Dusty Plasma Based Fission Fragment Nuclear Reactor

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We propose an innovative nuclear power generation system design using dusty radioactive (fissile or not) material plasma as a fuel. The fission fragments or decay products accelerated during the disintegration process to velocities of 3–5% of the speed of light are trapped and collected in a simple combination of electric and magnetic fields resulting in a highly efficient (90%), non-Carnot, DC power supply. In a conventional nuclear reactor this high kinetic energy of the fission fragments is dissipated by collisions to generate heat, which is converted to electrical power with efficiencies of no more than 50%. Alternatively, the fission fragments produced in our dusty plasma reactor can be used directly for providing thrust. The highly directional fission fragment exhaust can produce a specific impulse of one million seconds resulting in burnout velocities several thousand times those attainable today. Previous concepts suffered from impractical or inadequate methods to cool the fission fuel. In this work the heating problem is overcome by dividing the solid fuel into small dust particles and thereby increasing the surface to volume ratio of the fuel. The small size of the fuel particle allows adequate cooling to occur by the emission of thermal radiation.

I. Introduction

Planning for a mission to Pluto has shown that there is no such thing as a quick trip to the outer planets. Project Prometheus shows the promise of nuclear power in reducing transit times and providing adequate power for instruments. However, further improvements in nuclear propulsion system efficiency beyond nuclear-electric (NEP) are possible. The fission process accelerates the fission fragments to velocities between 3-5% of the speed of light, far faster than the 0.027% achieved by NEP, which uses a conventional nuclear reactor to convert the kinetic energy of the fission fragments into heat, the heat into electricity, and the electricity back into Xe ion kinetic energy with efficiencies much less than 40%. In the fission fragment reactor, the high-speed fragments are used directly as the rocket exhaust after charge neutralization. Therefore the fission fragment rocket can produce a specific impulse (Isp) greater than one million seconds.

Previous concepts[1,2] suffered from impractical or inadequate methods to cool the fission fuel. In this work the heating problem is overcome by dividing the solid fuel into small dust particles and thereby increasing the surface to volume ratio of the fuel. The small size of the fuel particle allows adequate cooling to occur by the emission of thermal radiation.

When an atom fissions, it generally splits into two fragments, a heavy and a light product atom. The heavy fragment typically possesses a kinetic energy approximately 0.5 MeV/amu and the light fragment 1.0MeV/amu, which is a velocity between 3–5% of the speed of light. With uranium fission, typically 81% of the energy released is the form of the kinetic energy of the fission fragments, with the remaining 19% released in the form of beta, gamma and neutrons, for a total of 207 MeV per fission. In a conventional nuclear reactor the high kinetic energy of the fission fragments is dissipated by collisions with other atoms to generate heat, which is extracted to produce energy through the Carnot cycle with efficiencies no more than 50%. In the fission fragment reactor, the high-speed fragments are used to either produce electrical energy

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through direct conversion methods or to produce reaction thrust for propulsion. In direct conversion the kinetic energy of the charged fission fragments is extracted by deceleration in an electrostatic field to directly produce electrical energy bypassing the Carnot thermodynamic cycle. Thus energy conversion efficiencies achievable with direct conversion methods approach 90%. In the case of propulsion, the fission fragments are used as the rocket exhaust after charge neutralization. The usual performance criterion for rocket propulsion is specific impulse (Isp), which is the exhaust velocity divided by 9.8 m/s^2. The fission fragment rocket could produce Isp of 10^6 seconds compared to 350–450 s for chemical rockets or 3000–10000 s for ion engines. As a result, burnout velocities several thousand times those attainable today would be possible.

A fission fragment reactor is a nuclear reactor operating in vacuum in which fission fragments are continuously extracted from the reactor core. A magnetic field is used to collect and collimate the fission fragments into a charged particle beam. The resulting charged particle beam is then available for either direct conversion to electrical power,[3] or, after neutralization, as a source of reaction thrust for a rocket propulsion system. The fission fragment rocket has been proposed previously,[1,2] however those concepts suffered from or impractical or inadequate methods to cool the fission fuel. Figure 1 shows a concept as proposed by George Chapline at LLNL. The nuclear fuel consists of thin carbon filaments coated with fissile material that are attached to a central hub and rotated at high speed. As they pass within the reflector moderator on each side, they form a critical reactor where they fission and generate high-speed fission fragments. The fragments that escape the 2 micrometer-thick fuel coating are collimated by the magnetic field, and are swept from the reactor core to form the rocket exhaust. The deficiency of this concept arises because a percentage of the fragments either fail to escape the fuel layer or recollide with the fuel fibers, which can overheat and melt the fibers. Therefore the fibers must be rotated out of the reactor at high speed where they can radiatively cool down before reentering the reactor.

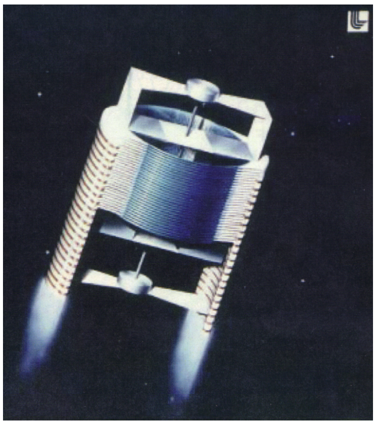

Figure 1. Fission fragment concept as proposed by Dr. George Chapline. The reactor consists of thin carbon filaments coated with nuclear fuel rotated at high speed through the core. Courtesy of LLNL.

II. Feasibility of the Dust Based Fission Fragment Reactor

In our concept of a fission fragment reactor (see Figure 2), the fuel consists of a cloud of nano-particle dust (< 100 nm diameter) composed of fissile material. This configuration of the fuel allows the fission fragments to escape from the fuel particle with a high probability.

In addition, the large surface to volume ratio of the fuel particles enables them to transfer heat effectively by radiation directly into the space environment. The fuel particles and the fission fragments in the core of the reactor form a dusty plasma cloud. The significant difference in both the energy per charge and the mass per charge ratios between the fuel particles (E/q = 10^{-5}eV/q, 10^5 amu/e) and the fission fragments (E/q = 10^3eV/q, 5 amu/e) allows the fissile dust to be electrostatically or magnetically contained within the reactor core while the more energetic fission fragments are extracted for power or thrust. The electrical conversion unit is in the exhaust chamber, which operates on the principle of direct collection of charged particles. The electrons are first separated electromagnetically from the positive ions and allowed to flow to the ground of the electrical system. The stream of positive fission fragment ions, carrying most of the energy, is composed of ions of different energies and is therefore of different electrical potentials. These ions are caught by

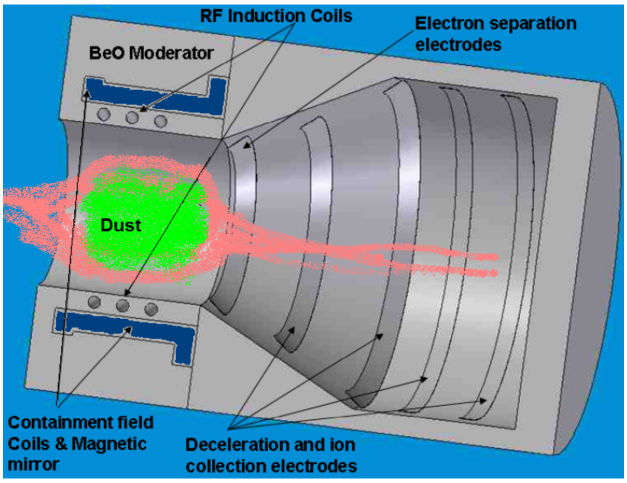

Figure 2. Schematic of proposed Fission Fragment Rocket. Fissile dusty plasma fuel is confined to dust chamber, where RF induction coils heat the plasma. Fission fragments are collimated by the magnetic field either to collection electrodes for power, or exit the reactor for thrust.

a series of electrostatic collectors, each one kept at slightly higher potential than the proceeding one. A common average potential will then be obtained by use of suitable dc voltage multipliers or reducers. The result is a high voltage dc power supply. A power plant of this type is not a heat engine, and therefore is not Carnot-efficiency limited, consequently efficiencies as high as 90% may be possible.[3] Another interesting feature of this system should be noted: by adjusting the strength of the magnetic mirror, the system can be adjusted to produce either high Isp thrust or electrical power or both. In the next section we demonstrate the feasibility of a dust-based fission fragment reactor.

A. Neutronic Analysis

A neutronic analysis has been performed by others using standard codes[4] as summarized in Table 1. The reactor has been shown to be homogeneous from the neutron's point of view, since the mean free path of the neutron is very long in this low density fuel. After a fission generates a neutron, it exits the core and is thermalized in the moderator, entering and reentering the core many times before it is absorbed. For the calculations shown in Table 1, the reactor core is assumed to have a one meter diameter and five meter length. Studies of other geometries, such as thin films,[5] lead to the conclusion that the ratio of fissionable fuel to moderator must be in the range of 1/500 - 1/1000. This result implies a required dust density of 1×10^{-4} g/cm^3. Laboratory RF-discharge dusty plasma chambers currently are producing this dust density.[6]

Table 1. Some critical masses

Fissile Isotope	Cross-section $\sigma\rho\nu$	Mass* kg
Am^{242m}	4.27×10^5	0.5
Cf^{251}	1.65×10^5	$0.9^\dagger$
Cm^{245}	9.34×10^4	1.1
Pu^{239}	4.04×10^4	5.6
U^{235}	2.31×10^4	11.0

* Assuming the fissile material uniformly fills a cylinder core with 1 meter diameter and 5 meter length inside an outer BeO neutron moderator.

† Interpolated from cross-section.

B. Fission Fragment Escape Probability

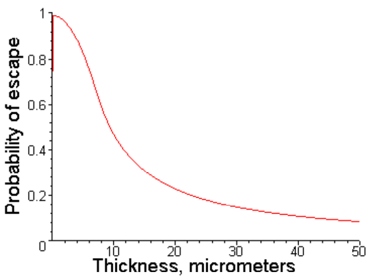

Figure 3. Fission fragment escape probability as a function of fuel particle size.

The fission fragment must escape the dust particle in order to produce thrust rather than heat. The probability for a fission particle to escape a single dust particle has been calculated in the references and by us. As shown in figure 3, the fission fragment escape probability is very high for small fuel dust particles, reaching nearly 100% for submicron particles.

Next the fission fragment must escape the dust cloud and the reactor to either produce reaction thrust or electrical power. This escape probability depends on the fission fragment trajectory. With no magnetic field the fission fragments generally follow straight-line trajectories. In this situation any fragment emitted toward the wall or backward would not escape the reactor. The worst case is for a fission fragment emitted at the center of a homogeneous dust cloud.

For a 40 cm thick cloud of 20 cm radius and density of 1×10^{-4} grams/cm^3, the escape probability is 11.4% without a magnetic field. The blue curve in figure 4b shows the escape probability as a function of emission angle through a homogeneous dust cloud. As expected, only fragments emitted in the direction of the reactor exhaust escape. The situation improves dramatically if a magnetic field is added to guide the fission fragments from the reactor. An axial magnetic field causes the fragments emitted toward the wall to move in circular trajectories and avoid the wall. Also if the magnetic field is stronger at one end it acts as a magnetic mirror reflecting the fragments headed in the wrong direction. Figure 4a shows the curved trajectories of 4 fission fragments as they exit the dust cloud following magnetic field lines. For a 40 cm thick cloud of 20 cm radius,

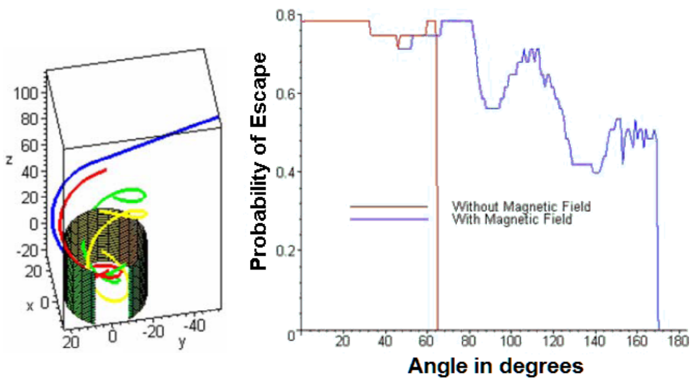

Figure 4. a) Trajectories of fission fragments from dust cloud, which reflect and exit the system. b) Histogram of escape probability for fission fragments as a function of direction and magnetic field.

the escape probability is 65% with a magnetic field. The red curve in figure 4b shows the escape probability as a function of emission angle through a homogeneous dust cloud in an axial magnetic field with a magnetic mirror at one end. As expected, additional fragments are now redirected out the reactor exhaust. So, even a fragment emitted from the center of the dust cloud has a 65% probability of escape. Another interesting feature of this system should be noted: by adjusting the strength of the magnetic mirror the system can be adjusted to produce either thrust or electrical power.

C. Thermal Management

The dust in the reactor becomes hot due to the fact that a small percentage of the fragments are captured in the fuel particles and because some escaped fission fragments recollide with the dust particles. The dust is able to cool itself by emitting IR radiation. Figure 5 shows a calculation of the equilibrium fuel temperature as a function of dust particle size and a table of the melting point for several nuclear fuel candidates. Unlike the carbon fiber fuel system, of the earlier version of the fission fragment reactor, which must be rotated out of the reactor core in order to keep the fibers from melting, the small size of the fuel dust particles in our conception of the fission fragment reactor can remain sufficiently cool to remain within the reactor without melting.

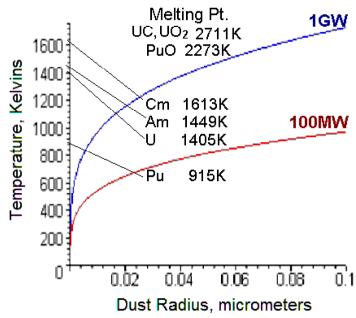

Figure 5. Equilibrium fuel particle temperature as a function of particle size.

D. Magnet Field Extraction of Fission Fragments Exhaust

The next issue is to consider how the fission fragments can be extracted from the dust cloud and diverted out the rocket exhaust. This can be done with a magnetic field, which bends the fission fragments according to the formula $B\rho = 14.A\sqrt{E}/Z_{\rm eff}$ in Tesla-meters. Table 2 shows the magnetic field strength necessary to confine heavy and light fission fragments and alpha particles. Field strengths between 0.33 and 0.63 Tesla-meters are required, which can be achieved with current magnet technology.

Table 2. Rigidity of various fission fragments.

Fission Fragment	Atomic weight	MeV / amu	Charge q	amu/ q	Speed c	Tesla-meters
Heavy	140	0.5	22	5.9	0.03	0.63
Light	95	1	22	4.3	0.05	0.60
Alpha*	4	1.42	2	0.5	0.05	0.33
Dust	10^8	10^{-15}	-100	-10^6	10^{-9}	0.001

* Alpha particle from Thorium decay.

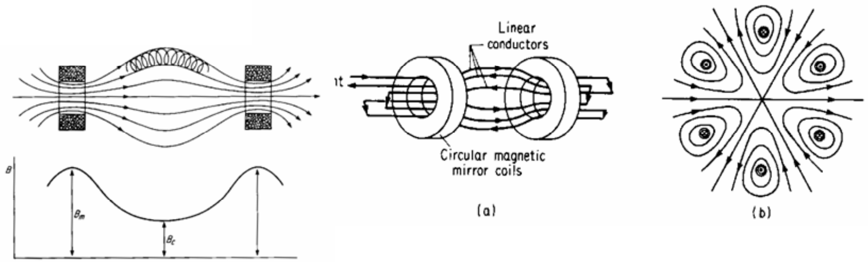

Figure 6. Magnetic confinement of fission fragments in a magnetic mirror. Stronger field on one end reflects fragments, weaker field on nozzle transmits particles. Wall fields are strengthened by multipole fields such as this hexapole current arrangement.

Several magnetic field configurations are possible, the simplest being a magnetic mirror concept as shown in figure 6a. The field strength requirement for a simple coil can be reduced, however, by supplementing with multiple current loops around the perimeter such as the hexapole shown in figure 6b, which can reduce the individual coil strength required by 300%. For cold-start applications such as space propulsion, this can also be implemented with a combination of permanent magnets and coils.

The confinement of positive ions by a multipole magnet is demonstrated by the following experiment.[7] A nickel-plated Neodymium-Iron-Boron magnet with surface field approaching 1 T aligned parallel to the cylinder axis was biased to -400V in a 100mTorr atmosphere to produce a dc glow plasma discharge. Electrons emitted from the magnet ionized air molecules, and the resulting low energy positive ions were then trapped in the strong magnetic field. Two trapping populations were discovered, an outer quasi-dipolar trapping region encircling the ring, and an inner, high-density trap inside the ring. Both the magnetic mirror force, and the geometry of the field lines prevent the positive ion plasma from impacting on the negatively charged magnet, demonstrating confinement of positive ions by multipole magnetic bottle geometry.

E. Charging of Dust Grains

The fuel particles and the fission fragments in the core of the reactor form a dusty plasma cloud. The small size of the grains allows the fission fragments to escape the fuel grains with high probability. The dust charge is a function of many factors: dust particle size, number of +22-charged fission fragments leaving dust, secondary electron production, and fission fragment collisions with dust.[8] The equilibrium charge on the dust can be computed.[9] We have computed the charge on fissioning dust using a computer code to calculate the equilibrium. We found that the large positive charge (+22) carried off by the fission fragments causes the fuel grains to acquire a high negative charge, which allows for the electrostatic containment of the fuel particles.

Figure 7. Magnetic quadrupole confinement of ion plasma.

F. Separation between Dust and Fission Fragments

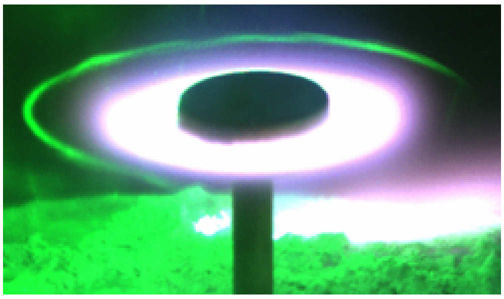

Figure 8. Magnetically confined dusty plasma cloud.

Discrimination between the confined dust and the collimated fission fragments is made possible by the vast disparity between mass to charge ratio and velocity. Table 2, shows a comparison between the mass to charge ratio for the fission fragments, alpha particles, and the fuel dust particles. Although the rigidity of the dust appears providentially small, suggesting magnetic confinement, the magnetic force exerted on the dust is insignificant compared to either collisions or electric forces, so that the dust is not significantly affected by the magnetic field. The electric fields that confine the dust are a product of externally applied fields and internal plasma equilibrium as described by dusty plasma physics.[6] This plasma equilibrium is determined by the density of negative dust, positive ions, electrons, and the plasma currents, which will probably require experimentation to determine. The MeV fission fragments, however, will not be constrained by the weak dusty plasma electric fields, but will be collimated by the magnetic field. Therefore large difference in E/q for fission fragments and dust, means that the dust can be electrostatically confined while the fission fragments remain magnetically collimated.

Figure 8 shows an example of a dusty plasma with electrostatically confined the dust and magnetically constrained plasma. The purple glow is a dc glow discharge plasma generated in a 150 mTorr atmosphere by applying -400V to a nickel-plated, 1cm diameter Neodymium-Iron-Boron magnet. The 3 micrometer SiO_2 dust grains in a tray below the magnet are negatively charged by arc discharge, levitate in a ring around the magnet, and are illuminated with a 532nm green laser. With fissile dust, the charging occurs naturally without the need for an arc discharge.

III. High Efficiency Isotope Batteries

All of the above technology can be applied to Earth based power plants. In this application, thrust is unnecessary, so both ends of the reactor core could be designed to extract power. As Chapline noted before, the extraction of fission fragment power permits the isotopic separation of fission fragments, and therefore the convenient separation of more active radioisotopes from less active ones.

However, when one calculates the energy density per unit mass, one must include the mass of the required neutron moderator. Since this is several tons, this technology scales up nicely, but not down. On the other hand, alpha-emitting radioisotopes do not need a moderator, and therefore can be made as small as is practical. Nor do they emit any radioactive fission fragments, so are inherently safe. Given these properties, they are often compared to battery power, but with a higher energy density. Since space applications are often mass-limited and may not always have sufficient solar power, nuclear batteries are aa an important a technology as fission fragment rockets.

Since heat is not an issue with these nuclear battery designs, one can replace the alpha-emitting dust with coated filaments, and use magnetic fields to extract the alpha particles. Such a battery would test many aspects of the reactor design without involving fissile materials.

IV. Fission Fragment Rocket Specifications

Since fission fragments have a 2cm penetration depth in air at 1 Atm, the fission fragment rocket can only operate at low ambient pressure, outside the atmosphere. Therefore we model a deep space unmanned probe to estimate its capabilities. Although many details of the system remain unspecified, several important conclusions can be reached with simple arguments.

In order to maintain the low density core needed to extract the fission fragments while also containing a critical mass of fissile dust, the reactor vessel must of necessity be large, with 1 meter diameter by 10 meter long cylinder favored by Chapline. The moderator thickness needed based on neutronic analyses for BeO, suggests a 30–50 cm blanket around this cylinder. Simply by these volume constraints, the moderator weighs 10-20 metric tons. To mitigate these problems, we suggest the use of LiH as a moderator, which estimate to be at least 1/4 the molar mass of BeO. We have not performed a neutronic analysis for LiH in this configuration, but its neutronic properties have been measured,[10] and found to be favorable: a density less than that of water 775kg/m^3, a stabilizing negative thermal coefficient for scattering neutrons, and a melting point of 688C. Scaling Chapline's moderator mass by 0.25 therefore, resulted in a 6 ton moderator, to which we added 2 tons for radiators and liquid metal cooling, 1 ton for magnets, power recovery, and coils, for a dry weight of 9 tons. Supposing an engineering and scientific payload of another ton, gives us an order-of-magnitude estimate of a 10 ton spacecraft. Such a spacecraft, we note, could be carried into orbit with existing space shuttle capabilities.

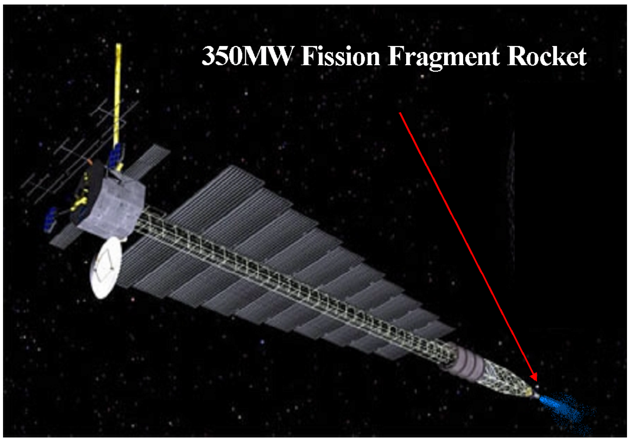

Figure 9. Artist's conception of a deep space mission powered by fission fragment rocket. Courtesy of NASA.

Then we use the rocket equation, based on the high exhaust velocity of the fission fragments, to estimate the fuel fraction of various missions by the required delta-V. The delta-V of a mission was calculated using the assumption of a single stage rocket that accelerates half the distance and then deaccelerates half the distance for a total specified time duration. For example, a 10 year trip to the gravitational lens point 550AU distant from the sun, would take a delta-V of about 2% the speed of light. We assumed that the fission fragments had an exhaust velocity of 0.05 c (Isp=1.5 million), to obtain a fuel fraction 3% that of the rocket. We then added the mass of the fuel to the mass of the rocket to get the total mass, and multiplied by the acceleration implied by the mission profile to get the thrust required. This thrust had to be provided by fission fragments, which gave us the power level of the reactor, assuming some 46% of the fragments provided thrust. From these considerations we could estimate the power required by the fission fragment rocket to enable various missions.

A 10 year mission to the 550AU gravitational lens point would require only 180kg of nuclear fuel, and a 350MW reactor power, well within the calculated thermal limit of 1GW. A 30 year trip to the Oort cloud at 0.5 Ly is more strenuous, requiring a 5.6 GW reactor. And a 50 year trip to Alpha Centauri, 4 Ly distant, is probably not feasible, requiring a 208 GW reactor, and consuming 240 tons of fission fuel.

A. Space Radiation Hazards

Since the thrust of a fission fragment rocket is radioactive nucleides, it would be prudent to estimate the environmental impact of launching such a space probe. From the mission profiles above, we can calculate the mass burn rate of the reactor and therefore the amount of nuclear ash. Because the fission fragments are highly charged, they are trapped by the magnetic field of the Earth until the rocket is outside the Earth's magnetosphere, or about 10 Earth radii. Given the acceleration of the rocket and its mass burn rate, we can calculate the number of moles of radioactive material that are injected in the magnetosphere, and we estimate that some fraction of them diffuse into the Earth's atmosphere. The 350 MW mission burns 720 g of Uranium inside the magnetosphere, whereas the 5 GW mission burns 3.7 kg of Uranium before passing into interplanetary space.

The short halflife isotopes generally decay into stable isotopes before entering the troposphere, whereas the very long halflife isotopes pose no threat of radioactivity. Accordingly we rank the top contributors by mole fraction and by Curie level. One difference is that some minor constituents have medium to short halflives, so their contribution to the Earth environment depends critically on the diffusion rate from the magnetosphere. We calculate two models, one with an unusually fast diffusion observed on space weather "stormy" days, and one with a more typical diffusion rate. In this calculation we use 2.3 kg of Uranium-235 (or Plutonium-239) as a typical burn. As can be seen, the worst offenders for Earth contamination are the 30-yr halflife isotopes of Strontium-90 and Cesium-137. Even then, the amounts reaching the Earth should be compared to the ∼300 Curies of Carbon-14 produced every year by cosmic rays.

Table 3. Earth contamination from 2.3kg Uranium

Ranked by moles			Ranked by Curies		
Isotope	Moles	Curies	Isotope	Fast Diff.	Slow Diff.
Nd 144	0.05	0.01nCu	Cs 137	3600Cu	3600Cu
Rb 87	0.1	1μCu	Sr 90	1800Cu	1800Cu
Sr 90	0.2	1800Cu	Pm 147*	2300Cu	930Cu
Cs 135	0.3	4mCu	Ce 144	1900Cu	770Cu
Cs 137	0.3	3600Cu	Ru 108*	204Cu	110Cu

* From Plutonium 239 fission.

V. Conclusion

In conclusion, fission fragment reactors have several substantial benefits over other reactor designs including higher electrical efficiency and higher specific impulse thrust. Previous designs had difficulties with keeping the reactor core cool, which we propose to overcome by using dusty plasma fuel. Several space missions are enabled by this technology, and we estimate that the environmental impact of such missions is negligible.

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