



# Magnetic Fusion Energy and Space Development

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# **Magnetic Fusion Energy and Space Development**

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## ABSTRACT

Large-scale space development will require efficient propulsion and power systems. Magnetic fusion energy conceptual designs are surveyed and indicate that fusion could provide attractive solutions to this need. Using deuterium and helium-3 as fuel gives fusion products that are primarily charged particles and could be guided by magnetic fields to allow high efficiency. The main 21st century source of  ${}^3\text{He}$  appears to be the lunar surface. Procuring  ${}^3\text{He}$  and producing efficient, economical fusion power face significant development paths, but both technologies plausibly can be developed on a relevant time scale—early in the 21st century. Possible future directions for space fusion energy research are also discussed.

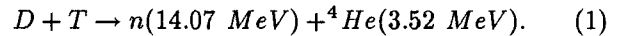
## 1. INTRODUCTION

The emerging science and technology of magnetic fusion energy may provide a critical capability for the expansion of humankind beyond Earth orbit—efficient space propulsion and power. Chemical rockets have served well in accomplishing the milestones of Earth launch to orbit and landing on the Moon. However, lunar settlements and missions beyond the Moon will need faster trip times and larger payload fractions. The key to satisfying these needs is high exhaust velocity ( $v_{ex}$ ), because payload fractions depend exponentially on  $-\Delta v/v_{ex}$ , where  $\Delta v \equiv (\frac{2}{m}\Delta E)^{1/2}$  and  $\Delta E$  measures the energy requirement of a mission. Consequently, a large amount of present research effort focuses on continuous, low-thrust, high-exhaust-velocity propulsion systems. Magnetic fusion lies within this class—plasmas exist at very high temperatures ( $>10^4$  K) and the confining magnetic fields insulate the plasma from material walls and allow the plasma to be guided to produce direct thrust or electricity.

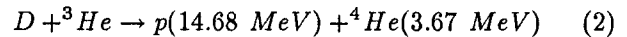
Key advantages expected for space applications of magnetic fusion energy include:

- No radioactive materials present at launch, and only low-level radioactivity present after operation,
- High specific power values,
- Direct conversion of energy to thrust or electricity,
- Thrust-mode flexibility over a wide range of thrust-to-weight ratios and specific impulses.

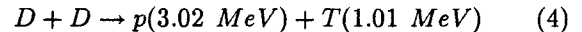
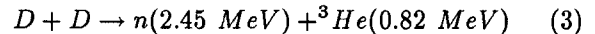
The fusion fuel that presently receives the most attention for terrestrial applications is based on the reaction of deuterium (D) and tritium(T):



However, applications of magnetic fusion energy in space would most likely burn deuterium and helium-3 ( ${}^3\text{He}$ ) as the main fuel, in the reaction



with a smaller contribution to the fusion power from the reactions



and the subsequent reaction of some of the T produced by the second D-D channel in D-T reactions.

The charged fusion products from the D- ${}^3\text{He}$  fuel cycle can be channeled to provide direct thrust or electricity, whereas 80% of the energy from D-T fuel 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 percent of fusion power produced as neutrons for the D-T, D-D, and D- ${}^3\text{He}$

fuel cycles, including secondary reactions, is shown in Figure 1 as a function of plasma ion temperature and fuel mixture.

Terrestrial fusion research has concentrated on D-T fuel because physics requirements for D-<sup>3</sup>He are more stringent—although many engineering requirements are eased—and because a feasible source of <sup>3</sup>He has not been discovered on Earth. The increased difficulty of the physics requirements is illustrated in Figure 2, which shows values achieved in tokamak experiments for the ion temperature plotted versus the confinement parameter,  $n_e\tau_E$ , where  $n_e$  is the plasma electron density and  $\tau_E$  is the plasma energy confinement time. The curves shown are the ignition boundaries for D-T and D-<sup>3</sup>He. A judgement on the relative difficulty of the major engineering issues for D-T and D-<sup>3</sup>He is shown in Figure 3 [1], and clearly favors D-<sup>3</sup>He.

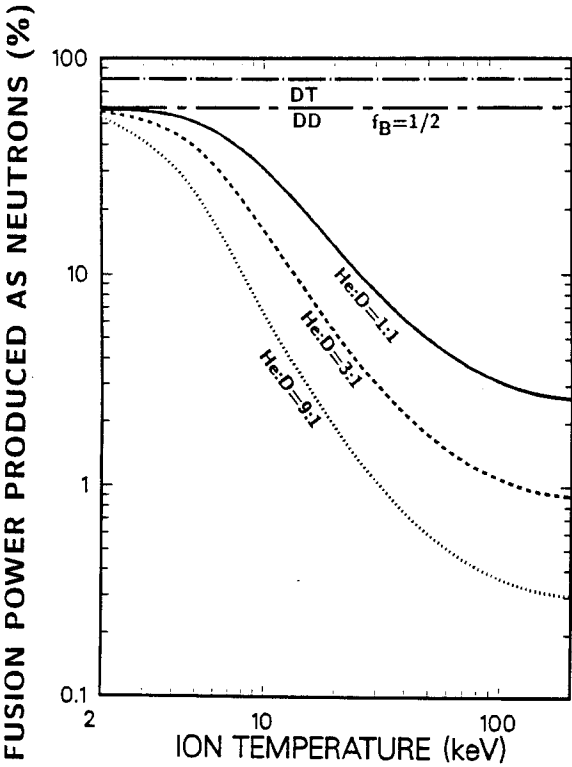


Figure 1. Percent of fusion power produced in neutrons for the main fusion fuel cycles[1]. One-half of the tritium produced by D-D reactions is assumed to be burned in subsequent D-T reactions.

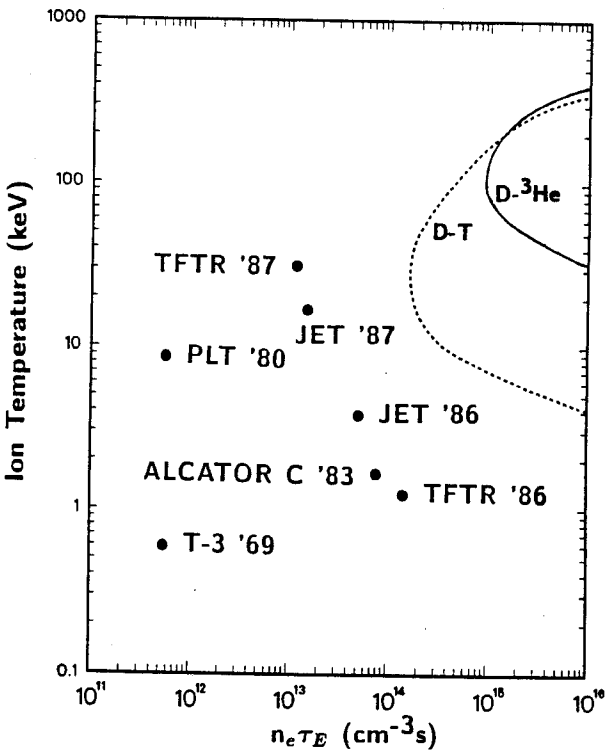


Figure 2. Achieved values of important physics parameters in tokamak experiments. Curves show the minimum values required for ignition[1].

AREA	HARDER	SIMILAR	EASIER
PHYSICS			
FUELING			
PLASMA HTG			
CURRENT DR			
FW HT FLUX			
MASS POWER DENSITY			
MATERIALS			
HIGH EFF. OP			
SAFETY			
ENVIRONMENT			
LICENSING			

Figure 3. Judgement of the relative difficulty of D-<sup>3</sup>He reactor physics and engineering compared to D-T reactors[1].

The  $^3\text{He}$  resource problem has been solved in principle by the recognition that a very large amount ( $\sim 10^9 \text{ kg} \sim 10^{10} \text{ MWe-y}$ ) of  $^3\text{He}$  exists in the first few meters of the lunar surface[2]. For long-term needs,  $^3\text{He}$  is abundant throughout the solar system, albeit mainly in gas giant planet atmospheres, so that local sources will be available once the requisite technology is in hand. Furthermore, D- $^3\text{He}$  reactions produce over 250 times the energy required to procure lunar  $^3\text{He}$  fuel[3], in contrast to matter/anti-matter annihilation which requires the production of anti-matter at an energy input 100 to 10,000 times the energy eventually released.

Recent developments have generated a revival of interest in space fusion power and propulsion. Key contributors to this rebirth have been:

- The identification of the lunar  $^3\text{He}$  resource,
- A national space policy that supports the expansion of humankind beyond earth orbit, and
- The emergence of high power density fusion concepts.

Although the difficulties lying along the development path for fusion power should not be underestimated, steady progress over thirty years has brought fusion science and engineering to the proof-of-principle stage[4]. In the context of space, the Committee on Advanced Fusion Power of the Air Force Studies Board, National Research Council, concluded in 1987 that[5]:

*“some fusion systems potentially offer specific powers (kilowatts/kilogram) and total power and weight characteristics that make them candidates for both space power and space propulsion applications.”*

Clearly, both procuring lunar  $^3\text{He}$  and producing efficient and economical fusion power have significant development paths remaining. Nevertheless, these technologies plausibly can be developed on a relevant time scale—in the early part of the 21st century. Fusion’s efficiency would increase useful power and decrease radiator mass, and studies project specific powers of 1-10 kW/kg[5,6,7]. Specific power is defined

here to be the thrust power divided by the masses of all the systems required to produce that power, including radiators and magnetic nozzles. Trajectory calculations show that these high performance levels would greatly enhance the efficiency and reduce the cost of transporting humans and cargo throughout the Solar System and of sustaining human presence. For example, as illustrated in Figure 4 [8], at payload fractions characteristic of chemical systems ( $\sim 33\%$ ), the trip time from Earth orbit to Mars orbit could be reduced from the nearly 9 months required by chemical rockets to less than 3 months[8]. For cargo missions, a fusion system allowing a 9 month trip time to Mars could give a payload fraction of over 80%, more than doubling that of a chemical system (see Figure 4 [8]).

This paper will briefly summarize historical work on magnetic fusion energy applications in space, will examine present thinking for both toroidal and linear systems, and will explore anticipated future directions. Only magnetic fusion energy will be treated, although some interesting work also exists on inertial confinement fusion for propulsion[9].

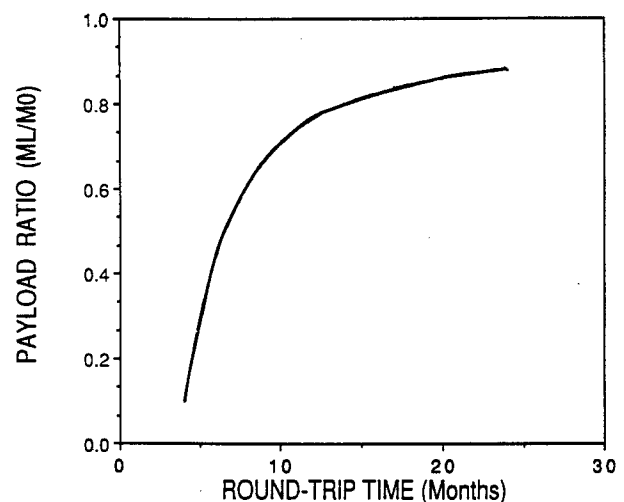


Figure 4. Dependence of payload ratio on round-trip time for Earth orbit to Mars orbit travel[8]. Assumes thrust system specific power of 1 kW/kg, typical of projected fusion parameters, and a varying acceleration magnitude ( $T/W < 10^{-3}$ ) and direction as given in Ref. 8.

## 2. EARLY STUDIES OF FUSION PROPULSION

Space applications of fusion energy began to be explored during the early days of terrestrial fusion power research[10,11]. The initial papers assumed the use of either the D-D or D-T fuel cycles, but groups at NASA Lewis Research Center[12] and Aerojet-General Nuclear[13] soon identified the D-<sup>3</sup>He fuel cycle as the most attractive for use in space. A space fusion research program also existed at the Air Force Office of Scientific Research[14]. Some of the ideas pioneered in the early work were:

- D-<sup>3</sup>He fuel,
- Plasma directly exhausted to produce thrust,
- Matter added to the exhaust to reduce specific impulse and increase thrust, and
- Superconducting magnets.

Most of the early work assumed a simple linear geometry, as shown in Figure 5 [12]. Although many good ideas originated in this research, the first concept investigated—a

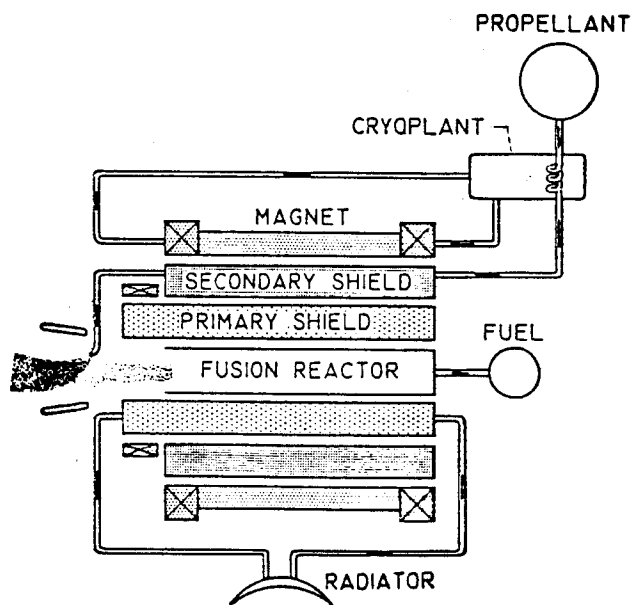


Figure 5. Earliest D-<sup>3</sup>He fusion rocket concept[12].

single, axisymmetric, magnetic mirror cell—was later shown to be unable to provide net power and was superseded by more complex configurations. Work continued at NASA Lewis Research Center throughout most of the 1970's, including conceptual designs of a toroidal system, the bumpy torus shown in Figure 6 [15]. This design serves to illustrate a generic feature of toroidal fusion propulsion systems—plasma diverted into a magnetic nozzle to provide thrust. Again, the D-<sup>3</sup>He reaction was usually identified as the most attractive fuel cycle.

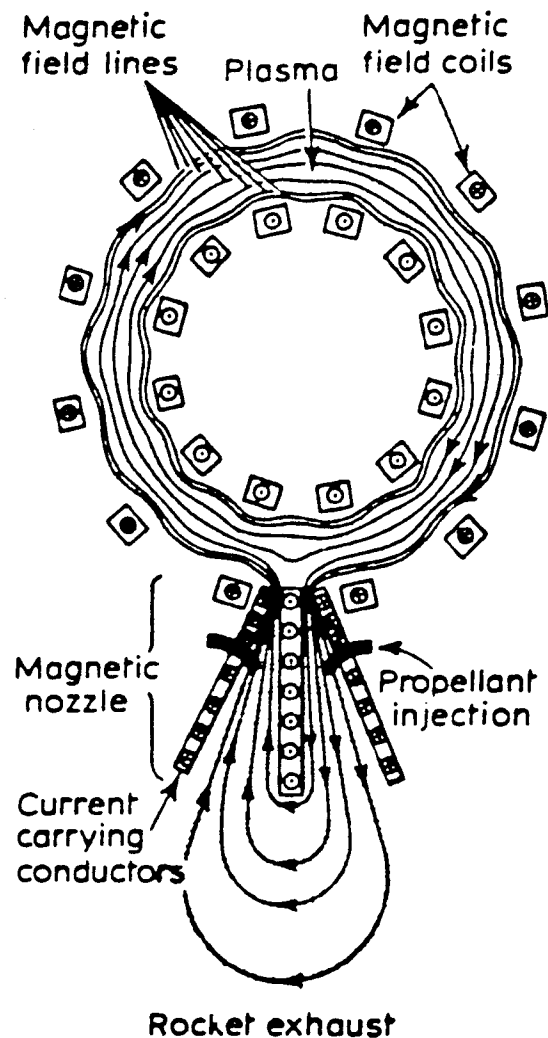


Figure 6. Toroidal fusion rocket concept midplane cross-section[15].

### 3. MODERN STUDIES

In the past fifteen years, only a few, relatively small studies of magnetic fusion energy in space have been performed, primarily during the three years since the connection was made between lunar  $^3\text{He}$  and fusion power[2]. These include generic analyses[16,17], and conceptual fusion propulsion system designs based on the spherical torus[7], the spheromak[7], the tandem mirror [6], and the field-reversed configuration (FRC)[18]. Despite varying assumptions, the key conclusion of both the generic work and the more detailed analyses was that fusion propulsion system specific powers of 1-10 kW/kg are feasible. In assessing these studies, an important consideration is that the most massive systems for the designs—the magnets, shields, and radiators—are well characterized, with masses that can be confidently estimated.

#### Thrust Modes

Three main thrust modes exist for a fusion propulsion system[6]:

- Directly exhausting the fuel plasma,
- Augmenting the exhaust with material to reduce specific impulse but increase thrust, and
- Strongly confining the plasma, generating heat on the walls, and transferring this heat to a fluid for use as propellant.

Typical ranges of specific impulses and thrust-to-weight ratios available from these modes are shown in Figure 7 [6]. The basic principles apply both to toroidal systems in which part of the plasma has been diverted away from the fusion core and to linear systems. A mode in which the gas-plasma interaction occurs at the edge of the plasma cylinder is also under investigation[19].

#### Tokamak

The tokamak concept is a toroidal magnetic bottle with the main field provided by external magnets and a twist in the field created by generating a toroidal current in the plasma. The tokamak dominates fusion research worldwide, but a direct extrapolation of a typical terrestrial tokamak

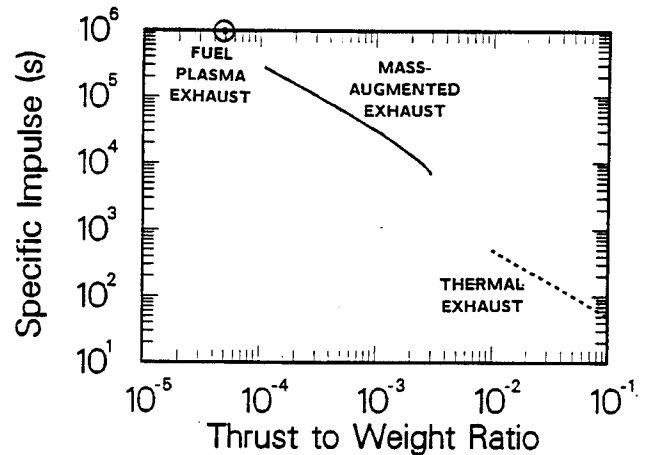


Figure 7. Typical ranges of specific impulses and thrust-to-weight ratios for D- $^3\text{He}$  fusion propulsion systems[6].

design to space would be impractically massive for the power produced. Because of the success of tokamak experiments, a strong incentive exists to identify tokamak variants of increased power density. The so-called spherical torus[20] has been extrapolated to D- $^3\text{He}$  operation and found to provide attractive parameters for space[7].

#### Tandem Mirror

The simple mirror systems investigated by early researchers evolved into configurations with successively better end-plugging of the linear magnetic bottle, and the present generation is named the “thermal barrier tandem mirror.” Budgetary reasons have caused the Department of Energy to mothball the mirror research program and, therefore, it faces a difficult development path. Nevertheless, the simple geometry of the tandem mirror holds considerable potential for space. Based on conceptual D- $^3\text{He}$  tandem mirror reactor designs for both Earth[21] and space[22,23], one propulsion system has been designed[6]. Figure 8 shows an extrapolation of this design, with details of the structure, radiators, shields, life-support systems, and maintenance added by students in the Engineering Mechanics Senior Design Project course at the University of Wisconsin[24].

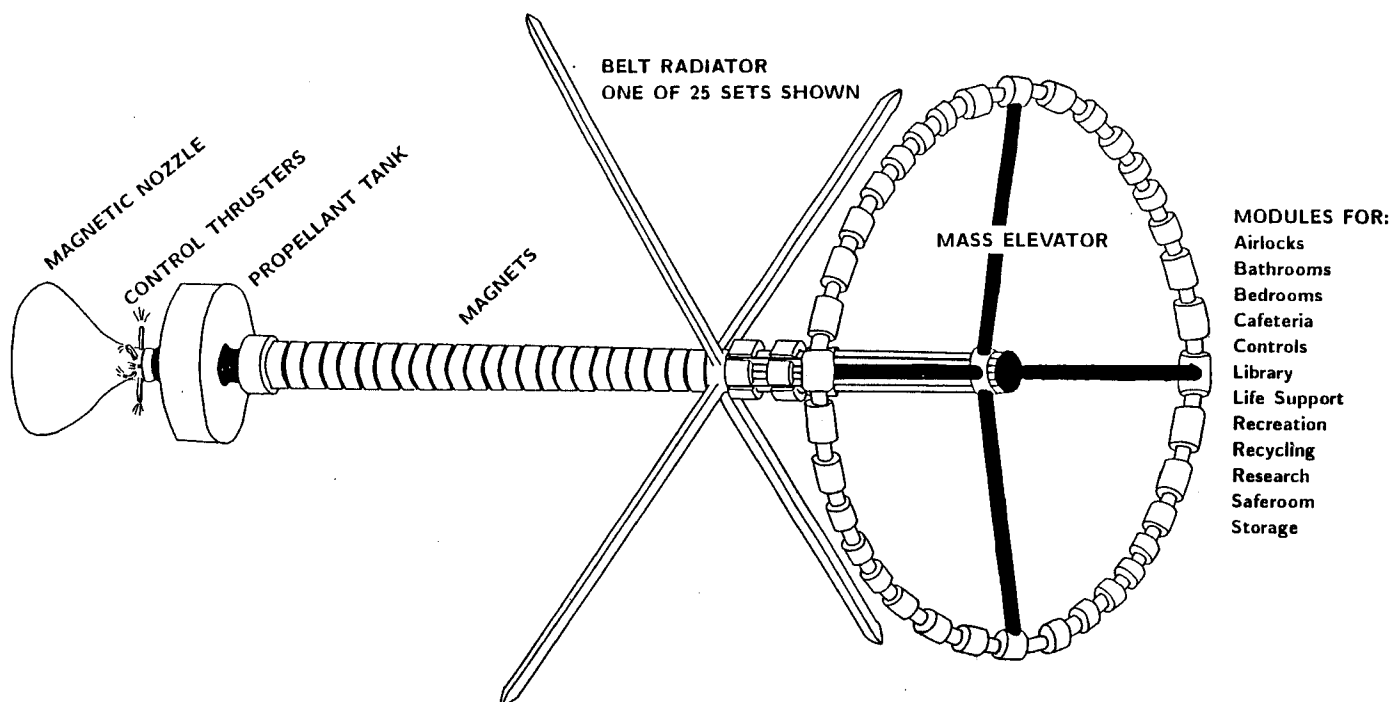


Figure 8. Fusion rocket concept by a University of Wisconsin Engineering Mechanics Department Senior Design Project student team, based on the tandem mirror[24].

## Spheromak

The spheromak fusion reactor concept is shown in Figure 9 [7]. It requires only axisymmetric coils, and induced currents generate a magnetic torus with approximately equal field magnitudes in the toroidal (inside torus) and poloidal (short way around torus) directions. A high specific power is expected because the system is compact, without the need for coils encircling the magnetic torus as in most other concepts. The spheromak is in an early stage of development, and a small worldwide research program exists.

A study is in progress to survey fusion propulsion systems for Air Force missions[25]. One interesting concept investigated during that study is the translating compact torus (TCT) and is based on either colliding or compressing spheromaks. Only preliminary information is available.

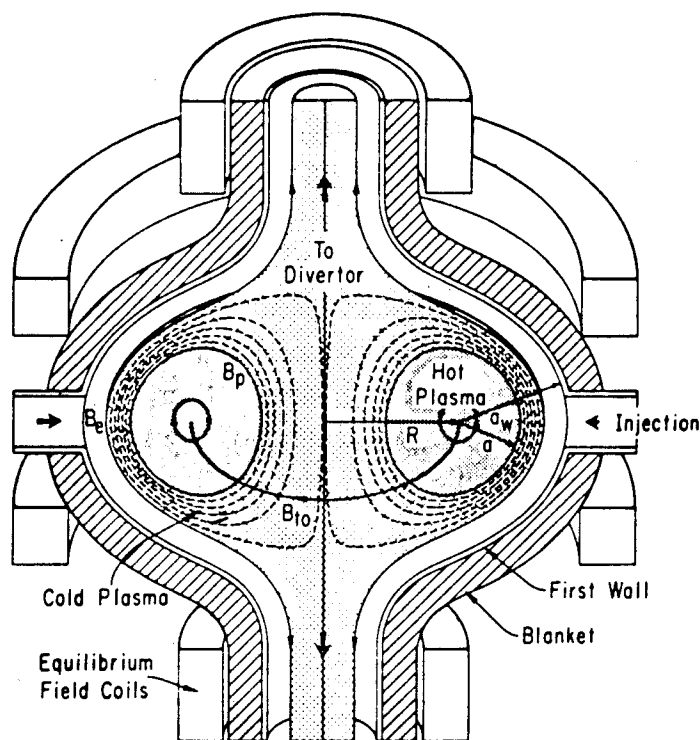


Figure 9. Configuration of the spheromak[7].



## Field-Reversed Configuration, FRC

The field-reversed configuration (FRC), shown in Figure 10 [18], is a potentially attractive D-<sup>3</sup>He fusion propulsion system. It is similar to the spheromak in that no magnetic field coils link the plasma, and it provides about four times higher plasma pressure for a given magnetic field strength. The attractiveness is intuitively reasonable, because a D-<sup>3</sup>He FRC provides efficient utilization of magnetic fields, requires only axisymmetric magnets of relatively low field strength, and allows direct conversion to thrust or electricity for a large fraction of the fusion power. Although the FRC is in an early stage of physics development, next generation devices should answer the critical physics issues and are now under construction. Some of the advantages of the FRC for space have been quantified, particularly regarding physics questions[18].

## Electric Power Production

Space fusion power research has focussed primarily on propulsion, because fusion systems will most likely be at levels (>100 MWe) where space applications of electric power are not easily identified. However, a recent design, SOAR—the Space Orbiting Advanced Fusion Power Reactor, exists for a tandem mirror providing burst-mode power in Earth orbit[22,23]. The key concept for power production in linear systems is that hot plasma can be directed mainly out one end of the device and guided by the magnetic field into a system of grids and plates (the direct converter) which converts the plasma energy directly into electricity. This concept applies also to field-reversed configurations and spheromaks, which are toroidal plasmas immersed in a linear magnetic field geometry. A direct converter in space can take advantage of the availability of high vacuum and expand to the large volume required by high heat fluxes without undue mass penalty.

## Other Options

Various other concepts have been investigated for space[26,27], but are not presently being pursued by the Department of Energy fusion research program. These have only a small data base and require substantial extrapolation of most parameters to reach the reactor regime. Although interesting, they must be considered speculative at present.

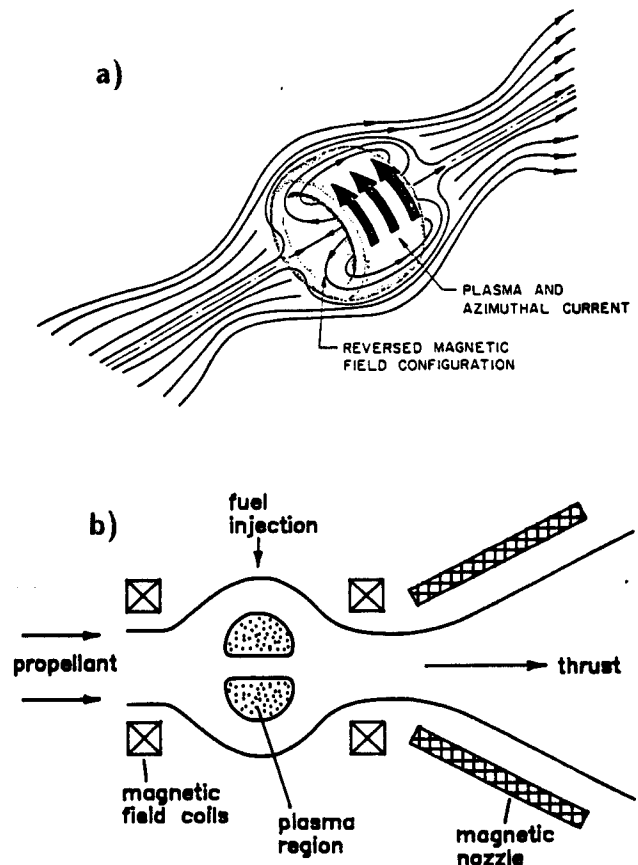


Figure 10. Configuration of the field-reversed configuration (FRC)[18]. (a) Basic concept. (b) Cross-section with magnetic thruster shown.

## 4. FUTURE SPACE FUSION DIRECTIONS

### Lunar $^3\text{He}$ and Space Development

The National Commission on Space recently identified advanced, low-thrust propulsion technology to be a critical need for large-scale space development[28]. The fusion propulsion systems discussed in this paper might fulfill that need, but three key questions must be answered:

1. *Is the lunar  $^3\text{He}$  resource technically and economically viable?*
2. *Will fusion energy be ready for space applications on the time scale required for space development?*
3. *Will the extent of human expansion into space become sufficiently large that the high power levels provided by fusion energy become necessary?*

The technical, economic, and legal viability of the lunar  $^3\text{He}$  resource is being examined intensely[29]. Regarding technical issues, a recent NASA workshop[1] reached the encouraging conclusion that "lunar mining of  $^3\text{He}$  is feasible." Initial research on the feasibility of lunar  $^3\text{He}$  procurement from energy[3] and economic[30] points of view is positive. The legal issues are complex, but no insurmountable difficulties have been identified in preliminary research[31]. Extrapolating to a future where Earth-Moon travel and terrestrial  $^3\text{He}$  use have become routine, the availability of  $^3\text{He}$  for space applications seems reasonably assured.

Whether fusion will be ready for space on the necessary time scale depends on when the exploration and utilization of space reach a magnitude where the high power levels of fusion become useful. A key difficulty in the scenario is that fusion may be the technology needed to enable routine, long-range space travel economically, so that the development paths of space and fusion would need to be on an intimately related and consistent time scale. A major incentive is that the capabilities fusion propulsion systems would bring could change the nature of space science and exploration from short-term, fly-by missions to long-term,

human-tended, scientific outposts—providing immense returns on the investment required to develop this technology.

### Future Space Fusion Concepts

The highest leverage research areas for space fusion power will aim at very large specific power values ( $>10$  kW/kg). However, even the  $\geq 1$  kW/kg projected for the concepts of the previous section would greatly facilitate space development, and it will be necessary to quantify potential performance in depth. Furthermore, modifications and extrapolations of these concepts and the invention of new ones will undoubtedly occur as fusion power comes of age.

Because present Department of Energy plans focus primarily on the tokamak, it is worthwhile examining extrapolations of this concept to space. The standard tokamak is inherently massive, and even terrestrial tokamak research seeks improvements in power density[32,20]. To increase the efficiency of fusion power, one option is based on the observation[33] that synchrotron radiation may be channeled by waveguides out of a D- $^3\text{He}$  conventional tokamak with high efficiency. The original concept was to directly convert this radiation to electricity by rectifying antennas but, for propulsion, it might be better to channel the synchrotron radiation to separate magnetic mirror cells with magnetic fields selected to cause a resonance and heating of a plasma with the synchrotron radiation. Because plasma in a magnetic mirror device will mainly flow out the end with a smaller magnetic field peak, such a system can be used to provide thrust. If extremely high specific impulses are desired, as in interstellar missions or missions to the Oort cloud, the synchrotron radiation produced in a tokamak plasma (up to about 60% of the fusion energy) could be directly exhausted, giving an exhaust velocity of the speed of light. However, specific powers higher than 10 kW/kg would be required for such missions and economy of scale would require very high power levels.

Perhaps the most attractive alternate concept to the tokamak for space is the field-reversed configuration (FRC), discussed briefly in the previous section. The FRC approaches

the ideal fusion system—a plasma pressure at 70-90% of the magnetic field pressure, cylindrical coils, and a linear geometry to allow direct conversion. The difficulties in developing the FRC are that its stability at reactor sizes remains uncertain, present startup methods extrapolate to large energy storage systems, and steady-state versions remain to be demonstrated. A modest experimental program is in place to address these issues. However, to develop the FRC on a relevant time scale for space will require a more intense effort.

An interesting new concept is the dipole reactor[34], which consists of a high field, cylindrical, magnetic coil with the fusion core plasma allowed to reach a natural equilibrium in the dipole magnetic field. The volume of plasma producing the fusion power is a small fraction of the total, leading to inefficient utilization of a vacuum chamber on Earth. However, this concept seems well suited to space, where good advantage can be taken of the readily available high vacuum. The possibilities of this configuration for space applications have recently begun to be explored[35].

## 5. CONCLUSIONS

In support of a large-scale expansion of humankind into the solar system, fusion system performance at the levels discussed in this paper would provide numerous advantages for space propulsion and power:

- Higher specific power values than projected for nuclear or solar electric propulsion,
- Higher, more flexible specific impulses than chemical, solar, or fission systems can achieve, allowing efficient long-range transportation, and
- Net-energy-producing fuel, available throughout the solar system.

Terrestrial fusion research is approaching the engineering proof-of-principle stage. Whether configurations developed for Earth can be attractive for space applications is unclear. Other options exist, however, and alternate concepts to the mainline terrestrial approach appear to be both attractive for space

and feasible to develop on a relevant time scale. The symbiosis between large-scale space development and fusion energy seems clear, and the key question is not if each will be developed but whether the time frames are consistent.

## Acknowledgments

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