Magnetic Fusion for Space Propulsion

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MAGNETIC FUSION FOR SPACE PROPULSION

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ABSTRACT

Magnetic fusion could enable the efficient, large-scale exploration and development of the Solar System. Several conceptual fusion reactor design studies indicate that magnetic fusion may be attractive for space applications, particularly space propulsion. These designs, based on various configurations, share the common characteristics that: (1) the D-^{3}He fuel cycle is used, (2) the plasma provides thrust directly, and (3) continuous, low-thrust trajectories are followed. This paper presents the generic arguments for magnetic fusion power in space, examines fusion fuels and configurations, discusses the trajectories fusion rockets would travel, and explores potential missions.

I. OVERVIEW

Thirty years ago, as the Apollo lunar-landing program got underway, several researchers turned their sights beyond the Moon to the rest of the Solar System.[1,2] They realized that, although chemical rockets can provide transport from Earth to orbit, efficient propulsion to the planets requires greatly enhanced capabilities, and they identified fusion energy as attractive for space applications. Many of the early ideas have remained valid, and some of them are listed in Table I. This paper will focus primarily on magnetic fusion energy (MFE) for propulsion, although some interesting work on inertial confinement fusion (ICF) propulsion has been performed,[3-5] and a few considerations will be mentioned where appropriate.

Research into long-range propulsion lay dormant for many years, primarily because the U.S. and Soviet space programs had focused on operations in Earth orbit. Recently, however, President Bush's Space Exploration Initiative (SEI) has given new impetus to human expansion into the Solar System.[6] The SEI, coupled with advances in fusion physics and technology and with the identification of a significant lunar resource of ^{3}He,[7] the most promising MFE-propulsion fuel (burned with D), motivated a fresh look at fusion power in space.

Two key factors drive the choice of propulsion systems for planetary missions: (1) Thrust power per unit mass must be high and (2) Optimal trajectories and high payload fractions require high exhaust velocities. Chemical and nuclear-thermal rockets achieve high specific power (kW/kg), but are limited to exhaust velocities of $\lesssim 10^4$ m/s, whereas efficient Solar-System propulsion requires at least ten times higher velocities. Nuclear-electric propulsion gives high exhaust velocities, but at specific powers about ten times lower than conceptual fusion reactor studies predict. The operating regimes for fusion and the main alternatives are shown in Fig. 1.[8] Only the fusion regime allows, for example, three-month trajectories from Earth to Mars with high payload fractions (~33%).

II. FUSION FUELS

Any fusion system with a plasma producing the thrust gives a very high exhaust velocity. In choosing a fuel cycle, specific power then becomes the determining factor, and the issues are considerably different from those for a terrestrial fusion reactor. Direct thrust appears neces-

TABLE I.
Ideas from the early days of investigating space fusion power.

- Exhausting the plasma directly to provide thrust,
- Adding matter to the exhaust to increase thrust levels,
- Using low-thrust, continuous-acceleration trajectories,
- Employing superconducting magnets, and
- Fueling with deuterium (D) and helium-3 (^{3}He).

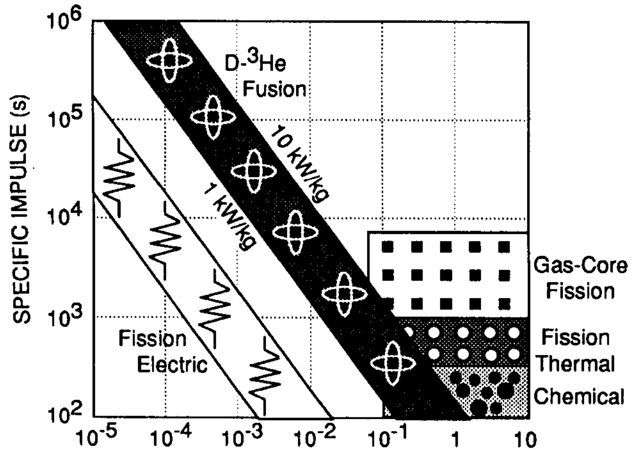

Fig. 1. Comparison of propulsion systems. The thrust-to-weight ratio refers to the power and propulsion system, referenced to Earth's surface gravity.

sary, as otherwise the performance is not likely to exceed that of nuclear (fission)-electric propulsion due to similar requirements for radiation shielding and power conversion. Thus, reactions producing large fractions of their fusion power as neutrons or bremsstrahlung radiation are unfavorable for magnetic fusion. For ICF systems, the microexplosions generally occur in space, so that most neutrons escape without hitting any structure. For such geometries, the higher power density of D-T fuel—even with only a 20% charged-particle power fraction—makes it the ICF fuel of choice, especially because D-^{3}He ICF requires very high pellet gains and, therefore, high power lasers or beams.

A difficulty with the choice of D-T fuel is that either a complex tritium-breeding 'blanket' and tritium-processing facility must be included (not possible if the neutrons escape to space) or a separate tritium-supply source must be used to provide, for example, the 2 Mg (tonnes) of tritium needed for a Mars mission.[5] For D-^{3}He fuel, because the propellant will be mostly matter added to the exhaust plasma to increase thrust, a relatively small amount of D-^{3}He fuel will be needed ($\lesssim$ 100 kg for Mars missions). The ^{3}He source will likely be the Moon[7] and, eventually, the gas-giant planets. In this regard, note that the fusion-rocket time frame is that of large-scale space exploration and development, when operations on the Moon and activities in the outer Solar System are frequent.

Some of the fusion reactions that have been examined for space applications are listed in Table II. Unfortunately, although p-^{11}B and p-^{6}Li produce all of the power from their primary reactions as charged particles, their fusion cross-sections are low. They are borderline for ignition, even including secondary reactions, because they produce large amounts of bremsstrahlung radiation. Thus, the power available for direct thrust for both p-^{11}B and p-^{6}Li is low and, furthermore, both have low power density. The D-D fuel cycle, plus 'catalyzed' variations where the reaction products are also burned, has a much lower power density than the D-T cycle and produces about one-half the number of neutrons per reaction, so little is gained by its use.

TABLE II.

The main fusion fuels. Some secondary reactions are also important, such as ^{6}Li +^{6}Li.

$$\mathrm{D} + \mathrm{T} \rightarrow \mathrm{n}\ (14.07\ \mathrm{MeV}) + {}^4\mathrm{He}\ (3.52\ \mathrm{MeV})$$
$$\mathrm{D} + {}^3\mathrm{He} \rightarrow \mathrm{p}\ (14.68\ \mathrm{MeV}) + {}^4\mathrm{He}\ (3.67\ \mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{n}\ (2.45\ \mathrm{MeV}) + {}^3\mathrm{He}\ (0.82\ \mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{p}\ (3.02\ \mathrm{MeV}) + \mathrm{T}\ (1.01\ \mathrm{MeV})$$
$$\mathrm{p} + {}^{11}\mathrm{B} \rightarrow 3\,{}^4\mathrm{He}\ (8.68\ \mathrm{MeV})$$
$$\mathrm{p} + {}^6\mathrm{Li} \rightarrow {}^3\mathrm{He}\ (1.72\ \mathrm{MeV}) + {}^4\mathrm{He}\ (2.30\ \mathrm{MeV})$$

The choice between the two remaining fuel cycles, D-T and D-^{3}He, is less obvious. The important *plasma* parameters are the neutron power fraction, shown in Fig. 2, and the fusion power density, shown in Fig. 3.

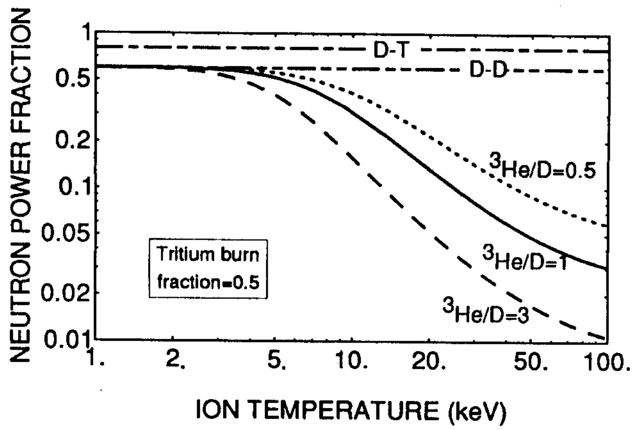

Fig. 2. Ratio of neutron power to fusion power for the D-T, D-D, and D-^{3}He fusion fuel cycles, with several values of the ^{3}He-to-D density ratio shown.

However, the figure of merit is the thrust power per unit reactor mass, not the power density in the plasma, and the *engineering* factors of higher direct-thrust efficiency, reduced radiator mass, and reduced radiation-shield mass favor the D-^{3}He fuel cycle. Furthermore, due to heat and neutron flux constraints, terrestrial D-T reactor designs often optimize at magnetic fields well below technological limits, so D-^{3}He versions can gain greatly by increasing the magnetic field, B, because the power density varies as B^4. The approximate gain in effectiveness due to these factors is given in Table III for the

TABLE III.
Gain in effectiveness for a D-^{3}He, space-propulsion reactor compared to a D-T, electricity-producing terrestrial reactor.

AREA	D-T MINIMARS[9]	D-^{3}He SOAR–Propulsion[10]	D-^{3}He Gain in Effectiveness
Normalized fusion power density in plasma	1	0.013	0.013
Efficiency (electricity or thrust)	0.36	0.77	2.1
Heat rejection	(1-.36)	(1-.77)	2.8
Blanket and shield thickness	1.07 m	0.40 m	2.7
Central cell magnetic field	3.1 T	6.4 T	18
TOTAL GAIN FACTOR			3.7

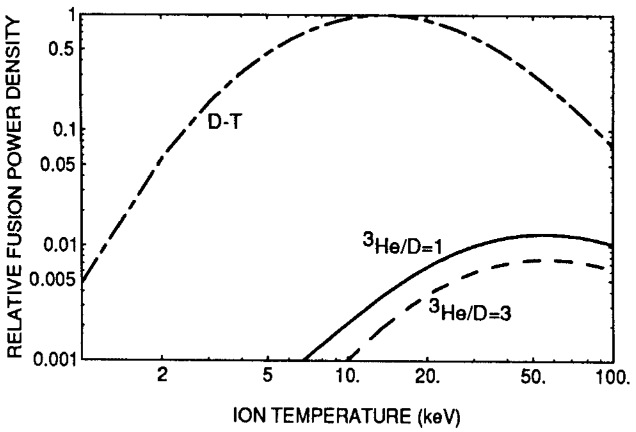

Fig. 3. Local fusion power density in the plasma for D-T and D-^{3}He fusion fuels, with several values of the ^{3}He-to-D density ratio shown.

TABLE IV.
Some fusion reactor configurations that have been studied for space applications.

- Simple mirror,[2]
- Tandem mirror,[10]
- Dipole,[8]
- Field-reversed configuration (FRC),[11,12]
- Colliding compact toroids,[13]
- Spheromak,[14]
- Spherical torus (ST),[14]
- Bumpy torus,[15] and
- Spherically convergent ion flow (SCIF).[16]

tandem mirror—where fairly detailed designs have been produced for both D-T[9] and D-^{3}He.[10] Table III only indicates trends, but it shows a considerable advantage for D-^{3}He.

III. CONFIGURATIONS

Several studies of space fusion propulsion have been performed, although all have been small in scope. They have included reactors of many configurations, some of which are listed in Table IV. The last of these, SCIF, is an ICF/MFE hybrid concept. A discussion of many of these concepts, including a brief historical overview, may be found in Ref. 18. Figure 4 shows some of these configurations, and illustrates the diversity of fusion propulsion options. Most D-^{3}He fusion propulsion reactor design studies predict specific power values in the range 1–10 $\mathrm{kW}_{thrust}/\mathrm{kg}_{reactor}$, including all of the power and propulsion system mass. This leads to the exhaust velocities and thrust-to-weight ratios (referred to Earth's surface gravity) shown in Fig. 1.

Although sufficient information for a definitive comparison to ICF propulsion does not exist, the projected specific power of VISTA[5] is 10–20 $\mathrm{kW}_{thrust}/\mathrm{kg}_{reactor}$, with the chief uncertainties lying in the mass of the ICF driver and of the magnet and shield. The VISTA power level is about ten times higher than that of the extant MFE propulsion designs, so economy of scale makes comparison difficult, but it appears that, if a suitable source of tonnes of tritium for ICF can be provided, the performance of MFE and ICF propulsion systems will be roughly comparable and will significantly outperform the alternatives.

Notable by its absence from Table IV is the tokamak. Although it dominates the terrestrial fusion research pro-

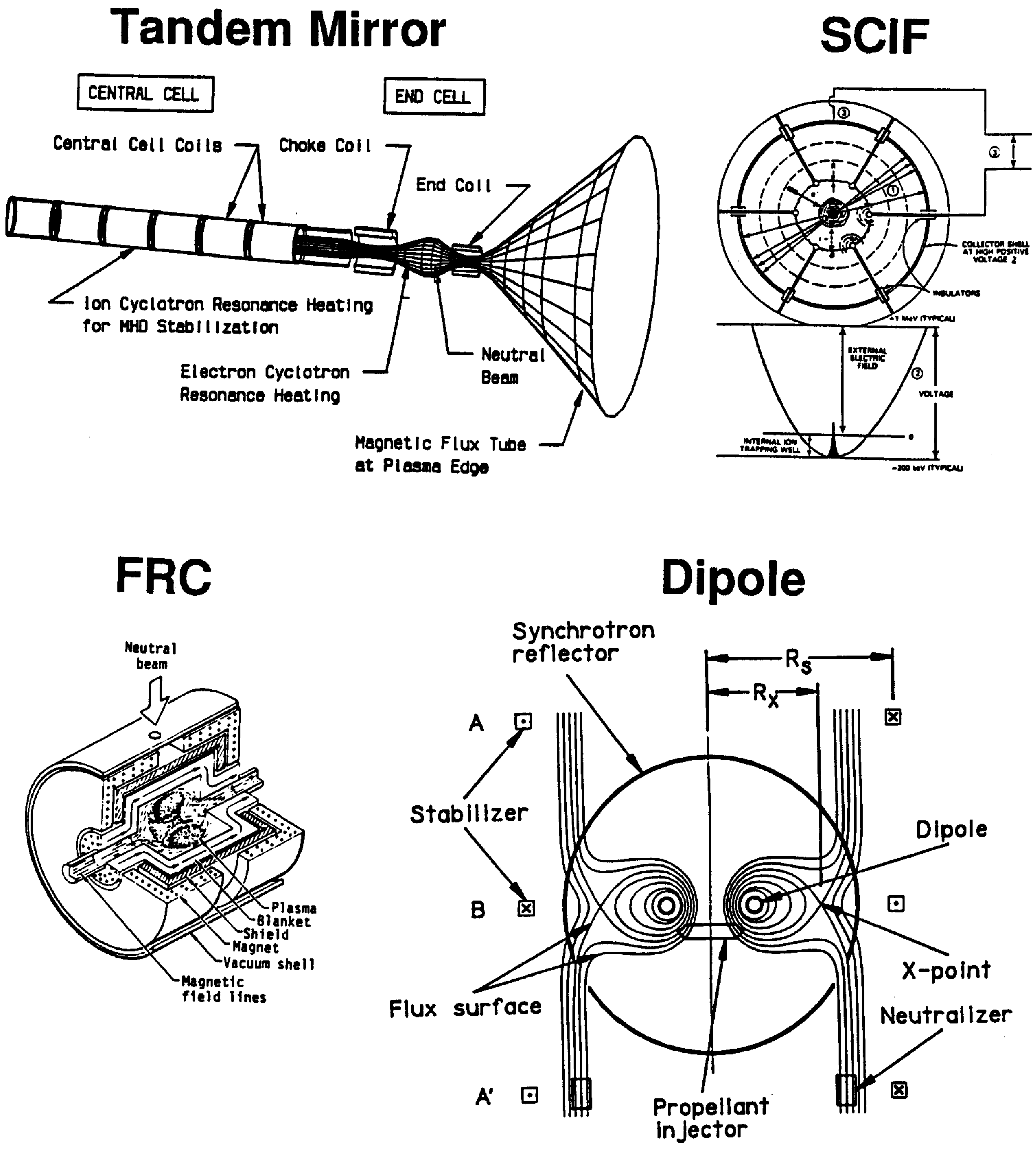

Fig. 4. Some potential D-^{3}He magnetic fusion propulsion configuration options.[10,17,16,8]

gram, the high magnetic field, low beta (plasma pressure/magnetic-field pressure), and large neutron production of the tokamak limit the achievable specific power. The magnetic field cannot be significantly raised to increase the plasma power density, nor can a magnetic flux tube be diverted for producing direct thrust without massive bucking coils. Advanced tokamak concepts, such as second stability, may allow betas of ~20%, but this value is low compared to most of the configurations listed in Table IV.

The concepts listed in Table IV are all 'alternate' concepts in the magnetic fusion program. Except for the simple mirror, whose power balance is unfavorable, they potentially provide enhanced performance over the tokamak, but their physics data bases are much smaller. They all allow plasma exhaust to provide direct thrust, perhaps with a modest-field bundle divertor. There appears to be little likelihood that the U.S. Department of Energy's terrestrial magnetic fusion research program, which has narrowed its options to focus exclusively upon the tokamak, will revive any alternate concept in the near future. Thus, the burden of developing fusion systems for space propulsion will fall upon the space community.

IV. TRAJECTORIES

In this section, only rocket trajectories between circular solar orbits are considered. A more complicated analysis—dealing with ellipticity, non-planar orbits, and transfer to planetary orbits—would not change the essential conclusions.

Two basic types of space propulsion trajectories exist: high-thrust and low-thrust. *High-thrust systems*, as shown in the lower-right corner of Fig. 1, include chemical rockets, nuclear-thermal rockets, such as NERVA,[19] and gas-core fission rockets. They perform well for launching payloads from a planetary surface into orbit. For long-range missions, however, their relatively low exhaust velocities limit their applicability. *Low-thrust systems* include fusion, nuclear electric, solar electric, and several exotic concepts, such as solar sails or beamed microwave power. They outperform high-thrust systems for long-range missions by thrusting continuously during most of the trip. The basic physics behind this performance gain is that the energy expended in adding momentum to a rocket is minimized when the exhaust is left with zero momentum in the observer's frame; that is, when the exhaust velocity matches the instantaneous rocket velocity. For long-range missions of relatively short duration, the rocket velocities reached must be much higher than the exhaust velocities attainable by high-thrust systems. Although the total energy expended is larger for fast missions, low-thrust systems consume the minimum energy that satisfies the time constraints.

High-thrust rockets follow trajectories between the planets that consume nearly the minimum total energy (Hohmann trajectories). In these, there is a short thrust phase at the beginning of a trip to put the rocket into an elliptical trajectory and another at the end to match the target planet's orbital velocity, as shown in Fig. 5. Momentum conservation for Hohmann trajectories leads to the *rocket equation*:

$$\frac{M_l}{M_0} = \exp\left(\frac{-\Delta v}{v_{ex}}\right) \tag{1}$$

where M_l is the final rocket mass, which includes payload and structure; M_0 is the initial rocket mass, equal to M_l plus propellant; Δv is the velocity increment for the mission; and v_{ex} is the exhaust velocity. Thus, with a limited exhaust velocity, maintaining a given payload mass means increasing the propellant mass exponentially with the total Δv requirement of a mission.

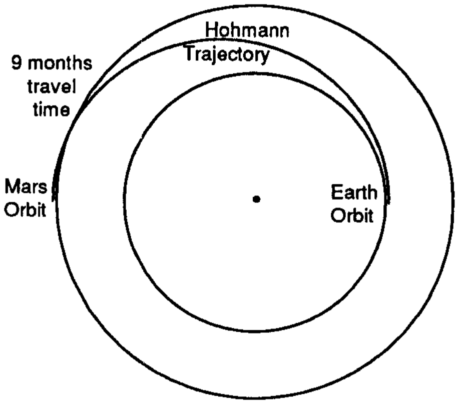

Fig. 5. A minimum-energy (Hohmann) trajectory—characteristic of chemical rockets.

For low-thrust rockets, the full trajectory-optimization problem is extremely complicated. A simplified discussion, assuming constant exhaust velocity and mass-flow rate, will be used here, based on Ref. 20. Somewhat better performance can be achieved with variable v_{ex}, especially for fast missions. A low-thrust rocket equation can be derived from momentum conservation[20]; it is

$$\frac{M_l}{M_0} = \exp\left(\frac{-u}{v_{ex}}\right) - \frac{v_{ex}^2}{v_{ch}^2}\left[1 - \exp\left(\frac{-u}{v_{ex}}\right)\right] \tag{2}$$

where the payload mass, M_l, is defined as in Eq. (1), M_p is the propellant mass, and u is the velocity increment for the mission. The symbol u has been used instead of Δv to emphasize that low-thrust missions require higher total energy expenditure than high-thrust missions. The *characteristic velocity*, v_{ch}, has been introduced as a convenient means of parameterizing the specific power, α

($\mathrm{kW}_{thrust}/\mathrm{kg}_{reactor}$) and τ, the thrust-on time; its definition is $v_{ch} \equiv (2000\alpha\tau)^{\frac{1}{2}}$. Equation (2) extends Eq. (1) to the case where the propulsion-system mass, M_w, is treated separately from M_l. A chemical rocket is approximately an $M_w = 0$ system, so $\alpha \rightarrow \infty$, in which limit Eq. (2) becomes Eq. (1).

The utility of Eq. (2) lies in the guidance it gives to the choice of low-thrust rocket parameters. Figure 6 shows the dependence of payload ratio upon v_{ex}/v_{ch} and u/v_{ch}. In conjunction with estimates of the distance to be travelled and the energy to be expended, Eq. (2) can be used to approximate the trade-off between M_L/M_0 and mission duration. The results of applying a characteristic velocity analysis to various missions of interest for magnetic fusion rockets will be discussed in the next section.

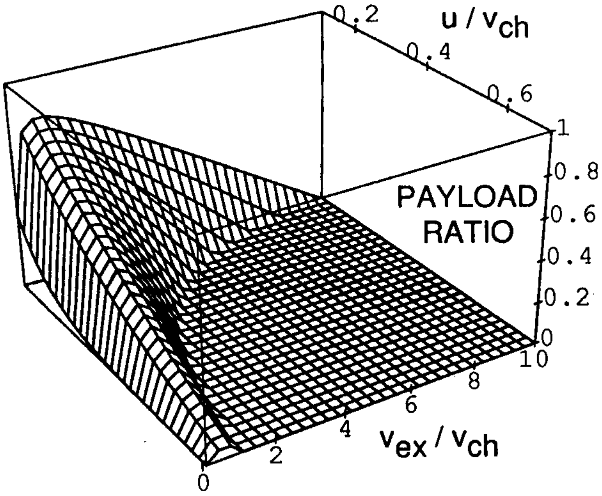

Fig. 6. Low-thrust propulsion payload ratio dependence upon exhaust velocity, v_{ex}, and mission velocity increment, u, normalized to the characteristic velocity.

V. MISSIONS

The exploration, development, and settlement of the Solar System badly needs the capabilities of fusion propulsion. As Fig. 1 indicates, there appears to be no feasible alternative for the thrust parameters required for fast missions or for efficient, large-payload missions to the planets. Population and pollution pressures will compel humankind to depend upon space for many resources and for energy. Yet, today, we can barely leave the Earth, and almost no work exists on propulsion systems capable of efficient travel throughout the Solar System.

Fusion can enable the opening of the Solar System. Fusion propulsion's capabilities will be illustrated here for three key applications:

- Mars: Settling the Solar System.
- Asteroids: Accessing vast resources.
- Jupiter: Scientific outposts.

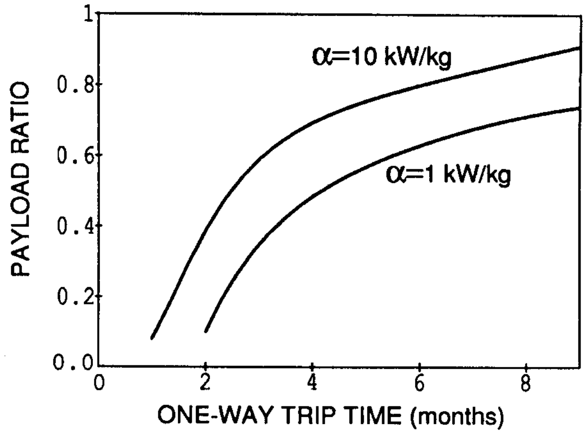

Fig. 7. Trade between payload fraction and one-way trip time for travel between Earth and Mars.

Figure 7 shows some possibilities for support of *Mars settlements*, for magnetic fusion propulsion systems capable of specific powers at both ends of the expected range of 1–10 kW/kg. Almost all of the conceptual designs discussed in Section III fall within this range. At 10 kW/kg specific power, magnetic fusion rockets could reach Mars from Earth in about one month, with payload fractions of ~8%. Fast missions, such as this, would allow transport of humans without the health risks associated with the nine-month travel times needed by chemical rockets. The same fusion rocket, operating at lower thrust but higher exhaust velocity, could follow a nine-month trajectory and reach payload ratios of over 80%, more than twice the payload ratio of a chemical rocket. Furthermore, while two-thirds of the chemical rocket's total mass is propellant, which must be re-supplied from Earth or elsewhere, only about 10% of the fusion rocket's mass would be propellant, so that the advantage of fusion increases even further for multiple missions. Even at 1 kW/kg, Earth-Mars trips of three months duration would have payload fractions of ~33%, while nine-month trips would reach ~67%. These values are still very attractive compared to chemical rockets. Only such capabilities will allow Mars settlements to prosper.

Asteroid resources will remain mostly unknown until we can begin voyages of geologic surveying and, eventually, prospecting. Magnetic fusion can enable such voyages. Figure 8 shows the trade-off between trip times and payload fractions between the Earth and the main asteroid belt. This figure, however, does not show some important advantages of fusion for such applications. First, the high fusion-fuel energy density means that excess fuel can easily be carried. Almost any local material can be used as propellant, because plasma temperatures are sufficient to ionize any matter. Thus, fusion provides great flexibility in travel between asteroids of varying distance and orbit. Second, the large range of exhaust velocities allows the tailoring of travel to the amount of cargo and the desired trip times. Third, part of the plasma could be diverted as a plasma torch[21] for processing and testing of ores.

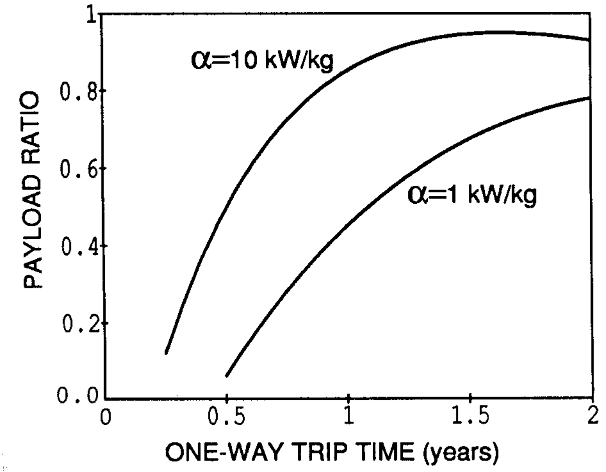

Fig. 8. Trade between payload fraction and one-way trip time for travel between Earth and the main asteroid belt.

Scientific outposts, analogous to antarctic bases, will be enabled by magnetic fusion propulsion. Figure 9 shows the trade-off of payload ratio and trip time for a potential outpost orbiting Jupiter—in whose planetary system the moons alone have a total surface area equal to that of Mars. For a scientific outpost, fusion can provide propulsion, power in orbit, power beamed to roving research groups, and materials processing. Beyond Jupiter, of course, are Saturn, Uranus, Neptune, and the Pluto/Charon system—all of which contain enormous scientific value and, eventually, further supplies of ^{3}He in the gas giants.

VI. CONCLUSIONS

The scientific and economic profit from the opening of the Solar System must be measured by the future, but the technological foundations clearly lie in efficient propulsion—a capability that magnetic fusion can supply. Several candidate reactor configurations appear attractive, but they all need substantial research and development. The fuel cycle choices are more limited and D-^{3}He fuel will likely power magnetic fusion propulsion reactors. Magnetic fusion should provide attractive mission parameters—one to three months to Mars or 60–80% payload fractions, for example, enabling settlements, acquisition of resources, and scientific outposts.

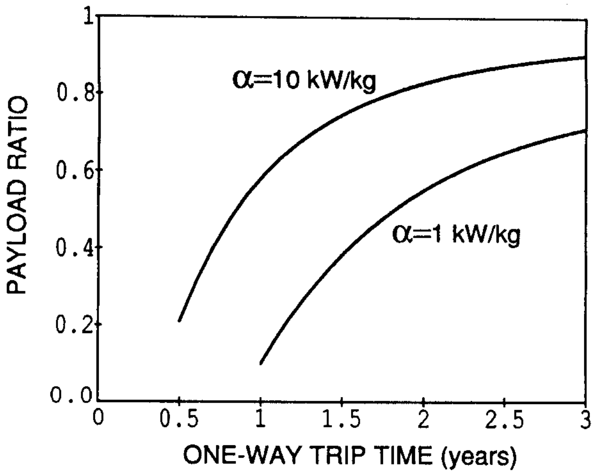

Fig. 9. Trade between payload fraction and one-way trip time for travel between Earth and Jupiter.

ACKNOWLEDGEMENT

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