D-^{3}He Magnetic Fusion for Space Propulsion

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Abstract

This paper gives a brief overview of the reasons why magnetic fusion energy using the D-^{3}He fuel cycle appears attractive for space applications—particularly space propulsion. The paper also surveys some fusion reactor configurations, examines the capabilities of these reactors, and explores the implications for space development. Based on several conceptual designs of fusion reactors for space propulsion, such systems could enable the efficient, large-scale exploration and development of the Solar System.

1. Overview

Modern developments in fusion reactor science and technology now make possible the realization of a thirty-year old idea: that D-^{3}He fusion reactors can provide very attractive space propulsion systems [1]. The key reason for this attractiveness is that high exhaust velocity (specific impulse) can be achieved at sufficient thrust-to-weight ratios for both fast, human transport and large-payload, cargo transport throughout the Solar System.

Advantages for D-^{3}He fusion over chemical or nuclear fission reactors in space include:

- No radioactive materials are present at launch, and only low-level radioactivity is present after operation;
- Conceptual designs project higher specific power values (1–10 kW$_{thrust}$/kg) for fusion than for nuclear-electric or solar-electric propulsion.
- Fusion gives high, flexible specific impulses (average exhaust velocity), enabling efficient long-range transportation.
- D-^{3}He produces net energy and is available throughout the Solar System.
- D-^{3}He fuel provides an extremely high energy density.

The fusion power density in a D-^{3}He plasma is smaller than that of a D-T plasma, and, for this reason, the D-T fuel cycle is more commonly investigated for terrestrial fusion reactors. These two main fusion reactions, plus the important 'side' D-D reactions are shown in Table 1.

The charged fusion products from D-^{3}He reactions can be guided to provide direct

Table 1. *Key fusion fuels, including main secondary reactions.*

$$
\begin{aligned}
\mathrm{D} + \mathrm{T} &\rightarrow \mathrm{n}\ (14.07\ \mathrm{MeV}) + {}^{4}\mathrm{He}\ (3.52\ \mathrm{MeV}) \\
\mathrm{D} + {}^{3}\mathrm{He} &\rightarrow \mathrm{p}\ (14.68\ \mathrm{MeV}) + {}^{4}\mathrm{He}\ (3.67\ \mathrm{MeV}) \\
\mathrm{D} + \mathrm{D} &\rightarrow \mathrm{n}\ (2.45\ \mathrm{MeV}) + {}^{3}\mathrm{He}\ (0.82\ \mathrm{MeV}) \\
\mathrm{D} + \mathrm{D} &\rightarrow \mathrm{p}\ (3.02\ \mathrm{MeV}) + \mathrm{T}\ (1.01\ \mathrm{MeV})
\end{aligned}
$$

thrust or electricity, whereas 80% of the energy from D-T reactions is produced as neutrons and requires more massive shielding, thermal cycle energy conversion at relatively low efficiency with larger radiator mass for waste heat rejection, and an intermediate system to convert the resulting electricity into thrust. The D-T fuel cycle also requires a tritium breeding blanket, adding a great deal of complexity to the system.

Depending on the configuration, the plasma exhausted from the core and used to provide thrust can range from ~10 eV to ~1 MeV. For hydrogen, this corresponds to $\sim 4 \times 10^4$ m/s to $\sim 10^7$ m/s. The high end of that range is not useful within the Solar System, so matter must be added to the exhausted plasma to decrease velocity and increase thrust. Traditionally, the average exhaust velocity is normalized to Earth's surface gravity and termed the *specific impulse*, $I_{sp} = v_{ex}/g_0$. A detailed discussion of rocket dynamics and so-called "low-thrust" trajectories may be found, for example, in Ref. [2].

In comparing D-^{3}He fusion to other options, the specific impulse and the thrust-to-weight ratio (T/W) for the propulsion system are useful indicators of performance. These are plotted in Fig. 1 [3]. Fusion's capabilities lie in a niche important for propulsion throughout the Solar System: $I_{sp} \sim 10^4$–10^5 s and T/W$\sim 10^{-3}$.

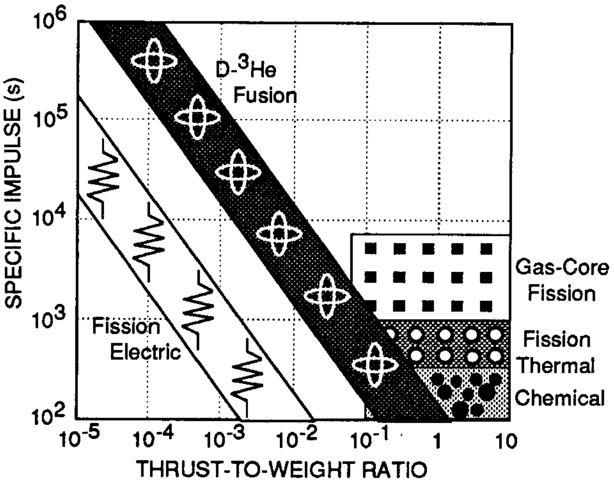

Figure 1: *Comparison of D-^{3}He fusion with chemical, nuclear thermal, and nuclear electric propulsion systems.*

In addition to the technical advances in fusion energy research, two factors increase the timeliness of studying space fusion propulsion: (1) U.S. President Bush's Space Exploration Initiative [4] provides a framework and incentive for long-range space development, and (2) the identification of major resources of ^{3}He on the Moon [5] solves, in principle, the problem of the scarcity of ^{3}He on Earth. A review of research on terrestrial and lunar ^{3}He resources is contained in Ref. [6].

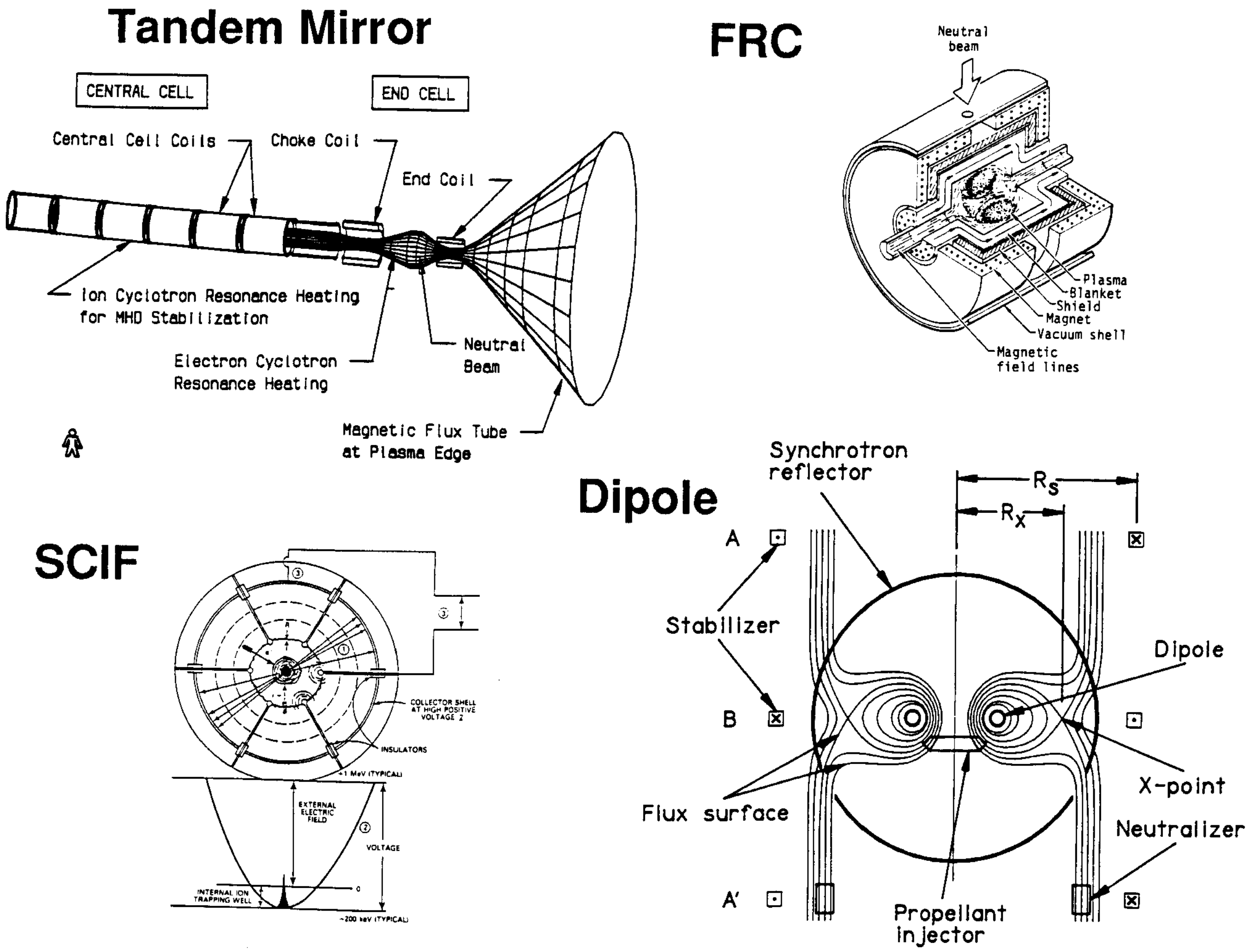

Figure 2. *Some potential D-^{3}He magnetic fusion propulsion configuration options [7, 16, 14, 3].*

2. Potential Configurations

Several studies of space fusion propulsion have been performed, although all have been small in scope. They have included reactors of many configurations, such as:

- Simple mirror [1],
- Tandem mirror [7],
- Dipole [3],
- Field-reversed configuration (FRC) [8, 9, 10],
- Colliding compact toroids [11],
- Spheromak [12],
- Spherical torus (ST) [12],
- Bumpy torus [13], and
- Spherically convergent ion flow (SCIF) [14].

A discussion of some of these concepts, including a brief historical overview may be found in Ref. [15]. Figure 2 shows some configuration examples, and illustrates the diversity of fusion propulsion options.

3. Mission Capabilities

Magnetic fusion propulsion gains greatly in comparison to other options by the ability to optimize the thrust parameters as a function of time along the trajectory. The advantages of tunable systems have been known for some time [2], but a typical nuclear electric system, for example, is limited in its range of exhaust velocities. Figure 3 shows optimized I_{sp} and T/W over a three-month trajectory from Earth to Mars [2]. Note, from Fig. 1, that these parameters fall within the projected range for D-^{3}He magnetic fusion propulsion systems.

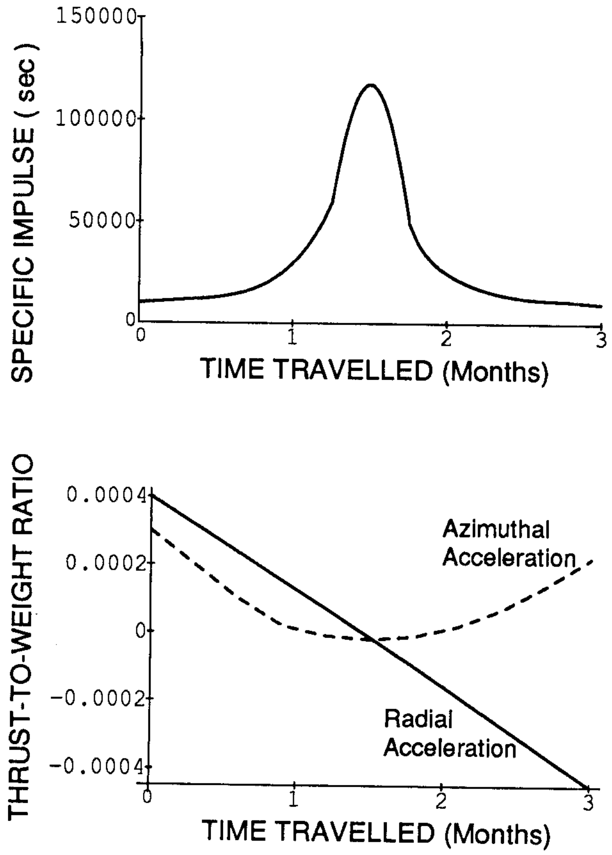

Figure 3. *Specific impulse and thrust-to-weight values during an optimized, three-month trajectory from Earth to Mars.*

Such performance leads to a continuum of capabilities from fast, human transport to large-payload, cargo transport. For these alternatives, D-^{3}He fusion propulsion is compared to chemical propulsion for one-way missions from Earth to Mars and to Jupiter in Figs. 4 and 5.

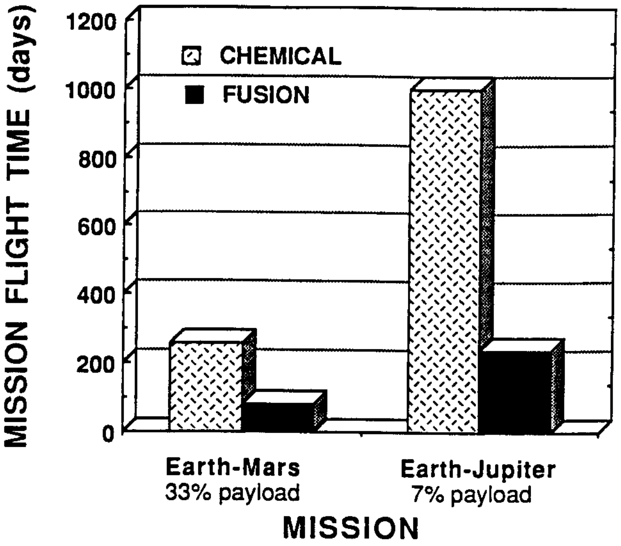

Figure 4. *One-way flight time at the same payload fractions for chemical and D-^{3}He fusion missions from Earth to Mars and to Jupiter.*

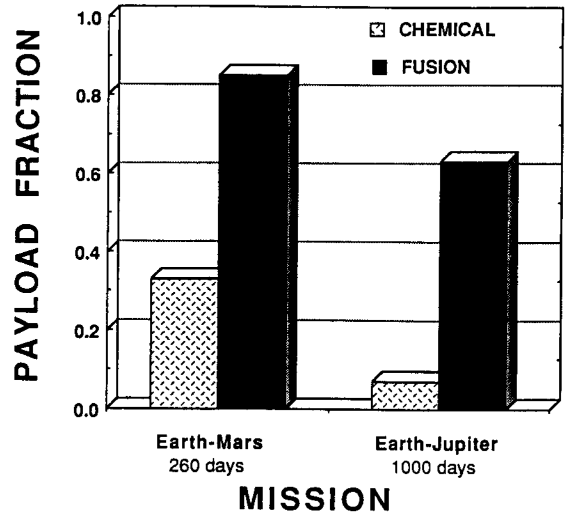

Figure 5. *Payload fractions for same flight time for chemical and D-^{3}He fusion missions from Earth to Mars and to Jupiter.*

These capabilities will enable large-scale development of the Solar System. Furthermore, D-^{3}He fusion systems will enable scientific outposts analogous to Antarctic bases—with groups of scientists and technicians in orbit around the gas giant planets, for example. Fusion will be able to provide propulsion, space power, beamed power to surface bases, and materials processing. In particular, there presently appear to be no alternatives to D-^{3}He fusion for the attractive ranges at very high specific impulse and modest thrust-to-weight ratios.

4. Conclusions

Magnetic fusion for space applications, particularly propulsion, appears attractive from both generic arguments and from preconceptual design studies. The key performance parameters are specific power $\sim$1–10 kW/kg, specific impulse $\sim 10^3$–10^6 s, and thrust-to-weight ratio $\sim 10^{-1}$–10^{-5}. Thus, D-^{3}He magnetic fusion power can provide safe, efficient transport of humans and cargo, and can enable large-scale settlement and exploration of the Solar System.

Acknowledgement

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