A Design Study of a p-^{11}B Gasdynamic Mirror Fusion Propulsion System

Chad Ohlandt[1], Terry Kammash[2], Kenneth G. Powell[1]

[1]Department of Aerospace Engineering, University of Michigan, Ann Arbor, MI 48109
[2]Department of Nuclear Engineering and Radiological Sciences, University of Michigan, Ann Arbor, MI 48109
734-764-7573, chadjo@umich.edu

Abstract. Fusion gasdynamic mirror (GDM) space propulsion concepts have been previously explored using deuterium, tritium, and helium-3 fuels. This work is a similar design study using the advanced fusion fuel combination, hydrogen and boron-11. A GDM using p-^{11}B is optimized for the parameters of temperature, density, fuel ratio, and mirror radius. Even after optimization, a traditional GDM using p-^{11}B and achieving breakeven appears to be impractical due to bremsstrahlung and synchrotron radiation losses. A nuclear electric assisted version of the system is examined and found to decrease the size and mass of the system. The optimal plasma temperature is also reduced by the assistance which decreases the technical requirements for magnetic confinement.

INTRODUCTION

Traditional fusion research efforts have discarded magnetic mirrors as a viable option due to the plasma losses from the open configuration. Fortunately, the primary design driver of a plasma propulsion system is significant plasma "loss" which results in thrust. Taking advantage of this, Kammash et al. designed a gas dynamic mirror fusion propulsion system (Kammash, 1995; 1997; 1998). While potentially feasible, the resulting GDM configurations had masses of 400-1000 metric tons (1-2.5 International Space Station Alphas for comparison) and are unlikely to be launched into space in the near future. Up to 75% of the GDM mass budget is devoted to thermal converters and radiators to eliminate waste heat primarily from neutrons produced by the fusion of the deuterium-tritium (D-T) fuel. A reduction in neutron production would significantly decrease the GDM mass requirements. Additionally, high energy neutrons require additionally shielding to protect system components. Finally, tritium is a radioactive fuel which creates safety concerns during launch into orbit or possible re-entry into the Earth's atmosphere. This work focuses on two possibilities to address these issues: advanced fusion fuels and/or assisted reactor systems.

Again, traditional fusion research has studied advanced fusion fuels such as D-^{3}He, ^{3}He-^{3}He, and p-^{11}B which all generate lower levels of neutron production or none at all. They have been generally been regarded as unsuitable for low β reactors such as the popular tokamak configuration and uneconomical for power production due to radiation power losses and limited Q-values(McNally, 1982; Kernbichler, 1987; Heindler, 1989; Best, 1990; Perkins, 1997). However, these fuels could be ideal for a high-β GDM propulsion system. While Q only needs to exceed breakeven and radiation can be used for thrust enhancement (Kammash, 1997), the aneutronic nature of the fuels could reduce the weight of a GDM propulsion system. Such a revolutionary system that is not limited by the traditional assumptions of the fusion research establishment would open the solar system to exploration and development.

Using advanced fusion fuels with no or minimal neutron production would reduce the waste heat and therefore the mass of the thermal converters and radiators. Table 1 lists various fusion fuels and their corresponding parameters. The aneutronic ^{3}He-^{3}He and p-^{11}B reactions avoid neutron energy loss, but require much larger ignition temeratures. The compromise reaction, D-^{3}He, has been studied and offers lower relative neutron power levels, but the resulting configuration is significantly more massive the the original D-T concept. As such, p-^{11}B is the most promising for further study.

CP654, *Space Technology and Applications International Forum–STAIF 2003*, edited by M.S. El-Genk

TABLE 1. Table of Fusion Fuels with Relevant Parameters.

Fuel	Products	Total Energy [MeV]	Charged Particle Energy [MeV]	Optimal Ignition Temperature [keV]
D-T	n + ^{4}He	17.6	3.5	10.5
D-D	p + T	4.0	4.0	15
	n + ^{3}He	3.3	.8	15
D-^{3}He	p+ ^{4}He	18.3	18.3	60
^{3}He-^{3}He	2p + ^{4}He	12.9	12.9	1000
p-^{11}B	3^{4}He	8.7	8.7	150

PROTON-BORON 11 OPTIMIZED GDM

The p-^{11}B appears very attractive given its largely aneutronic nature, availability, and reasonable ignition temperature. The primary challenge of advanced fusion fuels are the higher plasma temperatures. At these temperatures, bremsstrahlung and synchrotron radiation losses become so significant as to limit the Q factor or even the ability to reach ignition. Previously developed parametric models (Kammash, 1995; 1997) with p-^{11}B parameters were modified to take into account that T_e is not equal to T_i, using Dawson (Dawson, 1981) to find it, and to calculate bremsstrahlung power as does Nevins (Nevins, 1998). The important characteristics of this model include a high density Maxwellian plasma in a large aspect ratio GDM with homogeneous properties throughout, a Q of slightly greater than 1 to account for efficiency losses, and a mission trajectory which assumes a direct line from origin to destination with constant acceleration or deceleration during transit.

The charts in Figure 1 indicate radiation powers as multiples of the fusion power generated. With a reflectivity of .9, the synchrotron power is too much. Increasing the reflectivity to .99, a potential p-^{11}B system would work around 160 keV giving an optimal balance between bremsstrahlung and synchrotron losses. However, a $Q > 1$ is only possible when P_{rad}/P_f ratio is below 2. In the case of .9999 reflectivity, synchrotron radiation becomes unimportant. It should be noted that bremsstrahlung radiation is heavily concentrated in the x-ray band and cannot be easily reflected. In the remaining cases, T=300 keV and R=.9999 were assumed. Even in this best case scenario, radiation losses are a multiple of the fusion power (roughly 1.8) indicating that ignition is not possible and the GDM will function only in a driven mode. Fortunately, high Q is not necessary for GDM operation, only slightly greater than 1 is needed.

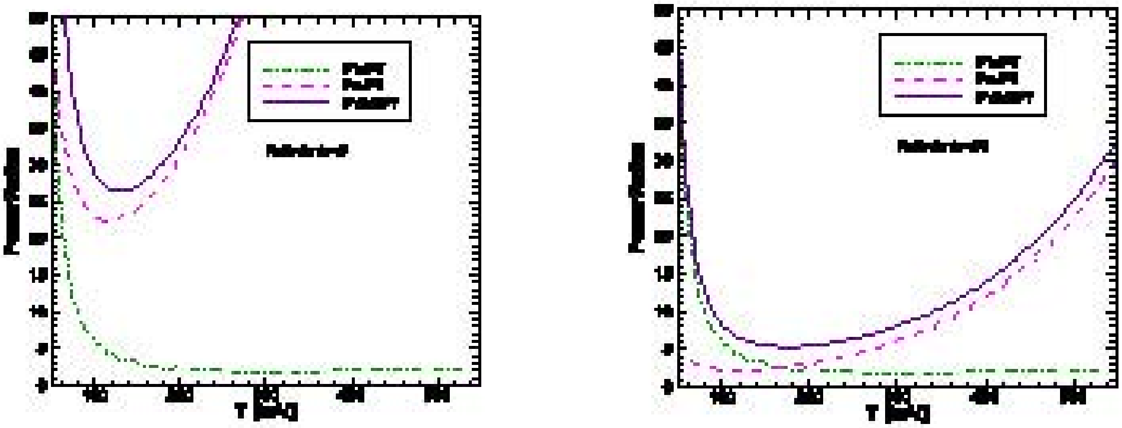

FIGURE 1A. Power Ratios as a Function of Temperature for Different Reflectivities (.9,.99).

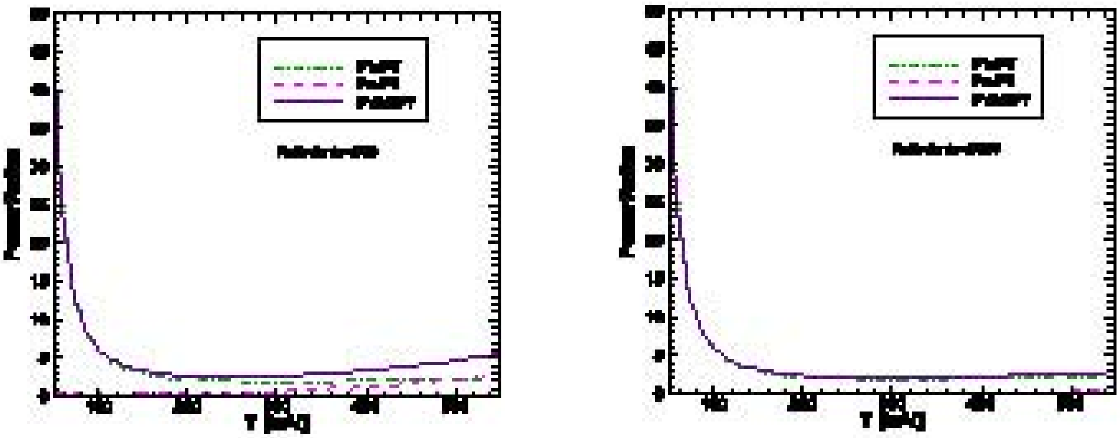

FIGURE 1B. Power Ratios as a Function of Temperature for Different Reflectivities (.999,.9999). P_b is Bremsstrahlung Radiation Power, P_s is Synchrotron Radiation Power, and P_{rad} is P_b+P_s.

Figure 2 explores the affects of plasma density on our GDM propulsion system. Greater density increases total fusion power and thrust, but it also increases the radiation load with corresponding thermal converters and radiators. The first chart indicates on optimum density of $2.0*10^{16}$ particles per cubic centimeter the leads to the minimum dry mass of the system as well as approaching the best trip time. The second chart explains this by showing how the thermal radiator mass dominates the system above this density.

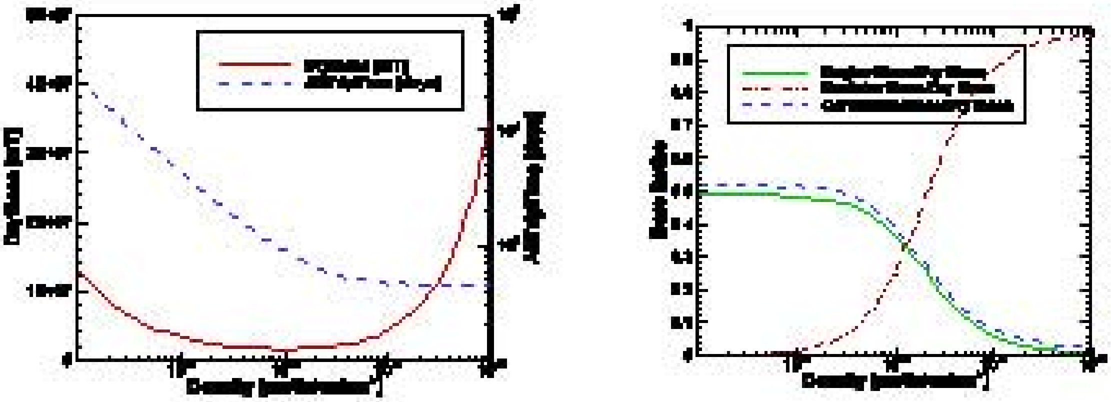

FIGURE 2. System mass, trip time, and component mass fractions as a function of plasma density.

The fuel ratio, n_B/n_p, also has a significant effect on the GDM system. The primary driver of this is the much greater charge of boron atoms (Z=5). ^{11}B contributes, on a per atom basis, much more to bremsstahlung radiation than protons. Additionally, it also adds to the electron density increasing the synchrotron radiation. Of course, too little ^{11}B reduces the fusion power. Figure 3 clearly indicates that a fuel ratio of .15 produces the optimal dry mass and trip time.

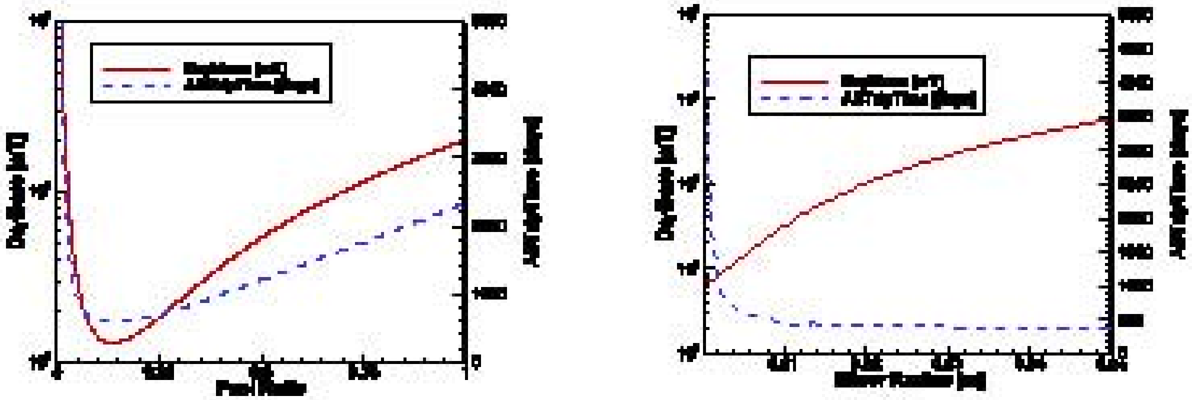

FIGURE 3. Fuel fraction and mirror radius impact on the system mass and trip time.

With the various system parameters optimized, the actual size of the system is directly a function of its radius which is specified through the mirror radius. Dry mass and trip time are plotted against the mirror radius in Figure 3. While the smaller dimension continues to reduce the total mass, the diminishing thrust increases travel time. A mirror radius of .005 meters gives close to optimal trip time with minimum mass.

As such, the best system possible requiring Q>1 is listed in Table 2. Unfortunately, such a system is 24 kilometers long, weighing over a million metric tons, and takes a year and half to reach Mars. Fundamentally, the large bremsstrahlung losses increase system size beyond a practical limit to achieve a Q>1design.

TABLE 2. Optimized Q>1 p-^{11}B GDM.

Chosen Parameters	Value	Calculated Parameters	Value
Reaction Type	p-^{11}B	Vacuum Magnetic Field	80.07 Tesla
Plasma Density	$2.0 * 10^{16}$ #/cm^3	Gain Factor, Q	1.222
Hydrogen Density	$1.74 * 10^{16}$ #/cm^3	Plasma Length	23635 m
Boron-11 Density	$2.61 * 10^{15}$ #/cm^3	Injection Energy	1464.34 keV
Electron Density	$3.04 * 10^{16}$ #/cm^3	Loss Energy	600 keV
Plasma Temperature	300 keV	Thrust	150985 N
Beta (vacuum)	0.95	Thrust Power	$4.44 * 10^5$ MW
Plasma Mirror Ratio	100	Injection Power	$2.17 * 10^6$ MW
Plasma Mirror Radius	0.005 m	Fusion Power	$2.65 * 10^6$ MW
Halo Thickness	0.1 m	Bremsstrahlung Power	$4.67 * 10^6$ MW
Shield Magnet Gap	0.1 m	Synchrotron Power	$1.67 * 10^5$ MW
Shield Thickness	0.19 m	Total Dry Mass	$1.28 * 10^6$ mT
Injector Efficiency	1.0	Engine Mass Fraction	0.29
Thermal Converter Eff.	0.45	Converters Mass Fraction	0.30
Direct Converter Eff.	0.9	Radiator Mass Fraction	0.41
Magnet Current Density	$2.5 * 10^8$ MA/m^2	Isp	693,791 s
Destination Mars	$7.8 * 10^{10}$ m	Round Trip Time	3.27 years
Reflectivity	0.9999	Trip Time AB	1.63 years
		Fusion Power	$1.43 * 10^{10}$ watts/m^3
		Bremstrahlung Power	$2.51 * 10^{10}$ watts/m^3
		P_b/P_f	1.76
		Synchrotron Power	$8.97 * 10^8$ watts/m^3
		P_s/P_f	0.06

NUCLEAR ELECTRIC ASSISTED GDM

If the Q>1 requirement is relaxed and supplemental power is generated with a nuclear electric fission reactor, the size of the system can be reduced. This is done by replacing the equation for the critical Q in the model (Kammash, 1997) with the following.

$$Q_c = \frac{1-\frac{1}{2}\eta_i\eta_D}{\frac{1}{2}\eta_i\eta_D + \eta_i \frac{P_{ne}}{P_f} + \eta_i(\eta_t - \frac{1}{2}\eta_D)\frac{P_n + P_r}{P_f}} \qquad (1)$$

By introducing supplemental power as a fraction of the fusion power and adding the mass of an advanced nuclear electric space power system using a specific power of 2000 W/kg (Smith, 2001), the reduced system parameters can be found in Figure 4. For a T=300 keV system, the effects are moderate overall. However, with Q<1 being acceptable, the temperature can be reduced to a lower 160 keV. It is notable that the higher temperature system is much less sensitive to the level of assistance.

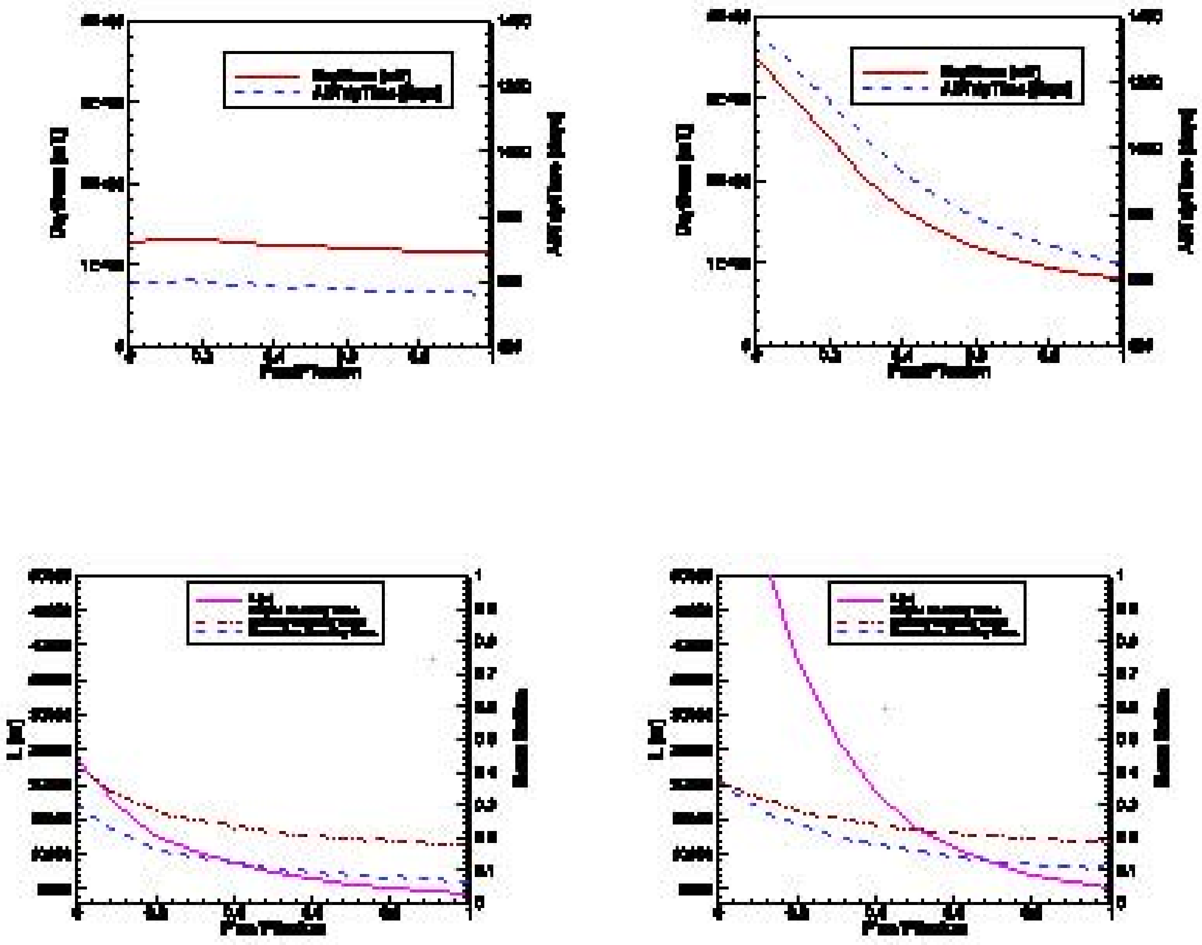

FIGURE 4. System parameters based on the nuclear assist fraction.
T=300 keV on the left and T=160 keV on the right.

The interaction of plasma temperature with nuclear electric assistance with over all performance can be seen in the Figure 5 plots. Nuclear assistance clearly reduces the total system mass and produces a marginal decrease in the trip time. Perhaps more importantly, it significantly reduces the optimal plasma temperature. A lower plasma temperature decreases the technical demands on the magnetic containment system. Nonetheless, the best system has a mass that is three orders of magnitude greater and is almost 10 times slower than previous designs using more traditional fusion fuels.

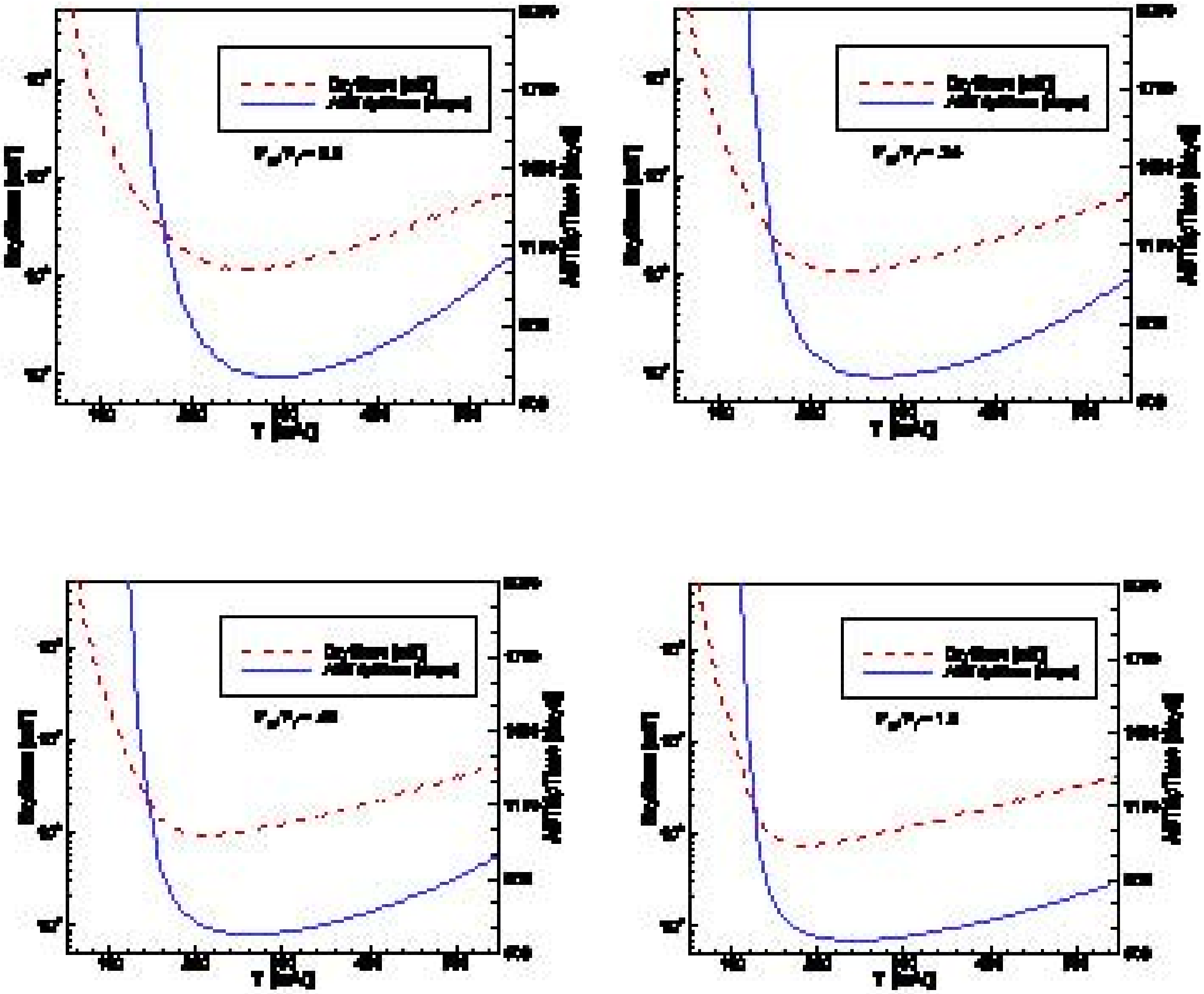

FIGURE 5. Increasing the level of nuclear electric assistance decreases the optimal plasma temperature.

CONCLUSIONS

The radiative losses from bremsstrahlung radiation in a p-^{11}B GDM system are too great to develop a practical system with a homogenous plasma and a direct mission trajectory. Even if you relax the expectation of Q>1 and assist with nuclear electric power, the system size and mass remain too large. Nonetheless, the aneutronic nature of advanced fuels, availability, and non-radioactive nature of advanced fusion fuels remains attractive. If such a system is to be developed, it will require a non-uniform plasma at lower temperatures and a computational MHD model to evaluate it. Further issues worth exploring are thrust enhancement and alternate mission trajectories.

FUTURE WORK

The authors previously have developed a MHD model for a GDM system (Ohlandt, 1999). The code has three major components, the geometry constructor, a grid generator, and the flow solver. The geometry constructor uses various simple shapes that can be rotated and extruded to produce complex 3-D geometries. The geometries consist of polygon mesh surfaces which are combined to create three dimensional objects. Initial grids are generated in a matter of hours using automated, Cartesian methods, and solution-based adaption allows the code to increase resolution around flow regions of interest during the flow solution. A finite volume conservation formulation is the basis of the various MHD solvers implemented (Powell, 1999).

However, the explicit nature of the algorithm was not effective at dealing with Aflven wave speeds that approach a few percent the speed of light. As such, an improved version of the code using a fully implicit solver is being developed. This will allow the concept of non-uniform plasma GDM systems to be explored.

NOMENCLATURE

P_b = bremsstrahlung power, MW
P_f = fusion power, MW
P_n = neutron power, MW
P_{ne} = power from nuclear electric fission reactor, MW
P_r = radiated power = $P_b + P_s$, MW
P_s = synchrotron power, MW
Q = fusion energy multiplier = P_f/P_i
R = wall reflectivity
T = plasma temperature, keV
β = plasma pressure and magnetic pressure ratio
η_D = direct converter efficiency
η_i = injector efficiency
η_t = thermal converter efficiency

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