The College of Engineering
University of Wisconsin-Madison

MAGNETIC FUSION PROPULSION: OPENING THE SOLAR-SYSTEM FRONTIER

WCSAR-TR-AR3-9307-2

Technical Report

WCSAR

Wisconsin Center for
Space Automation and Robotics
•
A NASA supported Center for
the Commercial Development of Space

MAGNETIC FUSION PROPULSION: OPENING THE SOLAR-SYSTEM FRONTIER

WCSAR-TR-AR3-9307-2

J.F. Santarius

Wisconsin Center for Space Automation and Robotics
University of Wisconsin
1500 Johnson Drive
Madison WI 53706

July 1993

Presented at the 2nd Wisconsin Symposium on Helium-3 and Fusion Power, 19-21 July 1993, Madison WI.

Magnetic Fusion Propulsion: Opening the Solar-System Frontier

John F. Santarius
University of Wisconsin–Madison
1500 Johnson Drive
Madison, WI 53706

ABSTRACT

The exploration and development of the Solar System require propulsion capabilities that only D-^{3}He magnetic fusion power appears able to deliver. Both conceptual design studies and generic arguments indicate that space propulsion systems based on D-^{3}He magnetic fusion reactors can provide performance dramatically beyond that of chemical, fission, and D-T fusion rockets for long-range missions. D-^{3}He fusion's capabilities include flexibility, a specific power of 1–10 $\mathrm{kW}_{thrust}/\mathrm{kg}_{reactor}$, and exhaust velocities up to $\sim$0.2 c (c $\equiv$ speed of light). Such capabilities, for example, allow two-month missions to Mars with the same payload as nine-month chemical missions or allow greatly increased payloads for longer durations. More distant missions, such as to the gas giant planetary systems, show D-^{3}He fusion to even better advantage. The mass estimates for D-^{3}He fusion propulsion systems can be made with some confidence, because the masses of the key components—shields, magnets, radiators, and refrigerators—can be calculated with good accuracy. The main uncertainties lie in the systems for input power and power conversion, but these corrections should only be tens of percent. Besides propulsion, fusion energy can provide power and materials processing capabilities. Three typical applications will be transporting humans and supplies to settlements, accessing the vast resources on asteroids and moons, and enabling scientific outposts analogous to antarctic bases. Thus, developing D-^{3}He magnetic fusion would open the Solar System to humankind.

1 INTRODUCTION

Every frontier motivates *exploration*, and space is no exception. The *development* of a frontier, however, inevitably awaits a *why*, usually an economic or political incentive. Yet a *why* alone is not sufficient for the development of a frontier—a *how* is also necessary. For space beyond Earth orbit, a major economic motivation may be the lunar resource of the isotope helium-3 (^{3}He) for use in terrestrial fusion power plants [1]. Eventually, humans will be tapping the even larger ^{3}He resources of the gas-giant planets, accessing the multitude of resources in the asteroids, and settling Mars and other Solar-System bodies. Thus, the *why* of space development exists, but the question of the *how* remains.

The outer Solar System has long been known to be beyond the capabilities of chemical rockets [2], and even very advanced systems such as gas-core fission or nuclear-electric propulsion greatly lose efficiency and attractiveness for destinations beyond Mars. The present situation parallels in many ways that of the American West in the year 1803, when Thomas

Jefferson is reported to have predicted that it would take 800 years to settle fully the newly acquired Louisiana Purchase [3]. Yet, in only 1907, Oklahoma achieved statehood—the last part of the Louisiana Purchase to do so. Why was Jefferson so far off in his prediction? He did not foresee the development of a new technology—the railway. Ironically, 1803 was the year in which the first public freight railway operated [4]. Solar System exploration and development require an analogous technology breakthrough. The thesis of this paper is that fusion power can be that enabling technology.

2 RATIONALE FOR ADVANCED SPACE PROPULSION SYSTEMS

Efficient long-range propulsion requires both a high specific power (ratio of the thrust power to the mass of the power and thruster systems) and a high exhaust velocity. This can be seen from the simplest form of the *rocket equation*, which is derived from momentum conservation for a rocket and its exhaust, assuming an impulsive thrust:

$$\frac{M_{final}}{M_{initial}} = \exp\left(\frac{-\Delta v}{v_{exhaust}}\right) \qquad (1)$$

where M_{final} is the mass with which the rocket arrives at its destination, $M_{initial}$ is the initial rocket mass including propellant, $\Delta v \equiv \sqrt{2\Delta E/M}$ indicates the velocity increment for a mission requiring energy ΔE, and $v_{exhaust}$ is the exhaust velocity. Chemical rockets are limited to exhaust velocities of ~5,000 m/s, and a minimum-energy 9-month trajectory between the orbits of Earth and Mars requires a Δv of about 6,000 m/s. Thus, for either a significantly faster (higher energy) or larger-payload-fraction mission, a higher exhaust velocity is required. Nuclear thermal (NERVA) rockets can approximately double the chemical exhaust velocity, but this gains only an incremental capability. Nuclear electric rockets can reach high exhaust velocity, but at low specific power levels, so their acceleration is very low and trip times are long. Only fusion systems appear capable of achieving both the exhaust velocities and specific powers necessary for efficient Solar System development. The operating regimes for various propulsion systems are indicated in Fig. 1.

Rocket trajectory analysis and optimization is, of course, much more complicated than discussed above, especially including gravity and long thrust times. Nevertheless, the essential rationale for advanced propulsion remains qualitatively similar to that based on Eq. 1. Section 3 examines the reasons why fusion propulsion systems can be expected to operate in the interesting parameter regime at the center of Fig. 1, and Sec. 4 discusses the mission implications of achieving those capabilities.

3 CAPABILITIES OF FUSION PROPULSION

The high exhaust velocity for fusion derives from the high temperature of the plasma used to generate the fusion reactions. The fusion core plasma temperature of ~100 keV (~10^9 K) for a reactor fueled with deuterium (D) and helium-3 (^{3}He) actually gives an exhaust velocity too high for most Solar-System applications. If this plasma is directly

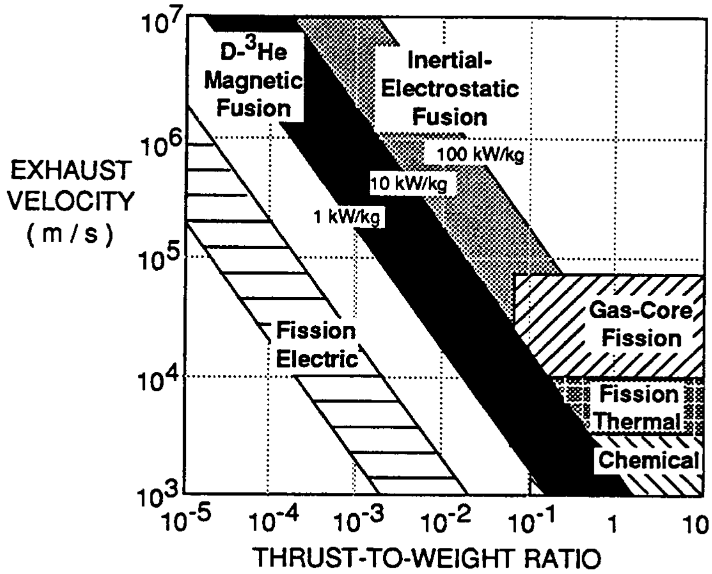

Fig. 1. Thrust-to-weight ratio and exhaust-velocity regimes for various space propulsion options.

exhausted, it must be diluted with other material, hydrogen for example, in order to reduce the plasma temperature and exhaust velocity while increasing thrust.

A high specific power, which allows useful thrust-to-weight ratios at relevant exhaust velocities, has been calculated in several fairly detailed recent conceptual design studies. Some of these are listed in Table I, as are two whose specific power was not calculated. These studies support the assertion that fusion will provide at least an order of magnitude higher specific power than typically predicted for the eventual performance of nuclear-electric propulsion systems. Note that the specific power goal for the SP-100 fission-electric space power plant is 0.03 kW/kg, even without a thruster system.

The magnetic fusion configurations required for space applications are generally at an early stage of development with regard to physics. Nevertheless, the total mass of the systems can be predicted with fair accuracy, because the masses of the key engineering components are well characterized. These components are the magnets, radiation shields, radiators, and helium refrigerators (for the superconducting magnets). A simple, generic fusion rocket model has been developed [5] and will be summarized in order to help give a qualitative understanding of the good performance calculated by the more detailed studies.

The generic model assumes cylindrical geometry, a LiH shield with 10% Al structure, magnet masses either current-density or virial-theorem limited, and the default parameter assumptions listed in Table II for mid-term (year 2020) and long-term (year 2050) cases. Both D-T and D-^{3}He fuels are treated, and optimization is done over the plasma density, plasma temperature, and shield thickness. The main results are shown in Fig. 2.

Table I. **Some Recent Conceptual Designs Studies of Magnetic Fusion Reactors for Space Propulsion.**

First Author	Year	Configuration	Specific Power (kW/kg)
Borowski [7]	1987	Spherical Torus	5.75
Borowski [7]	1987	Spheromak	10.5
Santarius [8]	1988	Tandem Mirror	1.2
Chapman [9]	1989	Field-Reversed Configuration	–
Haloulakis [10]	1989	Colliding Spheromaks	–
Bussard [11]	1990	Riggatron Tokamak	3.9
Teller [12]	1992	Dipole	1.0
Deveny [13]	1992	Tandem Mirror	4.3
Bussard [14]	1993	Inertial-Electrostatic	$\gg$10

Table II. **Default Parameter Assumptions for the Generic Fusion Rocket Model.**

Parameter	Mid-Term (2020) Cases	Long-Term (2050) Cases
β (P_{plasma}/P_{Bfield})	0.6	0.9
Surface heat flux limit, MW/m^2	5	10
Neutron wall load limit, MW/m^2	20	20
Magnet average current density, MA/m^2	50	250
He-refrigerator mass per heat pumped, kg/kW	1000	1000
Radiator: power rejected per unit mass, kW/kg	5	5
Transport power-to-thrust efficiency	0.8	0.8

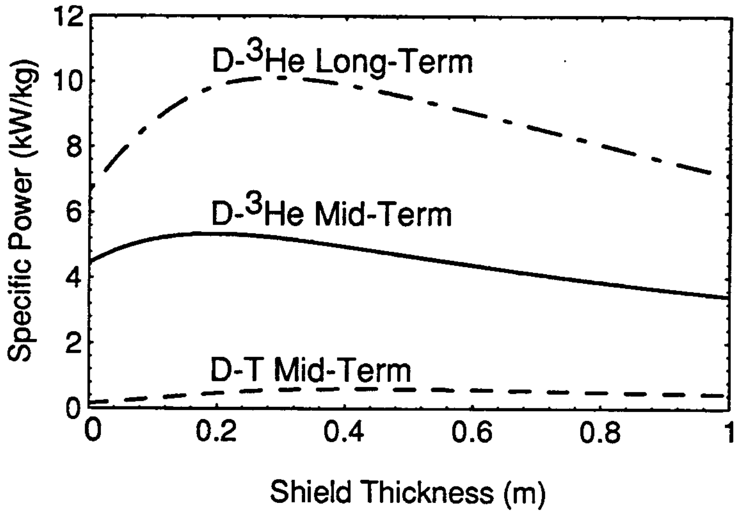

Fig. 2. Variation of specific power with shield thickness for D-T and D-^{3}He generic fusion rocket cases.

Both the detailed studies and the generic model find that D-^{3}He is the fuel of choice for space propulsion with magnetic fusion, as had been realized even in some of the earliest space fusion studies [6]. The reasons that D-^{3}He outperforms D-T, despite a lower fusion power density in the plasma, are the leverage gained by the high charged-particle fraction, which facilitates direct thrust, increases useful power and reduces radiator mass, and by the low neutron power, which reduces radiation shielding mass. Furthermore, the D-^{3}He fuel cycle does not require the very complicated tritium-breeding blanket and related systems necessary for D-T fuel. A fusion reactor burning D-^{3}He fuel also has the great political advantage over fission that no radioactive materials are present at launch and only low-level radioactivity is generated during operation.

4 MISSION IMPLICATIONS OF FUSION PROPULSION

The benefits of high exhaust velocity, even at low thrust levels, have been analyzed in detail [2]. For the present purpose of gaining a qualitative understanding of how magnetic fusion propulsion would enable Solar-System development, it suffices to look at two key missions in the approximation of transfer between circular orbits centered on the Sun. These missions are Earth–Mars and Earth–Jupiter. Fusion rockets at specific powers of 1 kW/kg and 10 kW/kg will be compared to chemical rockets.

Two typical applications will be considered: human transport and cargo transport. For humans, the key consideration is fast travel to avoid the harmful effects of low gravity, so the performance will be normalized by assuming the same payload fraction for each system. In the present context, 'payload' is defined as all of the mass delivered except the power and thrust systems (parameterized by specific power); that is, the rocket structure is part of the 'payload.' Figure 3 shows that Earth-Mars travel times (one-way) can be reduced from the 260 days for a minimum-energy chemical-rocket trajectory to 53–80 days for a fusion rocket, while Earth–Jupiter travel can be reduced from 1000 days to 150–240 days [15]. On the other hand, for cargo transport, now comparing to chemical-rocket minimum-energy-trajectory transport times, Fig. 4 shows that Earth-Mars payload fractions can be increased from 33% to 83–91% and Earth-Jupiter payload fractions can be increased from 7% to 60–90% [15].

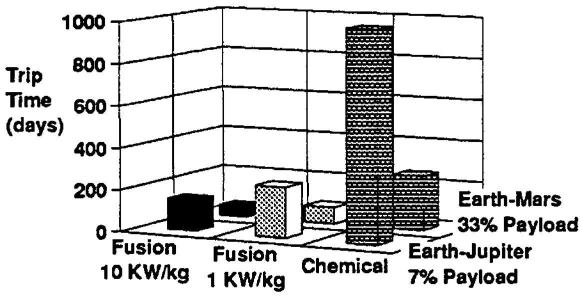

Fig. 3. One-way trip times for Earth-Mars and Earth-Jupiter travel, assuming chemical-rocket payload fractions.

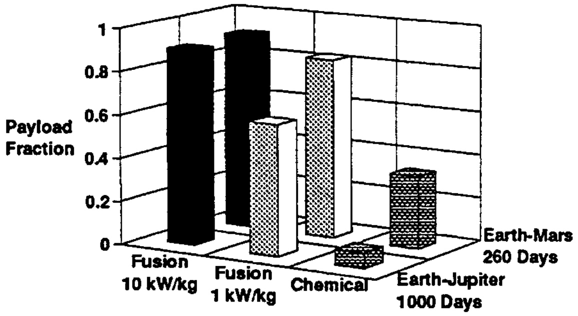

Fig. 4. Payload fractions for Earth-Mars and Earth-Jupiter travel, assuming chemical-rocket trip times.

This paper has focused on propulsion, but it is important to recognize that the fusion system which arrives at a destination has other applications. In particular, linear magnetic fusion systems could be converted with only a small mass penalty from producing thrust to producing electricity [16]. This would be accomplished by the installation of an electrostatic direct energy converter in the form of a spider-web conductor configuration. Another application for the system would be as a 'fusion torch' for processing materials [17]. Thus, a magnetic fusion system could provide efficient propulsion, power, and materials processing for many applications throughout the Solar System. Such magnetic fusion systems would enable

- human settlements on Mars and other rocky bodies or in space,
- scientific outposts near the gas-giant planets (analogous to antarctic bases), and
- access to the vast resources of the asteroids.

5 CONCLUSIONS

Detailed design studies calculate very attractive exhaust velocities (up to 10^7 m/s) and specific powers (1–10 kW/kg) for magnetic fusion propulsion systems, and a simple generic model has been used to understand this performance qualitatively. These performance levels would enable fast human transport or high-payload-fraction cargo transport throughout the Solar System. On this basis, I confidently predict that, as the train did in opening the American West, D-^{3}He magnetic fusion will open the Solar-System frontier.

ACKNOWLEDGMENTS

Useful discussions with Stuart Brandes and with colleagues in the UW Fusion Technology Institute are gratefully acknowledged. This research was supported by NASA and by the Grainger Foundation.

REFERENCES

[1] L.J. Wittenberg, J.F. Santarius, and G.L. Kulcinski, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technology* **10**, 167 (1986).

[2] E. Stuhlinger, *Ion Propulsion for Space Flight* (McGraw-Hill, New York, 1964).

[3] W. Ley, *Satellites, Rockets and Outer Space* (Signet, New York, 1958).

[4] P. Hastings, *Railroads: An International History* (Praeger Publishers, New York, 1972).

[5] J.F. Santarius and B.G. Logan, "Generic Magnetic Fusion Rocket Model," *29th Joint Propulsion Conference*, paper AIAA-93-2029 (1993).

[6] G.W. Englert, "Towards Thermonuclear Rocket Propulsion," *New Scientist*, **16**:16, 307 (1962).

[7] S.K. Borowski, "A Comparison of Fusion/Antiproton Propulsion Systems for Interplanetary Travel," *23rd Joint Propulsion Conference*, paper AIAA-87-1814 (1987).

[8] J.F. Santarius, "Lunar ^{3}He, Fusion Propulsion, and Space Development," in *Second Conference on Lunar Bases and Space Activities of the 21st Century* (Houston, Texas, April 5–7, 1988) (NASA Conf. Pub. 3166, Vol. 1, p. 75, 1992).

[9] R. Chapman, G.H. Miley, and W. Kernbichler, "Fusion Space Propulsion with a Field Reversed Configuration," *Fusion Technology*, **15**, 1154 (1989).

[10] V.E. Haloulakos and R.F. Bourque, "Fusion Propulsion Systems," *25th Joint Propulsion Conf.*, paper AIAA 89-2629 (1989).

[11] R.W. Bussard, "Fusion as Electric Propulsion," *J. Propulsion and Power* **6**, 567 (1990).

[12] E. Teller, A.J. Glass, T.K. Fowler, A. Hasegawa, and J.F. Santarius, "Space Propulsion by Fusion in a Magnetic Dipole," *Fusion Technology* **22**, 82 (1992).

[13] M. Deveny, S. Carpenter, T. O'Connell, and N. Schulze, "Mirror Fusion Propulsion System: A Performance Comparison with Alternate Propulsion Systems for the Manned Mars Mission," *29th Joint Propulsion Conference*, paper AIAA-93-2094 (1993).

[14] R.W. Bussard and L.W. Jameson, "The QED Engine Spectrum: Fusion-Electric Propulsion for Air-Breathing to Interstellar Flight," *29th Joint Propulsion Conference*, paper AIAA-93-2006 (1993).

[15] J.F. Santarius, "Magnetic Fusion for Space Propulsion," *Fusion Technology* **21**, 1794 (1992).

[16] J.F. Santarius, G.L. Kulcinski, L.A. El-Guebaly, G.A. Emmert, H. Khater et al., "Critical Issues for SOAR: The Space Orbiting Advanced Fusion Power Reactor," *Space Nuclear Power Systems 1988*, p. 161 (Orbit, Malabar, Florida, 1989).

[17] B.J. Eastlund and W.C. Gough, "The Fusion Torch—Unique Applications of Ultra-High Temperature Plasmas," *British Nuclear Energy Soc. Nucl. Fusion Reactor Conf.*, p. 410, Culham Laboratory, England (1969).