Magnetic Fusion for Space Propulsion: Capabilities and Issues

J.F. Santarius

July 1992

UWFDM-900

Proc. of the American Nuclear Society Topical Meeting on Nuclear Technologies for Space Exploration, 16–19 August 1992, Jackson Hole WY, p. 409.

Magnetic Fusion for Space Propulsion: Capabilities and Issues

J.F. Santarius

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu

July 1992

UWFDM-900

Proc. of the American Nuclear Society Topical Meeting on Nuclear Technologies for Space Exploration, 16–19 August 1992, Jackson Hole WY, p. 409.

MAGNETIC FUSION FOR SPACE PROPULSION: CAPABILITIES AND ISSUES

J.F. SANTARIUS
Fusion Technology Institute
University of Wisconsin
Madison, WI 53706
608/263-1694

ABSTRACT

The benefits of magnetic fusion for space propulsion were recognized during the early years of the terrestrial fusion research program. Recent studies, invoking modern fusion reactor configurations and technology, support the earlier conclusion. This paper describes the general arguments for expecting fusion to be an attractive space propulsion power source, and then examines three recent studies of fusion propulsion systems, based on a dipole, a field-reversed configuration (FRC), and a tandem mirror. These studies are used to assess fusion energy for space propulsion and to identify critical issues.

INTRODUCTION

The history of research into magnetic fusion for space propulsion goes back almost as far as terrestrial fusion research,[1] and many of the design solutions identified at that time are still valid. However, fusion reactor configurations and technology have evolved considerably, and the tools available for fusion reactor analysis have been greatly enhanced.

Numerous options exist for a space fusion propulsion power source, and the three selected for discussion here were chosen primarily because the author has recently been involved in studies of them for space applications. Several other options appear attractive, and the present selection should not be construed to suggest that research into any fusion configuration has been performed in sufficient detail to substantially narrow the options. In part, the difficulty arises because the present leading candidate for terrestrial fusion power, the tokamak, will almost certainly perform too poorly—in terms of thrust power per unit mass—to compete with fission power in space. Thus, almost all studies of fusion for space propulsion have selected 'advanced' configurations, whose projected performance surpasses that of the tokamak, but whose research programs and experimental data bases are far smaller. No system study of a space-propulsion fusion reactor has approached the major terrestrial fusion reactor system studies in depth of detail.

Although the terrestrial fusion research program focuses on the D-T fuel cycle, most work on magnetic fusion for space propulsion indicates that the D-^{3}He fuel cycle will dominate. The main fusion reactions involved are listed in Table I. The preference for D-^{3}He arises despite a lower fusion power density in D-^{3}He plasmas than in D-T plasmas, because the charged fusion products from D-^{3}He reactions can be guided to provide direct thrust or electricity, whereas 80% of the energy from D-T reactions is produced in neutrons. The D-T system, therefore, requires more massive shielding, thermal cycle

TABLE I.

Key Fusion Fuels, Including Main Secondary Reactions

D +T	→	n (14.07 MeV)+^{4}He (3.52 MeV)
D +^{3}He	→	p (14.68 MeV)+^{4}He (3.67 MeV)
D +D	→	n (2.45 MeV)+^{3}He (0.82 MeV)
D +D	→	p (3.02 MeV)+T (1.01 MeV)

energy conversion at relatively low efficiency, larger radiator mass for waste heat rejection, and an intermediate system to convert the resulting electricity into thrust.

The D-T fuel cycle requires a tritium breeding blanket and processing system, adding considerable complexity to the system. On the other hand, ^{3}He fuel is very rare on Earth, and this has driven much of the terrestrial fusion research program in the D-T direction. Recently, the problem of the scarcity of terrestrial ^{3}He has been solved, in principle, by the identification of a major resource of ^{3}He on the Moon.[2]

For the present paper, three configurations were selected: the dipole,[4] the field-reversed configuration (FRC),[5-7] and the tandem mirror.[8] Systems studies for all three configurations predict specific powers >1 $\mathrm{kW}_{thrust}/\mathrm{kg}_{reactor}$ at exhaust velocities $\sim 10^4$–10^7 m/s. The exhaust velocity is characterized here by the *specific impulse*, $I_{sp} \equiv v_{ex}/g_0$, where v_{ex} is the exhaust velocity and g_0 is Earth's surface gravity. The present range, $I_{sp} \sim 10^3$–10^6 s, is ideal for propulsion throughout the Solar System.[9] The specific-power capabilities of fusion are about ten times better than those of projected fission propulsion systems with similar performance—that is, nuclear-electric propulsion systems that can also achieve high specific impulses. The expected operating regimes for fusion, fission, and chemical propulsion systems are shown in Fig. 1.[10]

Fusion's excellent performance stems partly from its direct-thrust capabilities. Compared to systems that convert thermal energy to electricity and then to thrust, fusion gives a higher propulsion system efficiency, η, and also reduces waste heat, proportional to $(1-\eta)$. The result is a strong dependence of performance on efficiency, proportional to $\eta/(1-\eta)$; this function is shown in Fig. 2.

OVERVIEW OF THREE SPACE PROPULSION FUSION CONCEPTS

In many ways, the dipole, field-reversed configuration, and tandem mirror differ dramatically, but they share the key characteristic that the magnetic field lines escaping from the plasma are topologically linear. All are, therefore, well suited to providing direct thrust. The average plasma temperature of a D-^{3}He plasma in all three configurations would be 50–100 keV, and the plasma densities would be $\lesssim 10^{21}$ m^{-3}. The masses for the key propulsion-system components of all of these configurations can be estimated with reasonable accuracy, being dominated by the magnets, magnet-coolant refrigerators, shields, radiators, and input-power systems.

Projected parameters for space propulsion versions of the dipole,[4] FRC,[5] and tandem mirror[8] are given in Table II. All three would give high specific powers, at least 1 kW/kg,

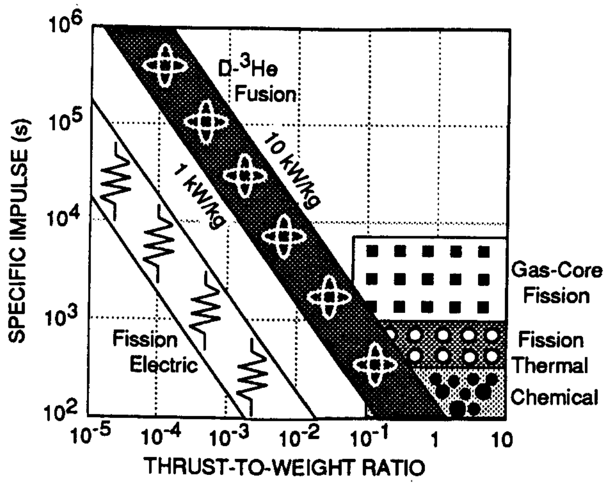

Fig. 1. Comparison of propulsion systems.[10] The thrust-to-weight ratio refers to the power and propulsion system only, referenced to Earth's surface gravity.

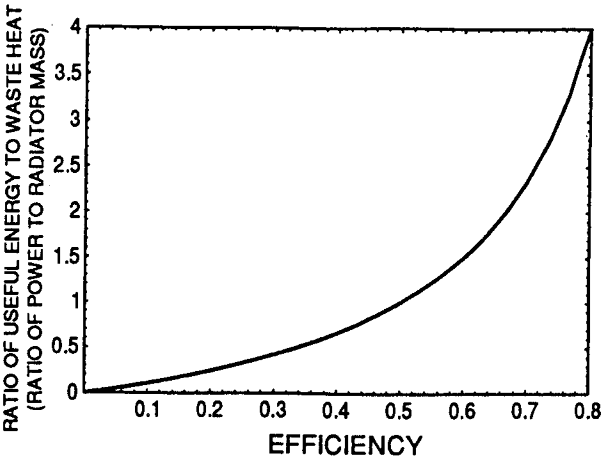

Fig. 2. Ratio of useful power to waste heat as a function of propulsion system efficiency.

TABLE II.

Projected Parameters for Three Fusion Propulsion Configurations

	Dipole[4] [a]	FRC[5] [b]	Tandem Mirror[8]
System Parameters			
Specific power $(\mathrm{kW}_{thrust}/\mathrm{kg})$	1	1.3	1.2
Fusion power (MW)	2000	500	1960
Thrust power (MW)	1250	330[c]	1500
Neutron power fraction	0.03	0.019	0.025
Neutron wall loading $(\mathrm{MW/m^2})$	0.069	?	0.17
Total mass [Mg (tonnes)]	1180	250	1250
Length or circumference (m)	38	9	113
Fusion Core Parameters			
^{3}He to D density ratio	1	1.5	1
Electron density (m^{-3})	4×10^{20}	?	5×10^{21}
Electron temperature (keV)	70	66	65
Ion temperature (keV)	70	100	79
Plasma radius (m)	—	1.5	0.41
Structure outer radius (m)	2.0	~2.7	1.0
Magnetic field (T)	5	5	6.4
Peak B field on coil (T)	18	~7	~8

---

[a] Peak plasma parameters are given.

[b] Some parameters are extrapolated and were not calculated in the original reference. The specific power would rise if the fusion power were raised.

[c] Extrapolated value based on the dipole and TMR efficiencies.

and the FRC would benefit from economy of scale if the design had been done at 2000 MW_{fus} rather than 500 MW_{fus}. With optimization or a small penalty in specific power, the dipole and TMR should be able to perform well at $\lesssim$ 1000 MW_{fus}. Nevertheless, it does not appear likely that these types of magnetic confinement fusion systems will provide high specific power in the 10's of MW_{fus} range, due to the required massive magnets and radiation shields.

Generic Issues

Redesign in several generic areas will be required in modifying terrestrial designs for space applications. In particular, low mass dominates materials costs when designing the magnets and radiation shields—which favors concepts with high beta and axisymmetry. Heat rejection, as in all space power systems, will be extremely important, as will directly converting the fusion power into thrust or other useful forms. Attention must also be paid to minimizing the mass of the input power and the recirculating power conversion systems.

The designs discussed here have taken steps in the direction of minimizing mass—the tandem mirror, for example, uses a LiH shield—but this activity has only begun. Although the magnets in these designs sometimes invoked high-strength structural materials, they did not assume such potential advances as beryllium stabilizer instead of copper or the use of high-T_c superconductors. Replacing helium coolant with hydrogen or nitrogen would greatly reduce the refrigerator mass and would allow higher nuclear heating levels in the magnets—reducing shield thickness. Advances in radiator technology would also improve performance—as in all space power systems.

Dipole

In a dipole fusion reactor, the plasma surrounds a single-loop magnet coil,[3] inverting, in a sense, the standard magnetic fusion reactor configuration. The dipole reactor geometry, shown in Fig. 3,[4] is somewhat analogous to that of the radiation belts of Earth and Jupiter. Although the geometry is simple, the system is complicated by the need to keep the superconducting magnet at very low temperatures. The good performance indicated in Table II derives from a study aimed at assessing feasibility,[4] and further work to optimize the design would almost certainly increase the specific power.

The dipole is the least developed of the three concepts presently under discussion, and its most important need is experimental verification of the basic physics, including the equilibrium profiles, MHD stability, and transport properties. The first steps in this direction will be taken in a small experiment this summer.[11] Critical physics issues for a D-^{3}He dipole space-propulsion reactor are listed in Table III. The magnitudes of the outward energy transport and the synchrotron radiation production are important for the overall plasma power balance. The inward energy transport must lead to surface heat fluxes lower than ~1 MW/m^2 in order for the ring surface to be radiatively cooled. Fueling and startup of a space dipole have not yet been addressed in detail.

The engineering challenge of a space dipole reactor lies primarily in integrating the electricity generators and heat pumps into the magnet shield and in designing the high-current-density, low-mass, high-field magnet. Critical dipole engineering issues are listed

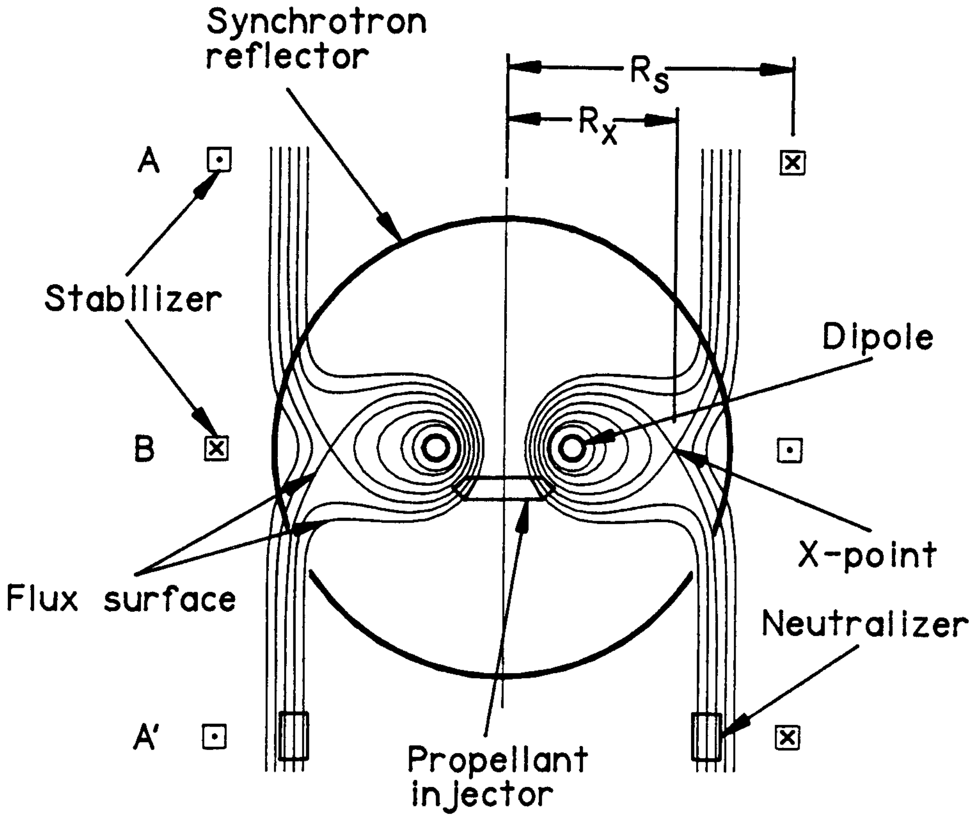

Fig. 3. Dipole configuration for space propulsion.[4]

TABLE III.

Critical Dipole Physics Issues

- Verification of predicted equilibrium profiles
- MHD stability
- Inward and outward transport
- Synchrotron radiation production
- Fueling
- Startup

TABLE IV.

Critical Dipole Engineering Issues

- High-field, low-mass, magnet design
- Internal ring electricity generation
- Internal ring cooling system demonstration
- Ring surface–plasma interactions
- Maintenance

in Table IV. Although the basic concept appears feasible, the integrated system remains to be demonstrated. Maintenance is a crucial area, because even the low D-^{3}He neutron flux will activate the ring sufficiently to force remote maintenance. Also, because the ring will dominate the total mass, repair rather than replacement will be necessary unless an optimized dipole reactor can operate at much lower powers, so that several dipole reactors could be used to power a single fusion rocket. An operational issue is that, as in space fission reactors, prohibitively massive shields would be needed to attenuate the radiation flux in all directions, so shadow shields must be used for crew quarters and care must be taken when traveling in the vicinity of space stations and other sensitive regions. On the other hand, because the heat also radiates directly to space, the dipole ring is the system's radiator, saving considerable heat-rejection mass.

Field-Reversed Configuration

The FRC is a plasma toroid, sustained by internal currents and immersed in an external magnetic field of linear topology.[12] The basic configuration of a space-propulsion FRC is shown schematically in Fig. 4.[5] Fig. 5 shows a more detailed view of the fusion core region of a terrestrial D-^{3}He FRC reactor that utilizes translation from a formation chamber into a burn chamber.[7] The magnetic mirror ratio for one end would be increased slightly, thus causing preferential loss out the other end for propulsion. The D-^{3}He FRC appears to possess many advantages for space propulsion,[5,6] including a high ratio of plasma pressure to magnetic field pressure (β), which effectively utilizes the solenoidal magnet configuration. Much of the thrust power will be in the form of edge plasma—where temperatures in the 10 eV to 10 keV range give useful specific-impulse values. The specific power given in Table II represents an estimate based on the parameters given in Ref. 6. A slightly different FRC configuration, the field-reversed mirror, in which neutral beams would create and sustain the plasma in a single chamber, may be preferable for minimizing the reactor mass.

The FRC has a small, but significant experimental data base.[12] Critical physics issues for a D-^{3}He FRC space-propulsion reactor are listed in Table V. The FRC MHD stability has generally been better than predicted theoretically, and testing whether this behavior continues in the reactor regime will be important. An advantage of D-^{3}He fuel over D-T fuel is that the large gyroradius of the D-^{3}He proton should contribute to stability. For space applications, it will be crucial to use a slow startup technique, because the mass associated with the power requirements of the present reversed-field theta-pinch methods appears prohibitive. Critical engineering issues are listed in Table VI. The main engineering questions for a D-^{3}He FRC in space relate to the masses required for startup and for either current drive or pulsed operation.

The FRC potentially could provide the highest specific power of the three configurations presently under discussion, perhaps $\lesssim 5$ kW/kg. The FRC's high beta, modest-field axisymmetric magnets, and direct-thrust capability would be ideal for space applications. If sufficiently low power levels can be attained efficiently, modularity and redundancy would be a significant advantage.

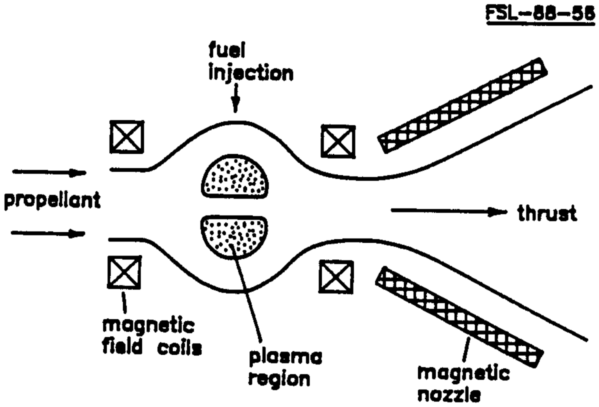

Fig. 4. Schematic FRC configuration for space propulsion.[5]

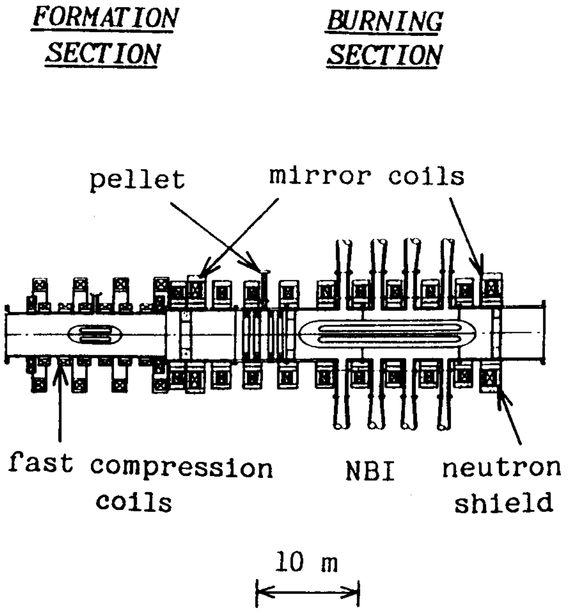

Fig. 5. Fusion core of a D-^{3}He terrestrial FRC reactor configuration.[7]

TABLE V.

Critical FRC Physics Issues

- Verification of MHD stability at reactor-relevant sizes
- Transport
- Startup
- Pulsed operation or current sustainment

TABLE VI.

Critical FRC Engineering Issues

- Startup system mass
- Current-drive system

Tandem Mirror

The tandem mirror reactor (TMR) consists of a solenoidal magnetic bottle—a central cell—with plasma end loss reduced by a combination of magnetic mirrors and electrostatic potentials in end cells.[13] For propulsion, the electrostatic potential in one end cell would be raised to increase confinement, resulting in preferential loss out the other end and, therefore, directed thrust. The ions lost out the end of a tandem mirror fall down a potential hill of about 1 MV, which gives too high a velocity to be useful within the Solar System, so matter must be added to the exhaust to increase the thrust, simultaneously decreasing the specific impulse.

The tandem mirror possesses the largest experimental data base of the configurations discussed here, but the program was small compared to that of the tokamak, and the U.S. Office of Fusion Energy has now eliminated all non-tokamak magnetic fusion research. Critical physics issues for a D-^{3}He TMR space-propulsion reactor are listed in Table VII. The demonstration of plasma end loss plugging in the reactor plasma regime is the chief generic TMR issue. In order to minimize magnet mass, the demonstration of axisymmetric MHD stabilization by radio frequency (RF) waves or by conducting walls will also be important. Substantial progress in each of these areas has already been accomplished. Fueling will be an issue if radial plasma profiles peaked on axis are required—which would probably necessitate fueling using small, D-^{3}He, compact toroid injection.

D-^{3}He tandem mirror critical engineering issues are listed in Table VIII. Because a D-^{3}He fusion plasma must operate in the 40–100 keV temperature range, the ions in the tandem mirror end cell must be sustained in an electrostatic potential of $\sim$1 MV, and the neutral beam injection energy must be $\sim$2 MeV, requiring the use of negative-ion sources. The necessary startup system for a space TMR must be defined, although advantage can be taken of electrostatic direct conversion to provide power quickly and minimize this mass.[14]

A key advantage of the TMR is its inherent modularity, because spare magnet and shield modules could be carried with only a small mass penalty. The TMR's projected specific power, at $\sim$1 kW/kg, would be very attractive for space propulsion and, although the FRC may eventually provide higher specific powers, the tandem mirror would more credibly allow the near-term construction of an engineering demonstration reactor.

SUMMARY

The dipole, field-reversed configuration, and tandem mirror have been identified as potentially attractive magnetic fusion systems for space applications. Projected specific powers are $\gtrsim$ 1 kW/kg at specific impulses of 10^3–10^6 s. An obstacle in developing these and other fusion options for space is that research on the D-^{3}He fuel cycle and on the most attractive configurations for space is not supported by the terrestrial magnetic fusion program, which has narrowed its options to the D-T tokamak reactor. Nevertheless, magnetic fusion possesses compelling advantages for space applications and warrants aggressive development.

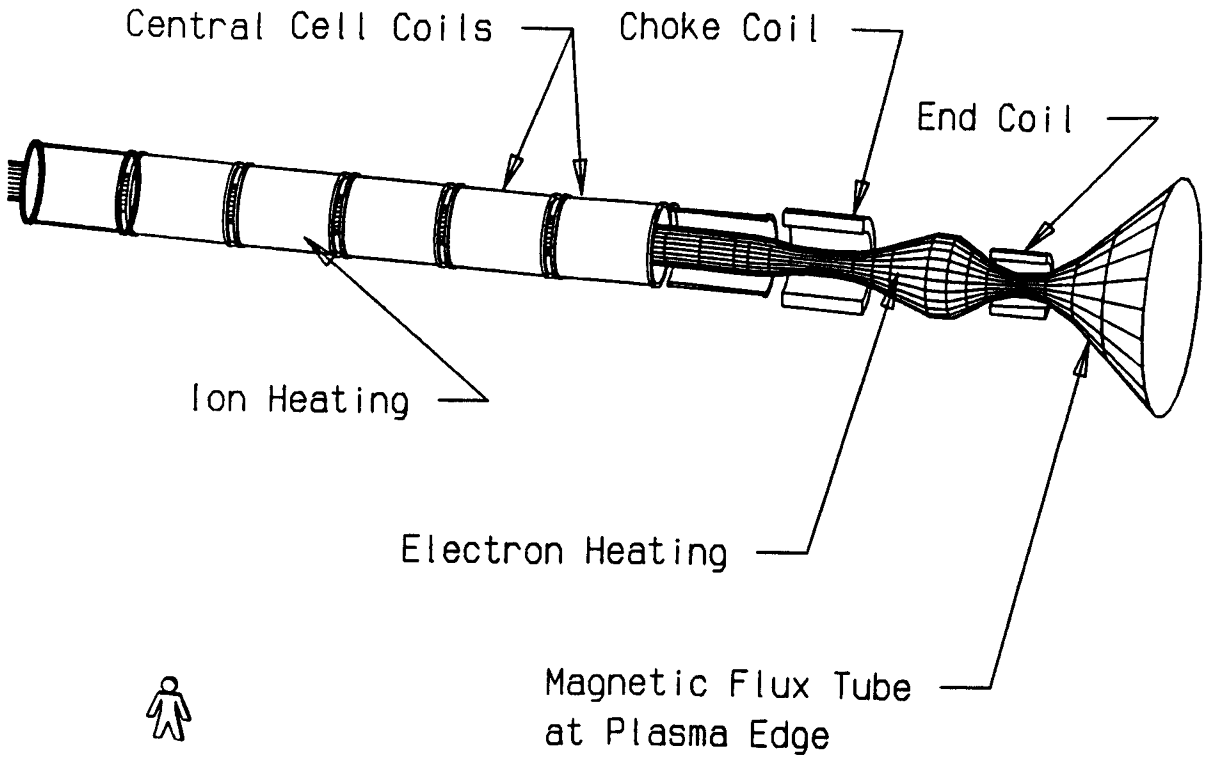

Fig. 6. Tandem mirror configuration for space propulsion.[8]

TABLE VII.

Critical TMR Physics Issues

- End-loss plugging at reactor parameters
- RF or wall MHD stabilization for axisymmetric operation
- Fueling
- Dilution of end-loss plasma into usable thrust plasma regimes

TABLE VIII.

Critical TMR Engineering Issues

- Negative-ion-source neutral beam development

ACKNOWLEDGMENTS

Helpful discussions with Randall Chapman are gratefully acknowledged. This research was supported by the Grainger Foundation and the University of Wisconsin.

REFERENCES

1. G.W. ENGLERT, "Towards Thermonuclear Rocket Propulsion," *New Scientist* **16**:16, 307 (1962).
2. L.J. WITTENBERG, J.F. SANTARIUS, and G.L. KULCINSKI, "Lunar Source of ^{3}He for Commercial Fusion Power," *Fusion Technol.* **10**, 167 (1986).
3. A. HASEGAWA, LIU CHEN, and M.E. MAUEL, "A D-^{3}He Fusion Reactor Based on a Dipole Magnetic Field," *Nucl. Fusion* **30**, 2405 (1990).
4. E. TELLER, A.J. GLASS, T.K. FOWLER, A. HASEGAWA, and J.F. SANTARIUS, "Space Propulsion by Fusion in a Magnetic Dipole," Lawrence Livermore National Laboratory Report UCRL-JC-106807, to be published in *Fusion Technol.* (1992).
5. R. CHAPMAN, G.H. MILEY, and W. KERNBICHLER, "Fusion Space Propulsion with a Field Reversed Configuration," *Fusion Technol.* **15**, 1154 (1989).
6. N.R. SCHULZE, G.H. MILEY, and J.F. SANTARIUS, "Space Fusion Energy Conversion Using a Field-Reversed Configuration Reactor," *Proc. NASA Space Transportation Propulsion Technology Symposium*, NASA Conference Publication 3112, Vol. 2, p. 453 (1991).
7. W. KERNBICHLER, M. HEINDLER, H. MOMOTA, et al., "D-^{3}He in Field Reversed Configurations—RUBY: an International Reactor Study," *Plasma Physics and Controlled Nuclear Fusion Research 1990, Vol. 3*, p. 555, IAEA, Vienna (1991).
8. J.F. SANTARIUS, "Lunar ^{3}He, Fusion Propulsion, and Space Development," in *Lunar Bases and Space Activities of the 21st Century–II*, Lunar and Planetary Institute, Houston, held 1988, to be published (1992). *Also see references therein.*
9. E. STUHLINGER, *Ion Propulsion for Space Flight*, McGraw-Hill, NY (1964).
10. J.F. SANTARIUS, "Magnetic Fusion for Space Propulsion," University of Wisconsin Report UWFDM-881, to be published in *Fusion Technol.* (1992).
11. M.E. MAUEL, private communication (1992).
12. M. TUSZEWSKI, "Field Reversed Configurations," *Nucl. Fusion* **28**, 2033 (1988).
13. R.F. POST, "The Magnetic Mirror Approach to Fusion," *Nucl. Fusion* **27**, 1579 (1987).
14. J.F. SANTARIUS, G.L. KULCINSKI, et al., "Critical Issues for SOAR: The Space Orbiting Advanced Fusion Power Reactor," *Space Nuclear Power Systems 1988*, p. 161, Orbit, Malabar, Florida (1989).