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ABSTRACT

The open cycle Gas Core Nuclear Rocket (GCR) is often mentioned as a second generation Nuclear Thermal Propulsion (NTP) system that could make a round trip manned mission to Mars in a few months instead of a few years. Such a capability is based on preliminary assessments of its propulsion performance as reflected in the high specific impulse and thrust it can potentially generate. The energy in this device is produced by a fissioning uranium plasma which heats, through radiation, a propellant that flows around the core and exits through a nozzle, thereby converting thermal energy into thrust. The relative motion between the propellant and the fuel is a source of hydrodynamic instability which, if not adequately addressed, could lead to a serious loss of the fuel in a very short time. This instability can, however, be suppressed by placing the system in a magnetic field with a configuration such that it will not interfere with the primary function of the device. In this paper, we introduce a model with which we study such magnetic containment and its impact on the performance of the system.

Introduction

One of the most promising approaches to advanced space propulsion that could meet the objectives of the Space Exploration Initiative is the open cycle Gas Core nuclear Rocket[1] (GCR) shown in Fig. 1. The principle of operation in this system involves a critical uranium core in the form of a gaseous plasma which heats, through radiation, a seeded hydrogen propellant which exits through a nozzle, thereby converting thermal energy into thrust as illustrated in Fig. 1. The temperature limitations generally associated with solid core thermal reactors are avoided in GCR since the nuclear fuel is allowed to exist in a high temperature (10^4 - 10^5 °K) partially ionized state. With this rocket concept, specific impulse values ranging from 1500 to 7000 seconds appear to be feasible[1]. This reactor concept requires a relatively high-pressure plasma (500 - 1000 atm) to achieve a critical mass. At these pressures the gaseous fuel is sufficiently dense for the fission fragment stopping distance to be comparable to or smaller than the dimensions of the fuel volume contained within the reactor cavity. The hydrogen propellant is injected through the porous wall with a flow distribution that creates a relatively stagnant, non-recirculating central fuel region in the cavity. These attractive propulsive characteristics of GCR are moderated somewhat, however, when a heat transfer analysis is carried out taking into account the wall material temperature and heat flux limits. It is found[2] that for a 7.5 GW reactor with a propellant flow rate of 5 kg/s, a specific impulse of 3300 s and a thrust of 200 kN can be obtained for a maximum heat flux of 100 MW/m^2.

These results may never the less be viewed as academic if some of the physics problems[3] associated with fuel containment and stability are not resolved. It is known, for example, that when a fluid (H) of density ρ_2 and velocity V_2 moves past a stationary fluid (U) of density ρ_1 under the influence of a gravitational acceleration g, the system

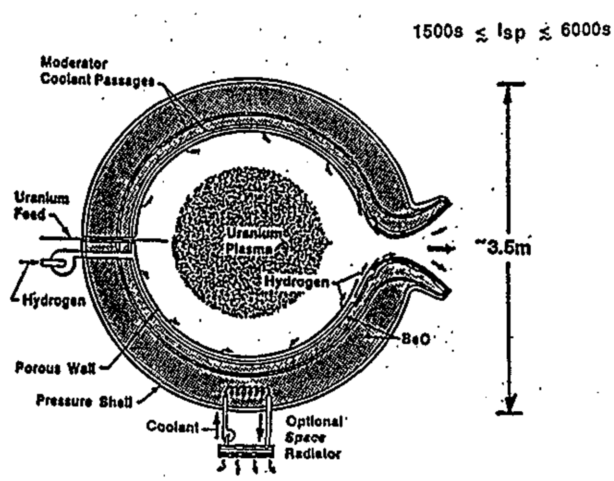

Fig. 1. High Specific Impulse, Porous Wall Gas Core Engine. (Courtesy of NASA, Lewis Research Center)

is susceptible to the well-known Kelvin - Helmholtz instability. The condition for this instability is expressed by[4]

$$V_2^2 > \frac{g(\rho_1^2 - \rho_2^2)}{k\rho_1\rho_2} \approx \frac{g\rho_1}{k\rho_2} \qquad (1)$$

where we have taken advantage of the fact that, for the temperatures and pressures of interest, the uranium density is much larger than that of the hydrogen. Moreover, the above equation reveals that the minimum wave number of the oscillation has the value

$$k = \frac{g\rho_1}{V_2^2\rho_2} \qquad (2)$$

At a pressure of 1000 atm, a hydrogen temperature of 17,500 °K, a uranium temperature of 35,000 °K, and a mean hydrogen flow velocity V_2 = 5 m/s (commensurate with a mass flow rate of 5 kg/s), it can be shown[3] that the above instability leads to a loss of approximately 3% of the fuel per second. Clearly, such a loss is unacceptably large, and could be reduced if the hydrogen flow velocity is drastically reduced. But decreasing this velocity beyond a certain value may not be compatible with the mass flow rate dictated by heat transfer needs.

One effective way of dealing with this instability is to place the system in an externally applied magnetic field pointed in the direction of the propellant flow. Such a field will act as a "surface tension" type of force that provides stability if the following condition[5] is satisfied:

$$\frac{\rho_1\rho_2}{(\rho_1+\rho_2)}V_2^2 \le \frac{B^2}{8\pi} \qquad (3)$$

For the example cited earlier, the above equation reveals that a minimum magnetic field strength of 54 Gauss is required. Clearly, the configuration of such a field must be such that it confines the uranium core and yet allows the propellant to exhaust through the nozzle. The most logical field topology is that of a "mirror geometry"[6] in which the field is stronger at the ends than it is at the center where the uranium core is to be situated. The ratio of the field strength at the "mirrors", where the plasma particles are reflected, to that at the center is referred to as the mirror ratio, R_m. The higher the value of such a parameter, the smaller is the loss of plasma particles through the mirrors. For GCR, a slight degree of asymmetry in the value of the mirror ratios at the two ends would be required in order to inhibit the loss of uranium from the end that is opposite to the nozzle. Moreover, total confinement of the fuel plasma is impossible since that would require an infinite mirror ratio; but a significant reduction in the losses may be effected with moderate values of R_m. The confinement of hydrogenous charged particles such as Deuterium or Tritium in simple magnetic mirrors is characterized by[7]

$$n\tau \approx 2.4\times10^{10}E^{3/2}\log_{10}R_m \qquad (4)$$

where n is the density of the plasma in cm^{-3}, τ is the confinement time in seconds, and E is the mean energy in kilo-electron-volts. The mirror ratio in effect defines a "loss cone" in velocity space. If, as a result of collisions with other particles, a plasma particle falls within this cone, it will escape through the mirror. It is clear that geometric location of the particle plays no role in its probability of escape; rather it is the change in its velocity vector resulting from a Coulomb collision with another charged particle that could place it inside the loss cone and allow it to escape.

Since the Coulomb cross section is inversely proportional to the mass, the electrons in the core plasma tend to scatter more often than the uranium ions, and as a result escape the mirror more readily, leaving behind a deficiency of negative charges that results in the buildup of a positive electrostatic potential. Such a potential has the effect of opening up the loss cone, thereby enhancing the losses of the positive ions. This effect can be accounted for in Eq. (4) by replacing the mirror ratio R by

$$R_{eff} = \frac{R_m}{1 + Ze\Phi/E} \qquad (5)$$

where Ze is the effective particle charge, Φ is the electrostatic potential, and E is the average energy as before. An assessment of how well the uranium plasma in the core of GCR can be confined by a mirror-type magnetic field can be obtained by solving an appropriate set of particle and energy conservation equations that utilize the confinement law given by Eq. (4). This will be done in the next section.

Conservation Equations for a Magnetized GCR

We take the core of the reactor to consist of the uranium ions, the fission fragment ions, and electrons. The particle and energy conservation equations for these components are given by:

$$\frac{dN_U}{dt} = S_U - \frac{N_U}{\tau_U} - S_{FF} \qquad (6)$$

$$\frac{d}{dt}(N_U E_U) = S_U E_{in} - \frac{N_U}{\tau_U}E_{LU} - S_{FF}E_U + N_U(N_e W_{eU} + N_F W_{FU} + W_{FFU}) \qquad (7)$$

$$\frac{dN_F}{dt} = \frac{N_{FF}}{\tau_{FF}} - \frac{N_F}{\tau_F} \qquad (8)$$

$$\frac{d}{dt}(N_F E_F) = \frac{N_{FF}}{\tau_{FF}} E_F - \frac{N_F}{\tau_F} E_{LF} - N_F\{N_U W_{FU} + N_e W_{Fe} - W_{FFF}\} \quad (9)$$

$$\frac{d}{dt}(N_e E_e) = N_e\{N_F W_{Fe} - N_U W_{eU} + W_{FFe}\} - \frac{N_e}{\tau_e} E_{Le} - P_B - P_S \quad (10)$$

where N_U is the number density of the uranium ions, E_U is the mean energy of these ions, and S_U is the source term for these particles, which represents the rate at which uranium fuel is added to the core. We distinguish in this analysis between "thermal" fission fragments, namely those which have reached thermalization and acquired an appropriate energy, and a "fast" group which is characterized by a birth energy appropriate to the fissioning of the uranium nucleus. We designate the first (thermal) group with the subscript F, and the second (fast) group with FF. The last term in Eq. (6), for example, represents the rate at which uranium ions are lost as a result of undergoing fission reactions. This term also serves as the source of the fast fission fragments, which obey the (equilibrium) relationship

$$\frac{N_{FF}}{\tau_{FF}} = 2S_{FF} \quad (11)$$

since each fission results in two fission fragments. τ_{FF} is the average time required for a fission fragment to slow down to thermal energy, where it then joins the "thermal" fission fragment group. The left hand side of Eq. (11) is thus the "source" of the thermalized fission fragments, as is seen in Eq. (8). The terms E_{Le}, E_{LU}, and E_{LF} represent the escape energy terms for the electrons, uranium ions, and thermalized fission fragment ions respectively, and are found from the Mirror Machine energy confinement equations[8]. It should be noted that $S_{FF} = N_U \phi \sigma_F$, where ϕ is the neutron flux and σ_F is the fission cross section for uranium. Furthermore, the electron density N_e is found from the Saha equations, which relate it to the densities and temperatures of the other species in the system[9]. For the electrons, we assume that the rate of change of their number density is much faster than those of the heavier positive species, so that the electron particle balance equation may be replaced by a steady state charge balance equation, i.e.

$$\frac{N_e}{\tau_e} - (Z_{eff})_U \frac{N_U}{\tau_U} - (Z_{eff})_F \frac{N_F}{\tau_F} = 0 \quad (12)$$

It should be noted that the energy produced by fission in the reactor, namely 175 MeV out of about 200 MeV, appears in the terms W_{FFU}, W_{FFF}, and W_{FFe}, i.e. as the kinetic energy of the fast fission fragments which as they thermalize pass it on to the uranium ions, thermal fission fragments, and electrons as seen in Eqs. (7), (9), and (10). In the last of these equations, the terms P_B and P_S represent respectively the Bremsstrahlung and synchrotron radiations emitted by the electrons. In the absence of particle losses from the system, the reactor power would ultimately appear in these radiation terms, which eventually manifest themselves as the black body radiation that heats the propellant.

At this time, rather than explicitly solving the system of equations presented above, we focus on the confinement law, Eq. (4) combined with Eq. (5) to get a sense of how adequate simple magnetic mirror confinement is for the Gas Core Nuclear Rocket. By modifying these equations to accommodate uranium ions, we find that the loss rate for these species can be written as

$$\frac{N_U}{\tau_U} = (3.844\times 10^{-12}) \frac{N_U^2 Z_U^4}{E_U^{3/2} \log_{10}\left(\frac{R_m}{1 + Z_U e\Phi / E_U}\right)} \quad (13)$$

We choose an initial uranium density of 1.53×10^{17} cm^{-3}, which corresponds to a fuel loading of 0.25 kg in a sphere of 1 m radius. For any given uranium ion average energy E_U, and assuming that the electron temperature T_e is equal to E_U, we can now estimate the effective charge of the uranium ions as well as the electrostatic potential that builds up in the system. For a mirror ratio of $R_m = 100$, we obtain from Eq. (13) the loss rates shown in Table 1.

TABLE 1

E_U (keV)	Z_U	$e\Phi$ (keV)	N_U/τ_U (cm^{-3} sec^{-1})
0.001	0.861	0.0051	1.231×10^{27}
0.002	1.812	0.0076	9.823×10^{27}
0.005	3.831	0.0133	5.756×10^{28}
0.010	5.832	0.0206	1.175×10^{29}
0.020	10.310	0.0282	4.440×10^{29}
0.050	18.001	0.0438	1.089×10^{30}
0.200	40.703	0.0756	3.511×10^{30}
0.500	63.452	0.1098	4.990×10^{30}
1.000	77.817	0.1614	3.798×10^{30}
2.000	82.293	0.2760	1.605×10^{30}
5.000	90.000	0.5674	5.549×10^{29}
10.000	91.106	1.0547	2.009×10^{29}
20.000	92.000	1.9877	7.242×10^{28}
50.000	92.000	4.7211	1.796×10^{28}
100.000	92.000	9.1476	6.274×10^{27}
200.000	92.000	17.8058	2.196×10^{27}
500.000	92.000	43.1815	5.492×10^{26}

We see that the loss rate is extremely high. In a steady state system, the fueling rate must equal this loss rate. This implies that effectively all the reactor power appears in the energy lost by the escaping particles and very little, if any, is left for the radiated energy needed to heat the propellant. Clearly, the propulsive capability of GCR will be nearly destroyed, according to these preliminary estimates, if magnetic mirror confinement is used.

The loss rates of Table 1 are much higher than we would expect for an unconfined plasma. Obviously, the magnetic mirror confinement does not actually worsen the confinement; the problem here is that a basic assumption of the mirror confinement law is violated. The mirror confinement formulas assume that a given particle makes, on the average, many transits of the core volume before sufering a collision. However, for the dense, highly charged uranium ions of the GCR, the reverse is true: a fuel ion typically suffers many collisions during a single transit of the core. The transit time τ_{tr}, which is also a measure of the time an unconfined plasma will remain intact, is given by

$$\tau_{tr} = \frac{r}{c_s} \qquad (14)$$

where r is the core radius and c_s is the thermal speed, $c_s^2 = T/M$. Because of the long-range nature of the Coulomb force, a charged particle is always in the process of "colliding" with one or more particles; however, a measure of the time between "major" collisions is the 90° collision time τ_θ:

$$\tau_\theta = (2.46\times10^{11})\frac{E^{3/2}}{nZ^4\ln\Lambda} \qquad (15)$$

where $\ln\Lambda$ is the Coulomb logarithm, and the density n is in cm^{-3} while the energy E is in keV. Table 2 shows how τ_{tr} and τ_θ vary as functions of the uranium energy E_U.

Since, over the entire energy range of Tables 1 and 2, τ_θ is much smaller than τ_{tr}, it is quite probable that the confinement law given by Eq. (13) is not appropriate for the high density, high charge plasma system represented by GCR. A resolution of this problem must await further research.

TABLE 2

E_U (keV)	Z_U	τ_{tr} (sec)	τ_θ (sec)
0.001	0.861	1.918×10^{-3}	2.418×10^{-11}
0.002	1.812	1.356×10^{-3}	4.204×10^{-12}
0.005	3.831	8.579×10^{-4}	9.491×10^{-13}
0.010	5.832	6.066×10^{-4}	4.952×10^{-13}
0.020	10.310	4.289×10^{-4}	1.639×10^{-13}
0.050	18.001	2.713×10^{-4}	6.971×10^{-14}
0.200	40.703	1.356×10^{-4}	2.087×10^{-14}
0.500	63.452	8.579×10^{-5}	1.262×10^{-14}
1.000	77.817	6.066×10^{-5}	1.325×10^{-14}
2.000	82.293	4.289×10^{-5}	2.357×10^{-14}
5.000	90.000	2.713×10^{-5}	5.116×10^{-14}
10.000	91.106	1.918×10^{-5}	1.160×10^{-13}
20.000	92.000	1.356×10^{-5}	2.721×10^{-13}
50.000	92.000	8.579×10^{-6}	9.071×10^{-13}
100.000	92.000	6.066×10^{-6}	2.294×10^{-12}
200.000	92.000	4.289×10^{-6}	5.865×10^{-12}
500.000	92.000	2.713×10^{-6}	2.058×10^{-11}

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