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ABSTRACT

A new reactor concept is described which would enable fission fragments to be continuously extracted from the reactor. Such a reactor has the potential of enabling extremely energetic and ambitious deep space missions. In this talk the basic physics issues involved in the operation of this type of reactor are outlined, and some possible applications to space exploration are described.

INTRODUCTION

As we're sure most of your are aware fission fragments come in two varieties: a) "heavy" fragments with a kinetic energy of approximately 0.5 MeV per AMU, and b) "light" fragments whose kinetic energy is approximately 1.0 MeV per AMU. In this talk we wish to discuss the possibility that these fission fragments can be used directly to propel a spacecraft.[1] The usual figure of merit for rocket propellants is specific impulse - the length of burn for which an acceleration of 1 g can be maintained. In a rocket exhaust fission fragments would give a specific impulse of 10^6 seconds. The best chemical rocket propellants currently in use have specific impulses of about 300 seconds. Thus the use of fission fragments could lead to burn-out velocities 3000 times those currently attainable. In terms of the speed of light this corresponds to velocities in excess of .05c!

Obviously the attainment of velocities on the order of .05c will open up new possibilities for the exploration of space beyond the solar system. Of course, the realization of these possibilities will depend on how easy it is to design a nuclear reactor that allows the fission fragments to escape. In ordinary solids or liquids fission fragments travel only a few microns before losing their energy. Thus the average density of material in the reactor core must be much smaller than solid density if the fission fragments are to escape.

Our basic conception for how a fission fragment rocket would work is very simple. The reactor core is in a vacuum and the fissile material is placed in the reactor core in the form of a coating on very thin (i.e., few micron) diameter fibers. The fission fragments are then guided out of the reactor core with magnetic fields. In a vacuum the mean free path for a fission fragment will be comparable to the size of the reactor core if the spacing between the fuel wires is sufficiently large. The fission fragment escape probability from an array of wires will be determined by the escape probability from a single fiber and the thickness of the array of fibers. In Fig. 1 we show the escape probability for fission fragments from a fiber coated with uranium carbide as a function of coating and fiber thickness. Escape probabilities were calculated using a integral transport code developed at the Idaho National Engineering Laboratory. Evidently with UC coating thicknesses of less than 0.5 μm, it is possible to achieve fiber escape probabilities exceeding 70%. The escape probability from a layer of wires will be determined by the product of the volume averaged density of material in the layer, ρ, and thickness of the layer, Δx. The range of fission fragments is about 2 mg/cm^2. Therefore, $\rho\Delta x$ for a fuel layer cannot exceed about 1 mg/cm^2.

While it is clear that it is possible in principle to achieve criticality with low fuel densities, one might guess that the reactor core size would be prohibitively large or that excessively large magnetic fields would be required to guide the fission fragments out of the reactor core. However, initial investigations of this concept resulted in two surprises. First, if one uses a good moderator-reflector and highly fissile isotopes then relatively small amounts of fissile material are required for criticality, and the reactor core need be only one or two meters across. Second, the magnetic fields needed to guide the fission fragments out of the reactor can be generated with currently available technology. To illustrate this last point we note that the magnetic rigidity of fission fragments with atomic weight A will be given by

$$Br = \frac{14.AE^{1/2}}{Z_{eff}} \text{ Tesla-cm} \tag{1}$$

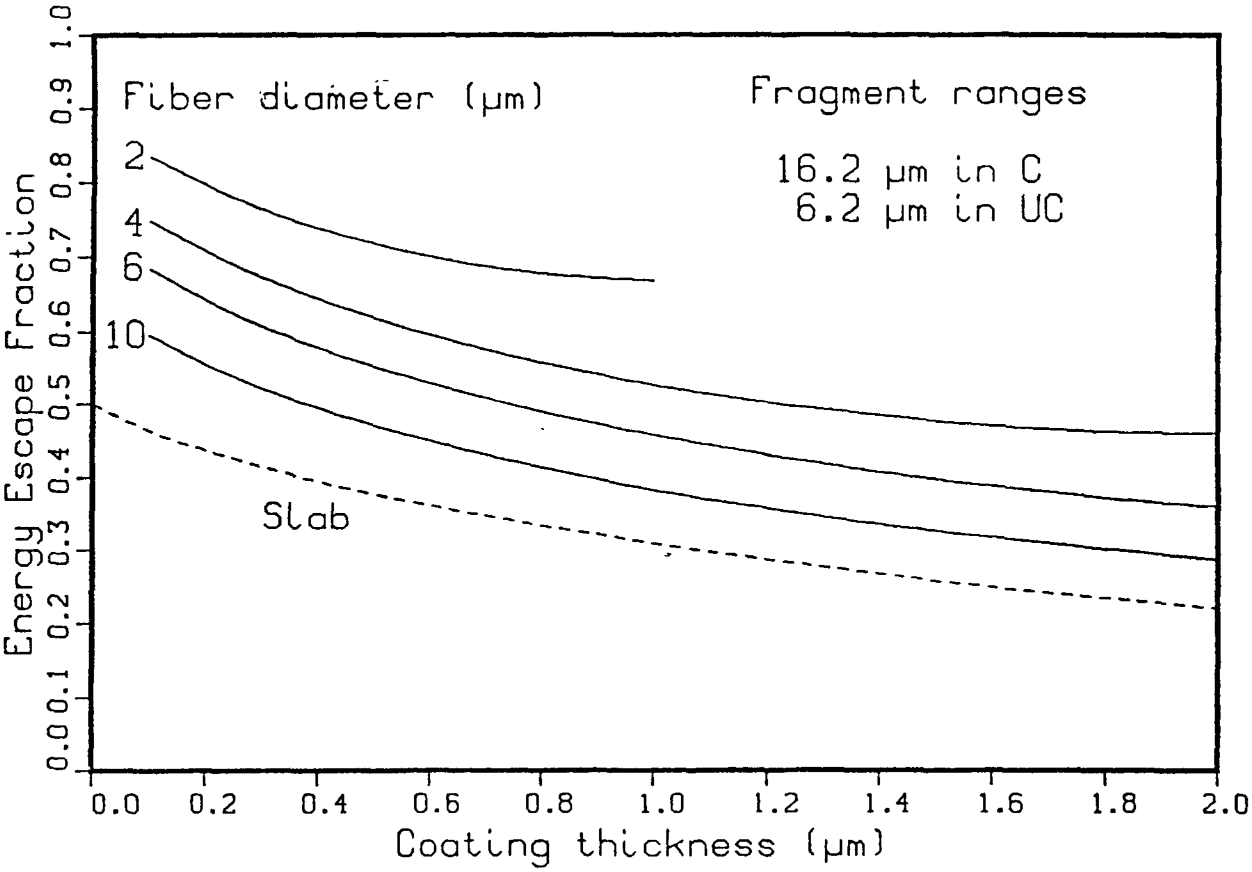

Figure 1. Fission fragment escape probability for uranium carbide coated graphite fibers.

where E is the kinetic energy of the fragment in units of MeV/amu and Z_{eff} is the effective charge. In estimating the effective charge we used a formula given by Srivastava and Mukherji, which corresponds to Bohr's idea that the effective charge is equal to the number of orbital electrons whose velocities are less than the ion velocity v. For the heavy fission fragments $v \simeq .03c$ and $Z_{eff} \simeq 22$. For nascent fission fragments the rigidity is about 0.5 Tesla-meters.

Our notion then for how a fission fragment rocket would work is that the fuel wires would be grouped into thin layers inside the reactor core while current carrying elements just outside the moderator would create magnetic fields between the layers. The magnetic field serves to both insulate the moderator and transport the fission fragments out of the reactor core (Fig. 2). The magnetic field strength must be such that the cyclotron radius is smaller than the distance between fuel layers but larger than the thickness of a fuel layer. The distance between layers of fuel wires will be determined by the escape probability desired and the average density of material inside the core. For example, if an escape probability of 50% is desired and the average density of material in the core is 1.0×10^{-4} gm/cm^3, then the maximum allowable distance between fuel layers will be approximately 10 cm.

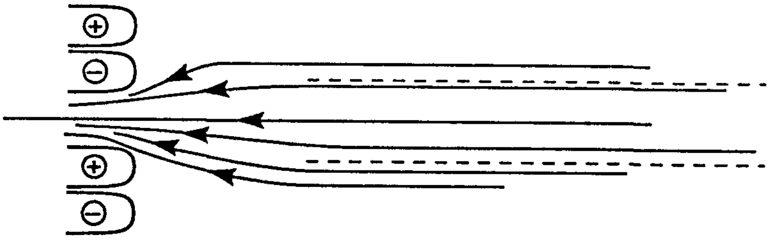

Figure 2. Fuel layers and schematic magnetic field for fission fragment extraction.

REACTOR PHYSICS

It is clear that the best chances for achieving a satisfactory level of performance lie with the utilization of fissile isotopes with the largest fission cross-sections. Because of the tenuous density of fuel in the core, the neutrons will make several passes into and out of the reflector; thus the fission fragment rocket will operate as a thermal reactor. The thermal neutron fission cross-section and neutron multiplicities for some candidate actinides are shown in Table I. Because of their large thermal fission cross-sections and neutron multiplicities the best fuels for a fission fragment rocket are ^{242}Am metastable (^{242*}Am) and ^{245}Cm. However, it should be possible to build a prototype reactor that uses ^{239}Pu or even ^{235}U. In Table II we show the critical mass for these isotopes for a 5-m long by 1-m diameter core surrounded by 3m of D_2O moderator.

TABLE I

CANDIDATE FISSILE FUELS

Material	ν	σ_f	ρ	$\nu\sigma_f\rho$
U^{233}	2.453	497	18.6	23,000
U^{235}	2.398	515	18.7	23,000
Pu^{239}	2.844	725	19.6	40,000
Am^{242m}	3.210	6694	19.9	427,000
Cm^{245}	3.600	1937	13.4	93,000
Cf^{251}	3.870	3168	13.5	165,000

TABLE II

CRITICAL MASS FOR 5-m x 1-m DIAMETER CORE

^{242*}Am	0.5 kg
^{245}Cm	1.1 kg
^{239}Pu	5.6 kg
^{235}U	11. kg

The 500-g critical mass for ^{242*}Am corresponds to a density $\rho = 1.2 \times 10^{-4}$ g/cm^3. If the ^{242*}Am were uniformly dispersed in the core at this density, the range for fission fragments inside the core would be about 18 cm. This means that 60% of the fuel is within a fission fragment range of the edge of the core. By segmenting the fuel into layers and using magnetic fields between the layers (cf. Fig. 2) we hope to achieve extraction efficiencies $\gtrsim$ 50%.

For spacecraft applications it is crucial that the reactor mass be kept as small as possible; therefore there is a strong incentive to use ^{242*}Am or ^{245}Cm as the fuel and to operate with the highest fuel density that is consistent with good fission fragment extraction efficiency. In Table III we show the results of some initial attempts to estimate the amount of moderator-reflector in fission fragments rockets using ^{242*}Am as the reactor fuel. The reactor core was assumed to be a cylinder surrounded by a uniform layer of moderator. Only prompt neutrons were included in the calculation. The fuel (consisting of 1 atomic part ^{242*}Am and 5 atomic parts ^{13}C) was uniformly distributed in the core. λ_{FF}/R is the ratio of the fission fragment range in the uniformly distributed fuel to the fuel radius.

The parameters for these critical assemblies were calculated using ALICE, a Monte-Carlo neutronics code developed at the Lawrence Livermore National Laboratory. The average fuel densities and core diameters were chosen to make it plausible that a fission fragment extraction efficiency of at least 50% is achievable. The moderator-reflector was chosen to be $^{13}CD_2$, which is about as good as D_2O as a moderator-reflector. In practice we have in mind using as a moderator/reflector some organic material such as a deuterated heavy wax. The potential advantage of using an organic material for the moderator is that the equilibrium vapor pressure of such a material may be

TABLE III

MODERATOR REQUIREMENTS FOR ^{242*}Am-FUELED PROMPT CRITICAL CONFIGURATION

Core Dimensions (m)	Fuel Density (mg/cm^3)	λ_{FF}/R	Moderator-Reflector Thickness/Mass (cm)/(metric tons)
10 x 1	0.12	.33	40/18.5
10 x 1	0.10	.40	50/26
10 x 2	0.05	.40	30/27
7 x 1.5	0.05	.53	55/30

much smaller than D_2O. For example, with the use of catalysts one might be able to shift the equilibrium towards non-volatile materials. One will still need a pressure vessel, but our hope is that the pressure will be low enough to be able to use graphite for the pressure bearing walls. To our knowledge graphite is the only structural material which can survive the large neutron fluence during the required operating life. In the case of ^{239}Pu calculations similar to those shown in Table III suggest that the minimum moderator mass will be approximately 100 tons.

The power that can be generated with a fission fragment rocket will be limited by the rate at which waste heat can be radiated away. Indeed, the mass of a spacecraft powered with a conventional reactor will generally be determined by the mass required for heat rejection. Fortunately, fission fragment rockets offer an extraordinary opportunity for heat rejection. The small diameter of the fuel wires means that the fuel has a large surface area, and the fuel itself can be used to radiate away waste heat. If we assume the fuel wires are 3-μm carbon fibers with a 0.4-μm thick coating of americium, then one metric ton of fuel wires will have an area of 2×10^9 cm^2. At a temperature of 1100 K this is sufficient area to radiate away 20 GW! Thus if the fuel wires are dispersed over a sufficiently large area they will radiatively cool themselves. This does not completely eliminate the need for conventional cooling, but one of the unique features of fission fragment rockets is that almost all the energy produced is either carried away by the fission fragments that escape the core or is deposited in the fuel wires.

Another factor that will limit the power that can be generated in a fission fragment rocket is the necessity of keeping the fuel elements in the reactor core from melting. As noted above one metric ton of fuel wires can radiate away 20 GW; however, only a few kilograms of fuel are inside the reactor core at any given time. Therefore, one is faced with the problem of rapidly circulating the fuel wires through the reactor core in order to keep them from melting. One way this might be accomplished is to string the fuel wires on a very large wheel which is rapidly rotating. To get some idea of how rapidly the wheel must rotate let us note that the heat input necessary to take americium up to its melting point (1449 K) is 10.5 kcal/mole or 182 kJ/kg.[2] If we assume that the heat capacity of the fuel wires is approximately 1 MJ/kg, a 2-meter diameter by 10-meter long reactor core in which the average density of fuel wires is 1×10^{-4} gm/cm^3 will have a heat capacity of approximately 3 MJ. The heat loading on the fuel wires inside the reactor core will be 4.5 GW. Thus at a total power of 10 GW and a 50% fission fragment extraction efficiency the fuel wires could spend no more than 10^{-3} s inside the reactor core. This means that the fuel must be circulated through the reactor core with a velocity of at least 1 km/s. If the fuel wires are rotated through the reactor core one must be careful that the centrifugal loading on the fuel wires does not exceed their strength. For example, if the wheel diameter is 200 meters and the wheel rim has a velocity of 1 km/s, then the centrifugal loading on a 3-μm diameter carbon fiber coated with 0.4 μm is americium is 4×10^4 MPa. This loading is a factor 10 less than the tensile strength of the strongest few micron diameter carbon fibers currently available. Therefore there is some room for optimism with respect to being able to operate fission fragment rockets at powers possibly as high as 10 GW. If we assume that the total mass of the fission fragment powered spacecraft is 100 metric tons, then 10 GW corresponds to a power-to-weight ratio of 100 kW/kg!

APPLICATIONS TO SPACE EXPLORATION

To illustrate the extraordinary possibilities opened up by the fission fragment rocket let us consider a mission to the nearest star, Alpha Centauri, 4.1 light-years from the solar system. The mission should start in a sufficiently high orbit so that the fission fragment exhaust will not harm earth satellites. Let us assume that we have an americium fueled rocket and include a device such that the fission fragments that are trapped on the carbon wires, along with the spent wires, are discarded periodically. We also assume a 10-GW reactor operating for about 40 years, the spacecraft coasting thereafter. For a fission fragment escape probability of 50% we can deliver a mass of payload plus structure of fifteen metric tons in 121 years or thirty metric tons in 148 years. If we could increase the escape fraction to 70%, we can deliver ten metric tons in 87 years, twenty metric tons in 101 years, or thirty metric tons in 113 years. Thus an americium-powered fission fragment rocket holds the potential of a less than 150-year mission to the nearest star if the payload and structure mass can be kept sufficiently small.

Of perhaps more immediate interest would be a scientific mission to a 10^3 AU (1 AU = earth-sun distance).[2] If we assume that the fission fragment extraction efficiency is 50% then a Pu fueled 1 GW fission fragment rocket could provide an acceleration on the order of 10^{-4} g for a 100 ton spacecraft. If the reactor operated for 10 years, then one would consume about 5 metric tons of ^{239}Pu and reach 10^3 AU in 20 years. One really exciting objective of such a mission would be to attempt to use the sun as a gravitational lens.[3] At radio wavelengths below 1 cm useful focal lengths for the sun as a gravitational lens lie in the range 550-2000 AU. Using radio receives no more sensitive than have already been developed for interplanetary spacecraft, it should be possible to image planets at a distance of 20 light years with a resolution of 15 km.[3] Needless to say, such a project would attract widespread interest.

Fission fragment rockets may also be useful for solar system missions. In particular, it may be possible to achieve significant reductions in solar system transit times; e.g. a 4 month transit time to Mars. For these missions, though, it would be advantageous to directly convert the fission fragment energy to electricity, which is used to power a more conventional ion propulsion system (e.g. using xenon as the propellant).

CONCLUSION

It should be noted that none of the components of the fission fragment rocket requires a new technology, except for the organic moderator if that is used. Of course, a significant infrastructure development would be required to produce large amounts of ^{242*}Am. However, less stressing missions, such as the TAU mission or rapid interplanetary travel, could be done with a plutonium-fueled, or maybe even a uranium-fueled rocket. Indeed, we believe that with sufficient funding a prototype fission fragment rocket using ^{239}Pu as the fuel could be flown by the end of the century or shortly thereafter.

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