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PROPULSION CAPABILITIES AND LIMITATIONS OF THE GAS CORE NUCLEAR ROCKET

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Abstract

The Gas Core Nuclear Rocket (GCR) has been viewed by many as a very promising propulsion scheme that could readily meet the objectives of the Space Exploration Initiative. The open cycle version of this concept has been shown to be capable of generating several thousand seconds of specific impulse and hundreds of kilonewtons of thrust; a property that would allow such a system to make a round trip to Mars in several months. Such a performance, however, is contingent on its ability to support among other things a sizable propellant flow rate, a sizable wall heat flux, as well as a sizable reactor pressure. In this paper we examine some of the physics and engineering issues that must be resolved in order for GCR to achieve these desirable propulsion characteristics. We find that the questions of fuel containment, turbulent mixing, acoustic oscillations and fueling are among the chief concerns that must be addressed if GCR is to live up to its expectations. If unresolved, these issues could seriously limit its performance as an advanced propulsion concept.

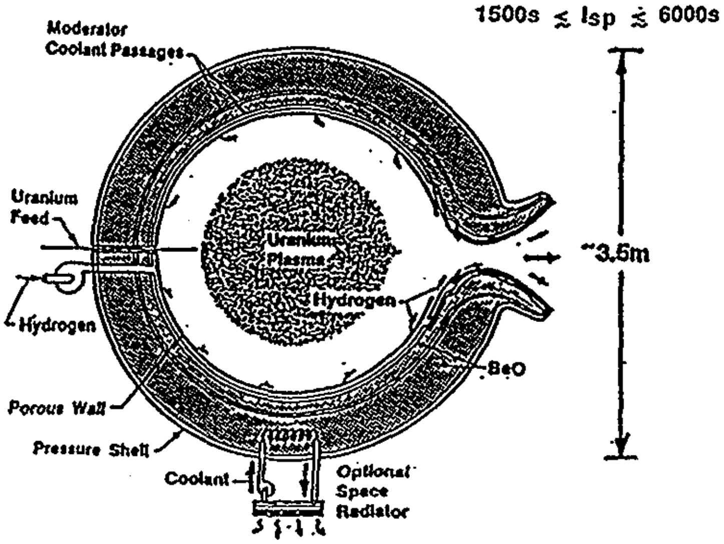

Fig. 1.
High Specific Impulse, Porous Wall Gas Core Engine.
(Courtesy of NASA, Lewis Research Center)

Introduction

One of the most promising propulsion schemes that has the potential of meeting the objectives of the Space Exploration Initiative (SEI) of sending a manned mission to Mars is the open cycle Gas Core Nuclear Rocket (GCR)(1) shown in Fig. 1. It has the capability of generating several thousand seconds of specific impulse and hundreds of kilonewtons of thrust to allow such journeys to be completed in several months instead of several years. Such a system consists of a core of a fissioning uranium plasma which heats through radiation a hydrogen propellant that exits through a nozzle thereby converting thermal energy into thrust. Since the nuclear fuel in GCR is allowed to exist in a high temperature (10,000–100,000 K) partially ionized state, it circumvents the temperature limitations imposed by material melting encountered in solid core nuclear thermal rockets. In this "gaseous or plasma core" the sphere of fissioning uranium plasma functions as the fuel element of the reactor. Nuclear heat released within the plasma and dissipated as thermal radiation from the surface is absorbed by the surrounding envelope of seeded hydrogen propellant which is then expanded through a nozzle to generate thrust. Propellant seeding is necessary to insure that the thermal radiation is absorbed primarily by the hydrogen and not by the cavity walls that surround the plasma. With the gas core rocket concept specific impulse values ranging from 1500 to 7000 seconds appear to be feasible(1). However, these figures must be viewed as somewhat idealistic since there are several physics and engineering phenomena that can impact the performance of GCR and potentially limit its ability to produce these highly desirable propulsion characteristics. We will examine some of these issues in this paper.

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Analysis and Results

We utilize a heat transfer model to assess the propulsion capability of GCR on the one hand, and to identify certain critical parameters which can exacerbate certain phenomena, and seriously detract from such a capability on the other. The underlying equations in this case are the standard conservation equations:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \underline{\upsilon} = 0 \qquad (1)$$

$$\rho \frac{D\underline{\upsilon}}{Dt} + \nabla p = 0 \qquad (2)$$

$$\rho C_p \frac{DT}{Dt} = -\nabla \cdot \underline{q} + Q \qquad (3)$$

where ρ is the fluid density, $\underline{\upsilon}$ is the mean velocity, p is the pressure, c_p is the specific heat at constant pressure, q is the radiative heat power and Q is the fission power generation term. When applied to the propellant, Q is set equal to zero. A diffusion model is used for the radiative heat transfer, namely

$$q = -k\nabla T \quad \text{with} \quad k = \frac{16\sigma T^3}{3k_R} \qquad (4)$$

where k_R is the mean Rosseland absorption coefficient, and σ is the black body constant. The above conservation equations become a closed system when we specify the fission power density Q, i.e.

$$Q = \alpha\psi\rho \qquad (5)$$

where α is a constant containing the fission cross section, and ψ is the neutron flux in the core. We apply these equations to a cylindrical system invoking azimuthal symmetry and steady state and allowing for no axial heat conduction or external forces. The results(2) in this case are summarized in Table 1.

Table I

Parameters of an Open Cycle GCR

Reactor power 3000 MW	Wall temp. 2200 K
Reactor pressure 1000 atm	Core length 2.0 m
Max.wall heat flux 100 MW/M^2	Fuel radius 0.8 m
Propellant flow rate 3.7 Kg/s	Outer wall rad.1.0 m
Inlet temperature 2200 K	Fuel temp. 65,200 K
	Prop. temp 17,960 K

The other example we choose is a preliminary design for which the relevant parameters are available(3). The radii of the uranium core and the outer wall are the same as the first example, as well as the pressure. The reactor power is however 7500 MW for which the propellant mass flow rate is 4.5 kg/s, and the fuel and propellant temperatures are approximately given by 35,000 K and 17,500 K respectively. For essentially the same wall heat flux and wall temperature the analysis yields a mean velocity for the hydrogen propellant of approximately 6 M/S. Since, in general, the mean velocity of the uranium in the core is taken to be 10-15 smaller than that of the hydrogen, the fuel can be safely assumed to be stationary in the analysis that follows.

It is a known fact that when a fluid of density ρ_2 moves with velocity υ_2 past another fluid of density ρ_1, which is stationary, in the presence of a gravitational force the (sharp) boundary between them will, upon perturbation, undergo oscillations which under certain conditions can become unstable. This instability, known as the Kelvin-Helmholtz instability(4) can lead to turbulent diffusion of material from one region into the other, and in the case of GCR, this could mean substantial flow of uranium from the core into the hydrogen and out through the nozzle. We estimate the impact of this effect by calculating the diffusion coefficient associated with this instability which in turn can be expressed in terms of the growth rate and the velocity of the relative motion between the two fluids. We find, for parameters of the second example, that about 7 Kg/sec of the uranium is lost through this process(5), and that is approximately 3% of the fuel escaping per second. Clearly, these values are unacceptably large and well over the 1% of the hydrogen mass flow rate (i.e. 45 gm/s) often cited as the loss due to turbulent mixing. Reducing the hydrogen flow velocity will reduce the growth rate of the instability, but decreasing it beyond a certain value may not be compatible with the mass flow rate dictated by heat transfer needs.

In obtaining these results we had employed the mean temperature and velocity values for both the propellant and the fuel. In reality, however, these quantities possess radial gradients which play a major role in stability considerations. When taken into account we find that an inverted density profile of the propellant is required to stabilize these modes. This means that the denser propellant layer be adjacent to the hot fuel and that is exactly what does not happen in the actual situation. Unless some means can be found (such as using a buffer layer) to generate the desired profile this instability and the resulting turbulent mixing will always persist in the Gas Core Reactor.

It is interesting to estimate the extent to which turbulent mixing can adversely affect the propulsive performance of GCR. We do that by calculating the round trip time to Mars for various ratios of uranium mass flow rate to the hydrogen mass flow rate. For a dry vehicle mass of 123 mT, and utilizing a continuous acceleration/ deceleration trajectory profile we find (for the parameters of the second example) that the round trip time is 198 days when the uranium mass flow rate is 1% that of the hydrogen mass flow rate, and this time goes up to 398 when the uranium mass flow rate becomes double that of the hydrogen. We recall that nearly doubling the mass flow rate was the outcome of the Kelvin-Helmholtz instability if allowed to arise. Since a remedy by profiling effects may not be feasible the use of an externally applied magnetic field may not be avoidable in this situation.

Another phenomenon which may adversely affect the propulsion capability of the gas core nuclear rocket is the acoustic instability[6] which comes about as a result of fluctuations in the density and temperature of the uranium plasma. If we visualize a standing sound wave to exist in a fissioning plasma that includes a constant background density of thermal neutrons, then in the wave compressions the fission power density increases due to the increased uranium density, while the opposite will occur in the rarefactions of the wave. This results in an increased pressure gradient associated with the wave which in turn leads to a transfer of fission power to the wave. A competing process is the transport of excess thermal energy out of the wave by the radiation generated in the system. This competition results in a critical wavelength below which waves are stable and above which they are unstable. For the example under consideration we find that the dimensions of the system (radius of 1 m) allow it to support unstable waves whose turbulence also leads to diffusion of uranium out of the core, into the propellant and out through the nozzle. In this case we find that 9% of the fuel is lost in this process per second, and when its impact on travel time is assessed we find that the round trip time to Mars is increased to about 500 days. Not only is the travel time affected but very little fuel will remain to complete the trip if left unreplenished.

Conclusion

In this brief and preliminary analysis we have shown that there are several phenomena which can occur in the open cycle gas core nuclear rocket that might limit its performance as an advanced propulsion scheme. These include stringent heat transfer requirements, as well as fuel escape arising from the hydrodynamic and acoustic oscillations that can, under certain conditions, turn turbulent. Control of such phenomena is critical to the success of GCR and that might not be achievable without the aid of magnetic fields.

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