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FISSION FRAGMENT ROCKETS -- A POTENTIAL BREAKTHROUGH

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ABSTRACT

A new reactor concept which has the potential of enabling extremely energetic and ambitious space propulsion missions is described. Fission fragments are directly utilized as the propellant by guiding them out of a very low density core using magnetic fields. The very high fission fragment exhaust velocities yield specific impulses of approximately a million seconds while maintaining respectable thrust levels. Specific impulses of this magnitude allow acceleration of significant payload masses to several percent of the velocity of light and enable a variety of interesting missions, e.g., payloads to the nearest star, Alpha Centauri, in about a hundred years or very rapid solar system transport. The parameters reported in this paper are based on a very preliminary analysis. Considerable trade-off studies will be required to find the optimum system. We hope the optimum system proves to be as attractive as our preliminary analysis indicates, although we must admit that our limited effort is insufficient to guarantee any specific level of performance.

CONCEPT DESCRIPTION

Fission fragment rockets are nuclear reactors configured in such a way that a substantial fraction of the fission fragments can escape from the reactor core and become the propellant. Because the power-to-weight ratio for a fission fragment rocket is potentially very high, fission fragment rockets may be unequaled as power sources for deep space missions. Furthermore because fission fragments have very high specific impulse, a fission fragment propelled spacecraft could attain velocities approaching 10% of speed of light!

Our basic conception for how a fission fragment rocket would work is very simple. 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

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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 Figure 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 special purpose 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 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.[1] Therefore, in order to achieve a 50% extraction efficiency, $\rho\Delta x$ for a fuel layer cannot exceed about 1 mg/cm^2. Even lower densities are required for higher escape fractions.

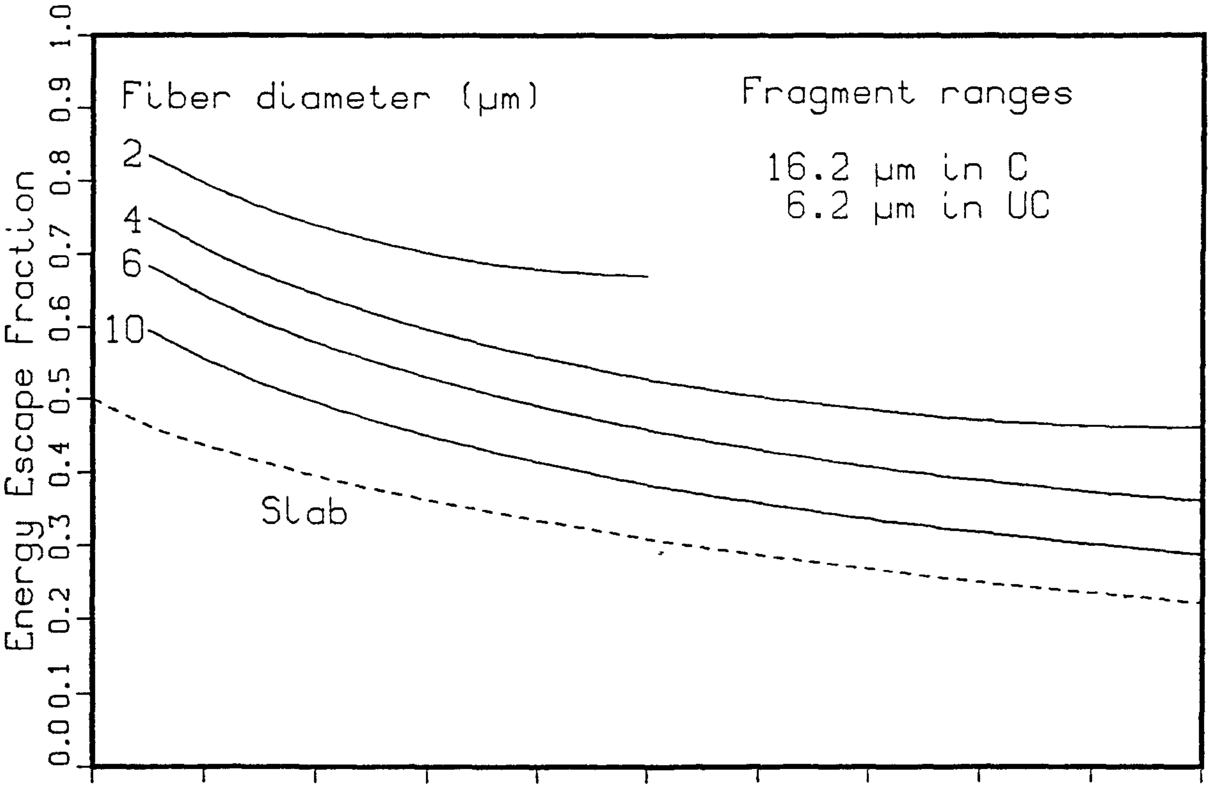

Figure 1. Fission fragment escape probability for uranium carbide coated graphite fibers.

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 are fairly modest in magnitude and are easily generated with currently available technology. To illustrate this last point we note that the magnetic rigidity of nascent fission fragments is about 0.6 Tesla-cm. In general, the magnetic rigidity of fission fragments will be given by

$$Br = \frac{14}{Z_{eff}} E^{-1/2} \text{ Tesla-cm} \qquad (1)$$

where E is the kinetic energy 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,[1] 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 $Z_{eff} \simeq 16$, while for the light fission fragments $v \simeq .05c$ and $Z_{eff} \simeq 22$.

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 inside the moderator would create magnetic fields between the layers (cf. Figure 2). The magnetic field serves to both insulate the moderator and transport the fission fragments out of the reactor core. If the current loop surrounding each fuel layer is in the form of a "baseball seam" then the current loop produces an expanding magnetic fan that carries the fission fragments radially outward and away from the layer of fuel wires. The magnetic field strength must be such that the cyclotron radius is small compared with 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. If the thickness of the fuel layer is 1 cm, then Equation (1) suggests that magnetic field strengths of a few kilogauss would be appropriate in the region between the fuel layers.

The probability for fission fragments to escape from the reactor core can be increased by decreasing the product, $\rho\Delta x$, for each of the layers of fuel wires. This can be accomplished by decreasing the amount of fuel in the reactor core or by decreasing the thickness of the layers. A decrease in the thickness of the fuel layers while keeping the total amount of fuel in the core fixed would have to be accompanied by a

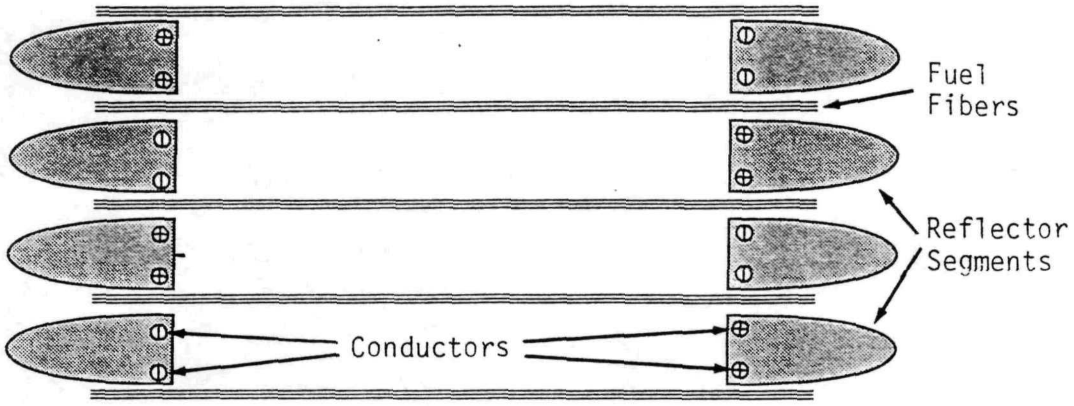

Figure 2. Fission fragment rocket fuel and magnetic field coil configuration.

decrease in the separation between fuel layers and a concomitant increase in the magnetic field strength. A decrease in the fuel density would have to be accommodated in one of three ways, all involving a penalty. Either the amount of moderator-reflector would have to increase, the size of the core would have to increase, or possibly some fuel would be required in the moderator-reflector to "drive" the wire core. Increasing the moderator-reflector adds mass, increasing the size of the reactor wire core makes it more difficult to extract the fission products, and adding fuel to the moderator-reflector requires added mass in the form of a heat rejection system. Thus, it is not clear, a priori, that a satisfactory level of fission fragment extraction can be achieved in a system with sufficiently small mass. Considerable trade-off studies will be required to find the optimum system. The parameters reported in this paper are based on very preliminary analysis. We hope the optimum system proves to be much better than this although we must admit that our limited effort is insufficient to guarantee even this level of performance.

It is clear though 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. 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 I we show the critical mass for these isotopes for a 5-m long by 1-m diameter core surrounded by 3 m of D_2O moderator.

The 500-g critical mass for ^{242*}Am corresponds to a density $\rho = 1.2 \times 10^{-4}$ g/cm³. 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 only 60% of the fuel is within a

TABLE I

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

fission fragment range of the edge of the core and the inward directed fragments would be lost; however, by segmenting the fuel into layers and using electrical conductors to produce magnetic fields between the layers (cf. Figure 2) we hope to achieve acceptable extraction efficiencies.

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 as the fuel and to operate with the highest fuel density that is consistent with good fission fragment extraction efficiency. In Table II we show the results of some initial attempts to estimate the amount of moderator-reflector in fission fragment 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.

TABLE II

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

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

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. The organic moderator could not be CD_2 of course but could conceivably be 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 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. These critical assembly calculations suggest that fission fragment extraction efficiencies of 50% can be achieved with reactor cores whose moderator mass is on the order of 25 metric tons. It is hoped that a significant reduction in this mass can be achieved through our future studies.

Another approach to reducing the fuel density in the core is to place fuel in the "moderator-reflector" to drive the core. In this case the moderator-reflector would be pure carbon. Pure carbon has good high temperature properties, is a good moderator, and can be fabricated into strong lightweight structural elements. We have not yet performed calculations on this approach, but we expect to be able to increase the fission fragment escape probability while decreasing the moderator mass. The disadvantage is that of disposing of the extra heat generated in the moderator. We plan to explore some ideas that may accomplish this heat disposal without needing an excessively massive radiator.

Of course, the power that can be generated with such a reactor 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.

There is direct heating of the moderator in a fission fragment rocket by neutrons and γ-rays; but even if the fission fragment escape probability is as low as 50% this only amounts to about 4% of the total power. If the total power is about 10 GW or less then the cooling of the moderator can probably be accomplished without significantly increasing the mass of the spacecraft beyond that required for the reactor itself. That of course applies to an unfueled moderator. It should be kept in mind though that the need to cool the moderator by conventional means is one of the factors that will limit the power of a fission fragment rocket.

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 average this with the high temperature heat capacity for carbon (1.5 kJ/kg-K) we obtain a heat capacity of 0.7 MJ/kg. However, americium compounds such as $AmNi_2$ may have significantly higher melting temperatures and specific heats than pure americium. We will assume that the heat capacity of the fuel wires can be increased to 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. However, one can always reduce the centrifugal loading to acceptable levels by making the wheel diameter sufficiently large. 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 of 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 as high as 10 GW in the wire core. If we assume that the total mass of the fission fragment powered spacecraft is 10 to 30 metric tons, then 10 GW corresponds to a power-to- weight ratio of 300 to 1000 kW/kg!

Hotel load power is easy to achieve. As noted earlier, a significant amount of heat must flow through the moderator-reflector surrounding the core. A simple thermoelectric conversion system can be placed in the moderator to generate power. The heat flow will be sufficient so that these low efficiency but highly reliable systems will be quite adequate. For the considerably reduced hotel load required for the coast phase, an auxiliary power system can be carried or, if the reflector-moderator contains fuel, the reflector-moderator reactor can produce hotel load power using the same thermoelectric generators.

POTENTIAL PERFORMANCE

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 device would start in a sufficiently high orbit so that the fission fragment exhaust will not return to earth. We assume that we have an americium fueled rocket and include a mechanical concept 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 system coasting thereafter. For a fission fragment escape probability of 50% we can deliver a mass of payload plus structure of six metric tons in 100 years, 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. It is thus easy to see that it is worth an increase in structural mass to increase the escape fraction if the goal is to minimize the transit time of the useful payload. Thus, an americium-powered fission fragment rocket holds the potential of a less than 100-year mission to the nearest star if the payload and structure mass can be kept sufficiently small--somewhat longer mission times are required if the mass is large.

Fortunately, the mission duration is not overly sensitive to a small reduction in reactor power. For a 30-metric ton payload and structure system, a 20% reduction in power would increase the trip time by only about 5%. As the power is reduced below 5 GW, the trip time begins to lengthen rapidly, but obviously, a power level somewhat below 10 GW is acceptable if it is found that the cooling requirements at 10 GW impose too much mass. Of course, the reactor operating time increases proportionately with a decrease in reactor power.

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. In addition, a significant infrastructure development would be required to produce large amounts of ^{242*}Am. Less stressing missions, such as deep but rapid interplanetary travel, would be much easier, of course. Such missions 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. In Figure 3 we show a artist's conception of a prototype fission fragment rocket.

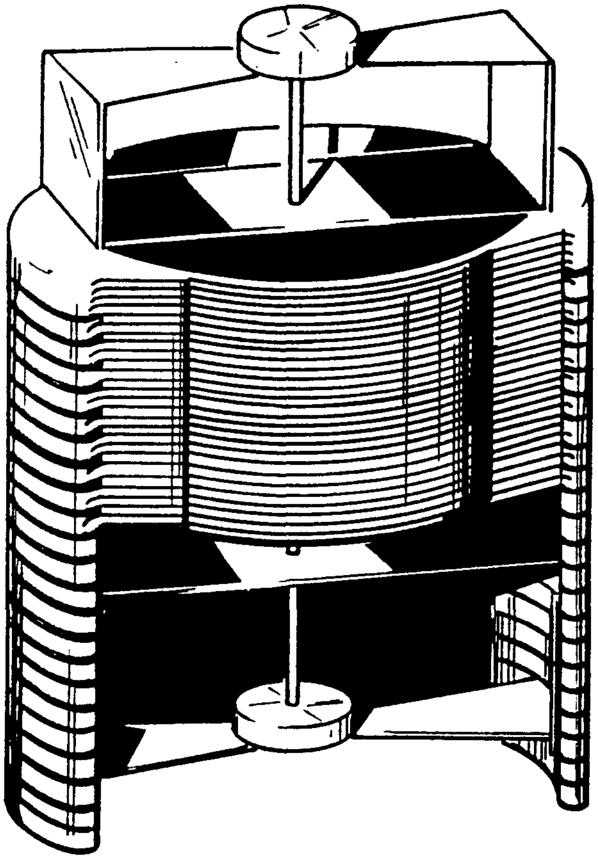

Figure 3. Fission fragment propulsion reactor concept.

FUTURE EFFORT

The effort to develop the concept is just beginning. Trade-offs must be made in determining the size of the reactor cavity, the size and spacing of the fuel, the type and thickness of the moderator, whether or not to include fuel in the moderator to drive the wire core, the magnetic field system, the heat rejection system, and the complex mechanical design to maintain a critical load of fuel in the cavity as the fuel is consumed, and the means to reject spent fuel wires. At the outset it was noted that it is not obvious that the results of the trade-off effort will be successful in developing a concept with a sufficiently short mission time to Alpha Centauri. It is more probable, although not yet proven, that the concept can be developed to provide an improved rocket for interplanetary missions. A modest effort by the Idaho National Engineering Laboratory in collaboration with personnel from the Lawrence Livermore National Laboratory is currently underway to explore the feasibility of the concept. Should this initial effort prove practical--and this initial effort doesn't cover every open question--a further conceptual development effort is planned beginning in FY 1989.

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REFERENCES

1. S. MUKHERJI and B. SRIVATARA, Phys. Rev. B9, 3708 (1974)

2. J. W. WARD et al., in Handbook of the Physics and Chemistry of the Actinides (North-Holland - 1986).