

Generic Magnetic Fusion Rocket Model

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A generic magnetic fusion rocket model is developed and used to explore the limits of magnetic fusion propulsion systems. Two fusion fuels are examined, $D-T$ and $D-^3\text{He}$, and the $D-^3\text{He}$ fuel cycle is predicted to give a higher specific power for optimized parameters. Other findings are that magnetic fusion should ultimately be able to deliver specific powers of ~ 10 kW/kg and that specific powers of $1-5$ kW/kg should be achievable with only modest extrapolations of present technology.

Nomenclature

B	= magnetic field
C_m	= magnet structure design safety factor
D	= deuterium
E	= energy per reaction
E_{stored}	= magnet stored energy
f_{burn}	= tritium burn fraction
^3He	= helium-3
^4He	= helium-4
M_m	= magnet mass
n	= density
n	= neutron
P	= power density
p	= proton
Q	= fusion power/input power
r_w	= wall radius
T_p	= plasma temperature
T	= tritium
V_{mag}	= volume enclosed by magnetic field
α	= specific power
β	= plasma pressure/magnetic-field pressure
Δ_s	= shield thickness
λ_s	= shield thickness for 10-fold reduction of neutron power
μ_0	= magnetic permeability of free space
$\rho_{\text{structure}}$	= density of magnet structure
σ_{stress}	= allowable magnet structure stress
$\langle \sigma v \rangle$	= Maxwellian-averaged fusion reaction rate

Subscripts

b	= bremsstrahlung
ddn	= D-D reaction neutron channel
ddp	= D-D reaction proton channel
e	= electron
f	= fusion
i	= ion
n	= neutron

t	= tritium
3	= helium-3

I. Introduction

THE promise of magnetic fusion power for space propulsion throughout the solar system was recognized in the late 1950s.¹⁻³ Since that time, fusion research has made great progress in experimental parameters, theoretical understanding, and the development of computer modeling tools. These advances have been used in several recent fusion space-propulsion conceptual design studies,⁴⁻¹⁰ listed in Table 1, which have predicted specific power values of $\alpha = 1-10$ kW_{thrust}/kg_{reactor}.

This paper describes a generic model of a magnetic fusion reactor for space propulsion. This model has been developed to examine the plausibility of the high specific powers that recent, more detailed studies have projected for fusion propulsion, and to explore the limits on the performance that rockets powered by magnetic fusion might eventually achieve. The paper focuses on magnetic fusion energy, but it should be noted that work also exists on fusion using inertial confinement^{11,12} and electrostatic confinement.^{8,13} Several fusion propulsion options are compared in Ref. 14, which attempts to evaluate the varying depths of detail of existing studies.

First, fusion fuels for space applications are discussed, followed by the equations used to model the physics and engineering systems. The results of parametric analyses are then presented and some optimized cases exhibited. Finally, conclusions are drawn. SI units are used, except that energies and temperatures are in keV.

II. Space Fusion Fuels

The two fusion fuel cycles expected to be most important for space-propulsion applications are the reactions of deuterium and helium-3, and of deuterium and tritium



The deuterium also increases the fusion power and the neutron production through the reactions



Burn-up of the tritium produced in the $p + T$ channel contributes significantly to the neutron production for $D-^3\text{He}$ fuel.

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Table 1 Recent conceptual designs studies of magnetic fusion reactors for space propulsion

First author	Year	Configuration	Specific power, kW/kg
Borowski ⁴	1987	Spherical torus	5.75
Borowski ⁴	1987	Spheromak	10.5
Santarius ⁵	1992	Tandem mirror	1.2
Chapman et al. ⁶	1989	Field-reversed configuration	—
Haloulakis and Bourque ⁷	1989	Colliding spheromaks	—
Bussard ⁸	1990	Riggatron tokamak	3.9
Teller et al. ⁹	1992	Dipole	1.0
Carpenter and Deveny ¹⁰	1994	Tandem mirror	4.0

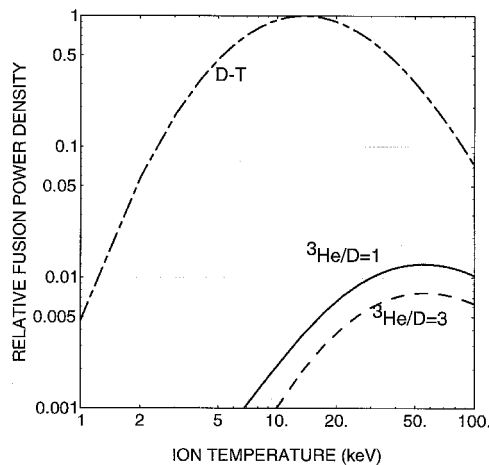


Fig. 1 Local fusion power density in the plasma for $D-T$ and $D-^3\text{He}$ fusion fuels, with two values of the ^3He -to- D density ratio shown.

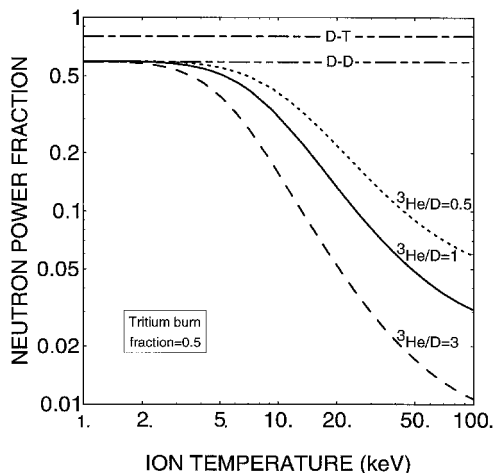


Fig. 2 Ratio of neutron power to fusion power for the $D-T$, $D-D$, and $D-^3\text{He}$ fusion fuel cycles, with three values of the ^3He -to- D density ratio shown.

Several factors differentiate these fuel cycles. The main benefit of $D-T$ fuel is that the fusion power density in the plasma can be much higher than for $D-^3\text{He}$ (Fig. 1), and this makes the required physics parameters easier to achieve. $D-^3\text{He}$ fuel, however, produces almost all of its fusion energy as charged particles, as shown in Fig. 2, and this results in the following engineering advantages.

1) Savings on the mass of the shield for the magnet and other components.

2) The possibility for direct conversion of fusion power to thrust by guiding charged particles along magnetic field lines.

3) Higher availability and longer component lifetimes because of reduced radiation damage.

4) Enhanced safety as a result of a lower radioactive inventory.

5) The elimination of a complex tritium-breeding blanket and processing system.

Advantage 5 in the preceding text assumes that tritium fuel would be bred onboard a $D-T$ fusion rocket. Otherwise, 100 kg or more of radioactive tritium would need to be bred in another powerplant, transported to the $D-T$ fusion rocket, and carried in storage, with resulting safety and environmental concerns.

The availability of ^3He is also an issue because ^3He is very rare on Earth. The ^3He resource problem has been solved, in principle, by the identification of a large amount of ^3He on the surface of the moon.^{15,16} On the time frame of humankind's expansion into the solar system, accessing the lunar ^3He resource appears to be well within technological capabilities.^{15,16} On an even longer time scale, the huge ^3He reserves of the Jovian planets should be within reach of human ingenuity. Suitable designs for breeding ^3He in $D-D$ or other fusion reactors have been sought for over 20 years, and this work is summarized in Ref. 17. Although its feasibility appears doubtful, breeding may eventually provide a ^3He resource option. Fortunately, for $D-^3\text{He}$ fusion research and development purposes, a sufficient ^3He resource does exist on Earth.^{15,16}

III. Model Description

A large variety of candidate magnetic fusion reactor configurations exists, with greatly differing geometries and plasma parameters. The present study assumes that the configuration of the external magnetic field coils is cylindrical, the choice of most of the detailed conceptual design studies for space propulsion.¹⁸ Toroidal systems can be modeled approximately by equating the circumference of the major axis of the torus to the length of this cylinder. Compared to a toroidal configuration, the open-ended cylindrical geometry facilitates using the plasma for direct thrust and raises the ratio of the magnetic field in the plasma to the field on the coils. The basic geometry is shown in Fig. 3; it is particularly appropriate to configurations such as tandem mirrors, field-reversed configurations, and spheromaks.¹⁸⁻²⁰ Although this model is very simple the major components contributing to the total propulsion system mass—the magnets, shields, radiators, and refrigerators—are included and their masses can be estimated with reasonable accuracy.

The most important omission in this generic approach is the neglect of the mass of systems for input power and power conversion, which will vary significantly for differing configurations. Because the input power will typically be 10–100 MW to compensate for plasma transport and radiation losses, there will be a lower limit on the fusion power for a high-performance system because of the recirculating power. Therefore, the propulsion system thrust level chosen for the reference cases is 600 MW. For a nominal input power of 60 MW, this gives $Q = 10$, which is an approximate lower bound for the mass of the recirculating power system to be less than 10% of the total mass. This estimate is based on a conceptual design for direct conversion and power-conditioning system masses

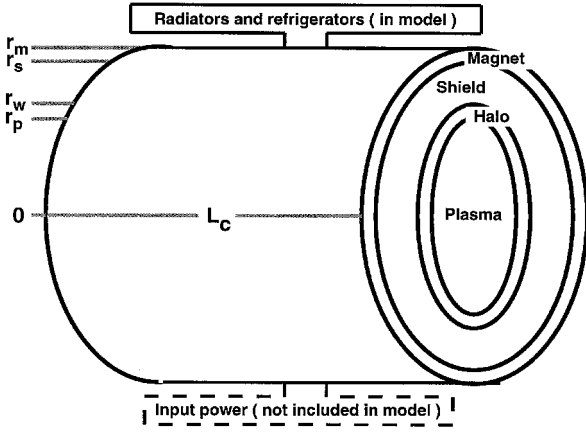


Fig. 3 Generic fusion rocket geometry.

in space^{21,22} plus the fact that neither radio-frequency antennas nor neutral beam injectors without their vacuum enclosures would have large masses.

A. Plasma Physics

A useful characterization of magnetic fusion configurations is by the ratio of the plasma pressure to the magnetic field pressure

$$\beta \equiv \frac{(n_e + n_i)T}{B^2/2\mu_0} \quad (1)$$

Typical fusion-reactor β values range from 0.02 to 0.1 for the tokamak configuration to ~ 0.9 for the field-reversed configuration. These values depend on detailed calculations of magnetohydrodynamic equilibrium and stability. Impurities and fusion ash are neglected here, and equal ion and electron temperatures are assumed; these assumptions lead to relatively small corrections. The plasma density and temperature are assumed to have flat radial profiles, which is approximately true of many, but not all, of the types of configurations under consideration. Radially peaked values would necessitate an increase in the plasma radius. A halo or scrape-off layer of low-temperature plasma separates the core plasma from the chamber wall. This gap is taken to be 0.1 m for the present calculations to keep fusion products from hitting the wall because of their large gyroradii when they are born near the plasma edge with a high velocity perpendicular to the magnetic field.

The calculation of the total fusion power and the neutron power is straightforward, but it is complicated slightly in the D - ^3He case by the need to include D - D reactions and the burn-up of the tritium produced. The fraction of tritium burned up before it can escape the core plasma is assumed here to be 50%, a typical value²³ based on the particle confinement time being nearly equal to the energy confinement time. The D - ^3He equations will be given explicitly; the D - T equations are analogous. The power density terms are

$$P_f = n_d n_3 \langle \sigma v \rangle_{d3} E_f^{d3} + (n_d^2/2) \langle \sigma v \rangle_{ddn} E_f^{ddn} + (n_d^2/2) \langle \sigma v \rangle_{ddp} E_f^{ddp} + f_{\text{burn}} n_d n_t \langle \sigma v \rangle_{dt} E_f^{dt} \quad (2)$$

$$P_n = (n_d^2/2) \langle \sigma v \rangle_{ddn} E_n^{ddn} + f_{\text{burn}} n_d n_t \langle \sigma v \rangle_{dt} E_n^{dt} \quad (3)$$

$$P_b = 5.4 \times 10^{-43} n_e^2 T^{1/2} [0.00414T + 0.070Z_c^{\text{eff}}/T^{1/2} + Z^{\text{eff}}(1 + 0.00155T + 7.15 \times 10^{-6}T^2)] \quad (4)$$

where it is important to include relativistic effects in the bremsstrahlung power density,²⁴ $Z^{\text{eff}} = \sum n_i Z_i^2/n_e$, $Z_c^{\text{eff}} = \sum n_i Z_i^3/n_e$, and the fusion reaction rate is given in Ref. 25.

Synchrotron radiation power will also be generated, and it causes an unfavorable, but small, correction for the high betas and relatively low magnetic fields of most interest for space propulsion. The synchrotron power will be neglected for the present analysis. The power density for the remaining power loss from the core plasma, charged-particle transport, can be calculated by subtracting the neutron and bremsstrahlung powers from the sum of the fusion and input powers. It is important to note, however, that the very difficult problem of the self-consistency of this transport power with the plasma dimensions and other parameters cannot be handled by a generic model, and transport sets a lower limit on the plasma radius. The transport power is available for generating thrust through the magnetic nozzle. These have received limited attention,^{26,27} and so it is unclear how high a thrust-to-transport power ratio (magnetic nozzle efficiency) will be attainable, and a reasonable value of 0.8 will be used here. The heat that must be rejected by the radiators will be the sum of the neutron and bremsstrahlung powers.

B. Engineering Systems

The total magnet mass is taken to be the larger of two estimates, based on either the magnet virial theorem or the winding-pack current density. The magnet virial theorem is related to the magnet structural mass limits because of material properties, and is given by

$$M_m = C_m \frac{\rho_{\text{structure}}}{\sigma_{\text{stress}}} E_{\text{stored}} \quad (5)$$

where $C_m = 2$, $\rho_{\text{structure}} \approx 2.5 \text{ Mg/m}^3$ for carbon/carbon-composite structure, σ_{stress} is assumed to be 1000 MPa, and E_{stored} is given by

$$E_{\text{stored}} \approx (B^2/2\mu_0)V_{\text{mag}} \quad (6)$$

The limit on the current density averaged over the magnet winding pack will be taken to range from 50 MA/m², typical of advanced fusion magnet conceptual designs and scheduled to be demonstrated on the large helical device fusion experiment in 1998,²⁸ to 250 MA/m², where superconductor quenching becomes a concern.

Assuming that conventional, low-temperature superconducting magnets are used and cooled by helium at 4.2 K, the mass of the helium refrigerators can be large. A value of 1000 kg/kW for the refrigerator mass per unit of heat deposited in the magnets is used here, which is ~ 10 times better than present terrestrial helium refrigerators,²⁹ because we have assumed improved technology, low mass as a design goal, and benefits from the low background temperature of space. Continued progress in high-temperature ($>20 \text{ K}$) superconductors at the present pace for magnetic fields and current densities³⁰ would substantially improve fusion-propulsion performance by allowing higher refrigerator efficiency and radiation heating of magnets, thus reducing the mass of refrigerators, radiation shields, and magnets.

A shield is necessary to reduce the neutron flux from the plasma core to levels that protect the magnets from radiation damage and localized heating that could induce quenches. An optimized lithium hydride shield is used here,³¹ with a density of about 1 Mg/m³. The neutron power absorbed in the magnet is

$$P_{\text{mag}} = P_n \left(\frac{r_w}{r_w + \Delta_s} \right) 10^{-\Delta_s/\lambda_s} \quad (7)$$

where the shield thickness required to reduce the neutron power by a factor of 10 is 0.31 m, and $r_w/(r_w + \Delta_s)$ is the geometric falloff of a line source with radius. The slight difference between the D - T and D - ^3He neutron energy spectra

is neglected. This assumption is conservative, particularly at high ^3He -to- D density ratios, where a larger fraction of the neutron power is in the form of lower-energy, less-penetrating D - D neutrons. A space of 0.1 m is included between the shield and the magnet to account for thermal insulation, maintenance-gaps, and support structure.

IV. Results

One purpose of the present study is to examine the likely performance of those fusion space-propulsion systems that may, with a reasonably well-funded development program, be ready for use early in the 21st century. Another goal is to examine the ultimate limits of magnetic fusion for space propulsion. Thus, we focus on two cases: 1) Midterm: a modest extrapolation of present technology and 2) long-term: an advanced case. The corresponding default assumptions are listed in Table 2.

To solve the equations presented in Sec. III, choices are made for β and the magnetic field. The specific power is then minimized over the variables shield thickness, plasma temperature, and ^3He -to- D density ratio, while varying the plasma length to give the desired thrust power and the plasma radius to satisfy either the heat flux limit in the D - ^3He case or the neutron wall load limit in the D - T case. The D - T and D - ^3He limiting effects differ because of the varying power distributions between neutrons and surface heat: Respectively, about 4:1 for D - T and 1:20–1:100 for D - ^3He . For very short trips (approximately three months or less), the surface heat flux in a D - T reactor would reach its limit before the neutron wall load reached a sufficient fluence to exceed the damage limits

for the structural materials. For uncrewed cargo missions, where a high payload fraction is more important than speed, or for travel to the outer solar system, the trip would require at least six months and neutron damage would dominate. Several iterations are performed until the parameters vary by no more than a few percent, and these values are used to calculate the remaining quantities of interest.

Table 3 shows parameters for midterm D - T and D - ^3He cases and for a long-term D - ^3He case. The calculations were performed using Mathematica™ on a NeXT™ computer. The midterm D - T case shows the difficulty of achieving high specific power for this fuel cycle in a direct-thrust mode. The neutron wall load limit was set by the requirement that the structures experiencing the most radiation damage would last at least the lifetime of the mission. This is, of course, mission dependent, but even at high specific powers of $\alpha \approx 10$ kW/kg the shortest one-way Earth–Mars travel times are one month for payload fractions over 0.1,^{18,32,33} and these still favor D - ^3He fuel.

The performance of D - T fuel will rise somewhat if more durable materials are developed, but dramatically improved performance appears unlikely. An interesting point for this case is that the superconducting magnets are optimized at a field of 5 T as a result of the neutron wall load constraint on the system, not intrinsic limits of the superconductors themselves. Rather than using only the transport power for direct thrust, if the thermal D - T fusion power is converted to electricity and used to power a plasma thruster, the system may have some safety and environmental advantages over fission systems. The thermal-conversion system will add a large mass, however, and

Table 2 Engineering parameter default assumptions

Parameter	Midterm	Long term
Surface heat flux limit, MW/m ²	5	10
Neutron wall load limit, MW/m ²	20	20
Magnet winding pack average current density, MA/m ²	50	250
Magnet stored energy per unit mass, kJ/kg	50	200
Magnet winding pack average density, Mg/m ³	6	6
He-refrigerator mass per heat pumped, kg/kW	1000	1000
Radiator: power rejected per unit mass, kW/kg	5	5
Shield density, Mg/m ³	1	1
Shield thickness for 10-fold magnet heating reduction, m	0.31	0.31
Shield-magnet gap, m	0.1	0.1
Halo thickness, m	0.1	0.1
Efficiency of transforming transport power to thrust	0.8	0.8

Table 3 Reference parameters for three generic fusion rocket cases

Parameter	Midterm, D - T	Midterm, D - ^3He	Long term, D - ^3He
β	0.6	0.6	0.9
Deuterium density, m ⁻³	5.7×10^{20}	3.7×10^{20}	6.4×10^{20}
T - or ^3He -to- D density ratio	1	0.68	0.66
Plasma temperature, keV	17	100	128
Plasma length, m	71	5.1	3.7
Plasma radius, m	0.25	1.12	0.67
Shield thickness, m	0.42	0.19	0.29
Magnetic field, T	5	10	12
Magnet stored energy, GJ	1.7	1.5	0.88
Thrust power, MW	600	600	600
Fusion power, MW	3960	992	968
Bremsstrahlung power, MW	45	196	176
Neutron power, MW	3166	46	42
Neutron wall load, MW/m ²	20	1.12	2.39
Surface heat flux, MW/m ²	0.28	5	10
Magnet mass, Mg	187	46	6.1
Radiator mass, Mg	642	48	44
Refrigerator mass, Mg	64	9.4	3.6
Shield mass, Mg	106	8.2	6.1
Total mass, Mg	999	112	59
Specific power, kW/kg	0.60	5.3	10.1

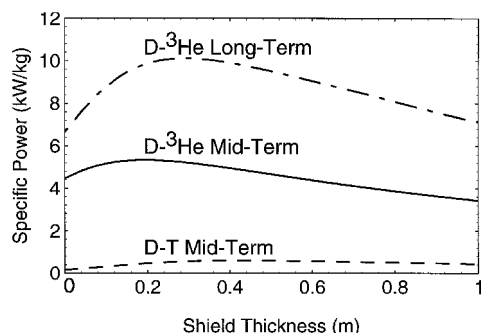


Fig. 4 Dependence of specific power on shield thickness for the generic fusion rocket reference cases.

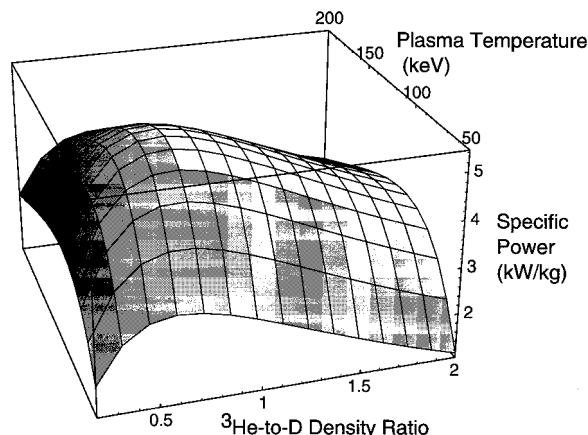


Fig. 5 Dependence of specific power on plasma temperature and the ${}^3\text{He}$ -to- D density ratio for the midterm $\text{D}-{}^3\text{He}$ fusion rocket reference case.

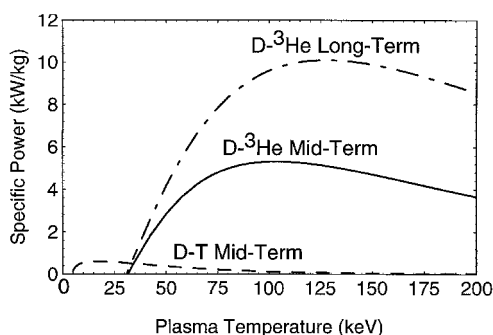


Fig. 6 Dependence of specific power on plasma temperature for the generic fusion rocket reference cases.

the power density for a $\text{D}-\text{T}$ reactor is expected to be near that of a fission reactor. It appears unlikely that specific powers significantly higher than the ~ 0.1 kW/kg expected of advanced fission systems will be reached.

The midterm $\text{D}-{}^3\text{He}$ case would provide an attractive specific power of ~ 5 kW/kg, suitable for greatly shortening trip times or increasing payload fractions compared to chemical or fission systems for travel throughout the solar system.^{18,32,33} The main extrapolation required is in the physics parameters, particularly for the linear, cylindrically symmetric fusion configurations, which presently have only a limited database. The projected performance is typical of earlier, more detailed studies of $\text{D}-{}^3\text{He}$ fusion space-propulsion systems, and shows why $\text{D}-{}^3\text{He}$ fuel has usually been chosen over $\text{D}-\text{T}$ fuel for space applications. The magnetic field optimized at 10 T in this case, representing a tradeoff between higher plasma power density, which scales as B^4 , and the surface heat flux limitation.

The long-term $\text{D}-{}^3\text{He}$ case, at ~ 10 kW/kg, is very attractive, although several of the engineering systems would require substantial development. The 12-T magnetic field is well below technological limits, as in the midterm cases. This case has reached the point where the radiator mass dominates the system and the dependence on the other parameters is weak. Thus, as with many space systems, improvements in radiator technology would have a significant impact on the design. This case may also be getting into a regime where neglecting the details of the heat transfer system and the mass of the input power and power-conversion systems is no longer valid. More careful consideration of these systems that extrapolate significantly beyond terrestrial experience requires detailed design that is outside the scope of the present paper.

The dependence of the specific power on the magnet shield thickness for the optimized reference cases is shown in Fig. 4. The optimization of the specific power with respect to both the plasma temperature and the ${}^3\text{He}$ -to- D density ratio is shown in Fig. 5 for the midterm $\text{D}-{}^3\text{He}$ reference case. The optimum temperature is much higher than that for the plasma power density shown in Fig. 2, because the neutron and bremsstrahlung power fractions decrease with temperature, and reducing them decreases the radiator and refrigerator masses. The dependence of the specific power on the plasma temperature for all three optimized reference cases is shown in Fig. 6.

V. Conclusions

Based on a simple, generic model of the potential performance of a magnetic fusion rocket, the values given by more detailed design studies of $1\text{--}10$ kW_{thrust}/kg_{reactor} are plausible. The model includes the masses of the systems expected to be the most important contributors to the total mass. Once the physics barriers have been overcome, magnetic fusion propulsion systems appear capable of reaching performance levels of ~ 10 kW_{thrust}/kg_{reactor}.

Acknowledgments

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