{3}$$

and

$$\bar{H} + H \rightarrow Pn + Ps, \tag{4}$$

where Pn, protonium, is an atom which is a bound state of a proton and an antiproton, and Ps, positronium, is an atom which is a bound state of an electron and a positron. In reaction (4) it is possible to obtain unbound $e^- + e^+$ instead of Ps. The p and $\bar{p}$ in Pn and the e^- and e^+ in Ps annihilate in times on the order of microseconds or less once the Pn and Ps are formed. The cross sections for reactions (3) and (4), which occur at incident energies of one reactant on the other from zero to about 1 ev, are known and have energy dependent values that lie between ordinary atomic areas and a few tens of times as great for energies in the thermal range. Estimates

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of these cross sections are given in references [6], [7], and [8] along with cross sections for certain other reactants. The cross section for reaction (3) is shown in Fig. 1.

4. Antimatter Storage

It can be readily demonstrated that substantive antimatter cannot be stored in any way in which it is allowed to come into contact with matter. Here "contact" refers to situations in which atoms of matter and antimatter can come closer than about 20 or 30 Bohr radii from one another, which is the case in all ordinary means of storage. For even milligram quantities of substantive antimatter, contact with matter will lead, at least, to electron-positron annihilation. This will, at least, produce intolerable heating in any surrounding matter in addition to vaporization and depletion of the antimatter.

Hence, ordinary methods of matter storage are not feasible for antimatter. The antimatter must be stored by suspending it electromagnetically in a high vacuum such as may be found in interplanetary space [9]. One such possibility is illustrated in Figure 2. Two sectioned, curved plates of opposite charge about 10 cm apart provide an electric field that suspends a charged sphere of solid antihydrogen. It is presumed that gravity or rocket acceleration forces on the sphere act downward in the figure. The charge on the plates may be adjusted to balance these forces. If the sphere and curved plates are charged to 100,000 volts, the suspension forces are sufficient to counter an upward acceleration of 3g ($g = 9.8\ m/s^2$). The negative charge on the antihydrogen sphere might be accomplished by ultraviolet irradiation of the sphere in an electric field. This would cause positrons to escape from the sphere, leaving behind an excess of negatively charged antiprotons.

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The form of the electrical field produced by the curved electrodes is such that a point of stable equilibrium exists for the sphere in the vertical direction. This reduces the precision by which the voltage on the plates must be controlled to keep the sphere near the center. No such equilibrium exists in the horizontal direction, however. Here the forces tending to move the sphere away from the center position are less than in the vertical direction. Its horizontal position can probably be adequately controlled by adjusting the voltages on the plate sections in a horizontally asymetric manner.

The position of the sphere could be sensed by the use of microwaves of sufficiently low intensity that they would have no significant effect on the solid antihydrogen.

Even in the case of suspension of antimatter in a nearly perfect vacuum there are potential problems with unwanted annihilation. Whereas the matter in the vicinity of the antimatter can be chosen to have a negligible sublimation rate, this may not be true of the antimatter (assumed to be solid for case of suspension). The sublimes antiatoms can annihilate with atoms of nearby matter. The rate of heat production within the antimatter due to such annihilations is

$$W = \frac{nf_1f_2A}{\tau} \times 10^6 \quad \frac{\text{calories}}{\text{mole sec.}}, \tag{5}$$

where m is the number of moles of antimatter, n is the number of antiatoms per antimolecule, f_1 is the fraction of the solid angle surrounding the suspended antimatter that is taken up by matter, f_2 is the fraction of the annihilation energy deposited in the antimatter, A is the lesser of the atomic numbers of the matter and anitmatter and τ is the mean lifetime against evaporation of the antimatter in years. For the case of one gram of solid antihydrogen equation (5) becomes

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$$W = \frac{f_1 f_2}{\tau} \times 10^6 \quad \frac{\text{calories}}{\text{sec.}}, \tag{6}$$

To maintain the antimatter at a constant temperature requires an energy loss rate from the antimatter equal to W. Assuming the loss mechanism to be thermal radiation, and applying the Stephan-Boltzman law for total thermal radiation from a black body to a one gram sphere of antihydrogen at its freezing point (14°K), the energy loss is

$$W = 1.4 \times 10^{-6} \quad \frac{\text{cal.}}{\text{sec.}} \tag{7}$$

where the mean temperature of the surrounding has been taken to be about 4°K. This is about the minimum that can be achieved in space through passive means such as shielding. Combining equations (6) and (7) gives

$$\tau = f_1 f_2 \times 7 \times 10^{11} \text{ years}. \tag{8}$$

Lowering the mean temperature of the surroundings to less than 4°K would have little effect for the antihydrogen at 14°K.

By making the region around the antihydrogen mostly open space it might be possible to make f_1 as low as 10^{-2} and by minimizing the size of the electrodes and moving them farther from the sphere than shown in Fig. 2 (with correspondingly greater voltages) it might be possible to make f_2 as low as 10^{-5}. A possible form of the resulting suspension mechanism that might accomplish these values of f_1 and f_2 is shown in Fig. 3. Here a shield has been added to provide at least some protection against micrometerites if such should be needed. Although it is clear from the figure that geometrically f_1 is not 10^{-2}, the same effect might be accomplished by the arrangement of surface angles so that sublimed antiatoms or antimolecules strike the

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surfaces at very small angles leading to a high probability of their reflection.

With the values of f_1 and f_2 given above Eq. (8) gives $\tau \approx 10^5$ years. Rough calculations based on the known vapor pressure of solid hydrogen at low temperatures indicate that this is several orders of magnitude greater than the mean lifetime against sublimation that can be expected of solid antihydrogen at $14^{\circ}K$ in a vacuum. Lowering the temperature of the antihydrogen to near absolute zero and surrounding it by matter at a distance of several meters that is actively refrigerated to a temperature even closer to absolute zero might help. This is because the sublimation rate decreases faster as the temperature is lowered below $14^{\circ}K$ that does the rate of energy loss through radiation.

A better solution to this problem might possibly be obtained through active refrigeration of the suspended antihydrogen by an electromagnetic means. This is done with some forms of matter in certain areas of experimental, low temperature physics. This possibility has not been investigated, but should it prove feasible a much higher rate of heating due to annihilation might be allowed. This, coupled with the lower temperature of the antihydrogen, could lead to values of τ that are tolerable in regard to the annihilation energy produced and in regard to avoiding any significant depletion of the antihydrogen.

Another solution, of course, would be to employ a heavier antimatter element than antihydrogen that would have a very long lifetime against sublimation in the solid state. However, such an element would, undoubtedly, be much more difficult to produce.

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5. Extraction and Transport of the Antimatter

In this section a description is given of a method by which antimatter may be continually withdrawn from storage and transported to other portions of the rocket. The feasibility of this method for accomplishing withdrawal and transport is demonstrated only on a semiquantitative basis.

The principal physical features associated with the method are depicted in Fig. 2. The magnetic field shown there is produced by and is inside of a solenoid which is not shown.

Extraction of the antiprotons occurs at the topmost point of the antihydrogen sphere in the figure and extraction of the positrons at the lowest point. In both cases extraction is accomplished by directing electromagnetic energy with roughly the wavelength of ultraviolet light at these points. For extracting the antiprotons the intensity, wavelength, and cross section of the electromagnetic light beam are chosen so that molecules of antihydrogen are dislodged from the surface and at the same time ionized into free antiprotons and positrons. For extracting the positrons the intensity, wavelength, and beam cross section are chosen so that only ionization occurs. The positrons become free, but the antiprotons remain bound to the sphere.

At the top the free antiprotons are accelerated upward by the electric field and continue into the antiproton transport region while being guided that way by the magnetic field. The associated positrons are drawn by the electric field back onto the sphere. At the bottom the free positrons are drawn downward by the electric field into the positron transport region while being guided that way by the magnetic field.

Depending on the voltage required for suspension, the energy of the extracted antiprotons will be between a few tens and a few hundreds of kev.

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With sufficiently strong magnetic and electric fields it should be possible to direct them to the rocket engine with little, if any, loss in their number. However, for annihilation to occur with the nuclei of matter (to be discussed in the following section) their energy must be reduced to about 1 ev or less (see Section 3) while making the cross section of their beam be on the order of 10 cm or less. The means to accomplish this energy reduction has not been investigated.

The positrons are directed by the magnetic field and, if necessary, electric fields to an auxiliary electric power generator [1]. Here they impinge upon matter wherein they annihilate with electrons. The gamma rays produced by reaction (2) (most will have an energy of about 1/2 mev.) pass through a series of metal plates where they dislodge electrons through compton scattering. The resulting charge on the plates is the source of electricity produced by the auxiliary power generator.

6. Rocket Motor with a High Velocity Exhaust

Thrust cannot be produced from matter-antimatter annihilation by simply feeding matter and antimatter into an ordinary rocket engine where they annihilate, as fuel and oxidizer are feed into the rocket engine of a chemical rocket. There are two principal reasons for this.

First, in order to avoid unwanted annihilation of the antimatter while passing into the engine, the antimatter must pass from a high vacuum in the antimatter transferral system into at least a fairly high vacuum in the interior of the engine. Without a vacuum in the engine, at least a significant portion of the antimatter would annihilate immediately upon entering and deposit an excessive amount of energy at the entrance point.

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Second, the majority of the energy from annihilation would be deposited outside the engine. Whatever elements of matter and antimatter are employed, a significant portion of the annihilation energy initially goes into charged pions as in reaction (1). The distance these particles will travel before being stopped in a gas, whose density is on the order of atmospheric density, is very roughly (depending on the kind of gas) on the order of a few kilometers [10]. Thus they will pass out of the engine. In surrounding solids their range will be very roughly on the order of a few meters. The muons, into which some of the charged pions will decay, have still longer ranges. The neutral pions produced by the annihilation have a very high probability of decaying into gamma rays before they interact with matter.

A type of rocket engine that overcomes these difficulties is shown in Fig. 4 The main feature of the engine is that it employs a non-uniform magnetic field to direct the changed annihilation pions rearward from the engine, thereby providing thrust. The particular engine shown in the figure is one which has about the minimum possible size under the constraints that the maximum value of magnetic field is 500,000 gauss and that at least 40% of the mass energy of the annihilating protons and antiprotons goes into directed thrust. As will be seen later the engine may have to be scaled up in size to provide adequate thrust. Nevertheless, the engine shown embodies all of the features, except for magnetic field strength and scale, of larger counterparts.

The magnetic field is produced by the turns of a coil that increase in radius and separation from left to right in the figure. The spacing of the turns is arranged so that the magnetic field lines form straight lines, all of which eminate from a common center on the engine axis 0.45 m to the left of the engine. Within the field is a vacuum except for the antiproton beam, the hydrogen beam, and the annihilation products.

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The beam of antiprotons enters from the left and collides at a right angle with a beam of hydrogen atoms or molecules coming from below. Under the assumptions that the two beams are of the same size and square in cross section, that the hydrogen beam consists of atoms, and that $\bar{p}$ - H elastic scattering can be neglected the annihilation rate of the antiprotons, R_a, is given by

$$R_a = -\frac{1}{\mu} \ln \left(e^{-\mu R_H} + e^{-\mu R_{\bar{p}}} + e^{-\mu (R_H + R_{\bar{p}})} \right) \tag{9}$$

where

$$\mu = \left(\frac{V_{\bar{p}}}{V_H} + \frac{V_H}{V_{\bar{p}}} \right) \frac{\sigma(V)}{hV} \quad \text{and} \quad V = \left(V_{\bar{p}}^2 + V_H^2 \right)^{1/2},$$

and where $R_{\bar{p}}$ and R_H are the rates (number per unit time) at which antiprotons and H atoms enter the region, $V_{\bar{p}}$ and V_H are their velocities, V is their relative velocity, h is the common width of the two beams and $\sigma(V)$ is the $\bar{p}$-H rearrangement scattering cross section discussed in Section 3. If R_p and R_H are 2×10^{20} particles or atoms per second (30 ampres), h is 10 cm, and V corresponds to a collision energy of 0.1 eV, then R_a is such that about 95% of the $\bar{p}$ beam is annihilated. The fraction of the hydrogen atoms whose protons are annihilated would be the same. If elastic scattering were considered, then some of the antiprotons would be scattered out of the region of intersection of the two beams and the fraction of antiprotons annihilated would be less than 95%. This reduction could be countered by making the current and width of the H beam greater. In this case the fraction of H atoms undergoing rearrangement and whose protons are therefore annihilated, would be reduced, and a significant portion of them would pass through the annihilation region. Nearly all of the H atoms passing through could be captured and recycled into the beam of H atoms. Such a procedure could, in fact, result in a nearly 100% annihilation of the antiprotons.

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It may not be feasible to produce a 30 ampre beam of antiprotons, with a cross section of about 10 cm and an energy about equal to 0.1 ev, from a beam whose initial energy would be on the order of a few hundred kev. A significant reduction of the $\bar{p}$ current and/or increase in beam size could overcome this difficulty. However, to achieve the same annihilation rate as with 30 amperes and a 10 cm beam it would be necessry to employ multiple antiproton and H atom beams and increase the size of the annihilation region. In addition it would be necessary to significantly increase the total current of H atoms relative to the total current of antiprotons resulting in a larger fraction that do not annihilate on the first time through.

The charged pions produced by the p-$\bar{p}$ annihilation follow paths in the magnetic field that may be described as follows. For each charged pion produced there is a unique imaginary surface in the shape of a cone. The surface of this cone is tangent to the velocity vector of the pion at the pion's point of origin and its vertex is at the common point where all of the magnetic field lines would intersect if they were continued to the left. The vertex angle of the cone depends on the velocity, charge, and mass of the pion and on the strength of the magnetic field at the point of tangency. The dynamics of the motion of the pion in the magnetic field confines the pion to the surface of this cone. Actually two cones satisfying the above conditions are present. The positive pions move on one and the negative pions on the other. The path a pion takes on the conical surface is equivalent to that of a thin strip of paper wound around the cone such that the angle between the strip and a magnetic field line at the point of production is the same as the angle between a magnetic field line and the velocity vector of the pion at that point. Thus a pion for which the preceding angle is greater than 90° will move to the right with an increasing angle that will not exceed 180°.

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A pion for which this angle is less than 90° will move to the left with the angle increasing as it undergoes a spiraling motion around the magnetic field lines. After the angle reaches 90° the pion will then begin moving to the right and eventually exit the rocket engine. Only a small fraction of the charged pions will have velocity vectors whose angle is sufficiently small that they will pass out of the engine on the left hand side.

Of the total mass energy of the protons and antiprotons annihilating, about 60% is converted into the kinetic energy of the charged pions produced. The mean number of charged pions produced per $p-\bar{p}$ annihilation is three. Each charged pion has a mean kinetic energy of about 360 Mev. Consideraion of the motion of these pions in the magnetic field leads to the result that 10% of them are lost through the sides of the magnetic field and 5% will pass out through the small end of the engine. Some of the charged pions will decay into muons and neutrinos before exiting the engine. A large fraction of the muons (which are charged) will exit to the right while contributing to the thrust, but the undirected neutrinos will remove about 10% of the initial kinetic energy of charged pions. In addition, about 5% of the energy is lost in momentum components of the exiting charged particles that are perpendicular to the engine axis. The net result is that about 40% of the $p-\bar{p}$ mass energy is converted into the directed kinetic energy of the charged particle exhaust that provides thrust. A reoptimization of the engine design concept, while keeping the same overall engine size, might increase this figure to 45% or 50%. The improved version would probably involve a magnetic field with curved lines of force and a repositioned annihilation region.

Only a small fraction of the mass energy that does not go into thrust will be absorbed by engine components. This is because the mean path length in solids of the annihilation products is, for the most part, much larger than the distances they will travel through the components. Thus, cooling required

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for the engine componets will not be substaintially greater than for a chemical rocket engine with the same energy production rate. The chief difference here will be in the fact that the heating is produced by high energy particle radiation. The long term effects of such radiation on the structural integrity of the engine have not been considered.

Although the power that goes into the production of thrust for the engine as shown in Fig. 4 is 2.4×10^4 megawatts (for 30 ampres of antiprotons) the thrust produced is only about 70 newtons (16 pounds force). This is a consequence of the fact that the exhaust has the extremely high velocity of about 95% of the velocity of light but a relatively low mass and, hence, low momentum.

With such a high exhaust velocity and low thrust a spacecraft employing such engines might be suitable only for interstellar travel. Consider a spacecraft whose total weight is roughly 100 times the thrust of each engine (1600 lb or 7000 kg). This is a base minimum mass sufficient to include 500 kg each, per engine, of hydrogen and antihydrogen, the mass of each engine (assumed to be about 100kg), plus other components. The mean velocity over its travel time up to fuel exhaustion is somewhat under one half the velocity of light. Such a spacecraft would have an acceleration of 0.1 m/s^2 (0.01g) and would reach a distance of roughly 10 light years from the solar system in a few hundred years. Travel times much shorter than this are desirable. They require a much larger acceleration which in turn requires a larger thrust and larger thrust to weight ratio for each engine.

A larger thrust to weight ratio might be achievable by scaling the engine to a much larger size than in Fig. 4. Let r be the linear scaling factor, i.e., the length and width of the engine increase by this factor. If the antiproton and hydrogen current densities are kept constant and the linear

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dimension of the cross section of the beams is increased by r, then the energy production rate and thrust increase by a factor of r^2. To have the charged particle trajectories scale with the engine size requires that the magnetic field strength be reduced by a factor equal to r. This results in a reduction in the coil current per unit area of the conical engine surface by the same factor.

Presuming that the coil weight per unit area decreases by the same factor, then the total weight of the coil and associated components and, approximately, the weight of the engine increase by the factor r. Since the thrust increases by r^2, the thrust to weight ratio will increase approximately by r. Thus by employing an engine like that of Fig. 4 but one hundred or more times larger in size it might be possible to make the thrust of the engine comparable to or greater than its weight. This in turn might allow accelerations on the order of one or a few m/s^2 on interstellar missions to the closest starts and travel times on the order of a few tens of years.

The above approximate results for the capability of a spacecraft employing engines of the type discussed in this section were based on the assumption of a single staged vehicle. Much improved capabilities could be achieved if the above spacecraft were the final stage of a multistage spacecraft. The lower stage or stages of such a multistage vehicle would have rocket engines of lower exhaust velocity and much higher mass and momentum flow as well as much higher thrust. A concept for an antimatter annihilation rocket motor that would have such exhaust properties is described in the next section.

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7. Rocket Engine with High Thrust

A rocket motor with a lower velocity exhaust and higher thrust than that described in the preceeding section would be achieved if some of the exhaust energy of that engine could be transferred to additional matter that would form part of the exhaust. A modest increase in thrust for a fixed rate of production of directed energy could result in an engine more suitable for the upper stage of an interstellar spacecraft. A substantial increase in thrust could result in an engine suitable for use in a high performance interplanetary spacecraft, in addition to being suitable for use in a lower or intermediate stage of an interstellar vehicle.

Transferral of exhaust energy to additional matter may be accomplished by a collision coupling system. In such a system matter in the form of a gas is introduced into the annihilation and/or exhaust region of the rocket engine. Collisions between the particles produced by annihilation and the gas atoms lead to a transferral of kinetic energy to the gas. In the process the gas atoms become ionized, hence they can be directed rearward from the engine by a magnetic field. The result is an exhaust of nearly the same energy as without the gas but with lower velocity and higher mass, momentum, and thrust.

A simple means to accomplish this would be to extend the conical coil of the engine shown in Fig. 4 (or larger versions of this) to the right and introduce a gas into the extended region. However, the collision cross section of pions with the nuclei is so low (roughly one hundred to a few hundred millibarns) that the pions would have to travel on the average a few to several kilometers before striking a nucleus when the gas is at a density as high as standard atmospheric density. Collisions with the electrons are no more effective as an energy transferral mechanism. If the gas were ionized to become a plasma, the pions would not have a significant increase in their

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energy loss over such distances. In such a collision coupling system a significant portion of the pions would decay into muons. The muons would have an even lower rate of energy transferral to the gas, since their nuclear collision cross section is less than that of pions, while other energy loss mechanisms would be about the same.

Thus, to achieve an effective collision coupling system requires that the charged pions from the annihilation and their decay muons be confined by a magnetic field for some time before having the possibility of exiting the engine. During this time they would travel great distances within the collision coupling region allowing them to transfer nearly all of their energy to the nuclei of a plasma occupying the region. Whereas this may be possible by employing time varying magnetic fields of the proper shape, it may be difficult to achieve. Calculations indicate that certain parameters of the system, such as confinement time, temperature, and density, have values that are greater than are required to achieve controlled themonuclear fusion.

A possible remedy to the above problem is to replace the hydrogen, with which the antiprotons annihilate, with an element or isotope with a greater atomic number. The antiprotons would annihilate with protons in the nuclei producing charged and neutral pions, both kinds of which have a high probability of interacting with the remaining nucleons in the nucleus. A likely outcome of the interaction would be a cascade process within the nucleus resulting in spallation, evaporation and possible fission leading to the production a few or several light nuclides and individual particles, all of which have higher mass and lower velocity than the pions. If the isotope chosen has nuclei of very high atomic number, e.g. 238 U, nuclear breakup in itself might provide some additional energy beyond that due to annihilation alone.

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Use of a heavier element than hydrogen would, therefore, result in the engine of Fig. 4 (or a scaled up version) having a lower exhaust velocity and higher thrust. This in itself may be more suitable for the rocket engines of the upper stage of an interstellar spacecraft. The use of a heavier element than hydrogen, combined with the use of a collision coupling system, provides the engine concept shown in Fig. 5. This would be suitable for use in an interplanetary spacecraft or in the lower or an intermediate stage in an interstellar vehicle.

The magnetic field in the engine is pulsed with a period of about 17 milliseconds. In Fig. 5 the field is shown in the maximum strength, or closed, configuration. In this configuration the field has its greatest strength of about 100,000 gauss at the entrance and throat. When the field is in the closed configuration, antiprotons are injected through the entrance of the engine and a beam of neutral high atomic number atoms are injected through the side. Annihilation occurs at the intersection point which is at the center, resulting in charged nuclear fragments that are confined by the magnetic field. The beam of atoms continues flowing after annihilation has occurred. In each pulse it has a much higher total number of atoms than are required for annihilation. This extra matter becomes ionized due to collisions with the nuclear fragments and forms a plasma which is confined by the magnetic field. The field is held in the closed configuration for 7 milliseconds. During this time the energy of the nuclear fragments is transferred to the unannihilated nuclei.

After the 7 millisecond confinement the field is opened by allowing its strength to decrease in the region of the throat. The plasma, whose mass and energy are held mainly by the unannihiated nuclei, escapes rearward from the engine providing thrust. For an average input of 2×10^{20} antiprotons per

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second the thrust is about 550,000 newtons (125,000 lb). Thus, for the same input rate of antiprotons, this engine has considerably more thrust than that considered in the preceeding section.

The principal characteristics of this engine are summarized in Table 1. These are based on certain assumptions in regard to the charge and mass distribution of the nuclear fragments. The maximum temperature of the injected matter is reached for only a very short time prior to the end of confinement. The mean temperature is much less. With this consideration the plasma confinement characteristics shown in the table are comparable to those of present day plasma confinement machines.

8. Summary and Conculsions

Concepts have been presented here for some of the major, unique componets of an antimatter annihilation rocket.

An electrostatic means appears feasible for storing solid antihydrogen (or other solid antimatter) by suspending it in a very high vacuum. However, a specific way has not been devised for the necessary continuous cooling of the antihydrogen.

It appears that antiprotons and positrons may be separately extracted from the solid antihydrogen through a particular means involving irradiation by untraviolet light. This concept has been examined on only a semiquantitative basis and more detailed quantitative work is required.

There seem to be no substantial problems involved in the transport of the positrons to an auxiliary power generator by the use of magnetic and electric fields. The same is not true, however, in regard to transporting the antiprotons to the rocket engine wherein they undergo annihilation. Whereas by the use of magnetic and electric fields they can indeed be moved from the

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storage region to the engine, they must be slowed to energies of less than 1 ev and be spatially concentrated. A means to accomplish this has not been devised.

Annihilation takes place within the rocket engine by crossing an antiproton beam with a beam of atoms or molecules of matter. The annihilation rate is governed by an atomic rearrangement collision that brings the antiprotons close to the nuclei. It is evident that cross sections for these rearrangement reactions are large enough so that nearly 100% of the antiprotons can be annihilated. However, the beam requirements for this are dependent on an improved knowledge of the cross sections. This is particularly important in regard to the low energy and high concentration requirements for the antiproton beam. Whereas the results of proton-antiproton annihilation are well understood, the results of the annihilation of antiprotons with heavy nuclei is not. Knowledge of the charge and mass distribution of the nuclear fragments would permit improved accuracy in the determination of the specifications of the high thrust annihilation rocket engine.

The concepts presented here for the two annihilation rocket engines demonstrate that thrust can be produced from matter-antimatter annihilation with an efficiency for annihilation energy to thrust energy conversion approaching 50%. The principles upon which these engines are based are fairly straightfoward, but many details are not treated here. Of particular importance are details relating to engine weights and optimization of design.

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ACKNOWLEDGEMENTS

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Fig. 1 $\bar{p}$-H rearrangement cross section as a function of collision energy E, where a_0 is the first Bohr radius of hydrogen and e is the charge of the electron.

Fig. 2 Suspension of stored antimatter in a vacuum by an electric field and transfer of antimatter from storage.

Fig. 3 Cross section of a mechanism for the vacuum suspension of antimatter designed in such a way that all evaporated antiatoms from the antimatter strike the matter surfaces at small angles.

Fig. 4 Concept for a high exhaust velocity antimatter annihilation rocket engine.

Fig. 5 Concept for a high thrust antimatter annihilation rocket engine.

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Table 1. Principal Characteristics of the High Thrust Engine.

antiproton flow rate average	2×10^{20} particles/sec.
injected matter atomic mass no.	240 (approx.)
injected matter flow rate (average)	9×10^{24} atoms or ions/sec.
full cycle	17 millisec
confinement time	7 millisec
plasma density in confinement	1.5×10^{16} atoms or ions/cm^3
maximum temperature	2.6×10^{8} ^{o}K
mean distance traveled by nuclide	500 km
exhaust kinetic energy	100 eV/atomic mass unit
exhaust velocity	140 km/sec.
thrust	550,000 Newtons (125,000 lb.)
fraction of annihilation energy converted into directed exhaust energy	50%

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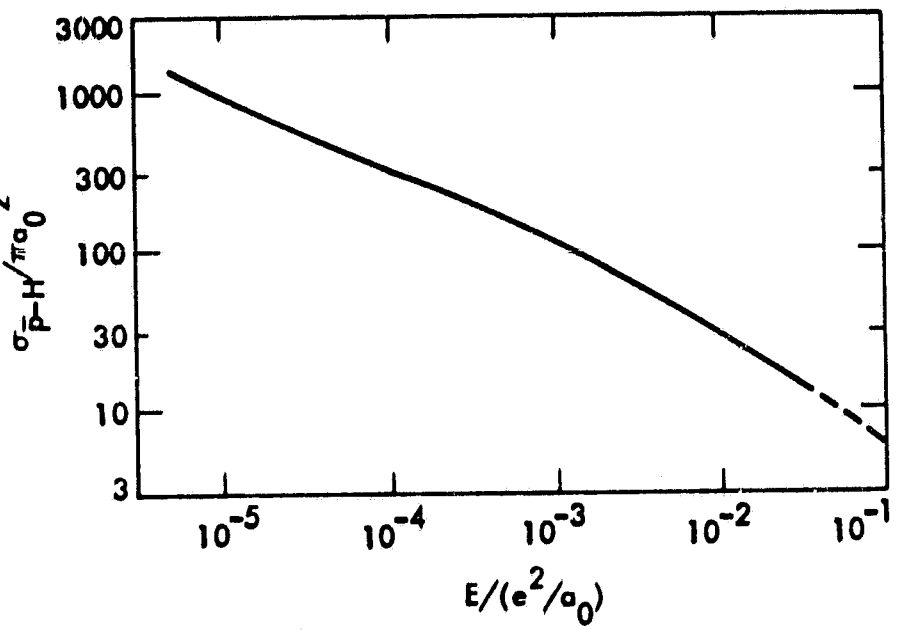

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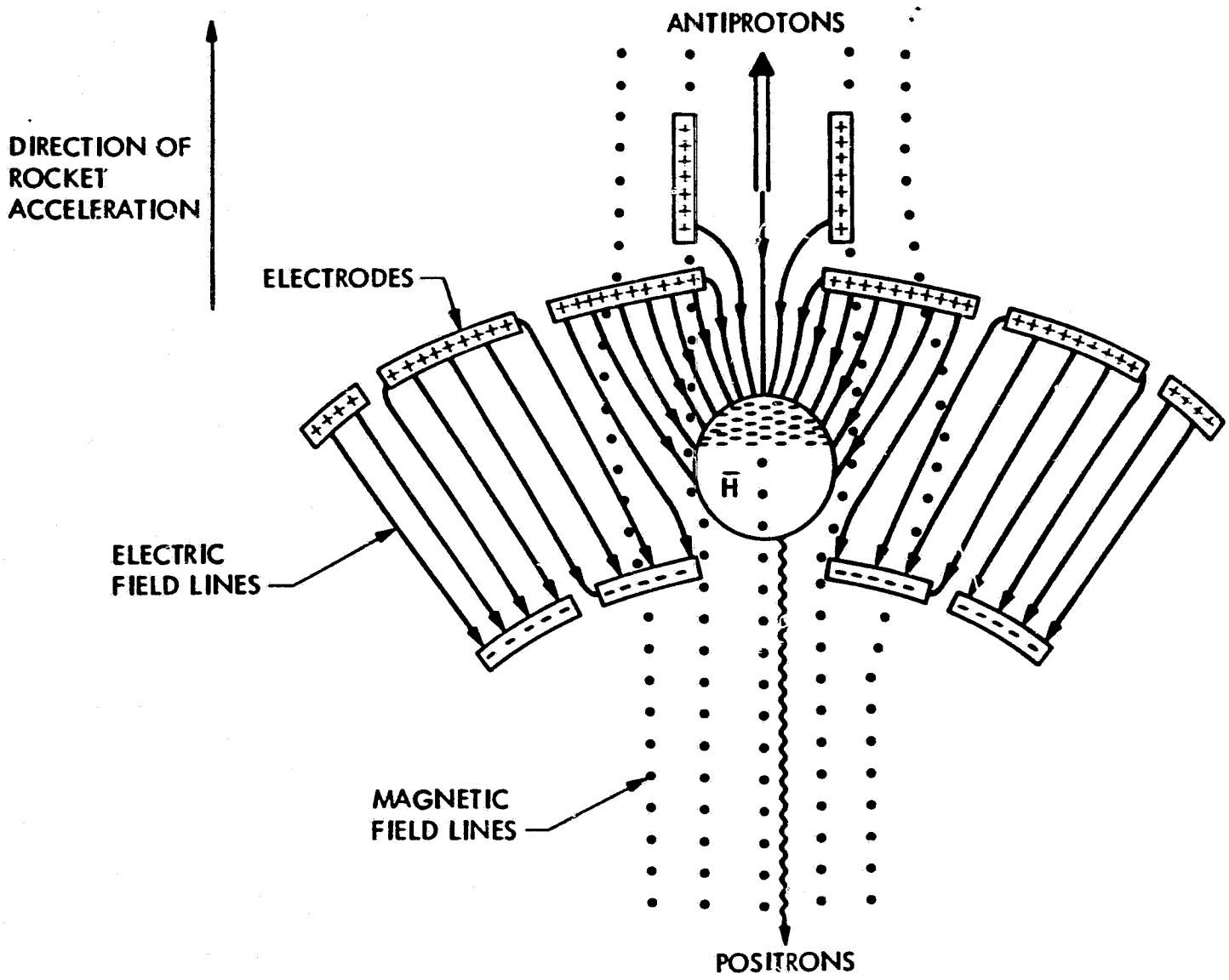

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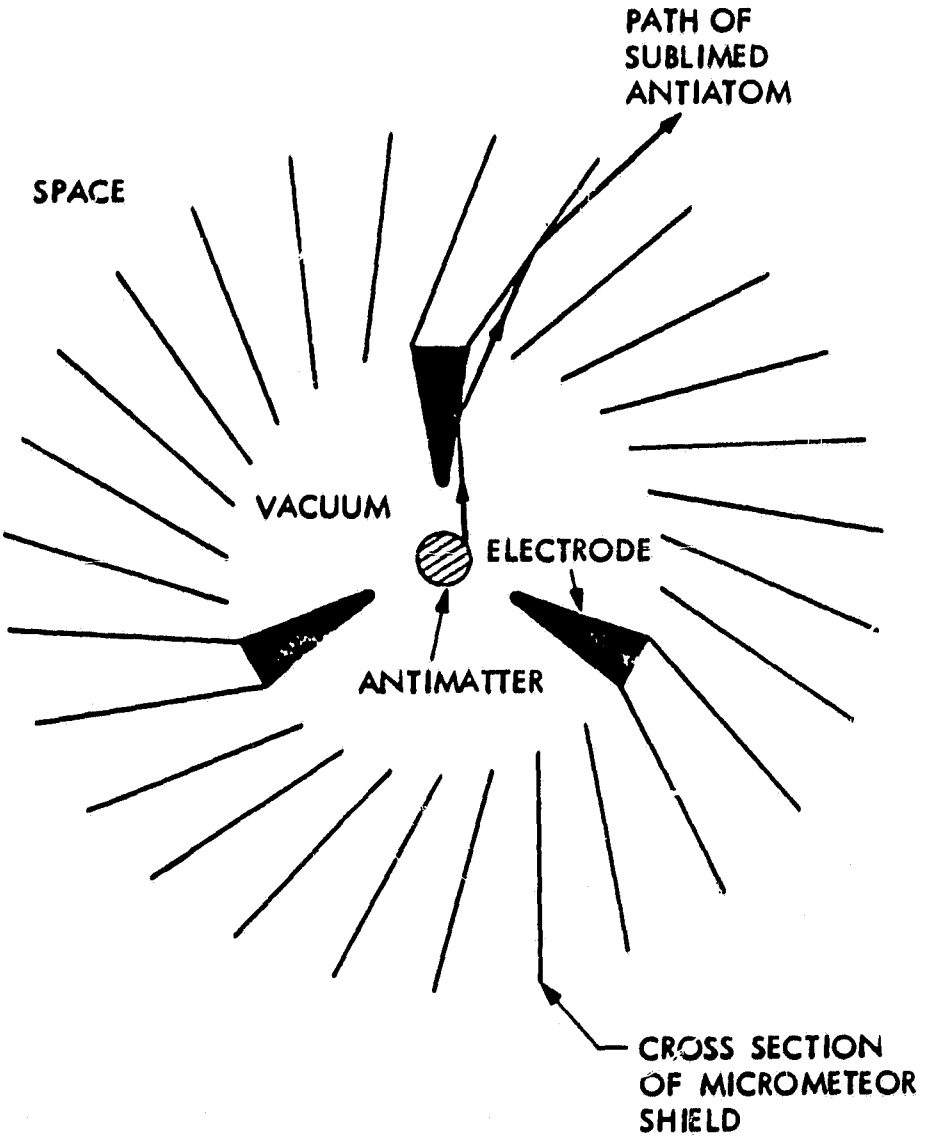

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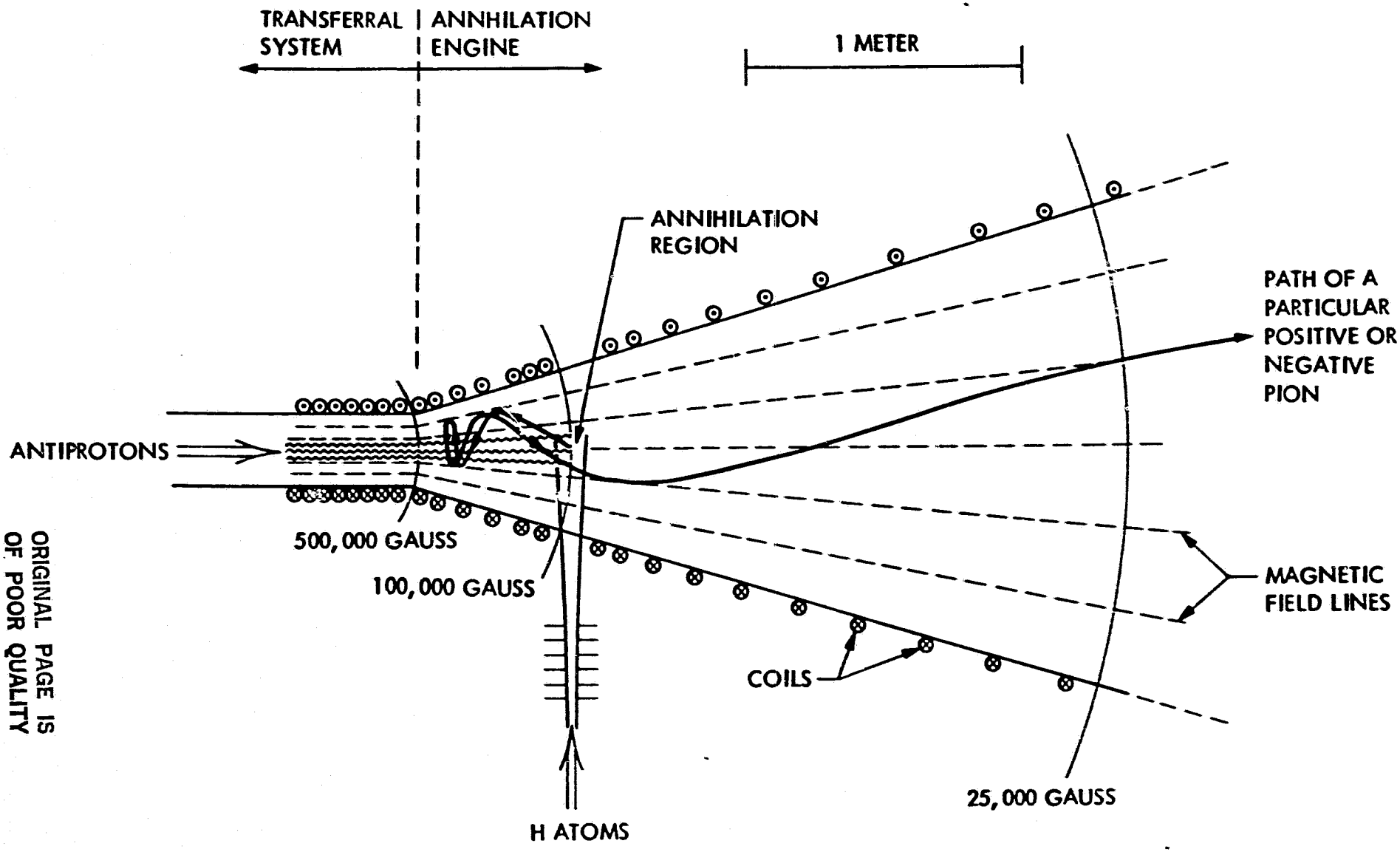

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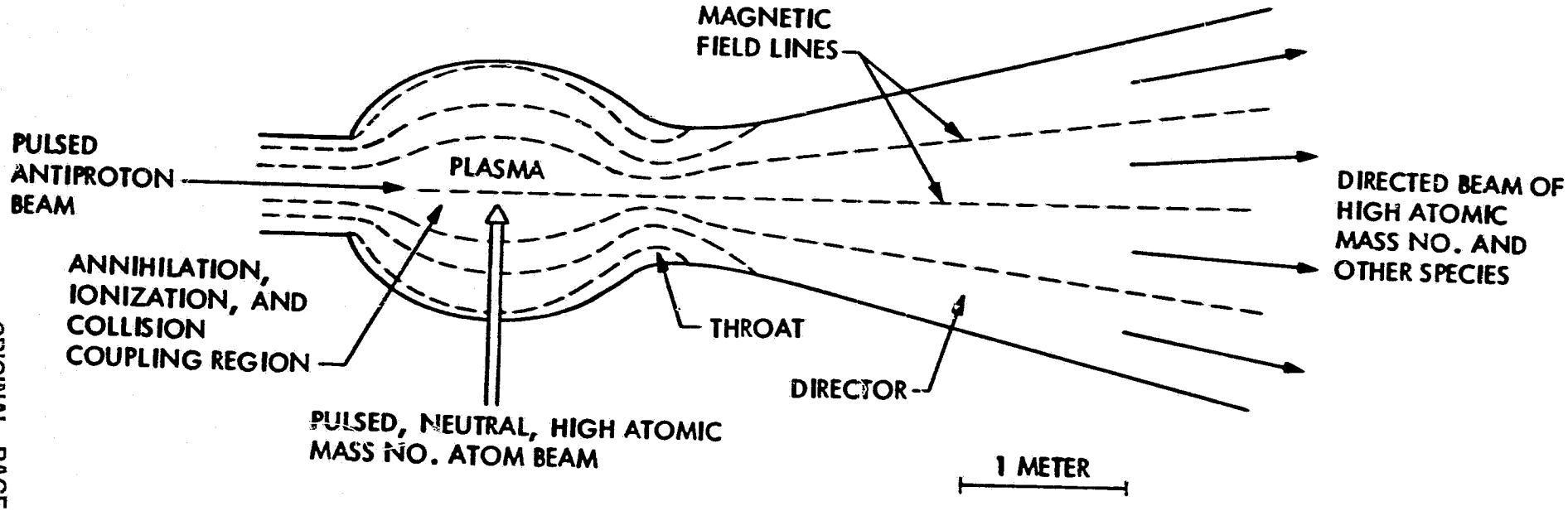

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