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A Compact Gas Core Nuclear Rocket for Space Exploration

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A COMPACT GAS CORE NUCLEAR ROCKET
FOR SPACE EXPLORATION

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Abstract

The open cycle Gas Core Nuclear Rocket (GCR) possesses, in principle, outstanding propulsion characteristics that make it especially attractive for advanced space propulsion. With uranium as fuel and hydrogen as propellant, it can generate several thousand seconds of specific impulse and hundreds of kilonewtons of thrust. In its standard configuration, however, GCR is susceptible to hydrodynamic and acoustic instabilities, which if not adequately addressed, could lead to significant loss of fuel and severe limitation on its propulsion capabilities. In this paper we examine the potential utilization of americium in place of uranium, and study the effect of such fuel change on the size reduction of the system as well as its impact on the hydrodynamic stability question. We find that the same propulsion performance can be achieved at a comparable fuel density but with a radial size reduction of both core and moderator/reflector of about 70%, and a corresponding stabilizing effect on the Kelvin-Helmholtz instability which lies at the heart of turbulent mixing in this device.

$1500s \leq Isp \leq 6000$

~3.5m

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

Introduction

The open cycle gas core [1] fission reactor (GCR) has been identified as a promising advanced propulsion scheme that could readily meet the objectives of the space exploration initiative (SEI) of sending a manned mission to Mars in the early part of the next century. The principle of operation in this system involves a critical fissile 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 illustrated in Figure 1.

In contrast to solid core reactors where temperature limitations, imposed by material melting, place severe constraints on rocket

performance, the gas core concept circumvents these limitations because the nuclear fuel is allowed to exist in a high temperature (10,000–100,000 K), partially ionized state referred to as the plasma. Nuclear heat released 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. With this scheme, specific impulses of several thousand seconds appear to be feasible.[1]

In a recent paper,[2] we examined some of the physics issues associated with fuel confinement and stability in GCR. We found that steady state operation of the reactor is possible only for certain core profiles which may not always be compatible with the radiative aspect of the system. Moreover,

we found that the system is susceptible to hydrodynamic and acoustic instabilities that could deplete the fuel in a short time if not properly addressed. In the absence of such problems, however, the propulsion characteristics of GCR can be assessed using a heat transfer model that utilizes a diffusion heat transfer analysis which takes into account the wall material temperature and heat flux limits [3]. It is found 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.

None of the physics and engineering problems that face the development of the gas core nuclear rocket is perhaps more challenging than that associated with startup. One of the proposed solutions to this problem that might become feasible in the time period when GCR might become a propulsion contender, is the use of antiproton annihilation to generate the required number of neutrons.[4] In calculating the amount of antihydrogen needed, a model consisting of a "cavity" reactor surrounded by a reflector-moderator is utilized, in which moderation of fast neutrons in the core is neglected, and thermal neutrons generated in the moderator-reflector enter the core to initiate the fission reactions. A two-group theory utilizing the time-dependent Fermi age and diffusion equations is used in which the fast neutron source is taken to consist of those resulting from the annihilation reactions and those resulting from the fission reactions taking place in the core. A D_2O moderator at room temperature is assumed, an effective multiplication factor, k_{eff} is calculated, and a power balance equation is utilized to calculate the neutron source strength needed to start the reactor. For the reactor described above, a source of about 10^{22} neutrons was found to be adequate for the startup.

GCR with Americium Fuel

One possible approach to enhancing the space applicability of GCR is to find ways by means of which we can reduce its size (and thus its weight) without diminishing its propulsion capability. Such an enhancement cannot be viewed as truly significant unless it is accompanied by some measure of hydrodynamic stabilization to the core. The most logical and perhaps intuitive approach lies in finding a fuel with a much higher thermal cross section than ^{235}U. The choice is clearly ^{242m}Am, which has the highest known

thermal fission cross section[5] and a half-life of 141 years, which render it especially attractive for space applications. As can be seen from the decay scheme shown in Figure 2, Americium-242 has three isomers: ^{242f}Am with a half life of 14.02 ms which decays by spontaneous fission and is of no special interest to the problem at hand, ^{242m}Am which is uniquely suited for the objective cited above and ^{242}Am which decays mostly (82.7%) by beta emission to $^{242}_{96}Cm$ which in turn decays by alpha emission (with 6.2158 MeV) at a half-life of about 163 days. The other branch of decay of $^{242}_{95}Am$ is by electron capture (17.3%) to $^{242}_{94}Pu$ which in turn decays by alpha emission (with 4.983 MeV) at a half-life of 3.76 x 10^5 years.
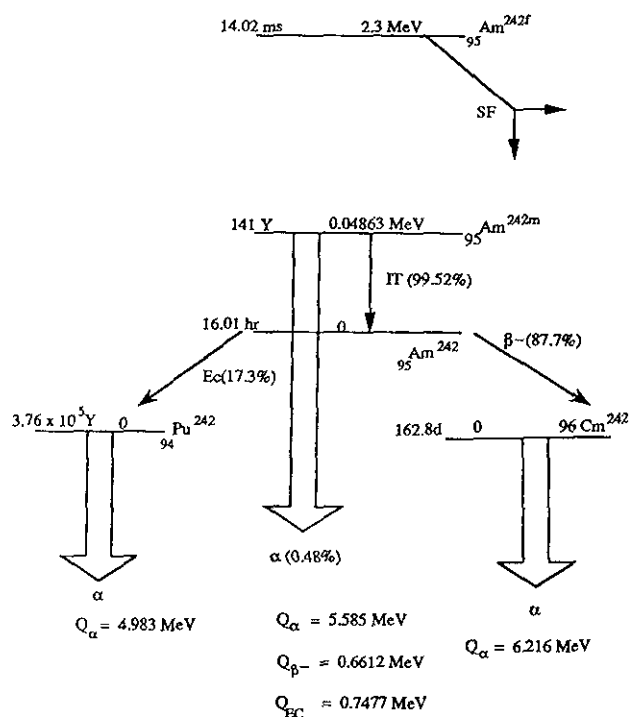

Figure 2. Decay Scheme of Am Isomers.

The isomer ^{242m}Am can be obtained from an (n,γ) capture reaction with ^{241}Am which itself has a relatively high thermal capture cross section. The isotope ^{241}Am, with a half-life of 433 years is obtained from the beta decay of ^{241}Pu which has a half-life of 14.4 years. It has been suggested[5] that the amount of ^{241}Pu in the discharged fuel of power reactors is relatively high. Typically about 9.5% of the plutonium discharged from a

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pressurized water reactor (PWR) is ^{241}Pu. As a result, a 1000 MW (electric) PWR with a fuel discharge burnup of 32,000 MWd/ton produces about 31 kg of ^{241}Pu every year.[5] Other estimates[6] place the current worldwide inventory of ^{241}Am in spent nuclear fuel at approximately 10 tons. With increasing commercial nuclear power production it is possible that sufficient ^{241}Am will be available in the not too distant future for potential use in space applications.

All these facts, namely high thermal cross section, relatively high ν (the number of neutrons produced per thermal fission), and long half-life make the isomer ^{242m}Am an especially desirable nuclear fuel where lower fuel weight (reactor size) is important such as in space applications. The important thermal data for this isotope are given in Table 1. Figure 2 also reveals that this isotope decays mostly by internal conversion (99.52%) to ^{242}Am, and by alpha emission at 0.48% with an energy of 5.585 MeV.

It is useful to examine this information to see whether the decay scheme of ^{242m}Am leads to heating of the fuel so as to maintain it in a plasma form that is compatible with a gas core reactor. The range of an alpha particle of energy of 5.585 MeV in an americium gas of density ~10^{18} cm^{-3} is about 45 cm which, as we will note shortly, is approximately the desired size. With an

TABLE 1. Thermal Data for ^{242m}Am.

Property	Value
1. Fission neutron yield per thermal neutron absorbed $\eta = \nu\sigma_f/\sigma_a$	2.693
2. Number of Neutrons produced per thermal fission ν	3.264
3. Thermal absorption cross-section; $\sigma_a = \sigma_\gamma + \sigma_f$	8000 b
4. Fission Cross-section	6600 ± 300 b (or 7350 ± 500 b)[a]
5. Radiative Cross-section, σ_γ	1400 ± 860 b (or 1650 ± 400b)[a]

[a] Ref. 5

ionization potential of 5.655 eV, we compare this value to the energy per atom associated with the alpha decay which we can readily calculate to be 8.700 x 10^{-4} eV/s. This means that, in the absence of radiation loss, it takes approximately two hours of decay to generate the ionization energy of 5.655 eV. However, the black body radiation from such a system is about 10^7 eV/atom-s, and the bremsstrahlung radiation (assuming instant ionization) is about 2.693 x 10^5 eV/atoms-s, thus the alpha decay is totally inadequate for ionizing the medium, and one must rely on the fission energy to achieve this objective.

As pointed out earlier, ^{242m}Am is obtained from an (n, γ) capture reaction with ^{241}Am, and since it has a high thermal fission cross-section itself, it would appear that due to the two competing processes, very little of ^{242m}Am would accumulate unless a steady supply ^{241}Am is provided. For a spherical reactor that produces 7.5 GW of power with ^{242m}Am fuel, at a density of 10^{18} cm^{-3} and a radius of 40 cm, a thermal neutron flux of 1.462 x 10^{17} cm^{-2}s^{-1} would be required. Noting however that each neutron captured

by $^{241}_{95}Am$ gives rise to 5.5 MeV in gammas, each ^{242m}Am gives 190 MeV in capturable fission energy, and each ^{242m}Am neutron capture gives rise to 6.32 MeV in gammas, then, on the average, each neutron absorbed in ^{242m}Am gives:

$$\left(\frac{\sigma_f}{\sigma_f+\sigma_c}\right)(190) + \frac{\sigma_c}{\left(\sigma_f+\sigma_c\right)}(6.32) = 144 \ MeV \ (1)$$

and in steady state the total energy released is 149.5 MeV/cm^3-s. If such a steady state reactor produces 7.5 GW of power then the rate of supply of ^{241}Am required is given by:

$$\frac{dN_{41}}{dt} = V\varphi \ \sigma_{41}N_{41} = V\varphi\sigma_{42}N_{42} \qquad (2)$$

where V is the volume of the reactor, φ the flux, σ the absorption cross section, and N is the density. With $\sigma_{42} = 8000$ b, and $N_{42} = 10^{18}$ cm^{-3} and the flux and size as noted above, we see that the rate of supply of ^{241}Am is 1.2599 x 10^{-1}g/s; or 10.885 kg/day. For a journey that takes 6 months on the basis of a continuous burn, acceleration/deceleration type of trajectory, approximately 2000 kg of ^{241}Am will be needed.

Returning to the comparison of a ^{242}Am-fueled GCR and one that uses ^{235}U, with the same

moderator-reflector composition and reactor performance characteristics, we should note that the moderator neutron properties remain the same. These include the thermal age, the thermal transport mean free path, the thermal diffusion length, the thermal macroscopic absorption cross section, the thermal diffusion coefficient, and the thermal diffusion time. Clearly, the core properties will change, and these include the absorption cross section, the "interior greyness" factor, and both k_∞ and k_{eff}. In the uranium version[4] a k_{eff} of about 1.2 was obtained for a 7.5 GW reactor operating at 500 atm pressure and 65,000 K temperature. Figure 3, which shows the variation of k_{eff} vs. the reactor core radius, reveals

that $k_{eff} \approx 1.2$ can be obtained at a radius of 40 cm in the case of ^{242m}Am, and that an optimum value of moderator thickness occurs at 0.6 of the core radius. This means that a total radial dimension of 64 cm will provide the same performance as a ^{235}U reactor with a total dimension of 200 cm, or a reduction in a radial size of about 70%. The reduction in volume is clearly more dramatic, and for space applications this could be significant if not critical.

As for the stability consideration we first note that the so-called Kelvin-Helmholtz (K-H) instability arises when a fluid (such as the propellant) of mass density ρ_2 and velocity V_2
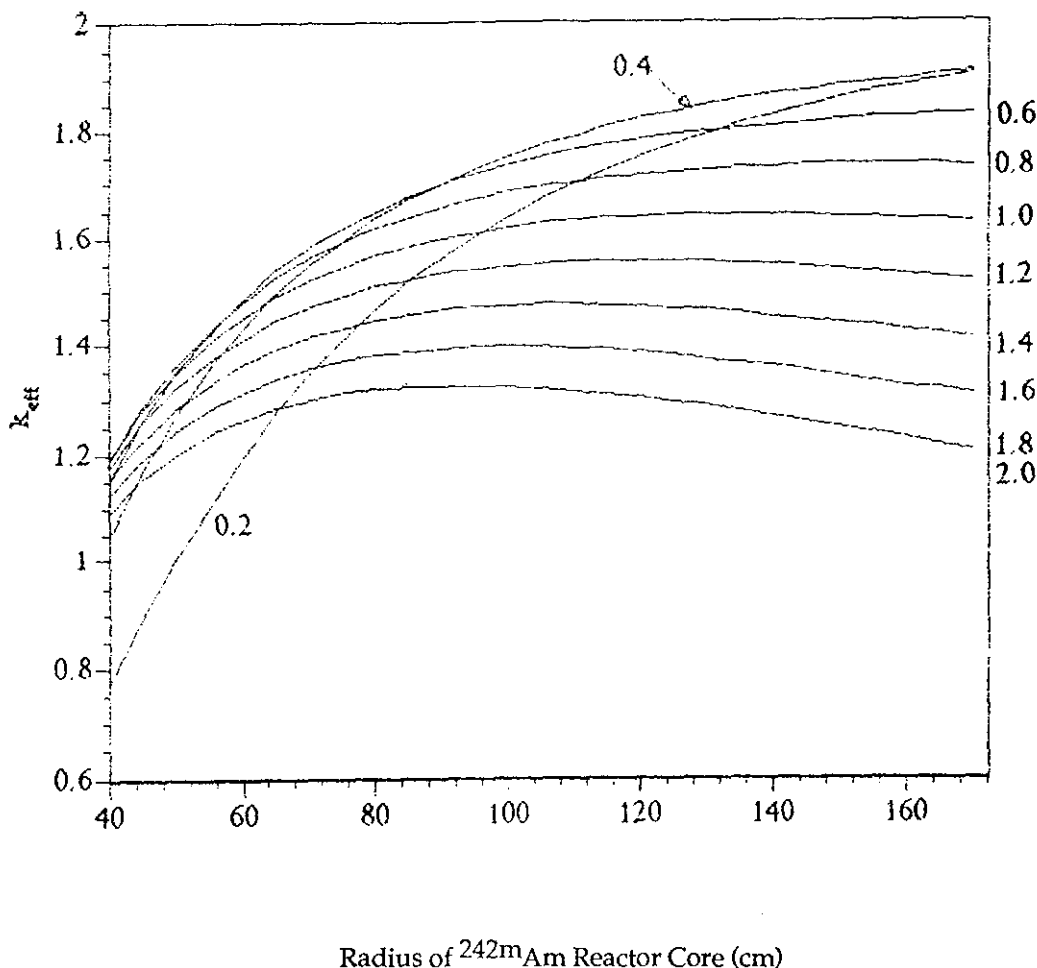

Radius of ^{242m}Am Reactor Core (cm)

FIGURE 3. k_{eff} versus Radius of ^{242m}Am Gas Core for Different Values of α, where α is the Ratio of Moderator Thickness to Reactor Core Radius. ^{242m}Am Density is $1 \times 10^{18} cm^{-3}$.

moves past a stationary fluid (such as the fuel in the core) of density ρ_1 under the influence of gravitational acceleration g. The condition for such an instability can be written as[7]

$$V_2^2 > \frac{g\left(\rho_1^2 - \rho_2^2\right)}{k\,\rho_1\rho_2} \cong \frac{g\rho_1}{k\rho_2} \qquad (3)$$

where k is the wave number of the oscillation. In writing the above equation we have taken advantage of the fact that for the temperatures and pressures that are expected in GCR, the fuel (uranium or americium) density is much larger than that of the hydrogen propellant. For a reactor operating in space, the quantity g is the centrifugal acceleration experienced by the propellant as it moves past the spherical core, or $g = V_2^2/R$, with which Eq. (3) assumes the form

$$1 > \frac{\rho_1}{kR\rho_2} \qquad (4)$$

Although short wave length oscillations (large k) tend to be more unstable, their effect on the disruption of the core and potential loss of fuel is relatively small since the activity is restricted to a small region of the core. By contrast, a long wave oscillation will be more damaging since it encompasses a larger region, and corresponding turbulence can thus result in a significant loss of the fuel. We focus therefore on the minimum wave number or the maximum wave length for such an instability given respectively by

$$k_m = \frac{\rho_1}{R\rho_2}$$

$$\lambda_m = 2\pi R \frac{\rho_2}{\rho_1} \qquad (5)$$

The last expression reveals that the maximum unstable wavelength is given by that fraction of the core circumference given by ρ_2/ρ_1, i.e. the density ratio of propellant to fuel. We readily note from Eqs. (4) and (5) that americium is less unstable than uranium since its density is larger. Moreover, the growth rate of the K-H instability is given by[7]

$$\gamma = V_2 k_m \sqrt{\frac{\rho_2}{\rho_1}} = \frac{V_2}{R}\sqrt{\frac{\rho_1}{\rho_2}} \qquad (6)$$

where we have made use of the first of Eq. (5). The coefficient of the fuel diffusion associated with this instability can be approximated by

$$D = \frac{\gamma}{k_m^2} = V_2 R \left(\frac{\rho_2}{\rho_1}\right)^{\frac{3}{2}} \qquad (7)$$

from which we can express the particle flux as

$$F = D\frac{\rho_1}{R} = V_2\rho_2 \sqrt{\frac{\rho_2}{\rho_1}} \qquad (8$$

where once again we note that R is the radius of the spherical core. It is clear from the above expression that an americium-fueled reactor with the same thermal power as a uranium-fueled reactor, with both systems utilizing a hydrogen propellant at the same mass flow rate, the americium-fueled reactor will lose less fuel as a result of this instability than the uranium-fueled counterpart due to its larger density.

Conclusion

We have examined in this paper the potential use of the americium isotope [242m]Am in a gas core nuclear rocket that could readily meet the objectives of SEI. Due to its large thermal fission cross section we find that a significantly smaller reactor could produce the same propulsion characteristics as a counterpart with [235]U. We have also seen that although both reactors suffer from the Kelvin-Helmholtz instability that arises from the relative motion of propellant to fuel, the americium-fueled reactor tends to be less unstable, and lose less fuel as a consequence, due to its larger mass density. It is not clear that total hydrodynamic stability can be achieved in either system without the aid of an external force such as a magnetic field. This aspect will be explored in a future publication.

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