LUNAR ^{3}He, FUSION PROPULSION, AND SPACE DEVELOPMENT

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The recent identification of a substantial lunar resource of the fusion energy fuel ^{3}He may provide the first terrestrial market for a lunar commodity and, therefore, a major impetus to lunar development. The impact of this resource—when burned in D-^{3}He fusion reactors for space power and propulsion—may be even more significant as an enabling technology for safe, efficient exploration and development of space. One possible reactor configuration among several options, the tandem mirror, illustrates the potential advantages of fusion propulsion. The most important advantage is the ability to provide either fast, piloted vessels or high-payload-fraction cargo vessels due to a range of specific impulses from 50 sec to 1,000,000 sec at thrust-to-weight ratios from 0.1 to 5×10^{-5}. Fusion power research has made steady, impressive progress. It is plausible, and even probable, that fusion rockets similar to the designs presented here will be available in the early part of the twenty-first century, enabling a major expansion of human presence into the solar system.

INTRODUCTION

Recently, a connection between the Moon and future terrestrial energy needs was recognized: the lunar resource of the isotope helium-3 (^{3}He) can provide a clean and safe source of energy on Earth for centuries (*Wittenberg et al.,* 1986). Measurements of lunar regolith samples from the Apollo and Luna programs show significant quantities of ^{3}He (*Cameron,* 1991). The burning of ^{3}He with deuterium (D) as a fusion fuel has been known for many years to be attractive, but no significant terrestrial source has been found (*Miley,* 1976; *Dawson,* 1981; *McNally,* 1982). The present paper examines the implications of lunar ^{3}He for space development in the context of one possible fusion propulsion system and the capabilities it would provide.

The lunar ^{3}He resource is estimated to be ~10^9 kg (*Wittenberg et al.,* 1986; *Kulcinski et al.,* 1991). The presumed source of this ^{3}He is the solar wind; ^{3}He has been deposited on the lunar surface over the past 4 b.y. and spread a few meters deep into the regolith by meteorite bombardment. To put this resource into perspective, 10^9 kg of ^{3}He burned with D would provide 2000 years of present world energy consumption or, using the fusion rocket design discussed in this paper, would allow 10,000,000 one-way trips to Mars of 90-day travel time with 12,000-Mg (metric tonne) payloads.

Fusion reactors for space propulsion were first investigated in the 1950s, and the first D-^{3}He version was published in 1962 (*Englert,* 1962). Many of the concepts proposed in the early work remain valid. However, since that time, a great deal of progress has been made in understanding both the science and the technology of fusion energy. In particular, configurations have evolved and the sophistication of experimental, theoretical, and numerical tools has increased dramatically (*Post,* 1987).

After a brief examination of fusion fuel cycles, concentrating on their use in space, one potential fusion propulsion system will be described. The capabilities of such systems for increasing payload fractions or decreasing flight times will be assessed. The timeframe for fusion power development will be compared with that needed for a major human expansion into space, and the implications of the availability of D-^{3}He fusion propulsion on space development will be discussed. Finally, conclusions will be drawn.

FUSION FUEL CYCLES FOR SPACE APPLICATIONS

The main consideration in choosing a fusion fuel for space applications is the achievable specific power in terms of kilowatts of thrust per kilogram of total rocket mass. Therefore, the selection criteria are heavily weighted toward reactions producing a high fraction of power in charged particles—which may be converted to electricity at very high net efficiency (*Santarius,* 1987; *Santarius et al.,* 1987, 1988) or may be channeled by a magnetic field to provide direct thrust. Consequently, less heat must be rejected and radiator mass is reduced. A low fraction of energy in neutrons also allows substantial reduction in the mass of biological and magnet shielding.

Fusion fuel cycle physics has been extensively studied, and good summaries are available (*McNally,* 1982; *Dawson,* 1981). The most important fusion fuel cycles are based on the primary reactions given in Table 1. Of particular interest are the D-^{3}He fuel cycle, which produces 95% to 99% of its energy (including side reactions) in charged particles; the D-T cycle, which burns at the lowest temperature; and the D-D cycle, whose fuel is most plentiful on Earth. The "catalyzed" D-D cycle, in which the D-D fusion products T and ^{3}He are both subsequently burned, produces about the same energy fraction in neutrons as D-D, but achieves a power density comparable to D-^{3}He. Secondary and tertiary reactions with fusion products make the analysis of the ^{6}Li cycles difficult. However, detailed analyses (*McNally,* 1982) of the ^{6}Li cycles indicate that their power density is lower than the first three fuel cycles and that significant quantities of neutrons are produced by side reactions. The p-^{11}B reaction, although it gives no neutrons, is marginal for ignition, and would therefore produce almost all its power as thermal (bremsstrahlung)

TABLE 1. Primary reactions for the most important fusion fuel cycles (side reactions also occur, as do secondary and tertiary reactions with fusion products).

$D + {}^3He$	$\rightarrow$ p (14.68 MeV) + ^4He (3.67 MeV)	
D + T	$\rightarrow$ n (14.07 MeV) + ^4He (3.52 MeV)	
D + D	$\rightarrow$ n (2.45 MeV) + ^3He (0.82 MeV)	(50%)
	$\rightarrow$ p (3.02 MeV) + T (1.01 MeV)	(50%)
$^3He + {}^3He$	$\rightarrow$ 2p + ^4He	(12.86 MeV)
$p + {}^{11}B$	$\rightarrow$ 3 ^4He	(8.7 MeV)
$p + {}^6Li$	$\rightarrow$ ^3He (2.3 MeV) + ^4He (1.7 MeV)	
$D + {}^6Li$	$\rightarrow$ five primary reactions, D-D reactions, ^6Li-^6Li reactions, and secondary (fusion-product) channels	

radiation. The ^3He-^3He reaction, although also neutron-free, has a very low cross section.

Figure 1 shows the approximate distribution of fusion power among charged particles, neutrons, and surface heat for the eventual energy loss of D-^{3}He, D-T, and catalyzed D-D plasmas, which differs from and is more relevant than the initial distribution of energy among reaction products. The D-^{3}He fuel cycle shows a clear advantage. This is diminished somewhat by a lower plasma power density (see Fig. 2), but the benefits of an efficient direct-thrust system over a thermal cycle for conversion of fusion energy to electricity and a further cycle to power ion thrusters, along with the reduction in shield mass, will be shown to lead to better performance from a D-^{3}He fusion propulsion system than from a D-T system.

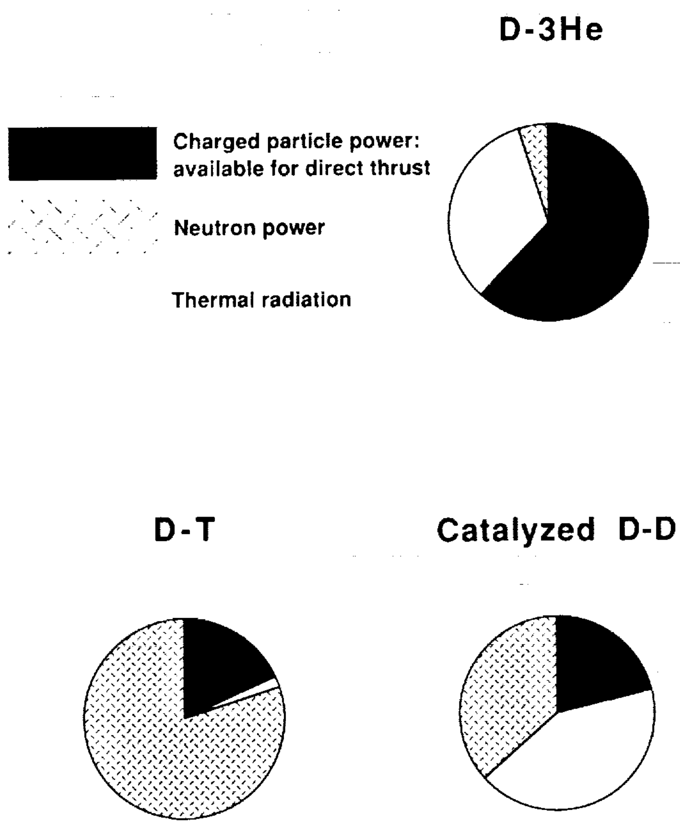

Fig. 1. Approximate distribution of energy loss among charged particles available for direct thrust, neutrons, and thermal radiation that appears as surface heat.

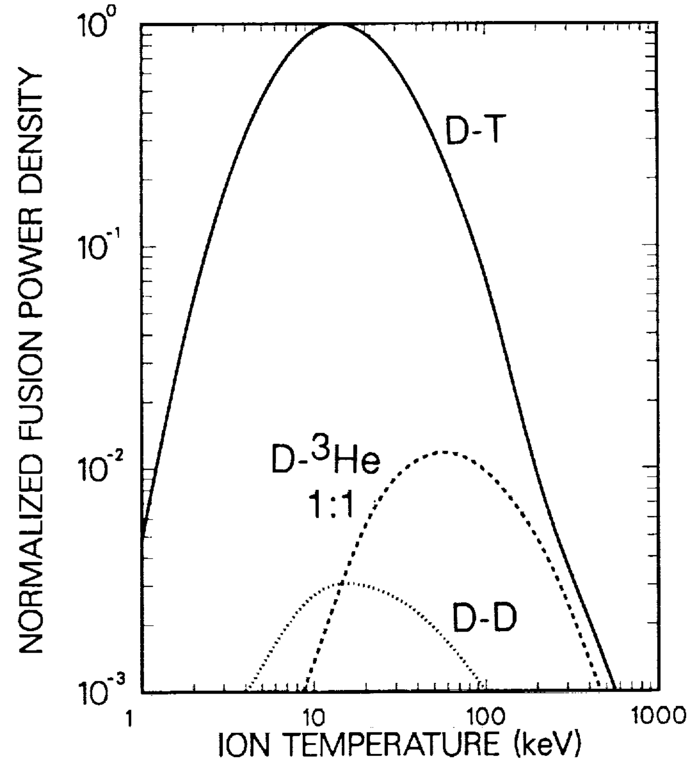

Fig. 2. Plasma power density for the major fusion fuel cycles.

ONE POTENTIAL FUSION PROPULSION SYSTEM DESIGN

Two key choices underpin a fusion rocket design: the fuel cycle and the configuration. Some of the earliest work on fusion propulsion, at NASA Lewis Research Center (*Englert,* 1962) and at Aerojet-General Nucleonics (*Hilton et al.,* 1964), applied essentially the same reasoning as in the present paper to identify linear fusion reactors burning D-^{3}He fuel as attractive options. In the intervening years, not only has the lunar ^{3}He resource been recognized, but fusion power research has undergone considerable evolution and, in particular, linear systems have progressed from the single-cell magnetic mirrors of the early 1960s to tandem mirrors (*Dimov et al.,* 1976; *Fowler and Logan,* 1977) and to thermal barrier tandem mirrors (*Baldwin and Logan,* 1979). This progression provides better confinement for the magnetic "bottle" at the cost of a more complicated containment scheme (see Fig. 3). Although a linear device will be used to illustrate D-^{3}He fusion propulsion's attractiveness here, toroidal devices also merit attention and some work on their design for space is extant (*Roth et al.,* 1972; *Borowski,* 1987).

A linear D-^{3}He fusion rocket has been designed by extrapolating from conceptual designs of D-^{3}He fusion reactors for power in orbit (*Santarius et al.,* 1988, 1989) and on Earth (*Santarius et al.,* 1987). The high efficiency of direct thrust and the reduced shield mass lead to a specific power value of ~1.2 kW/kg, based on the configuration shown in Fig. 3 and the parameters summarized in Table 2. Thrust is produced by driving one end cell more vigorously to increase axial confinement on that end, thereby unbalancing the end loss of plasma. All these coils are solenoids, and magnetohydrodynamic (MHD) stability is pre-

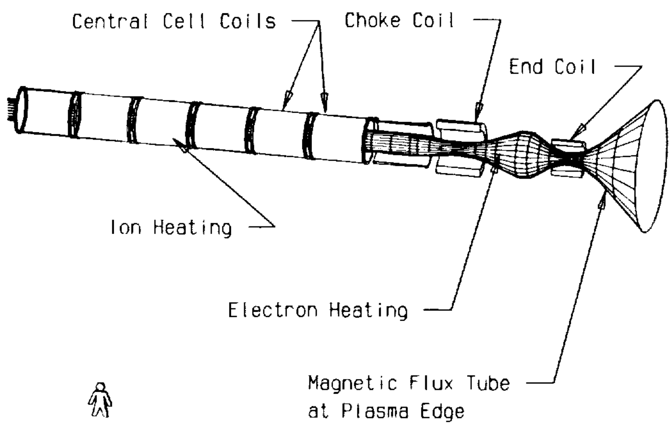

Fig. 3. Basic configuration for a thermal barrier tandem mirror reactor.

TABLE 2. D-^{3}He tandem mirror fusion propulsion system design parameters.

Parameter	Value
Thrust power per unit power system mass	1.2 kW/kg
Fusion power	1959 MW
Input power	115 MW
Thrust power	1500 MW
Thermal power (bremsstrahlung and synchrotron radiation, neutrons, plasma not usable for thrust)	574 MW
Neutron wall loading	0.17 MW/m^2
Total mass	1250 Mg (tonnes)
Total length	113 m
Central cell outer radius	1.0 m
Central cell on-axis magnetic field	6.4 T
Electron density	1.0×10^{21} m^{-3}
Helium-3 to deuterium density ratio	1
Electron temperature	87 keV
Ion temperature	105 keV
Fuel ion confinement time	6 sec
Ion confining electrostatic potential	270 kV

sumed to be provided by 25 MW of ion cyclotron range of frequencies power in the central cell. This is one method of several proposed to allow axisymmetric magnetic mirror machines to achieve MHD stability at high beta (ratio of plasma pressure to magnetic field pressure), and it has been demonstrated experimentally at low density and temperature (*Breun et al.,* 1986). The magnet shield material is LiH, and the magnets in the central cell are made of NbTi superconductor. Higher-field magnets are required for the end cells: on each side are one 12-T (on-axis) Nb_3Sn magnet and one 24-T magnet whose field is generated by 16 T from Nb_3Sn superconductor and 8 T from a normal-conducting Cu insert that requires 8 MW of power.

An important aspect of fusion propulsion is the flexibility inherent in the ability to tailor the thrust program to a wide variety of missions. This flexibility stems from three main operating modes: direct exhaust, mass-augmented exhaust, and thermal exhaust. These modes are shown schematically in Fig. 4. Typical burning plasma temperatures are 40-100 keV (500-1200 million K), so that exhausting the plasma directly would lead to extremely high specific impulses (exhaust velocity divided by standard Earth surface gravity) of about 10^6 sec. Lower specific impulses are also available, ranging continuously from about 10^5 sec to about 200 sec at thrust-to-weight ratios ranging from about 3×10^{-4} to 0.03, as shown in Fig. 5. The midrange is reached by adding a low-field magnet onto the end of the device and injecting matter, which is ionized by the end-loss plasma

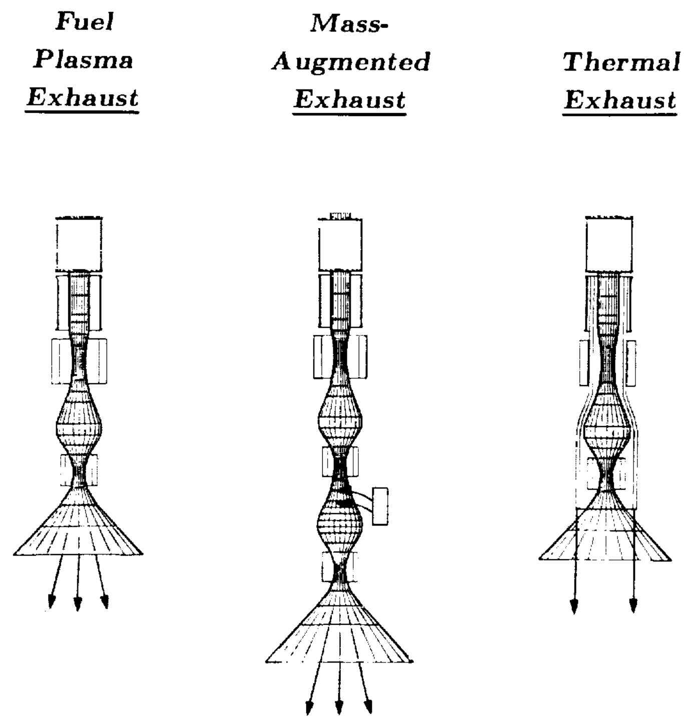

Fig. 4. Thrust mode options for a linear fusion propulsion system.

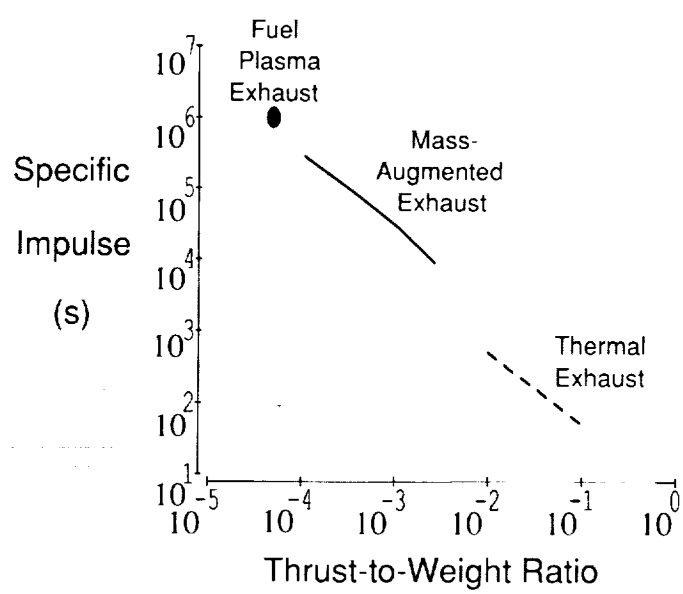

Fig. 5. Range of specific impulses and thrusts available from the fusion propulsion system discussed in this paper.

energy. The new cell would have a higher field on the rocket side than on the space side, creating a magnetic mirror in which ions reflect a few times off the magnetic field axial gradients (mirrors) before they collisionally scatter into the mirror "loss cone" and produce thrust. This process, which derives from the well-verified basic principle (adiabatic confinement) of magnetic mirrors, lowers the exhaust plasma temperature and increases the thrust. Higher thrust can be achieved by heating a gas with thermal (bremsstrahlung and synchrotron) radiation in a blanket surrounding the plasma and then exhausting the gas. Parameters typical of chemical systems, limited by materials considerations to about 1600 K, are available from this mode.

CAPABILITIES OF FUSION PROPULSION

The benefits of high specific impulse and continuous thrust, even at low thrust-to-weight ratios, have been known since the early 1950s, and detailed discussions of trajectory optimization are summarized in the classic references by *Ehricke* (1962) and *Stuhlinger* (1964). Although more total energy is required compared to chemical systems, much less fuel mass is needed and trip times can be shortened or payload mass fractions (payload mass/initial rocket mass) can be increased. The fusion propulsion system of the previous section, which produces power at ~1.2 kW/kg, can thus provide either fast human transport or large-payload-ratio cargo vessels. Using *Stuhlinger's* (1964) simile, these are like sports cars or trucks.

Fusion propulsion's capabilities are best illustrated by comparison with the primary chemical propulsion mode: minimum-energy, elliptical trajectories (Hohmann orbits). The calculations are based on *Stuhlinger* (1964) and are optimized assuming an acceleration of constant magnitude, but optimized direction. For a 1-kW/kg system and a 90-day, one-way, Earth-Mars mission, that assumption requires tuning the specific impulse over a range of 10,000 sec to 200,000 sec, which Fig. 5 shows to be attainable with the mass-augmented exhaust mode. Figure 6 shows the sports car mode and gives flight time for the same payload fraction, while Fig. 7 gives payload fraction for the same flight time—the truck mode. These figures show that fusion propulsion performs approximately as well as chemical systems even for low Earth orbit (LEO)/Moon missions, and far surpasses chemical propulsion performance for missions to Mars or Jupiter. For Earth-Mars missions, the trade-off between payload fraction and trip time is plotted in Fig. 8 (based on *Stuhlinger,* 1964).

Deuterium-helium-3 fuel possesses an extremely high energy density (19 MW-yr/kg), surpassed only by matter/antimatter, and is the highest energy density fuel presently known of those that

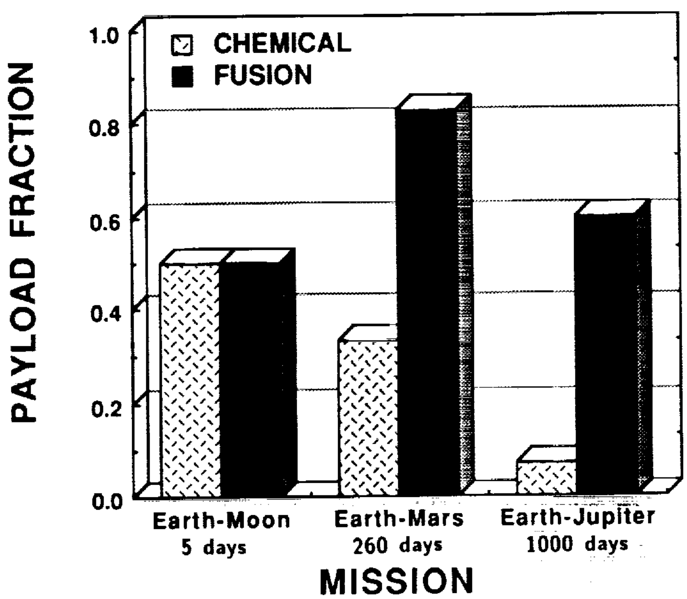

Fig. 7. Payload fraction for the same flight time (truck mode).

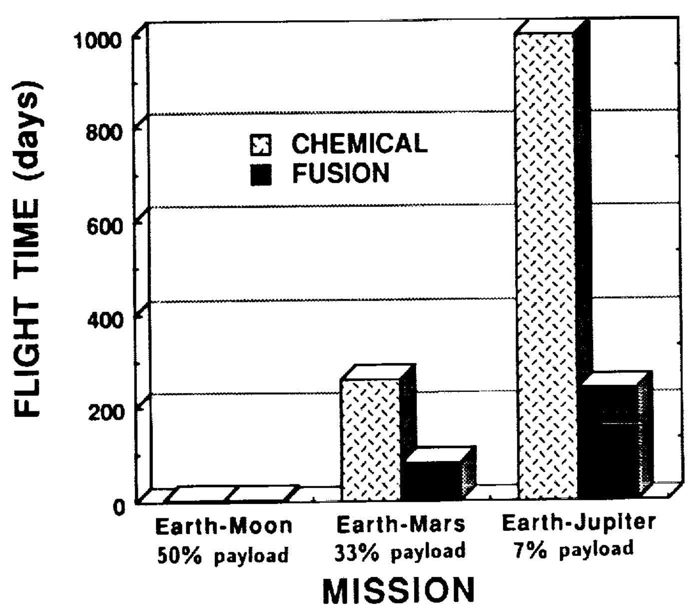

Fig. 6. Flight time for the same payload fraction (sports car mode).

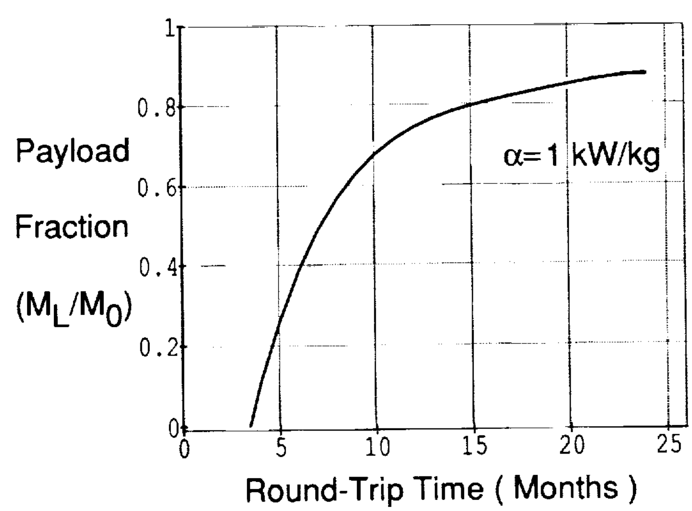

Fig. 8. Payload fraction vs. round-trip flight time for an Earth-Mars mission.

release more energy than is required to procure them. Once a fusion rocket is constructed in orbit, much of its mass will be reusable. A chemical rocket, with most of its mass in fuel/propellant, will require much more mass to be placed in orbit for each mission than will a fusion rocket, which uses negligible fuel mass and considerably less propellant mass. Mass requirements for an Earth-Mars round trip are compared in Table 3. Transporting 12,000 Mg between Earth and Mars would require orbiting an extra 47,000 Mg for chemical rockets and 3000 Mg for D-^{3}He fusion rockets.

Few constraints exist on the type of matter used as propellant in the mass-augmented mode of a fusion system; local sources such as regolith could probably be used because plasmas are hot enough to ionize almost all matter. Fusion's advantage would then be increased, since propellant for the return trip would not need to be carried. The high energy density of D-^{3}He also enhances the flexibility of a fusion propulsion system, since a reserve of fuel could easily be carried without a substantial rocket mass increase.

TABLE 3. Masses required for fusion and chemical transport between Earth and Mars, assuming a nine-month trip time each way.

	Chemical	D-^{3}He Fusion
Payload (each way)	11,800 Mg	11,800 Mg
Propellant	47,200 Mg	2,000 Mg
Fusion reactor	—	1,000 Mg
D-^{3}He fuel burned	—	0.08 Mg
Nonpayload mass orbited	47,200 Mg	3,000 Mg

FUSION POWER DEVELOPMENT TIMEFRAME

A key question in discussing space applications of fusion energy is whether fusion could be developed on the timescale required for a major human thrust into the solar system. Fusion progress over the past 30 years is illustrated in Fig. 9, where experimentally achieved values of the product of the three most important fusion physics parameters (plasma temperature, electron density, and energy confinement time) are plotted vs. time. The requirement for an ignited plasma, whose energy losses are sustained by the fusion power it produces, is also shown. Although the next step is by no means a trivial one and other important issues exist besides these three parameters, the six orders of magnitude already overcome suggest that the remaining hurdles can at least plausibly be surpassed on the timescale required by present space development plans (*National Commission on Space,* 1986).

The present terrestrial fusion research program, however, is focused mainly on the D-T fuel cycle because it is easier to ignite than is D-^{3}He. This is shown in Fig. 10, where curves are given for ignition of D-T and D-^{3}He against losses due to the finite plasma energy confinement time and bremsstrahlung radiation. Experimentally attained values of plasma temperature vs. the confinement parameter $n\tau_E$ are also plotted. The physics requirements on temperature and energy confinement are each about a factor of 4 higher for D-^{3}He than for D-T. Another difficulty in the context of this paper is that budget considerations have focused the present Department of Energy development plan for terrestrial fusion reactors on the tokamak—a toroidal system (*U.S. Congress OTA,* 1987). However, substantial progress on linear systems and other toroidal configurations had been made (*Callen et al.,* 1986) and a small effort remains, so a strong foundation exists.

Fortunately, the development of D-^{3}He fusion power promises to be much easier than the previous paragraph suggests. The key consideration is that, although the physics development for D-^{3}He fusion will be more difficult than for D-T, the reactor technology development will be faster and easier. The demonstration of D-^{3}He physics, suggested by *Atzeni and Coppi* (1980) and by *Emmert et al.* (1989) as possible even in next-generation D-T experimental test facilities, could quickly lead to a prototype, power-producing, D-^{3}He reactor. Sufficient ^{3}He exists on Earth for this purpose (*Wittenberg et al.,* 1986). Specifically, materials are already known that have been demonstrated to withstand the lower neutron fluence of D-^{3}He reactors, whereas materials

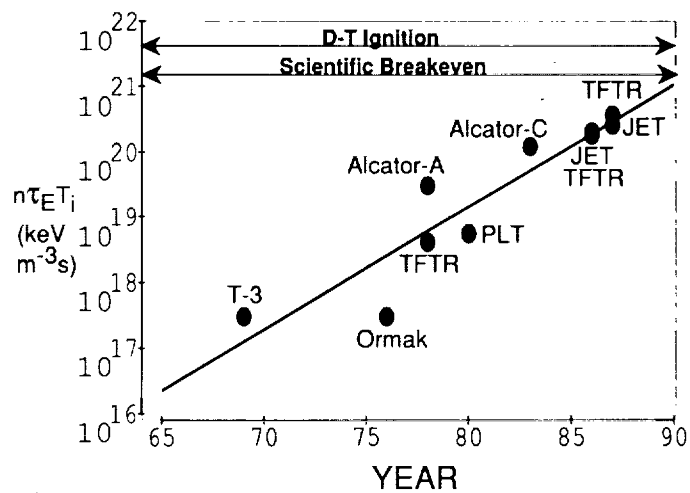

Fig. 9. Experimentally achieved parameter progress in fusion research.

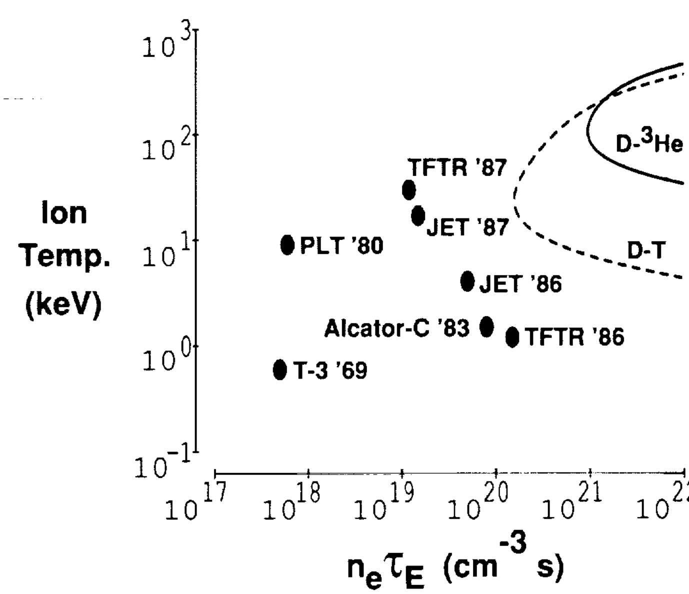

Fig. 10. Plasma ignition requirements for D-T and D-^{3}He plasmas.

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suitable for the high neutron fluence of D-T reactors remain to be identified and would require an additional test device (or separate demonstration program). Also, the breeding of T fuel in a "blanket" surrounding the plasma requires considerable development and testing. There appear to be only a few areas where D-^{3}He propulsion systems could not rely on developed materials and technology. These include fueling, plasma current drive, and high-heat-flux materials. All these issues will be similar for D-^{3}He and D-T; they will, therefore, be addressed within the present D-T fusion program.

IMPLICATIONS FOR SPACE DEVELOPMENT

The development of terrestrial D-^{3}He fusion power will have an enormous impact on Earth's energy future and on lunar development. In space, D-^{3}He fusion will be an enabling technology for a large-scale human presence beyond Earth orbit, and the eventual impact may be even greater than on Earth. The high performance and flexibility of fusion propulsion will greatly expand the options available in building a major space infrastructure as the need for such systems begins to gain prominence early in the twenty-first century.

A fleet of fusion rockets could provide much of the "Bridge Between Worlds" of the *National Commission on Space* (1986). Figure 11 illustrates some potential space applications of fusion propulsion and power. It also shows the use of important by-products of ^{3}He mining, the other released gases such as CO_2 and N_2 for life support (*Bula et al.,* 1991). These rockets would vary only modestly in design, but would operate in the optimal thrust mode for a given mission, carrying humans quickly or cargo efficiently throughout the solar system. Although D-^{3}He fusion would provide high performance for large-scale operations beyond Earth orbit, present designs are inherently low thrust-to-weight systems, and alternatives would be required for surface-to-orbit operations except on asteroids and small moons. The specific D-^{3}He fusion system discussed in this paper remains attractive down to powers of ~100 MW, but other fusion configurations or nonfusion sources would be needed at low power.

Noteworthy for operations in the outer solar system is that D-^{3}He fuel is more abundant than any fuel except the proton-proton fuel of stars. Assuming a primordial composition, the gas giant planet mass fractions are approximately 10^{-5} ^{3}He and 3×10^{-7} D (*Weinberg,* 1972). Unfortunately, it appears that the probability of finding fossil fuels in the solar system beyond Earth is

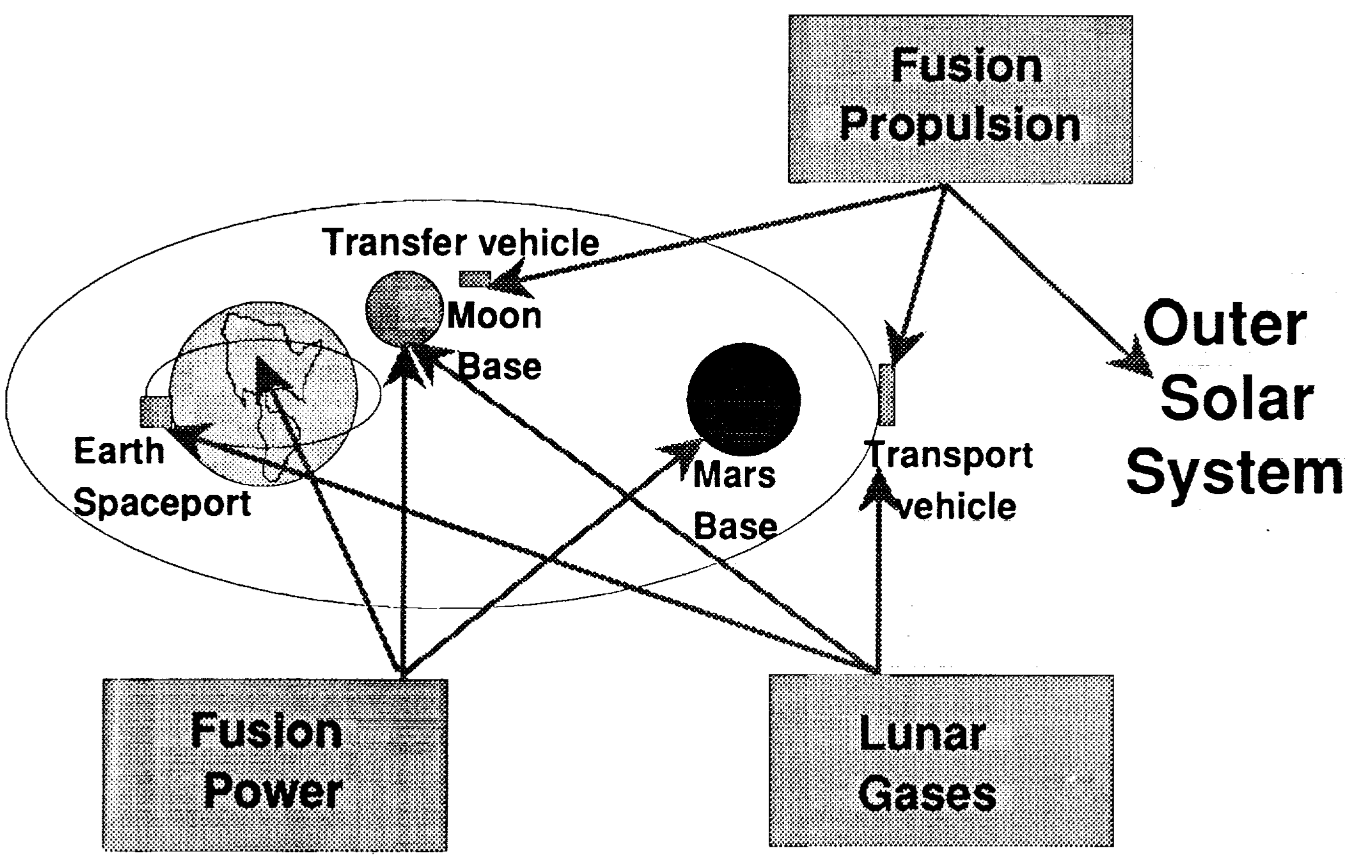

Fig. 11. The potential impact of D-^{3}He fusion on the "bridge between worlds" discussed by the *National Commission on Space* (1986).

very small, and the processing of fissile fuel, even if it exists in relative abundance, will require a massive and complex technology. On the timescale that a small percentage of the lunar surface can supply ^{3}He—a few hundred years—it is reasonable to anticipate development of the technology required to access the enormous quantities of D and ^{3}He in the gas giants.

Fusion propulsion, therefore, will dominate future transportation throughout the solar system. For missions beyond the Moon, where chemical systems quickly become inefficient in both payload fraction and trip time, fusion represents a key enabling technology.

CONCLUSIONS

The main conclusions of this analysis of the space applications of D-^{3}He fusion power are

1. Deuterium-helium-3 fusion will provide safe, efficient propulsion, offering a wide range of options—from fast, pilot missions to slower, cargo transport.
2. Linear systems most obviously provide an efficient means of producing direct thrust, but numerous options are likely to develop, and toroidal configurations also appear promising. The linear rocket design presented in this paper would provide a specific power of ~1.2 kW/kg.
3. The D-^{3}He fusion fuel cycle possesses distinct advantages over other candidate fusion fuel cycles, fission, and chemical systems for space applications.
4. Fusion power using D-^{3}He can be developed on a timeframe consistent with space development needs.
5. D-^{3}He fusion propulsion will enable a major expansion of human presence into the solar system.

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