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Antimatter Propulsion and its Application for Interstellar Travel: A Review

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Abstract: This paper reviews antimatter propulsion for interstellar travel and space exploration. Firstly, the specific energies of different reactions are compared with matter-antimatter annihilation and the viability of antimatter as a fuel is considered. Next, the different production and storage methods and the problems faced by the above-mentioned are discussed. Finally, the conceptual rockets which would utilize antimatter as a fuel were reviewed along with some limitations and the methods to overcome those limitations and optimize the rockets.
Keywords: Antimatter, Propulsion, Production, Storage, Specific Impulse, Thrust, Design, Optimisation, Conceptual Rockets.

I. INTRODUCTION

Space exploration has always been a fascinating aspect of the development of humans as a race; the concept of interstellar travel is miraculous. The current technology being used for space exploration yield infinitesimal results in comparison to the amount of space left unexplored, the high specific impulse propulsion system requirement for interstellar travel is the most significant reason for this. The limited energy released during chemical combustion is insufficient and makes even the most developed chemical rockets inapplicable [1].

Antimatter-matter annihilation is a leading prospect to achieve the high specific impulse required for interstellar missions to delve into the heliopause, for a visit to the Oort Cloud and is needed if we intend to put in effort for a rendezvous with the closest star systems [2]. This is probable because elevated exhaust speeds and high thrust at a low mass can be achieved through annihilation [3]. This annihilation reaction results in the greatest probable physical energy density among all acknowledged reaction substances. The reactor systems needed for this reaction need not be complex because of the spontaneity of this reaction [4]. To determine the feasibility of antimatter as a fuel and the probability of it being used for propulsion and interstellar applications, several steps need to be followed. Firstly, the required antimatter production rate and the current antimatter production rate need to be compared. Then, efficient storage of antimatter and efficient conversion without many losses need to be looked upon. Lastly, the utilization of the generated energy to yield the best possible results needs to be analyzed.

Various estimates based on numerous experimental and theoretical research over the last decades' point towards the idea of antimatter being a feasible option for interstellar travel after a few decades.

II. ANTIMATTER AS A FUEL

All the mass of antimatter is converted to energy during its annihilation with the matter, making it an excellent energy source [5]. The energy released from this reaction is estimated to be eight orders of magnitude greater than the energy released by chemical combustion [1]. Thus, antimatter comes across as a prospective cheap fuel in space, wherein all the fuels are expensive. It has been estimated that a milligram of antimatter, i.e., 10^{21} antiprotons, is required for a simplistic orbit shift maneuver and the requirement for interstellar flyovers goes up to tons [4]. A two-way trip to Mars involving a 500-ton mass in one hundred and fifty days would need 12g of antimatter [6].

Rocket engine prospects that involve comparatively low specific impulses seem viable due to the energy of the products of annihilation and these engines have about 50% efficiency when converting annihilation energy to propulsion energy [7].

Robert Forward [5] proposed that antimatter should be present as antiprotons and not as antielectrons because the annihilation of antiprotons does not yield gamma rays. Charged particles called pions are discharged which make up two-thirds of the energy yielded. The conversion of the kinetic energy of these pions is possible through user interaction with a magnetic nozzle or a working fluid. This converted energy can be used to produce the required thrust by direct or indirect means.

The generation of antimatter is possible in particle acceleration using the collision of extremely highly energized protons with solid matter. However, the storage of these antiprotons poses a problem, they need to be stored in antiproton rings. These rings make use of magnetic and electric fields to embody these particles [9].

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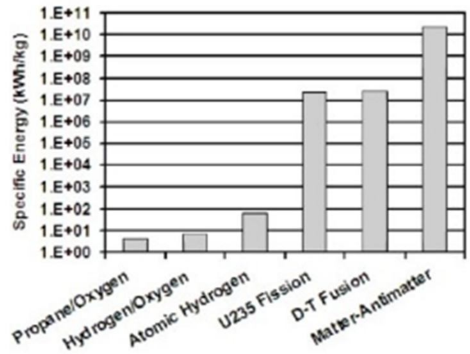

Fig 1 Comparison of Specific Energies for various reactions [10].

A. Production

The most significant hurdle faced by the idea of antimatter propulsion is the efficient production of antimatter. It has been evaluated that the production of antimatter using current technologies would be costly and ineffectual. Hence, the need for the examination of effective processes arises. Presently, the production of antimatter involves the collision of highly energized protons with fixed heavy elements, for example, Tungsten.

Brice N. Cassenti (January 2000) discussed two methods to improve the production rate [8], [31].

In method 1, antiprotons and pions generated due to highly energized protons colliding with the fixed heavy elements are gathered. The number of protons generated exceeds the number of antiprotons. The pions are aimed and fired at the same target or another target. The prospect of production of antiprotons is greater when pions and heavy nuclei collide and hence the number of antiprotons generated would be greater.

Method 2 includes the production of numerous collisions, nearing a resonance, by a recirculating electron/positron collider, with the use of a beam wiggler. The number of interactions would go up significantly leading to a proportionate increase in the number of antiprotons produced.

Gerald P. Jackson (2009) puts forth an argument in favor of harvesting antimatter in space [10]. He proposes the idea of giant embedded spherical nets on which electric charges are imposed. He argues that a filter that only allows antiprotons to enter the center of the harvester can be formed by adjusting the charge levels.

6×10^8 antiprotons were being produced per hour in the Accumulator in Fermilab [11]. This would amount to 0.85ng of antiprotons per year. A facility named New Injector which was supposed to turn on in 1998 would be capable of producing a total of 14ng per year. A conceptual Recycler Ring which would be placed inside the Main Injector Ring would increase the production rate by 10, which would result in maximum production of 140ng per year. Fig. 2 shows the schematic of the Antiproton Catcher Trap at CERN.

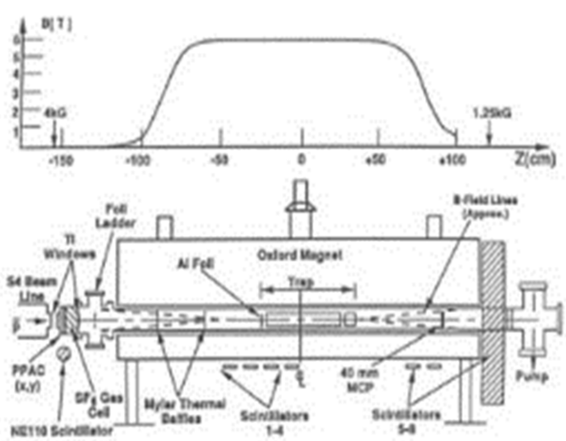

Fig. 2 Schematic of the Antiproton Catcher Trap at CERN [11]

The present method for cooling antiprotons involves injecting electrons into the beam of antiprotons. If this method is used for the production of milligrams of antiproton per year, the production costs would skyrocket.

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B. Storage

Several methods have been studied for the storage of antimatter which includes but are not limited to using storage devices like Stellarators, magnetic mirrors and storage rings, electromagnetic levitation, Coulomb scattering, and so on [20].

The antimatter needs to be stored at high density as required by most propulsion systems. The way to proceed is to neutralize the antimatter with antiprotons [21], [22]. As a result of experiments on protons and electrons, using low-energy antiprotons and positrons to make antihydrogen while making no contact with the walls of the container seems plausible [23], [24]. Gabrielse stored about one thousand anti-protons for two months with no detectable annihilations [25].

Thus, it can be inferred that the formed antihydrogen needs to be stored at cryogenic temperatures after cooling [20] and kept in a distinctive vacuum.

III. ANTIMATTER SPACE PROPULSION SYSTEM DESIGN

A. Conceptual Designs

1) *Solid Core Rocket:* These rockets can have specific impulse as high as 1000 s and thrust-to-engine mass ratio of 100 g. The limiting factor for the performance for these rockets is the temperature of the core [13].

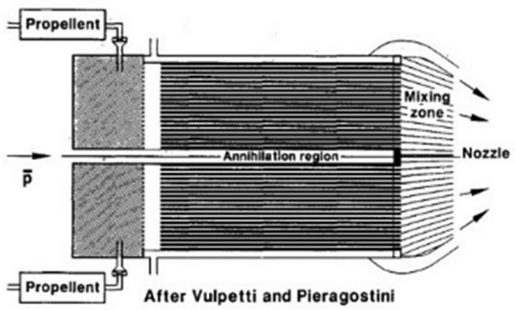

Fig. 3 Conceptual Design of Solid Core Rocket [13], [27]

2) *Gaseous Core Rocket:* In these rockets, a gaseous propellant is heated by the charged particles formed as a result of annihilation. A magnetic bottle is used as a container for the charged annihilation products. The limiting factor for these rockets is the heating of nozzle and chamber wall [13].

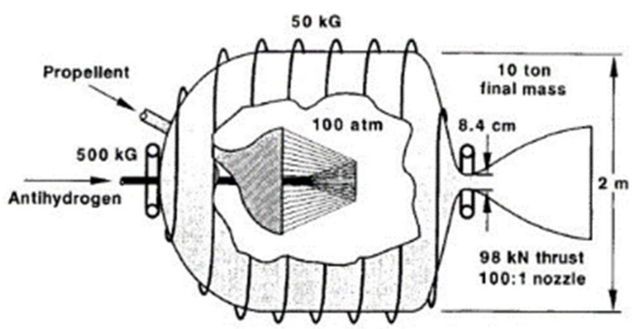

Fig. 4 Gaseous Plasma Antimatter Rocket [13]

3) *Interstellar Ramjet:* Bussard [28] proposed the concept of an interstellar vehicle which utilizes the matter throughout our galaxy for propulsion, which he called the Interstellar Ramjet. Jackson [16] put forth the concept of using antiproton annihilation to heat hydrogen collected in space. The two main factors to be taken into consideration while designing an antimatter and fusion RAM-augmented interstellar rocket are mass ratio and reactor conditions.
4) *Plasma Rocket:* In these rockets, the nozzles and chamber could be removed by heating the propellant to ionization temperature and then containing and directing the plasma with the help of magnetic or electric fields [13]. Specific impulses of 100,000 s or higher are achievable through this rocket.
5) *Pion Rocket:* Despite a specific impulse of 20 x 10^6 being achievable by a pion rocket, the thrust-to-mass ratio of 0.01 g limits its utilization. Morgan [29] and Hora and Lob [30] optimized the rocket to obtain an efficiency of 40% and 75% respectively. In these rockets, the pions produced through annihilation would be directed with the help of magnetic fields.

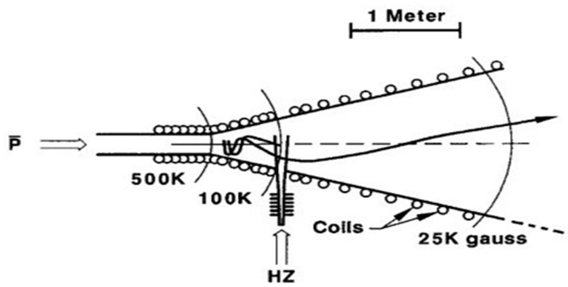

Fig. 5 Conceptual Pion Rocket after Morgan [13]

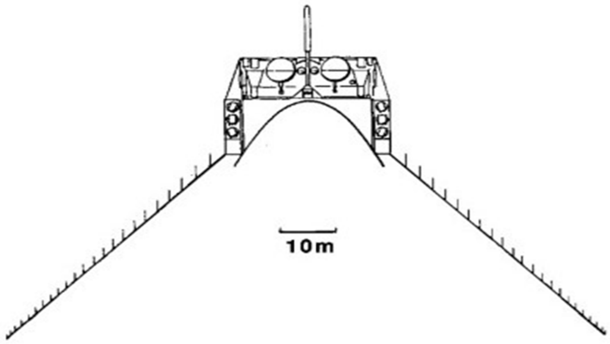

Fig. 6 Conceptual Pion Rocket after Hora and Lob

6) *Comparison:* It can be inferred from the maps above that the thrust-to-mass ratio decreases with an increase in specific impulse. Upon comparing Fig. 7 and Fig. 8, it can be seen that only fusion rockets are capable of competing with mass annihilation rockets.

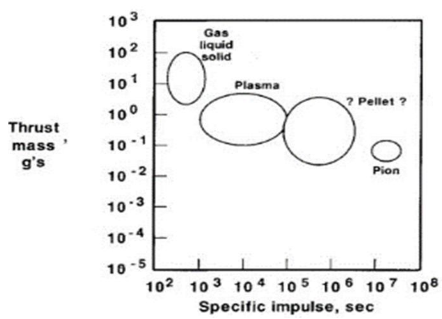

Fig. 7 Conceptual Rocket Performance Map [13]

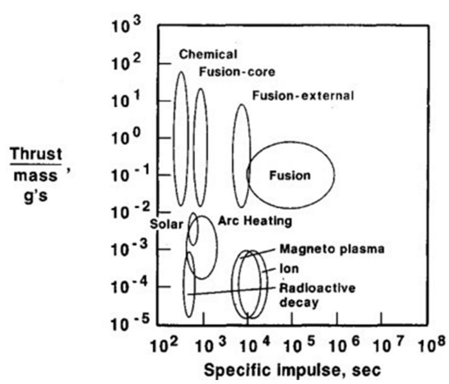

Fig. 8 Practical Rockets Performance Map [13]

B. System Level Considerations

1) *Relativistic Antimatter Rocket:* The two major constraints associated with antimatter propulsion, i.e. production and storage can be overcome if the requirement of antimatter could be drastically reduced. Relativistic velocities have been used to arrive at this solution. The third major constraint is the efficient use of the resultant products of antimatter annihilation. Simulations of the reactions can be applied to the design of the magnetic fields to project the resultant products in our desired direction. This would increase the efficiency in utilizing the resultant products. The expansion of the liquid hydrogen needs to be taken into account while heating it. Through the use of calculated energy distributions, specific magnetic fields in the direction of charged particles need to be considered. For the magnetic fields, the effect of particle spin needs to be considered [15].
2) *Orbital Transfer Vehicle:* The most significant consideration for OTV powered by antiproton annihilation is the bounding of annihilation products [19]. These bound products will then heat the propellent, say Hydrogen, which in turn minimizes the amount of antimatter required [26]. The biggest challenge would be to generate and maintain a magnetic field capable of bounding these particles.
3) *Radiation Safety Issues in SSTO:* Radioactivity is induced in the engine components because of particle fluxes and protons. There are two radiation threats that need to be examined and removes: i) The danger from high-energy gamma radiation produced as a result of annihilation and ii) The danger caused by the radiation due to photonuclear activities of gamma radiation and shield nuclei [12]. The radioactivity needs to be considered and the engine needs to be protected.
4) *Advanced Propulsion Technology Vehicles:* Reference [14] tells us about the different aspects of vehicle subsystem and vehicle sizing that need to be taken into consideration such as electric power system, payload, dust shield, system mass contingency etc.

C. Optimization

Robert H Frisbee [18] performed mission analysis using the Relativistic Rocket Equation and to try and find methods of optimizing an Antimatter Rocket with regards to trip time and propellant mass. Brice N Cassenti [17] concluded that variable antimatter and propellant flow rates permit savings up to 35% with regards to the amount of antimatter required in comparison to constant flow rate. Tarpley, Lewis and Kothari [12] proposed an engine design to eliminate the risks associated with radioactivity. This engine would be shielded with tungsten and would be a gas-core engine with a specific impulse of 1630s. The working fluid used would be Hydrogen.

Fig. 9 shows the conceptual shielded annihilation chamber made of Tungsten.

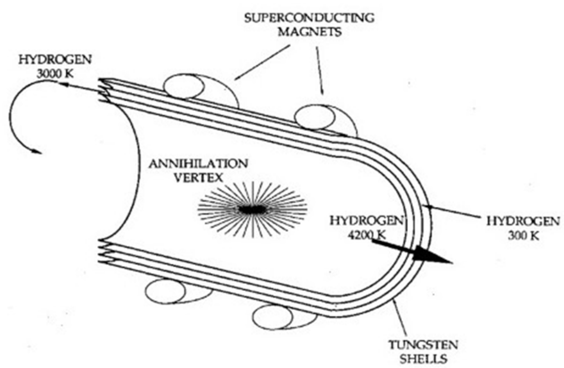

Fig. 9 Tungsten Shell Annihilation Chamber [12]

IV. CONCLUSION

Despite the numerous limitations, antimatter propulsion has the potential to become a breakthrough in space exploration. For long interstellar missions, it would be the cheapest and most efficient method despite its high production cost and the problem of storage. Fig. 1 shows the difference between the energies released by various reactions in comparison to matter-antimatter annihilation; the gap is visible. Extensive research would be required in the field of production and storage and new technologies would need to be invented. A lot of research would also be required in designing an efficient rocket that would be able to function on antimatter propulsion and utilize the products of annihilation successfully.

Due to these factors, antimatter propulsion is not a viable option for interstellar travel in the next few decades, but it is one with the most potential in the long run.

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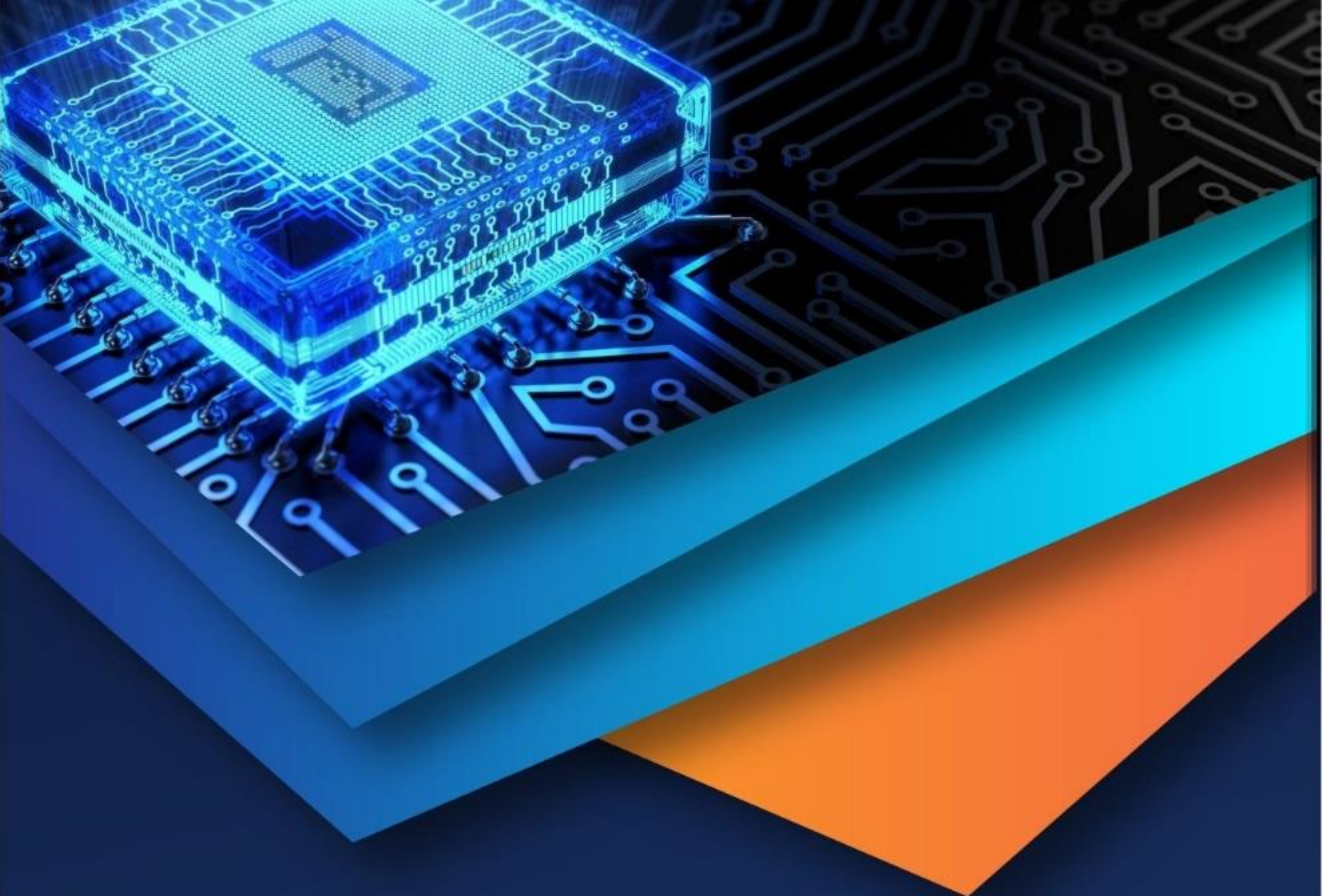

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