SOME EXAMPLES OF PROPULSION APPLICATIONS USING ANTIMATTER

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Reasonable macro applications of antimatter and annihilation energies to various interesting uses outside the current use in very high energy physics generally presuppose the solution of basic production and storage problems.

If these basic problems are resolvable [1], a very wide range of potential applications exists.

Of special interest are propulsion applications.* Here there are identifiable missions which are important and interesting, and which are simply not achievable by conventional means. Using annihilation energies gives us means for accessing effective exhaust velocities from, say, 10 Km/sec to a major fraction of light velocity (of course the conceptual engine designs will be varied and will reflect the exhaust velocity ranges sought). Studies exist on various implementation schemes. Basically, the promise of antimatter can here be very simply illustrated by considering a "mix ratio" r = amount of normal matter/amount of antimatter and calculating the effective attained temperature of the mixture as ~ 2 GeV/r (so that, e.g., mixing one metric ton of normal hydrogen with one milligram of antihydrogen gives an upper mixture temperature of ~ 2 eV). Naturally, ensuring that this mixing produces high temperatures and that the energy does not largely escape from the mix is part of the art of utilizing annihilation energies.

The immediate product of nucleon-antinucleon annihilations is almost wholly pions. The details of the subsequent reaction trains and the ultimate forms of the end products, their spectral attributes, the decay or capture mechanisms, etc., are well documented, although certain features of very low kinetic energy annihilations warrant more analysis.

During the pion lifetimes one can treat the pions in two alternative ways. One way focuses on the pions which emerge from the nucleus in which annihilation has occurred. These pions are very

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penetrating particles which can go through materials many centimeters thick before capture or decay.

Another way focuses on the subsequent history of the annihilation pions within the nucleus where annihilation takes place. The mechanisms here are believed to be relatively well understood. Some of the pions are captured within that same nucleus, an effect which increases with increasing atomic numbers; some, while still escaping, are degraded in energy by scattering within that nucleus. These processes excite the nucleus, which then deexcites by particle emission, etc. Two effects arise: An initial intense local deposition of energy in the regions where annihilation occurs, and a shorter penetration length for a portion of the emerging pions [2], setting in train a complex series of phenomena.

Propulsion regimes can be divided into three major classes which can be illustrated by examples. The first example considers a very simple concept, borrowing much from nuclear rocket technology [3], in which annihilation products heat a tungsten heater through which hydrogen working fluid flows. At a weight not exceeding a few hundred kilograms, nearly all of the annihilation energy which does not appear as neutrinos can be stopped by solid tungsten (for the mean pion energy of ~ 250 MeV, the range in tungsten is ~ 10 cm). In this application the annihilations take place in a cavity in the tungsten, so that the annihilation products see tungsten through a 4π solid angle. The tungsten then also acts as a shield and as a means for recovering the neutral pion decay gamma ray energy. If we are limited to the operating temperature of solid tungsten, the heated hydrogen can achieve specific impulses of ~ 1000 to 1300, depending on the pressure the hydrogen operates at, and still achieve high thrust/weight ratios with "modest" antimatter consumptions, giving very interesting mission capabilities (since, e.g., 1 milligram of antimatter will heat about 6-7 metric tons of normal hydrogen to the required temperatures of about 1/4 eV).

At the other end of the scale are very high specific impulse concepts. A very simple conceptual engine version of this regime again uses a tungsten block or another suitable high temperature material to absorb some of the high energy pions, producing a thrust generating net momentum flux. The annihilations now take place outside the tungsten block (which also acts as a shadow shield), so that the annihilation products see somewhat less than a 2π solid angle. The tungsten block is cooled by the phase change and heating of a fluid which is then continually circulated through a radiator and reused. For the heat transfer fluid we assume materials such as B (vaporization temperature 2820 deg K, heat of vaporization 53 KJ/gm) or Li (vaporization temperature 1615 deg K, heat of vaporization 23 KJ/gm); for the sake of calculation we use B. If each annihilation dumps ~ 1 GeV into the absorbing block, or 1.6×10^{-10} J per annihilation, and we assume a B circulating flow rate of 10^{2} Kg/sec, we can use about 3×10^{19} annihilations/second, corresponding to an antimatter consumption of ~ 50 μg/sec. Corresponding to this we use a momentum of ~ 400 MeV/c per annihilation, giving an effective thrust of ~ 6 Newtons. If the total mass of the vehicle could be held to a (probably optimistic!) mass of 1000 Kg, the acceleration of the vehicle would be 6×10^{-3} meters/sec^{2}, so that in 10 years of operation the vehicle would achieve a velocity increment of ~ 2×10^{6} meters/sec, or nearly one percent of light velocity, at an expenditure of ~ 15 Kg of antimatter. All these values can of course be scaled in a number of evident ways. Another embodiment [4] of this scheme would propose use of directing magnetic fields acting on the charged pions; in principle this could somewhat raise the system propulsive efficiency, at the expense of introducing other problems. Thrust/I_{sp} trades exist via several other schemes.

The third regime is in many ways both the most interesting and most technically complex one. Here we seek specific impulses in, say, the 2000 to 20000 range, at reasonable thrust-to-weight ranges. There are a number of options to consider, singly or combined: Use annihilation energies to generate electrical power to employ in one of the many classes of electrical propulsion concepts; use very large systems, where the scale size of the engine corresponds roughly to the range of pions in the working fluid; develop schemes, presumably using electromagnetic fields and analogous to current plasma confinement ideas, which confine the charged annihilation products and their secondary particles in volumes much smaller than that corresponding to the ordinary range of the pions in the working fluid, allowing greater energy density depositions in the working fluid (Morgan considers a particular case of this) [5]; develop concepts analogous to the liquid or gaseous core nuclear rocket concepts, so removing the temperature limit imposed by operating at solid tungsten temperatures; exploit certain features of intranuclear absorption of pions, which in principle in specific circumstances allow very large energy depositions in materials, say, ~ 10^7 J/gm or more, producing a blowoff hot dense plasma which with some manipulation could be directly used or used as an intermediary to effectively heat a working fluid [6]; Polikanov [7], also proposes use of antiproton beams to produce inertial confinement fusion drivers. One can be reasonably confident that one or several of these options will work, although the technical challenges of any one of them is great, and that goals of a specific impulse of the order of $2x10^3$ to $2x10^4$ at a thrust/weight ratio of 10^{-1} or greater could well be achievable using antimatter as the energy source.

A very simple conceptual example in this third regime again can borrow from nuclear rocket technology. This example considers use of a dense, high temperature material in the liquid state. Working fluid (e.g., hydrogen) is "bubbled" through the liquid metal to achieve temperatures intermediate between the melting and boiling temperatures of the selected material. Candidate materials include again tungsten (density 19.3 g/cc, boiling temperature T_B = 6170 degrees K), and such other possibilities as Osmium (density 22.5 g/cc, T_B = 5770 degrees K), rhenium (density 21.0 g/cc, T_B = 6170 degrees K), perhaps tantalum (density 16.6 g/cc, T_B = 6370 degrees K), etc. For engineering reasons, a large temperature spread between melting and boiling is also useful.

The general arrangement contemplated uses a cylindrical shell of molten material held against an outer wall by centrifugation (which can be accomplished by proper injection of the working fluid or by mechanical drives). The bulk of the working fluid is injected radially inward, establishing a temperature gradient which serves to cool the outer containing wall while in principle permitting the gas exiting from the inner surface of the molten material and entering the core of the engine to attain nearly the maximum temperature of the melt. Questions of bubble size, flow conditions, material entrainment, sequence of startup operations, etc., are all clearly important. However, this design is "simpler" (albeit still complex!) than the corresponding nuclear rocket design, where many more constraints are operative. The material used in this concept is kept molten by absorption of annihilation products introduced in one of several ways. For test purposes one can start with materials molten by external means (several schemes are directly applicable) and get data on working fluid temperature rise and the other questions just noted. The effective absence of neutronics issues should make this a relatively clean initial test, if one wishes it carried out to get early information.

The effects occurring and necessary to take into account at molten metal temperatures include dissociation and recombination; radiation transport to the working fluid, particularly if additives increasing absorptivity are used; and, if we consider additives to hydrogenous propellants which ionize at relatively low temperatures, the increased rate of energy transport from ionization effects. If, for example, cesium is used, cesium atoms may be ionized by contacting a surface such as tungsten whose work function is greater than the cesium ionization potential.

Estimates of the net consequences (in, e.g., I_{sp}) of all these effects are best done by numerical calculations when the impacts of working fluid operating pressure, finite nozzle size (which affects recombination), etc. are also desired. However, it is possible to make relatively simple calculations showing that I_{sp} in the range 1500-2600 should be possible at working fluid operating pressures $\gtrsim 1$ atmosphere and working fluid operating temperatures consistent with the boiling temperatures of the four materials mentioned earlier.

These examples are intended to make clear that *if* we had enough antimatter, schemes for using it for propulsion are conceptually available--and in a sense do not require totally new inventions but mostly adaptations of existing ideas. Reduction to engineering practice of such schemes would appear possible in all three regimes, at varying levels of difficulty. Knowledge of material properties is critical.

Many interesting theoretical and computational issues arise, particularly in the third regime. Notably this occurs in following the energy transport, energy deposition, and particle motion subsequent to the intranuclear phenomenology of excitation and deexcitation. This phenomenology is quite complicated and requires at a minimum the coupling of good intranuclear cascade codes with transport codes which can handle the three-dimensional problems involved. Such combined codes are necessary to do a good job in a number of the interesting propulsion concepts. Codes developed for propulsion applications will have significant utility in several other possible applications of antimatter annihilation energy release.

The availability of antimatter propulsion would make a profound difference in many difficult, interesting missions which require high mission characteristic velocities. If we focus just on the simplest concepts which can work with good thrust-to-weight ratios--and which can to a certain extent borrow from nuclear rocket concepts--the previous discussion suggests that certainly I_{sp} in the approximate range of 1000 to ~ 2600 can be considered. The impact of such capabilities in antimatter propulsion is discussed in recent papers [8].

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