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Gas Core Fission and Inertial Fusion Propulsion Systems--A Preliminary Assessment

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

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GAS CORE FISSION AND INERTIAL FUSION PROPULSION
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T. Kammash and D. L. Galbraith
Department of Nuclear Engineering
The University of Michigan
Ann Arbor, MI 48109

Abstract

Using a Mars mission as basis, we carry out a preliminary assessment of two propulsion approaches: an Open Cycle Gas Core fission reactor (GCR), and the Magnetically Insulated Inertial Confinement Fusion (MICF) concept. The first utilizes a uranium fuel in a gaseous plasma form that heats a hydrogen propellant and, in so doing, converts thermal energy into thrust. The second relies on a laser beam to ignite a deuterium-tritium (DT) plasma within a metallic pellet, which at the end of the fusion burn is exhausted through a magnetic nozzle to provide propulsion. A very preliminary design of each concept is analyzed, and major technological problems are identified. It is shown that while travel time for each scheme may be comparable, the GCR system must overcome such serious problems as fuel confinement and replenishment, and turbulent mixing and startup, among others, while the fusion approach must find ways to reduce the driver energy needed to initiate the burn.

Introduction

The Space Exploration Initiative calls for, among other things, a manned mission to the planet Mars sometime 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. Two promising approaches in this regard are the open cycle gas core[1] fission reactor (GCR) and an inertial confinement fusion scheme known as the Magnetically Insulated Inertial Fusion (MICF) concept[2]. 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. The MICF is a fusion scheme that combines the favorable aspects of inertial and magnetic fusions into one where

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

physical confinement of the plasma is provided by a metal wall, while its thermal energy is insulated from that wall by a strong self-generated magnetic field as illustrated in Fig. 2.
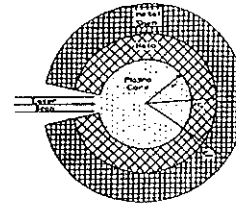
(a)
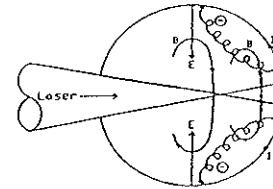
(b)

Fig. 2.
Schematic Diagram of (a) Plasma Formation and (b) Magnetic Field Formation in MICF.
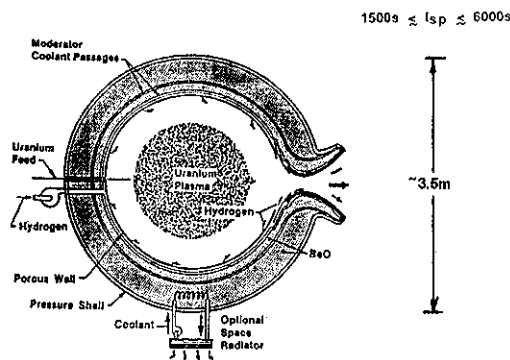
The temperature limitations imposed by material melting as encountered in solid core thermal rocket designs is avoided in GCR since the nuclear fuel is allowed to exist in a high temperature ($10,000 - 100,000 °K$) partially ionized state. In this so-called "gaseous - or plasma core" concept, the sphere 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 graphite 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 GCR 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 ($500 - 2000$ atm) to achieve a critical mass. At these pressures, the gaseous fuel is sufficiently dense for the fission fragment

1

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[3] that a small amount of fissionable 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 which 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.

Though an inertial confinement scheme, the Magnetically Insulated Inertial Confinement Fusion (MICF) concept makes use of a very strong magnetic field which the incident laser beam generates through the "thermoelectric effect". When the plasma, created through wall ablation by the laser beam, possesses a density gradient which is normal to a temperature gradient, the resulting electric field gives rise to a time dependent magnetic field. This magnetic field is subsequently carried away from the focal point by the electromagnetic drifts of the plasma particles. Because of the high plasma pressure, the resulting field does not serve as a confining magnetic field; rather it serves as a thermal insulator that retards the flow of heat from the plasma to the metal shell. It has been shown[4] that the lifetime of the plasma in MICF is about two orders of magnitude longer than in the standard implosion type inertial fusion where confinement is dictated by the sound speed in the plasma itself. In MICF, the confinement time is dictated by the shock speed in the metallic shell, whose density is much larger than that of DT and whose temperature is significantly colder due to the thermal insulation provided by the magnetic field. Moreover, MICF does not suffer from the Rayleigh – Taylor instability (which has hampered implosion type inertial fusion) due to the fact that the light fluid (plasma) is supported by the heavier fluid (metal shell) against the acceleration associated with the expansion of the hot plasma core, a situation known to be stable.

The dynamics of the plasma in MICF is governed by a coupled set of quasi one-dimensional, time dependent conservation equations[5] that include radiation (bremsstrahlung) transport from the hot plasma to the various regions of the pellet, as well as particle and energy transport across the magnetic field between the hot core and the cold plasma region (halo) in both directions. The alpha particles generated by the DT fusion reactions are usually assumed to slow down and eventually thermalize in the hot core without crossing the magnetic field, on the premise that their thermalization time is shorter than their diffusion time. However, closer examination of their stopping distance as well as their gyroradii reveals that these are comparable to the dimensions of the regions on both sides of the magnetic field, and hence they can deposit their energy outside the core. It turns out[6] that about 60% of the fast alphas end up depositing their energy in the halo region, and this appears to

increase the gain factor Q (ratio of fusion energy to injected laser energy). This is due to the fact that the heating of the halo region increases its pressure, which results in compressing the hot core, thus raising the core density and correspondingly the fusion energy produced. As a propulsive device, MICF pellets are injected into a burn chamber at a certain repetition rate, and upon being zapped by a laser they ignite, producing fusion energy at a high gain factor (see Fig. 3). Upon completion of the
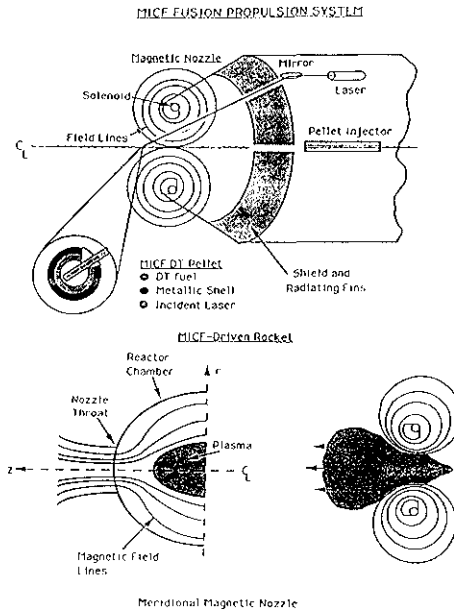

Fig. 3.
Schematic of MICF Rocket and Magnetic Nozzle.

burn, the DT and the metallic shell plasmas are exhausted through a magnetic nozzle, producing specific impulses of several thousand seconds and thrusts in the tens of kilonewtons. The need for larger thrusts or specific impulses is met by proper design of the pellets through careful choice of the metallic component and the dimensions of the various regions. Once the pellet design is fixed, the thrust may also be varied by adjusting the firing repetition rate.

Some Technological Issues

To highlight some of the major physics and engineering issues which both propulsion approaches must overcome, we choose in each case a preliminary design for which the relevant parameters are available. In the case of the open cycle gas core reactor, we identify a reactor design[7] 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 $35,000°K$[8]. Our elementary analysis of this system shows that the mean velocity of the hydrogen, which is commensurate with a cited mass flow rate of 4.5 Kg/sec, is approximately 5 m/sec. The mean velocity of the uranium in the core is generally taken to be 10 – 15 times smaller than that of the

propellant[9]. 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[10], 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]

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

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

$$k_{min} = \frac{g\rho_1}{v_2^2 \rho_2} \tag{2}$$

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

$$\gamma_{min} = v_2 k_{min} \sqrt{\frac{\rho_2}{\rho_1}} = \frac{g}{v_2}\sqrt{\frac{\rho_1}{\rho_2}} \tag{3}$$

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

$$D = \frac{\gamma}{k^2} \tag{4}$$

from which we can write the particle flux as

$$F = \frac{D\rho_1}{R} \tag{5}$$

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

$$U_t = 4\pi R^2 F = 4\pi R D \rho_1 \tag{6}$$

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

$$\frac{U_t}{U_s} = \frac{4\pi R D \rho_1}{\frac{4}{3}\pi R^3 \rho_1} = \frac{3D}{R^2} = \frac{3\gamma}{R^2 k^2} \tag{7}$$

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/cm^3 and 5.53×10^{-2} gm/cm^3. 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

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

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:

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

We see that, for the case at hand, a minimum magnetic field strength of about 54 Gauss is required. The shape of such a field is likely to be "mirror"-like in order to accomodate the flow around the sperical 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[11] 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[12], we can estimate the pellet ablation time t_A from

$$t_A = \frac{r_p n_s \epsilon}{q_o} \tag{8}$$

where r_p is the radius of the injected pellet, n_s is the solid state density, and q_o 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, $q_o = 6.2 \times 10^{28}$ eV/cm²-sec, and for a pellet radius of 5 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[13] 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 5 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.

TABLE I
Injection Parameters for Various GCR Pellet Sizes

Radius r_p (cm)	Mass M_p (g)	Injection Rate (sec⁻¹)	V_{inj} (m/sec)	F_{inj} (dynes)
0.25	1.2226	5725.5	133.76	1.0938×10^6
0.50	9.7808	715.69	66.882	2.1876×10^6
1.00	78.247	89.461	33.441	4.3752×10^6
2.00	625.97	11.183	16.721	8.7504×10^6
5.00	9780.8	.71569	6.6882	2.1876×10^7

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

$$F = \sum_j \dot{m}_j v_j \tag{9}$$

$$I_{sp} = \frac{F}{g \sum_j \dot{m}_j} \tag{10}$$

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

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

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	88.5	1820	213
0.5	92.2	1390	280
1.0	96.8	1098	344
2.0	106.02	940	398

The propulsive capability of the Magnetically Insulated Inertial Confinement Fusion (MICF) concept has been examined in several previous publications[14,15]. As may be noted from Fig. 3, the principle of propulsion in this scheme is the ignition of the fusion target in the reaction chamber by an incident laser beam, and the exhaust of the hot plasma at the end of the burn through a magnetic nozzle to generate the thrust. Typical design parameters for a deuterium-tritium (DT) burning target and a reaction chamber with an appropriate nozzle are shown in Table III.

TABLE III
MICF Target and Nozzle Parameters

Inner Radius of Fusion Fuel	0.25 cm
Outer Radius of Fusion Fuel	0.30 cm
Outer Radius of Metal Shell	0.547 cm
Input Laser Energy	2.59 MJ
Initial Plasma Density	5×10^{21} cm⁻³
Initial Plasma Temperature	11.785 keV
Total Pellet Mass	8.75 gram
Energy Gain Factor Q	724
Reaction Chamber Volume	4.189×10^3 cm³
Nozzle Throat Area	19.63 cm²

The propulsive capability of an MICF engine whose pellets contain a tungsten shell, that physically contains the hot plasma, is given in Table IV. The laser driver (lasers, radiators, optics, energy

TABLE IV
MICF Propulsion Parameters

Average DT Ion Energy at End of Burn	1.10 keV
Fuel Ion Exhaust Velocity	376 km/sec
Tungsten Ion Exhaust Velocity	43.8 km/sec
Effective Specific Impulse I_{sp}	0.451×10^4 sec
Firing Rate ω	≤ 6422 Hertz
Total Thrust F	$0.412\,\omega$ kN
Jet Power P_{jet}	$9.70\,\omega$ MW

handling) along with the thrust chamber and the overhead components for the above propulsion device are estimated[16] to be 564 metric tons (mT). We arbitrarily add 100 mT payload, and assume that the dry weight for the vehicle is 664 mT. Using a continuous burn (constant thrust) acceleration/deceleration trajectory profile, as we did in generating the results shown in Table II for the GCR, we calculate the round trip journey time to Mars by MICF to be 138 days. A special feature of MICF propulsion is the ability to provide variable thrust and/or variable specific impulse on demand. This can be accomplished by programming beforehand the design and the number of pellets needed to generate an additional amount of thrust at the expense of specific impulse. Such objectives can be achieved by increasing the thickness of the metal shell while reducing that of the fusion fuel coating on its inner surface. The opposite can be done if the opposite objective is deemed necessary. One can, therefore, visualize an MICF engine in which two (or more, for that matter) types of target pellets are carried on board, and injected into the reaction chamber on command when a particular propulsion performance is called for.

Further enhancement of the performance of MICF can be obtained, not just by changing the dimensions of the metal component of the target pellet, but also by changing its composition. In obtaining the results cited earlier, only the charged particle (alpha particles resulting from the DT fusion) reaction products' energy was utilized in heating the plasma that was exhausted through the nozzle to generate the propulsion parameters. Eighty percent of the fusion reaction energy resides in the neutrons, which are presumed to escape the target instantly. Clearly, a marked improvement in the performance could be obtained if the neutron energy were somehow utilized in the energy multiplication of the system and correspondingly the energy content of the exhausted species. One step toward achieving this is to replace the tungsten portion of the target by uranium (U^{238}), which we know to undergo fission reactions upon bombardment by neutrons. Since the neutrons generated by the DT fusion reactions are high energy neutrons (14.1 MeV), the fission cross section for U^{238} at these energies is about 1 barn (10^{-24} cm^2). The energy enhancement due to fission for the same thickness of the metal shell is about 1.66. The specific impulse is little changed since the increase in charged particle energy release is balanced by the heavier shell atoms (U^{238} instead of W^{184}). The thrust increase goes as the square root of the energy enhancement, or about 1.29. The new F for the case shown in Table IV is $0.542\,\omega$ kN.

Assuming no enhancement by the secondary neutrons generated from the fission process, we can readily show that the round trip to Mars for the same case is reduced by about 9 days by this simple change. Larger pellet designs might show a greater enhancement by capturing a larger fraction of the escaping fusion neutrons. In obtaining these results, it was assumed that the confinement characteristics of MICF were not drastically changed upon replacement of the tungsten shell by its uranium counterpart. It might be noted that an appreciable savings in fuel consumption can be achieved if the travel trajectory profile is changed from that of continuous acceleration/deceleration to one in which one or the other is held constant, while coasting for a number of days on each leg of the journey. For example, the fuel consumption can be greatly reduced without increasing the thrust requirement by utilizing a mode in which 12 days of constant acceleration is followed by 45 days of coasting followed by 12 days of constant deceleration. The travel time in this new mode is slightly longer, but the difference is only 4%, while only one-fifth as much fuel is required! A seventeen percent reduction in travel time can be achieved using the constant thrust operating mode if the rocket engine is turned off in mid-flight to allow a 25 day period of coasting on both the outbound and the return flights; this mode also saves fuel, using only 45% as much as when the rocket is operated continuously. A 55 day coasting period brings the trip duration back up to that required for continuous rocket operation, but only 17.5% as much fuel is consumed. The MICF propulsion scheme lends itself rather well to such operating scenarios, but it is not clear that the GCR can do the same without raising serious questions concerning shutdown, restart, maintainability of criticality, and rejection of large amounts of waste heat.

Conclusion

We have examined in this paper two potential propulsion schemes that could readily meet the objectives of the Space Exploration Initiative in the early part of the next century. One uses uranium plasma as the fuel of a Gas Core Reactor in which energy is produced from fission reactions, while the other employs the fusion reactions of deuterium and tritium in a unique confinement concept that combines inertial and magnetic confinement properties into one fusion reactor. Using a round trip to Mars as the basis of comparison, a preliminary design of each scheme was evaluated in terms of its propulsive capability. It is shown that while trip times may be comparable, serious technological problems must be overcome in each case before they can be viewed as viable propulsion schemes. For the Gas Core Reactor, problems associated with fueling, turbulent mixing, and cooling of various components may seriously limit its propulsive capability, while MICF must find means to reduce the input laser energy required for large energy multiplication. The fusion scheme also appears to have more versatility concerning various travel scenarios that may allow a Mars mission to be undertaken in shorter times.

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