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FIELD REVERSED CONFIGURATION (FRC) FUSION ROCKET

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Abstract

A design study of a D-^{3}He fueled fusion rocket employing field-reversed configuration(FRC) is carried out for the purpose of understanding the issues that need further study and illustrating the potential advantages of this approach. The design is evolved from a terrestrial fusion power reactor ARTEMIS. From the design study ,it is found that the FRC rocket could achieve a high specific power of about 1 kW/kg.

INTRODUCTION

Fusion rockets have potential advantages over conventional ones such as chemical rocket. These advantages include (1) high characteristic exhaust velocity (or specific impulse),(2) high engine thrust-to-weight ratio,(3) high power level and (4) long mission life. Thus,design studies have so far been carried out both for magnetic confinement fusion(MCF) scheme(Santarius1991,Teller et al. 1992) and for inertial confinement fusion(ICF) one(Hyde et al.1972,Orth et al. 1987). Recently,a new confinement approach ,that is,inertial electrostatic confinement(IEC) has also been proposed as a power source for space application(Miley 1993).

Of the fusion reactions considered,a fusion reaction using D-^{3}He fuel is characterized by its low neutron production rate and high power fraction carried by charged particles. Hence, the D-^{3}He fuel is desirable for use in space because it could reduce the radiation shielding mass and increase the power available for thrust.

Conventional approaches such as the Tokamak appear marginal for burning the fuel. Recently, the D-^{3}He fueled FRC reactor has been proposed by Momota et al.(1992) as a power source for terrestrial application. In the FRC,the plasma is confined by closed lines of force for good confinement and surrounded by open field lines of force for extraction of charged particles. The design study revealed the attractiveness of the reactor in that the reactor is environmentally acceptable in terms of radioactivity and fuel resource,and the estimated cost of electricity is low compared with a light water reactor. Although the use of the FRC in space has been proposed by Chapman et al.(1989) and Schulze(1991) ,no detailed study has been performed.

The purpose of the present paper is to carry out the conceptual design study of the FRC for use in space in order to clarify the critical issues that need further study and illustrating its attractiveness provided.

OVERVIEW OF FRC ROCKET

A cross-sectional view of the possible configuration of the FRC rocket considered here is illustrated in Fig.1 ,indicating the cylindrical symmetry of the system. An overview of the rocket is given in Fig.2. An FRC plasma is produced at the start by the conventional reverse-biased fast theta-pinch method in a formation chamber and then translated to a burning chamber. A combination of deuterium neutral beam injector (NBI),fueling,and a slow magnetic compression in the burning chamber brings the volume ,the temperature,and the number density of the plasma up to those for the D-^{3}He burning state. Most of the fusion energy carried by charged particles is guided along the magnetic line of force,thereby producing thrust for propulsion. A small fraction of the energy is leaking through a mirror magnet composed of normal/superconducting hybrid coils to reach a direct energy

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converter. The converter produces the power to drive the NBI and to sustain the auxiliary systems. The energies carried by neutrons and photons are deposited in a LiH radiation shield layer that protects the superconducting magnet (SCM) from excessive radiation damage and nuclear heating. A propellant material such as hydrogen is fed from a tank and mixed with the leaking plasmas in a magnetic nozzle region to increase the thrust. A power flow diagram is given in Fig.3.

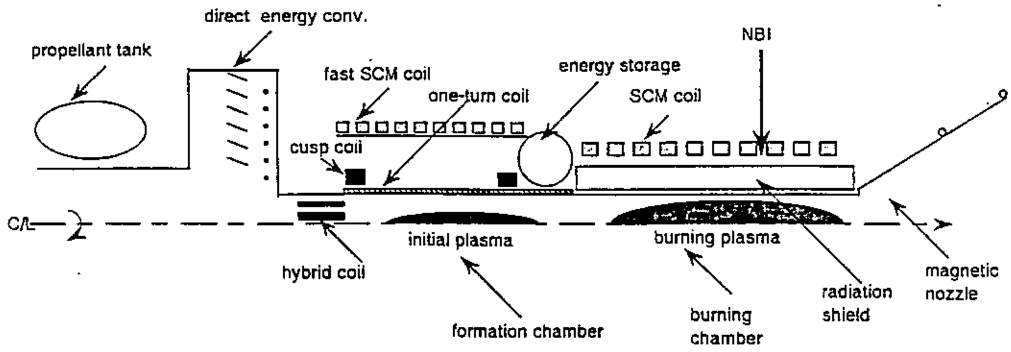

FIGURE 1. A Schematic Illustration of an FRC Rocket

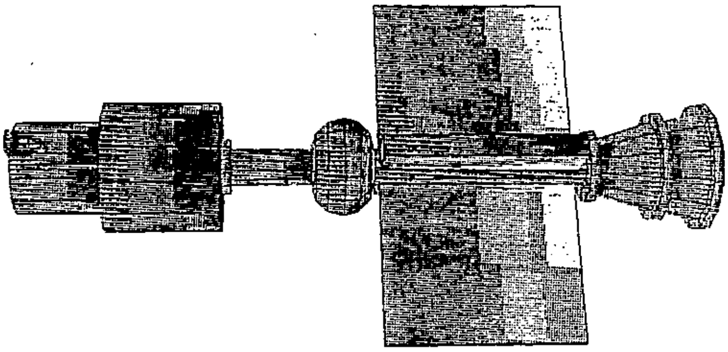

FIGURE 2. An Overview of the FRC Rocket

The main difference from the ARTEMIS design is in that one of the pair direct energy converters in the ARTEMIS is removed and the hybrid coil is added in front of the other converter. This decreases the amount of the charged particle energy dealt by the converter and a large portion of the energy is leaving through the magnetic nozzle to produce thrust.

COMPONENT DESIGN

Fusion Plasma

The plasma parameters adopted in the present design are derived from the ARTEMIS design. The plasma temperature is 87.5 keV and the electron density is $6.6 \times 10^{20}/m^3$ with a ^{3}He-to-deuterium density ratio of 1:2. The required energy confinement time is 2.1 sec and the assumed beta value is 0.9. The plasma produces a total fusion power of 1539 MW ,resulting in thrust power of 1098 MW as shown in Fig.3. In contrast to the ARTEMIS, the neutron production rate is reduced by a factor of 10 to account for possible suppression of the D-D reaction rate by polarizing the spins of the interacting deuterons(Kulsrud et al. 1986).

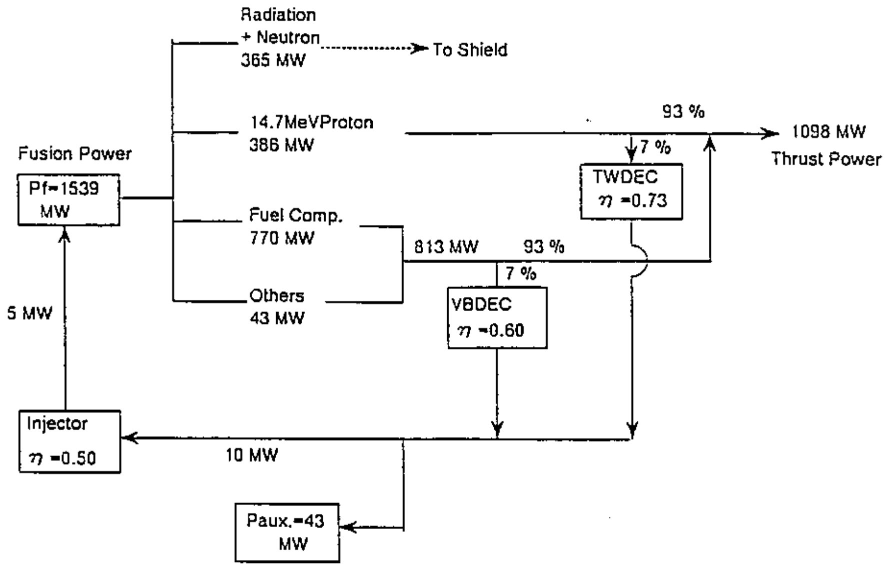

FIGURE 3. Power Flow in the FRC Rocket

Energy Storage

About 5GJ is needed to start up the burning of the D-^{3}He fuel by using the NBI. 100 ton is allotted to the magnetic energy storage system based on a specific weight of 50 kJ/kg(Bourque 1988).

Formation Chamber

The chamber has a radius of 1.8 m and is 15 m long. Its wall is made of a 3 cm-thick alumina. The 10 m long one-turn pinch coil is used to produce an initial FRC plasma and it has a radius of 2.0 m and is made of a 2 cm-thick Al. The fast SCM coils with a radius of 5 m give a maximum field of 4T and they are used to supply the guide magnetic field that connects the burning chamber and the direct energy converter. A pair of cusp coils are used to translate the FRC plasma formed to the burning chamber.

Burning Chamber

The chamber has a radius of 2.0 m and is 25 m long. Its wall is made of a 5 mm-thick Mo alloy.

A set of ten SCM coils of 3.0 m radius is installed in the chamber and produce a magnetic field of 6.7 T. A current density of 120 MA/m^2 is assumed in the NbTi super conductor. Aluminum is adopted as a stabilizer with a 1:3 NbTi:Al cross sectional area ratio. The hoop stress resulting from extensive Lorentz force is taken up by a carbon fiber reinforced plastic with a density of 2.0 g/cm^3 and an allowable stress of 350 MP.

LiH is used as shielding material because of its efficient slowing down properties for neutrons with light weight and its thickness is estimated so as to reduce the heat load in the SCM to a total of 50 W. About 20cm-thick LiH is required to attenuate the heating rate by an order of magnitude. The radiation power deposited in the shield is rejected to space by heatpipe radiators.

Direct Energy Converter

A Venetian-blind-type generator is applied for thermal component of the plasmas,while for 14.7-MeV fusion protons,a traveling wave type is developed. The former (VBDEC) employed five-stage fin arrays with an energy conversion efficiency of 60 %. The latter system (TWDEC) with an efficiency of 73 % is assumed to have the same mass as the former.

In front of the converter, the hybrid coil is placed to choke the plasma flow. Of the total plasma power, only 7 % can reach the converter. The hybrid coil produces a total field strength of 20 T with a 5-T Cu normal conducting coil and 15-T Nb_3Sn SCM coil. Their respective radii are 0.3m and 1.0m.

Magnetic Nozzle

In the FRC, a directional plasma flow through the open field lines into the nozzle is achieved. A pair of toroidal coils are located to guide and exhaust the plasma from the nozzle,thereby producing the thrust.

NBI System

To heat the plasma as well as drive the plasma current needed to sustain the plasma in a steady equilibrium ,injection of 1 MeV deuterium neutral beam particles is employed. A maximum power of 100 MW is required for startup and 5 MW to sustain the plasma in the steady burning state. 20 units of 5-MW NBI are considered for use. The NBI system is composed of ion source , grid accelerator, neutralizing cell,beam dump, and beam port.

Refrigeration

The 4.5 K refrigeration required for the SCM coils is provided by a Claude cycle refrigerator and its mass is estimated according to Hyde et al.(1972).

Miscellaneous Components

100 ton is reserved to account for the masses of fuel injection system , structure ,and so on.

CALCULATION OF MASS AND DISCUSSIONS

The masses are calculated for each component and a total system mass is obtained by summing up the component masses. The results are given in Figs.4 and 5. From these figures, it is found that the coil mass (component numbers from 7 to 10 in Fig. 4) amounts to 448 ton ,and occupies as high as 42 % of the total system mass which is 1070 ton ,although we employed ,as a stabilizer in the SCM, light weight Al rather than Cu adopted in the ARTEMIS design , and a carbon composite rather than stainless steal as structural material . (The mass of the magnet coils amounts to 1760 ton in the terrestrial reactor ARTEMIS.) The contribution from the shield is also large,amounting 28 % of it. These results are contrast to the ICF rocket where the dominant contribution comes from the driver system,the magnet and shield contributions being smaller on account of its intrinsic characteristics of the rocket structure(Orth et al. 1987).

The specific power defined as the ratio of the thrust power to the total system mass is 1kW/kg, being about ten times better than nuclear electric fission systems. This vehicle is capable of interplanetary flight to Mars in 90 days with a payload fraction of 0.35(Teller et al. 1992).

For comparative purposes, the results are obtained for the case where the spin-polarized D fuel is not adopted,the neutron production rate being increased by a factor of 10 from the reference case.

It is found that the shield mass increases by about 70 ton from the reference case and it occupies 31 % of the total mass. The coil radius increases from 3.0 m to 3.2 m to accommodate the increased shield thickness. These result in the specific power of 0.94 kW/kg.

If the spins of ^{3}He fuel as well as those of D fuel are completely polarized,the D-^{3}He fusion reaction rate is increased by 50 %. This would decrease the NBI power required to initiate the fusion burning of the D-^{3}He fuel by a factor of 2(Mitarai et al. 1992),thus reducing the energy storage mass to 50ton.

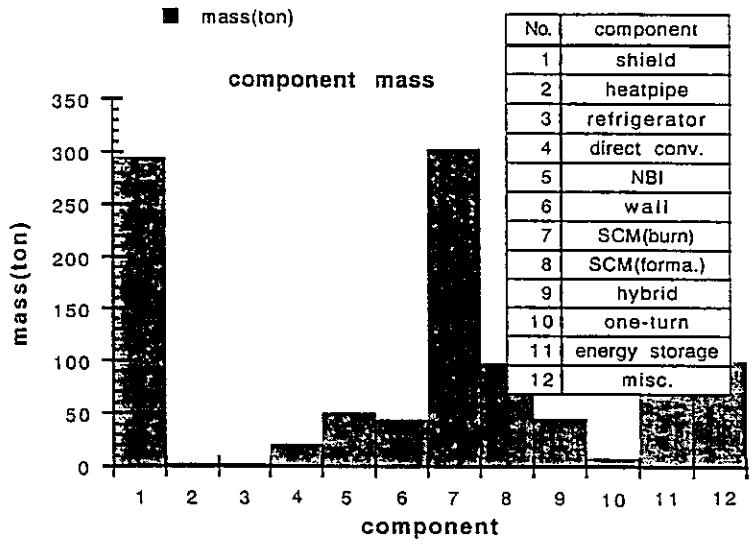

FIGURE 4. Summary of Component Mass

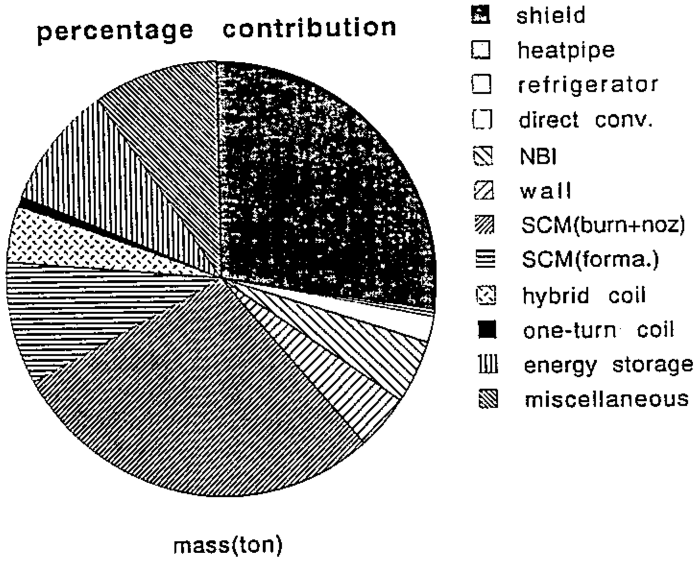

FIGURE 5. Percentage Contribution from Each Component

These results indicate the potential attractiveness of the FRC rocket as an interplanetary transport vehicle, however there exists many problems to be solved before realization such as experimental verification of stability of the FRC plasma, and developments of 1-MeV NBI and direct energy converter as required in a terrestrial application. In addition, development of a light weight magnet as pursued in particle astrophysics in space(Mito et al.1989) is needed ,when considering its dominant contribution to the system mass.

Furthermore,a parametric design study is needed to optimize the plasma parameters for space application , although in the present design the parameters are taken from the terrestrial reactor.

CONCLUSION

A conceptual design study of the FRC fusion rocket was performed. The design was evolved from a terrestrial version of the D-^{3}He fueled FRC reactor ARTEMIS. The study revealed its attractiveness as an interplanetary transport vehicle.

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