AIAA

AIAA 91-3650

Some Physics Issues Facing the Open-Cycle Gas Core Nuclear Rocket

T. Kammash and D. Galbraith
The University of Michigan
Ann Arbor, MI

AIAA/NASA/OAI Conference on Advanced SEI Technologies
September 4-6, 1991 / Cleveland, OH

SOME PHYSICS ISSUES FACING THE OPEN CYCLE GAS CORE NUCLEAR ROCKET

T. Kammash and D. L. Galbralth
Department of Nuclear Engineering
The University of Michigan
Ann Arbor, MI 48109

Abstract

The Open Cycle Gas Core Nuclear Rocket (GCR) offers attractive propulsion characteristics that might allow round trip missions to Mars to be undertaken in reasonably short times. In this scheme, the heat generated by a fissioning uranlum plasma core heats, through radiation. a hydrogen propellant which, when exhausted through a nozzle, converts thermal energy into thrust. This type of confinement is, however, subject to hydrodynamic instabilities which could result in the loss of a significant portion of the fuel in a relatively short time. Moreover, acoustic instabilities arising from density and temperature fluctuations could result in serious control problems for GCR. In this paper, we address the underlying physics of these phenomena and estimate the impact they may have on travel times to Mars.

Introduction

The Space Exploration Initiative calls for, among other things, a manned mission to the planet Mars sometlme in the early part of the next century. Since space travel is hazardous and man is unable to endure long journeys without experiencing physical and mental degradation, it is imperative that such missions be completed in the shortest possible time. This in turn means that one or more "advanced" rocket propulsion schemes must be developed to meet these objectives. One promising approach in this regard is the open cycle gas core[1] fission reactor (GCR). The principle of operation in GCR involves a critical uranium core in the form of a gaseous plasma that heats, through radiation, a hydrogen propellant which exits through a nozzle, thereby converting thermal energy into thrust as demonstrated In Fig. 1.

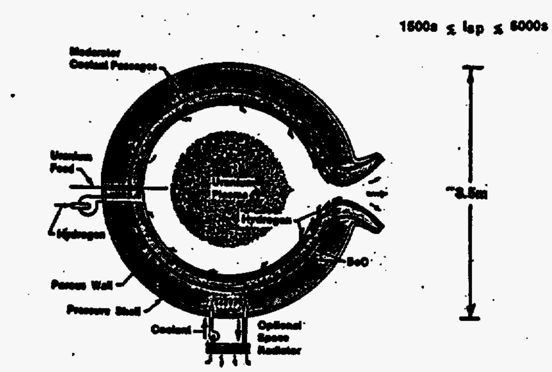

Fig. 1.
High Specific Impulse, Porous Wall Gas Core Engine. (Courtesy of NASA, Lewis Research Center)

The temperature limitations imposed by material melting as encountered in rolld core thermal rocket designs is avoided in GCR since the nuclear fuel is allowed to exist in a high temperature (10.000 - 100.000°K) partially ionized state. In this so-called "gaseous - or plasma core" concept, 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 a surrounding envelope of seeded hydrogen propellant which is then expanded through a nozzle to generate thrust. Propellant seeding with small amounts of graphlte or tungsten powder 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]. As shown In Fig. 1, the open cycle CCR Is basically spherical in shape and contains three solid regions: an outer pressure vessel, a neutron reflector/moderator, and an inner porous liner. Because of its high operating temperature and its compatibility with hydrogen, beryllium oxide is usually selected for the moderator material. This reactor concept requires a relatively high pressure plasma (600 - *2000* atm) to achieve a critical mass. At these pressures, the gaseous fuel is sufficiently dense for the fission fragment stopping distance (average distance travelled for energy deposition) 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. It has been suggested[2] that a small amount of fisslonable fuel (up to 1% of the hydrogen mass flow rate) gets exhausted along with the heated propellant under normal conditions. It is also noted that, due to the transparency of both the uranium plasma and the hot hydrogen, 7 - 10% of the total reactor power appears as radiation whlch is ultimately deposited principally in the solid regions of the reactor wall. It is the ability to remove this energy. either by means of an external radiator or regeneratively using the hydrogen propellant, that determines the maximum power output and achievable specific impulse for GCR engines.

Some Physics Issues in GCR

To highlight some of the major physics and engineering issues which this propulsion approach must overcome, we choose a preliminary design for which the relevant parameters are available. We identify a reactor design[3] In which the radius of the uranium core, R, is 1 meter; the pressure in the system Is 1000 atm; and the hydrogen temperature is about 17,500°K, which suggests that the fuel temperature is about 35,000°K[4]. Our elementary analysis of this *7500* MW system shows that the mean velocity of the hydrogen, which is commensurate with a cited mass flow rate of 4.6 Kg/sec, is approximately 6 m/sec. The mean velocity of the uranium in the core is generally taken to be 10 − 16 times smaller than that of the propellant[8]. As a result, it can be safely assumed to be stationary in the analysis of the relative motion of two superposed fluids.

It is a known fact that when a fluid of density ρ_2 moves with velocity v_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[6], 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 thus out through the nozzle. Not only will the loss of uranium affect the criticality of the system if not replaced appropriately, but also the flow of hydrogen into the core will affect its composition and ultimately its criticality.

To assess the importance of this phenomenon, we apply it to the GCR design noted above. We recall that in that example the mean velocity of the hydrogen is about 5 m/sec, with the uranium in the core treated as immobile. As a result, the system can be viewed as consisting of a fluid (H) of density ρ_2 and velocity v_2, moving past a stationary fluid (U) of density ρ_1 under the influence of a gravitational acceleration g. In this case, the instability condition can be written as[10]

$$v_2^2 > \frac{g}{k}\frac{(\rho_1^2 - \rho_2^2)}{\rho_1\rho_2} \approx \frac{g\rho_1}{k\rho_2} \qquad (1)$$

where we have taken advantage of the fact that, for the pressure and temperature under consideration, the uranium density is much larger than that of hydrogen. The above equation reveals that the minimum wave number k of the oscillation is

$$k_{min} = \frac{g\rho_1}{v_2^2\rho_2} \qquad (2)$$

while the corresponding growth rate γ of the instability can be put in the form

$$\gamma_{min} = v_2 k_{min}\sqrt{\frac{\rho_2}{\rho_1}} = \frac{g}{v_2}\sqrt{\frac{\rho_1}{\rho_2}} \qquad (3)$$

The diffusion coefficient D for the uranium flow into the hydrogen can be approximately expressed by

$$D = \frac{\gamma}{k^2} \qquad (4)$$

from which we can write the particle flux as

$$F = \frac{D\rho_1}{R} \qquad (5)$$

where R is the radius of the spherical uranium core mentioned earlier. The amount of uranium escaping per second by this diffusion process, U_L, can finally be written as

$$U_L = 4\pi R^2 F = 4\pi R D\rho_1 \qquad (6)$$

or, as a fraction of the total uranium U_s present in the sphere.

$$\frac{U_L}{U_s} = \frac{4\pi R D\rho_1}{\frac{4}{3}\pi R^3\rho_1} = \frac{3D}{R^2} = \frac{3\gamma}{R^2k^2} \qquad (7)$$

At a pressure of 1000 atm, a hydrogen temperature of 17.500° K, and a uranium temperature of 35,000° K, the densities of hydrogen and uranium are, respectively, 4.64×10^{-4} gm/cm³ and 5.53×10^{-2} gm/cm³. With these values, and $v_2 = 5$ m/sec, Eqn. 6 yields about 7 Kg/sec uranium loss, while Eqn. 7 shows that approximately 3% of the fuel escapes per second. Clearly, these quantities are unacceptably large, and well over the 1% of the hydrogen mass flow rate (i.e. 45 gm/sec) often cited as the loss due to turbulent mixing. In addition, this loss is far greater than the Uranium burnup rate (0.1 gm/sec of U^{235}). As can be seen from Eqn. 3, the growth rate for a fixed wave number (i.e. a fixed wave length) is smaller for smaller hydrogen flow velocity. But decreasing this velocity beyond a certain value may not be compatible with the mass flow rate dictated by heat transfer needs. The synergetics of problems dealing with turbulent mixing and concomitant loss of uranium, criticality requirements and associated fueling, and heat transfer requirements. not only of the propellant but components subjected to high heat loads, may prove to be a formidable problem indeed for the gas core reactor.

In obtaining the above results, we had employed mean temperature and velocity values for the propellant and the fuel. In reality, however, the density, temperature, and velocity of the propellant possess radial gradients which play a major role in stability considerations. Noting that the ratio of the buoyancy force to the inertia is given by the Richardson number J, where

$$J = -\frac{g}{\rho_1}\frac{\partial\rho_2/\partial z}{(\partial v_2/\partial z)^2}$$

it can be shown[10] that $J > \frac{1}{4}$ leads to stabilization of the Kelvin–Helmholtz instability. It is clear from the above expression that an "inverted" propellant density profile. with the denser layer being adjacent to the fuel, is required for stability. This is difficult to achieve since the hotter (and hence less dense) region is adjacent to the fuel. 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.

If profiling effects cannot be achieved or sustained. then perhaps the use of magnetic fields to suppress this instability may not be totally avoided. It has been shown[10] that if a magnetic field B is introduced in the direction of the propellant flow, then it can act as a "surface tension' type of force that provides stability if the following condition is satisfied:

$$\frac{\rho_1\rho_2}{(\rho_1+\rho_2)}v_2^2 \le \frac{B^2}{8\pi}$$

We see that, for the case at hand, a minimum magnetic field strength of about 64 Gauss is required. The shape of such a field is likely to be "mirror"-like in order to accommodate the flow around the spherical uranium core. Although such a field can bring about stabilization of the Kelvin–Helmholtz instability, it is much too small to confine a uranium plasma at 1000 atmospheres pressure, but might be adequate to respond to pressure fluctuations that may occur in the system.

The problem of uranium loss due to turbulent mixing is closely linked to that of fueling, since the latter must also take into account the loss due to burnup. We propose "pellet" fueling to compensate for these losses! This approach has the potential of injecting fuel into the hottest region of the core, where it can readily vaporize and ionize, with the added advantage of minimally disturbing the homogeneity of the uranium plasma core. Moreover, this method could also be utilized in the presence of magnetic fields[7] should uranium confinement by such fields prove feasible and desirable.

To get an idea of how fast suitably chosen uranium pellets must be injected into a spherical uranium core, we use the parameters of the reactor design alluded to earlier. namely $R = 1$ m, $T_H = 17{,}500°K$, $T_U = 35{,}000°K$, $P = 1000$ atm. Noting that the ionization potential "ϵ" of uranium is 6.18 eV[8], we can estimate the pellet ablation time t_A from

$$t_A = \frac{r_p n_s \epsilon}{q_e} \quad (8)$$

where r_p is the radius of the injected pellet, n_s is the solid state density. and q_e is the heat flux which, in the case of a uranium plasma, is associated primarily with the electrons. At a fuel temperature of 35,000°K, $q_e = 6.2\times10^{28}$ eV/cm^2-sec, and for a pellet radius of 6 cm, the ablation time is 1.5×10^{-5} sec.

The velocity with which this pellet must be injected, to reach the center of the core before being totally ionized. is $v_{inj} = R/t_A$, and for $R = 1$ m, it has the value of about 67 Km/sec. This is a very high speed. and is perhaps out of reach for current or near term technology. But this number should not be taken seriously, since a "bare" pellet does not remain bare once it enters the hot uranium core. In fact, it can be shown that a "neutral' shield forms around the pellet when it enters the core, and this shield drastically reduces the heat flux impinging on the pellet, thereby greatly increasing the ablation lifetime. It has been shown[9] that a reduction of 10^4 in the required Injection velocity may result from the presence of the shield and, for the case at hand, the injection velocity reduces to 6.7 m/sec, which is well within the technology capability.

With 6 cm radius pellets of uranium, less than one pellet per second is required to make up the turbulent mixing loss. However, such a pellet is relatively massive, and may seriously distort the fuel distribution in the reactor until it ablates and is redistributed. In addition, while the injection velocity for such a pellet is relatively small, accelerating such a massive object to this speed requires a greater acceleration force than would be required to give a smaller pellet a much greater speed. Table I shows the trade-offs between pellet size, injection rate, injection velocity V_{inj}, and the force F_{inj} required to achieve this velocity assuming that the injector accelerates the pellet uniformly over a distance of one meter.

As an indication of how seriously turbulent mixing can affect the propulsive performance of the Gas Core Reactor, we have calculated the round trip time, τ_{RT}, to Mars for various ratios of uranium mass flow rate to hydrogen mass flow rate using the dry vehicle mass of 123 MT given in the design

TABLE I
Injection Parameters for Various CCR Pellet Sizes

Radius r_p (cm)	Mass M_i (g)	Injection Rate (sec^{-1})	V_{inj} (m/sec)	F_{inj} (dynes)
0.26	1.2226	6726.6	133.76	1.0938×10^6
0.60	9.7808	716.69	66.882	2.1876×10^6
1.00	78.247	89.461	33.441	4.3752×10^6
2.00	626.97	11.183	16.721	8.76043106
6.00	9780.8	.71569	6.6882	2.1876×10^7

cited earlier. Noting that the thrust, F, and the specific impulse, I_{sp}, can be written as

$$F = \sum_i \dot{m}_i v_i \quad (9)$$

$$I_{sp} = \frac{F}{g\sum_i \dot{m}_i} \quad (10)$$

where g is the gravitational acceleration, and the round trip time τ_{RT} as

$$\tau_{RT} = \frac{4D}{g I_{sp}} + 4\sqrt{\frac{D m_f}{F}} \quad (11)$$

where D is the one way distance and m_f is the dry mass, we obtain the results shown in Table II for a propellant temperature of 17.500°K and uranium temperature of 35,000°K.

TABLE II
Effects of Turbulent Mixing

$\dot{m}_U/\dot{m}_H$	F (KN)	I_{sp} (sec)	τ_{RT} (days)
0	87.6	1987	197
0.01	87.7	1970	198
0.1	88.6	1820	213
0.5	92.2	1390	280
1.0	96.8	1098	344
2.0	106.02	940	398

Another problem of major concern in CCR has to do with acoustic instabilities that might arise as a result of fluctuations in the density and temperature of the fissioning uranium plasma. The mechanism for the generation of such oscillations can be described as follows[10]: We imagine a standing sound wave to exist in a bounded region of a fissioning plasma that includes a constant background density of thermal neutrons. In the wave compressions, the fission power density increases due to the increased uranium density, while in the rarefactions the power decreases. This results in an increased pressure gradient associated with the wave, which in turn leads to a transfer of fission power to the wave. It occurs because the dense portion of the wave tends to expand faster than it was compressed. But competing with this is the fact that radiation also tends to transport the extra thermal energy out of the wave compressions. Moreover, radiation diffusion tends to smooth out the temperature fluctuations of waves more rapidly as their wavelengths become shorter. This results in a critical wavelength below which waves are stable and above which they are unstable. If the characteristic dimension of the system, such as the core radius, is larger than this critical wavelength, then the system will be subject to these instabilities, which could precipitate significant pressure fluctuations and thus present serious control problems for thls englne. In addition, such unstable waves could also glve rise to a slgnlflcant uranium loss from the core; thls fuel would mlx wlth the propellant then exiting through the nozzle.

It can be shown(10), wlth the aid of standard fluld equations for the uranlum plasma, that if the charge state of the uranium lon (assumed here to be singly ionized) does not change during thls phenomenon, then the llnear growth rate of the acoustic lnstabllity can be written as(10)

$$\gamma = \frac{\{2P_f/M - k^2 K_R [V_s^2 - 2KT_0/M]/K\}}{6N_0 V_s^2} \quad (12)$$

where the sound speed. V_s, is glven by

$$V_s = \left(\frac{10}{3}\frac{KT_0}{M}\right)^{1/2} \quad (13)$$

and P_f, N_0, and T_0 are respectively the fission power density. uranium density, and uranlum temperature. The uranium mass is glven by M, the Boitzmann Constant by K, the wave number of the oscillatlon by k, and the radlatlon dlffuslon coefficient by K_R which is deflned as

$$K_R = \frac{16}{3}\frac{\sigma_s T^3}{k_R} \quad (14)$$

wlth σ_s belng the black body constant and k_R the mean Rosseland opacity coefficient. We note from Eqn. 12 that a positive numerator gives rise to an lnstabllity (i.e. a wave wlth growing amplitude) while a negative value denotes a damped wave. The transition from one to the other is characterized by a crltlcal wave number k_c glven by

$$k_c = \left[\frac{5KP_f}{MV_s^2 K_R}\right]^{1/2} = \left[\frac{3}{2}\frac{P_f}{T_0 K_R}\right]^{1/2} \quad (15)$$

which. upon substltutlon in Eqn. 12, yields

$$\gamma = \frac{K_R}{15KN_0}\left\{k_c^2 - k^2\right\} \quad (16)$$

For the reactor example presented earlier. the above equation becomes

$$\gamma = 3.7\times 10^2\left\{k_c^2 - k^2\right\} \quad (17)$$

and upon lnsertlng the appropriate parameters we find that the crltlcal wave number value is $k_c = 0.084$ and the crltlcal wavelength is $\lambda_c = 75$ cm. Since the radlus of the core is 1 m, it is clear that such a system will support acoustic lnstabllltles, and for wave numbers corresponding to thls dlmenslon, Eqn. 17 shows that the e-foldlng time is about 0.9 seconds. Although detalled non-llnear analysls is required to assess the impact of these lnstabllltles, one can estlmate the loss of fuel from the core due to these oscillations by using Eqns. 6 and 7 along wlth 16. One flnds, for the case at hand, that about 9% of the uranlum plasma per second wlll be transported **out** of the core, which corresponds to a fuel mass flow rate of about ***20* kg/sec.** Assuming that such losses can be replenished by appropriate refueling schemes, one can also see, from an extension of Table II to include thls case, that such a uranium mass flow rate wlll result in a round trip to Mars of about 600 days.

Conclusion

We have examlned brlefly in thls paper several physics phenomena that mlght have adverse effects on the vlabllity of the open cycle gas core rocket as a potentlal propulsion scheme for the space exploration lnltlatlve. The flrst has to do wlth vortex confinement of the fuel, which renders it unstable to hydrodynamic lnstablltles of the Kelvln - Helmholtz type, and the other has to do wlth acoustlc lnstabllltles arlslng from density and temperature fluctuations. In both cases. substantial amounts of uranium may be transported out of the core and expelled through the nozzle, wlth the unwelcome result of slgnlficantly reducing the speclflc impulse and lncreaslng the travel time. These phenomena also present serious challenges concerning the fuellng of the reactor to maintain crltlcallty, and general dynamics and control problems for such an englne. Finally, it mlght be noted that the Light Bulb Concept(11) which employs a barrier to separate the fuel from the propellant may not experlence a Kelvln-Helmholtz lnstabllity that ejects uranlum from the core, but it is more llkely to experlence the acoustic lnstabllity since the barrier is bound to impede the escape of radlatlon from the core.

References

1. R. G. Ragsdale, Nuclear Thermal Propulslon A Jolnt NASA/DOE/DOD Workshop, Cleveland, OH, July 10-12 (1990)

2. R. G. Ragsdale and E. A. Willis, Jr., AIAA Paper 71-641, 7th Propulslon Jolnt Speclalist Conference, Salt Lake City, Utah, June 14-18 (1971)

3. S. K. Borowskl, NASA Technical Memorandum 101364, July 18 (1987)

4. A. F. Kascak and A. J. Easley, NASA TN D-4882, August 6 (1968)

6. R. E. Hyiand. R. G. Ragsdale, and E. J. Gunn, NASA TN D-1676, March (1963)

6. S. Cnandrasekhar, Hydrodynamic and Hydromannetlc Stability, Dover Publications N.Y. (1961)

7. G. Zavala and T. Kammash, Fuslon Technology 6, 30 (1984)

8. M. Benedlct, T. Pigford, and H. Levl, Nuclear Chemical Ennlneerlng, McGraw Hill, N.Y. (1981)

9. C. Chang et. al., Nuclear Fuslon 20, 869 (1980)

10. D. A. Tidman, 2nd Symposium on Uranlum Plasmas: Research & Appllcatlons Atlanta, Nov. 16-17 (1971) p. 99

11. T. S. Latham, AIAA 71-642, June (1971)