Dusty Plasma Based Fission Fragment Nuclear Rocket

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ABSTRACT

Building on previous work,[1] we present a dusty plasma fission fragment rocket (DPFFR) for a manned mission to Callisto. The design effort revealed tradeoffs on the length of the mission, the mass of the moderator, the shielding of the magnets, and the thrust of the engine that led to substantial constraints. With a system engineered rocket concept, we confirm that the physics and engineering of a multi-gigawatt nuclear reactor/rocket for interplanetary missions is entirely possible with technologies that we currently possess. The design does not include nuclear fusion, antimatter propulsion, ultra-high temperature materials or super-emissive radiators, but every component, excluding the dusty plasma alone, is itself a high-TRL (technology readiness level) unit. Since the design depends upon the mission duration, we optimize our simulation codes for acceleration, rather than thrust or efficiency. We conclude that a high-power reactor is a more significant factor to shorter mission times than a higher efficiency or thrust, because the fission fragments are an insignificant contributer to total thrust, which must also include an Isp-to-thrust converter. Then the most critical component of a successful rocket design is the power-to-mass ratio of the nuclear engine. Since dusty plasma fission fragment reactor is capable of multi-gigawatt power levels for a mass less than 300 tons, the DPFFR is sufficiently robust to accommodate all mission constraints.

I. INTRODUCTION

All previous analyses of interplanetary manned missions have concluded that only nuclear fuel provides the energy to mass, or energy density necessary for the lengthy trip. That is, due to the exponential dependence in the rocket equation, the delta-v needed for a short duration trip also necessitates engines with Isp greater than 1000 seconds, which is not possible with chemical fuels.

The two most developed nuclear propulsion concepts have been nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP). In both methods, the nuclear engine is a compact, self-contained unit that simply produces energy, while the thrust is developed from an external, expendable gas source.

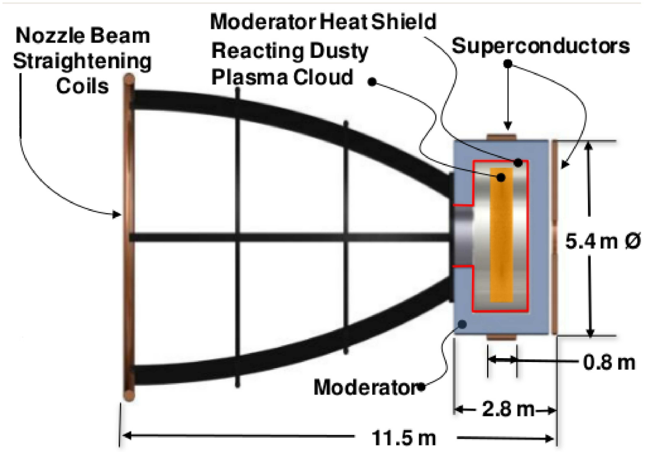
In the case of NTP, the gas is hydrogen, which flows through the nuclear reactor, cooling it, and providing 900-1000 seconds of Isp thrust. The efficiency of NTP is directly proportional to the Isp which is directly proportional to the temperature of the nuclear reactor. The disadvantages of NTP are related to the difficulty of running the reactor at extremely high temperatures (greater than 2000K) for extended periods of time, and simultaneously storing hydrogen at low temperatures (less than 40K) for extended periods of time.

In the case of NEP, the propulsion gas is generally xenon, which is ionized and accelerated through high-voltage grids, both of which are energized by the nuclear reactor. The efficiency of NEP is directly related to the efficiency of converting nuclear to electric power. The disadvantage of NEP is that electrical conversion efficiencies are low, causing most of the nuclear power to be dumped as unusable heat, so that the thrust obtained is miniscule compared to the mass of the system. Higher thrust per megawatt-thermal is only possible at higher electrical conversion efficiency, which presently is proportional to the temperature-dependent Carnot efficiency.

In practice, both concepts are limited by the need to run the nuclear reactor at the highest temperature before the nuclear fuel or fuel elements begin to melt or disintegrate. If the reactors could be run at higher temperature, then the NTP would achieve higher Isp, and the NEP would achieve higher electrical power for a fixed mass. Therefore it might be argued that all previous nuclear propulsion techniques suffer from inadequate methods to cool the fission fuel while running at higher temperature.

This makes the accomplishments of the DPFFR all the more significant, because it not only provides the necessary nuclear power source for interplanetary travel, but it also solves the cooling problem of operating a reactor in space. A generic 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.[2] The resulting charged particle beam is then available for either direct conversion to electrical power,[3] or, after neutralization and conversion of Isp to thrust (afterburner), as a source of thrust for rocket propulsion.[1]

In our dusty plasma design of a fission fragment reactor (see Figure 1), the fissile fuel consists of a cloud of nanoparticle dust (< 100 nm diameter) magnetically confined to a reaction chamber, which nonetheless allows the fission fragments to escape from the chamber while keeping the neutrons sufficiently dense to achieve criticality. The fuel particles and the fission fragments form a dusty plasma, but 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 ($E/q = 10^{3}$eV/q, 5 amu/e) al-



Master Equip List Mass incl 30% MGA	
FFRE System Total, mT	113.4
Nozzle	6.4
Magnetic Mirror	28.6
Exit Field Coil	11.1
Moderator	51.2
Moderator Heat Shield	0.1
Control Drum System	0.7
Electrostatic Collector	0.3
Dust Injector	7.2
Shadow Shield	7.8

Distribution	(MW)
Total Reactor Power	*1,000*
Neutrons (30% to FFRE)	24.2
Gammas (5% to FFRE)	95.6
Other	70.2
Thermal (IR)	699
Jet Power	**111**

Performance	
Thrust	43 N (9.7 lbf)
Exit Velocity	5170 km/s
Specific Impulse	527,000 s
Mass Flow	0.008 gm/s

Fig. 1. Schematic of proposed Fission Fragment Rocket. Fissile dusty plasma fuel is confined to dust chamber by electrostatic fields. Fission fragments are reflected and collimated by the magnetic field, exiting the exhaust port to produce thrust.

lows 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 large surface-cooling to volumetric-heating ratio of the fuel particles enables them to radiate heat effectively to the polished carbon-carbon mirrors with 95% reflectivity that direct the infra-red radiation (IR) out to space, or as needed, into the power/thrust conversion modules. At these sub-micron fuel particle sizes, the emission rate is high enough to cool a 1 GW reactor, which enables the 50-70% of the reactor power that unavoidably goes into heating the fuel elements to be shed from the reactor as IR. There will still be heating of the engine from the neutrons and gamma rays emitted by the fissioning fuel, but this is expected to be no more than 19% of the total reactor power, so that for the same amount of radiators as NEP, the DPFFR can tolerate five times higher power levels. This is the first, and most important reason that DPFFR can exceed the megawatt level of NEP or the gigawatt level of NTP nuclear reactors.

The second reason that DPFFR can achieve better performance than NTP or NEP, is that the nuclear energy is extracted non-thermally and therefore with higher efficiency than either NEP or NTR. As described above, the reactors in both NEP and NTP are run at high temperature with subsequent Carnot efficiency of the working fluid, whether it be the ∼1000K HeXe gas for a Brayton-cycle or ∼2500K hydrogen gas for propulsion. In contrast, the DPFFR magnetically extracts the fission fragments (FF) non-thermally, admittedly with some unavoidable friction as the FF collide with other dust grains on their way out of the reactor. We can treat this partial thermalization as if the FF are composed of two populations: one that heats the dust when it is "stopped" inside a dust grain; and one that escapes the dusty plasma cloud with reduced energy. When comparing the original FF energy to that which is emitted, we derive the 50-70% figure for the energy that is "lost" to friction, and is ultimately emitted as IR. The remaining 30-50% of the FF energy is kinetic energy at a velocity corresponding to 500,000 seconds of Isp, where the precise amount depends strongly on geometry and magnetic strength of the reactor design. Since the thermal energy of 2800K fuel is only about 1000 seconds of Isp, this 500,000 second FF thrust is highly non-thermal, or conversely if thermalized, would correspond to millions of degrees. Since the Carnot efficiency is ($T_{initial}$ - T_{final})/$T_{initial}$, the conversion of this million degree component of nuclear power into electricity or into thrust can occur at greater than 90% efficiency. Since this efficiency is far better than the 40% or 20% conversion efficiency of NTP and NEP, the DPFFR has another factor of two or three improvement in performance in thrust per megawatt of nuclear power.

There are other refinements to DPFFR that may add a few more percent improvement over NTP or NEP, such as the direct conversion of FF to electrical energy using the "venetian blind" charging of high-voltage capacitors, or the direct conversion of FF to thrust through Coulomb collisions in a dense gas, rather then through enormous electric fields on a singly-ionized, low-density plasma. All these refinements, however, are more a matter of practical engineering of less significance than the order-of-magnitude improvement due to the first two considerations, which completely determine whether DPFFR is a viable alternative to the more developed NTP and NEP. That is to say, this paper will mention but not discuss the technology of direct conversion of FF to electricity, or the direct conversion of FF to thrust, not because it is unimportant, but because it is a small refinement to the more fundamental question of whether a space nuclear reactor can be run at high power without melting down. Therefore this paper will focus on the power, mass, and acceleration constraints on the nuclear reactor of a DPFFR model mission to Callisto.

II. OVERVIEW OF DPFFR

The concept of a DPFFR was explained in our earlier paper,[1] which we quickly review here. As discussed in the introduction, the division of the fissile fuel into sub-micron particles and their suspension as a dusty plasma permits them to simultaneously cool themselves radiatively, and emit fission fragments into the vacuum. An ambient magnetic field both confines the dusty plasma through field-aligned potentials of a few volts, as well as direct the FF toward the exhaust port.

Since the levitation of milligram quantities of dusty plasma has been accomplished in the laboratory in a 1g gravitational field, there is no concern that the acceleration of 0.1g or less will detrap the dust. On the other hand, all dusty plasma research to date has been performed on non-radioactive dust, and it remains an open question whether the charge state of fissile dust inside an operating reactor will perform similarly. For example, a simple calculation of the current carried by departing positively charged fission fragments reveals that electromagnetic stresses will be an important part of the dusty plasma equilibrium, requiring some active control over the electron return currents from the walls. And of course, there are the unavoidable engineering difficulties of scaling up the dust suspension from milligrams to tens of kilograms with the accompanying collective plasma instabilities. All these related problems of radioactive dusty plasmas will have to await both better experimentation and better theory, but we are confident that no laws of physics prevent the eventual success of such a project. Therefore in the models that we develop here, we ignore all details of the microphysics of dusty plasmas, and treat it as simply a static, low-density neutral fluid threaded by the magnetic field through which the FF travel.

While details of the dusty plasma equilibrium are beyond the scope of this paper, we are able to calculate the dynamics of the FF, the photons, and the neutrons emitted by the fissile dust. That is to say, we assume a static distribution for the dusty plasma, but we calculate the dynamic equilibrium for all the other components of the nuclear reactor needed to integrate it into a complete rocket system. We break this down into five overlapping pieces: the neutronics, the magnetics, the thermal management, the thrust, and the optimization procedure.

III. NEUTRONIC ANALYSIS

In our previous work, we indicated that several nuclear fuels had significant advantages for reduced critical mass such as Am^{242m} and Cf^{251}. Practically, however, the most abundant fissile materials are based on U^{235} and Pu^{239}, and accordingly our designs used these two materials. We used state-of-the-art software, MCNPX, to determine the "k-effective", k_{eff} of the design, where the fissile fuel was modelled as a low-density fluid suspended in a vacuum that was enclosed by a moderator. Several of the neutron models included the magnetic coils and the carbon-carbon reflecting heat shields, but from a neutronics perspective, these were not as important as the design of the much larger moderator. As it turned out, the various DPFFR designs were nearly indifferent to which nuclear fuel was used, since maintaining sufficient neutron density was the

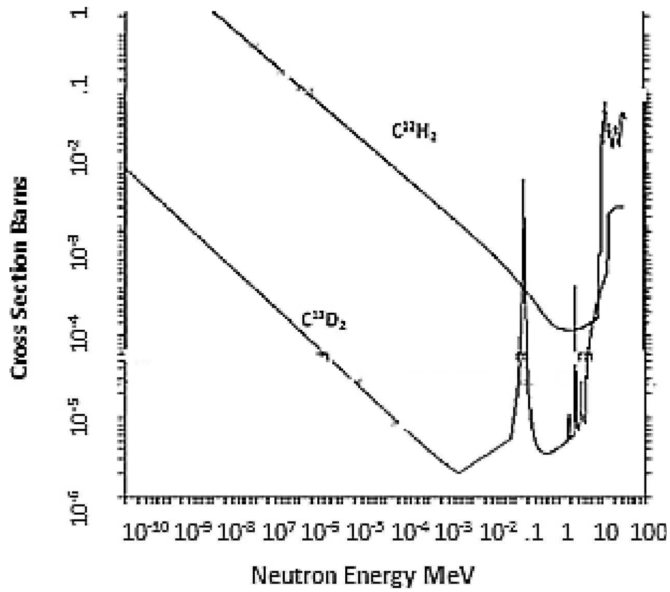


Fig. 2. Neutron absorption cross sections for polyethylene as a function of energy for normal and heavy isotopes of carbon and hydrogen.

greatest hurdle in the design rather than the details of thermal neutron cross-sections. Two factors turned out to be important in achieving a $k_{eff} > 1$: using an advanced moderator material such as deuterated C-13 polyethylene; and minimizing the effective aperature of the exhaust port.

Advanced moderators were necessary because the density of the fuel was so low that the probability of a neutron capture in one transit through the reactor core was much less than one. Therefore each neutron had to make many such transits, which is the characteristic of a "re-entrant" nuclear design. Many moderator materials that are effective in solid-core reactors have a neutron absorption cross-section that is too high for a re-entrant design, so we had to carefully choose moderators with low absorption cross sections, as we illustrate in Figure 2. We found that Beryllium, Carbon-13 and Deuterium all had sufficiently low absorption cross-sections, but sufficiently high scattering cross-sections to provide effective reflection/moderation.

The re-entrant design of the reactor also makes the exhaust port of the reactor effectively a neutron absorber whose area had to be minimized. But if the port was made smaller, the percentage of FF fragments that escape was also smaller, converting more of their energy into the heating of the dust. Initially we thought we could resolve these conflicting requirements by "bunching" the magnetic field lines to direct them through a smaller exhaust port, as illustrated in Figure 1. While this certainly allowed some FF to escape that would otherwise be trapped, the increase in magnetic field strength due to the bunching acted as a magnetic mirror that reflected as many FF back in as it additionally directed out. The net benefit of this solution was negative, so we searched for other

TABLE I. Rigidity of various fission fragments.

Fission Frag.	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.

solutions.

Bending the magnetic flux through a sharp corner without increasing its field strength could direct the FF through the exhaust port while neutrons remained trapped, but the extra volume required a greater mass of moderator as well. So while we did find solutions that achieved $k_{eff} > 1$, it was at the cost of increasing the DPFFR engine mass. This necessitated an optimization code that we will discuss in the last section, but for the Callisto mission analysis that preceded that optimization, we made the contradictory assumption that the original "pancake" design of Figure 1 could have a large exhaust port for FF, but a small exhaust port for neutrons. As it turned out, the optimized DPFFR with consistent exhaust ports achieved the same acceleration as the original design despite the increased moderator mass, so that nearly all the details of the mission–excepting the number of launches to assemble in orbit–remained the same.

IV. MAGNETIC ANALYSIS

The FF are directed by the magnetic field from their origin in a fuel grain to the exit port where they are neutralized and possibly converted from high-Isp low-thrust to low-Isp high-thrust plasma. The magnetic field is critical in keeping the FF fragments from colliding with the walls of the reactor chamber, where they would otherwise heat and erode the carbon-carbon heat shield and destroy the chamber. Since the FF have approximately 2 MeV/nucleon energies, this means that the magnetic field must be strong enough that the vacuum gap between the fuel and heat shield is greater than a gyroradius. Table I shows the magnetic field strength necessary to confine heavy and light fission fragments and alpha particles, where clearly it is the heavy fragments that determine the necessary magnetic field strength.

Complicating this analysis, is that the gyroradius also depends upon charge, and as the FF gyrate around the magnetic field line, they lose energy to the dusty plasma cloud and lower their charge state accordingly. We used several semi-empirical theories to estimate both the energy loss and the equilibrium charge state for FF and discovered that the energy and charge state conspire so that the gyroradius is nearly a constant as the FF plow through the dust cloud. Having removed this dependence, we treat the gap between the fuel cloud and the heat shield as a simple function of the magnetic field strength. As the field strength is increased, the vacuum gap is decreased, and the volume of moderator is reduced, and the mass is also reduced. However, the increase in magnetic field strength requires more magnet volume and higher current densities, which also increase the mass of the power supplies and the cooling system for the magnets. In addition, when the magnetic field strength exceeds about 0.5 Tesla, standard copper electromagnets must be replaced with superconducting magnets and a low-temperature cryogenic cooler added.

In our original "pancake" design (see Figure 1), the magnetic field was "capped" at one end with a mirror field, so as to provide a single exhaust port for the FF. In this design, the magnetic mirror necessitated a greater than 0.5 T field strength and superconducting magnets. Later designs made the reactor chamber "double-ended", which removed the need for a magnetic mirror, but we kept the requirement for superconducting magnets on the assumption that this was an enabling technology. Accordingly, we modeled the magnets as a High-Tc (T_c ~140K) material with a cryogenic cooler, using a commercial software package, BiotSavart, to calculate the magnetic field from proscribed current loops. Magnet mass and volume constraints were determined from empirical fits to both the ITER accelerator and to superconducting power-grid conditioners presently in use. The magnetic field was used to trace FF trajectories using an ODE solver, and the resulting thrust calculated. By wrapping the magnet coils with 1 meter thick moderator, a mass model for the entire engine could be determined, and the thrust converted to acceleration. This acceleration became the optimization goal of a software package that modified the shape of the conductors and currents of the conductors. We discovered that if the mass penalty for larger magnetic fields was too small, the optimization code would shrink the vacuum gap between the fuel and heat shield by increasing the magnetic field until we reached the material limits of the superconductors.

This suggests that the magnetic field strength is not the critical element of the design, since there is no abrupt transition at some specific value, but rather the incremental improvement depends on overall geometry considerations. If so, then we can also reduce the magnetic field requirements to below 0.5 T and thereby enable the use of conventional electromagnets, albeit at larger diameter due to the larger gyroradii. The greater mass of the reactor with conventional magnets is offset by the elimination of the cryogenic cooler and associated low-temperature radiators. Since these two items largely compensate each other, it would seem that the extra risk of superconducting magnets would only be necessary if there are specific advantages to high-magnetic field systems in addition to the ones we have in our model. Nevertheless, the rough mass equivalence of these two approaches means that the mission profiles will be identical, and in what follows, we have modeled the use of superconducting magnets.

V. THERMAL MANAGEMENT

As we discussed in our previous paper, the dust in the reactor becomes hot, not because it is emitting FF, but because FF are constantly colliding and passing through the dust, which we refer to as "friction". This frictional heating is a function of the geometry and magnetic field of the dust cloud, and can be as little as 20%, or as much as 100% of the FF power. Whatever the power load into the dust, the cooling mechanism remains the same–thermal emission to the walls of the reactor chamber. The walls remain cooler than the dust both because they are polished so as to reflect IR into the exhaust port, and because they are threaded with a high-temperature (roughly 1000K) NaK cooling system. If they are highly polished, then the dust particles "see" the walls as essentially space at 3K, so radiative thermal equilibrium is never achieved, which is to say, the dust can radiate at the full rate of $A\sigma T^4$. Since the dust is many hundreds of degrees hotter than the walls, the power radiated from the dust to the walls is much greater than from the walls to the dust, and we can set the dust radiative output power equal to the FF heating of the dust.

The FF power intercepted by any one fuel grain is proportional to its volume, while the thermal power radiated is proportional to its surface area. Therefore the equilibrium temperature of any fuel grain is a strong function of the size, r. Solving for the maximum nuclear power we can tolerate in a 40% efficient DPFFR, we set,

$$P_{grain} = P_{tot} \times \%\text{friction}/N = \sigma A_{grain} T^4 = 4\sigma\pi r^2 T^4 \quad (1)$$

where P is the power, A is the area, T is the temperature, σ is the Stefan-Boltzmann constant, and N is the number of dust grains. Since the number of grains is fixed by the critical mass, M, for $k_{eff} > 1$, we can solve for N given the density D,

$$N = M/(4/3\pi r^3 D) \quad (2)$$

Combining equations then give us,

$$P_{tot}\% f(4/3\pi r^3)D/M = 4\sigma\pi r^2 T^4 \quad (3)$$
$$P_{tot} = 3M\sigma T^4/(rD\% f) \quad (4)$$

Using the melting point of Uranium mononitride (UN) at 3080K for T, 15kg for M, 14,300 kg/m^3 for D, 60% for friction, and 1000nm for r, we get 26 GW as the maximum reactor power before the fuel particles began to melt. Even if they do melt, the Coulomb repulsion between the charged droplets would keep them from coalescing so the reactor would convert from a "dusty plasma" to a "foggy plasma". The physics of foggy plasmas is not well explored, though it is expected that the charge state on the droplets will be less than that on the dust (due to enhanced thermal electron emission) and that the properties will smoothly interpolate from the melting point to the boiling point. This changing charge state will have to be compensated by the electrostatic confining charge as is done

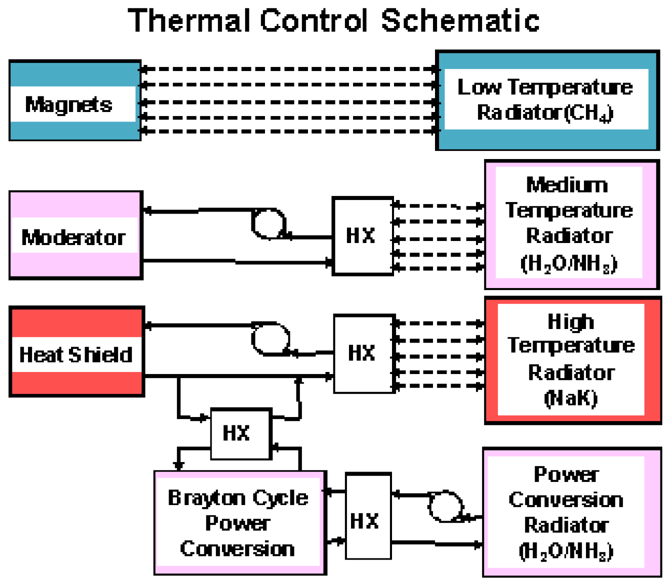


Fig. 3. Details of the three thermal radiators.

for the dust, but nothing in the phase transition suggests an abrupt or positive feedback instability.

While data on the boiling point of Uranium nitride is lacking, Uranium dicarbide has a boiling point of 4500K, which suggests that a foggy plasma reactor will be stable over a considerable range above the melting point. Plugging in 3800K as a potentially stable foggy UN plasma gives 62 GW maximum power. This suggests that even if the friction were to rise to 100% and no FF exit the DPFFR so that the entire output of the DPFFR were emitted as IR, there would be no danger of a boiloff, for then the DPFFR becomes a GW model of an M-type star.

Should the fuel begin to boil, or at least, start to convert to a gas, the equilibrium charge state of the gas at 4000K is mostly neutral, and the gas would no longer be magnetically or electrically confined to the center of the chamber. The resulting expansion of the gas cloud (and loss through the exhaust port) would decrease the neutron cross-section, and shut down the nuclear reaction. Therefore the foggy plasma reactor has a built-in negative feedback that under normal circumstances cannot lead to nuclear runaway.

More restrictive than the need to keep the fuel from boiling, is the need to handle the heat load from neutrons and gammas that penetrate the carbon-carbon heat shield and deposit their energy in the moderator and gamma shielding. While the heat shield will provide a small amount of gamma and neutron shielding, its primary purpose is to reflect IR, so we assume the full 19% of non-FF energy is absorbed by the engine. There will be a small amount lost to the exhaust port, but once again, this cannot be a large number or else the $k_{eff} < 1$.

Since the re-entrant nuclear design must use thermal neutrons, our advanced moderator must include hydrogen or deuterium, and must not contain any elements with large neutron absorption cross-sections. This very limited palette of isotopes can be combined into various molecular compounds, but all of them have the disadvantage that they bind hydrogen rather weakly. As a consequence, the moderator must be kept below 550K lest the materials dissociate and the hydrogen diffuse away. This temperature requirement requires active cooling of the moderator, which we refer to as the medium-temperature radiator, see Figure 3. Note that the Prometheus NEP mission used a fast-neutron reactor so as to dispense with both moderator weight and moderator radiators, which is not possible for our re-entrant reactor.[4]

Therefore the thermal management for the DPFFR must include a high-temperature radiator scaled to handle 19% of the full power of the system, which in our design below, is over-engineered to a 1GW heat load, corresponding to the non-FF power of 5 GW reactor.

VI. FISSION FRAGMENT THRUST

The DPFFR provides thrust by directing FF out the exhaust at ~2% of light speed, $5{\times}10^6$ m/s, which when divided by constant g, the acceleration due to gravity at the Earth's surface, gives 500,000 seconds of Isp. In principle, the large amount of energy emitted as heat or IR could also be harvested for thrust, in much the same manner as a NTR heats a gas and directs it through a Laval nozzle to generate thrust. At lowered efficiency, the heat or IR could be converted to electricity, and the gas could be electrically accelerated as is done in NEP. These alternative methods of converting nuclear energy to thrust remain viable options for the DPFFR as well, with the added twist of having megawatts of IR radiation available as an ionization or heat source for the gas.

The focus of this paper, however, is to explore the properties of the FF themselves for potential thrust, since FF alone can provide the enormous Isp needed for truly distant missions. That is, optimizing a mission profile for the minimum travel time finds an optimal Isp for a selected target mission, dependent on the payload and rocket combination.[5] Applying these criteria to our DPFFR show that the optimal Isp for Mars is on the order of ten thousand seconds, which roughly doubles for Jupiter and higher for Pluto or the gravitational lens point at 550 AU. Since down-converting high-Isp/low-thrust to low-Isp/high-thrust is trivial compared to the much harder problem of up-converting Isp, this paper will focus on the thrust of pure FF. For if we can design a pure FF thrust, we gain not only the ability to explore the distant solar system, but through Isp conversion, missions to all the nearer objects as well.

The amount of thrust generated at high Isp is roughly,

$$P_{FF} = 1/2(dm/dt)v^2 \quad (5)$$

$$\text{Thrust} = d(mv)/dt = v(dm/dt) = 2P_{FF}/(gI_{sp}) \quad (6)$$

Then if we have a 2.5 GW reactor producing 1 GW of FF power at 500,000 Isp, we are generating all of 400 Newtons of thrust, or barely enough to escape the Earth's gravity well. It is the realities of this high-Isp, low-thrust DPFFR that cause the mission to Callisto to require 16 years.

TABLE II. Concept DPFFR Mission to Callisto.

Attribute Comparison	HOPE	DPFFR
Payload Mass (Crew+Science)	60	60
Total Mass (mTonne)	890	296
Dry Mass (mTonne)	460	303
Total Radiator (m^2)	3498	6076
Continuous Power (MW)	34	1000
Thrust (lb-f)	126	10
Specific Impulse (s)	8000	527,000
Acceleration (milli-g)	0.063	0.016
Outbound Trip (days)	833	2665
Return Trip (days)	693	2854
Total Duration (years)	4.5	16

This is not a fatal flaw, however, for if additional gas is introduced into the FF exhaust, Coulomb collisions with the neutral gas are sufficient to both accelerate and ionize it. Conserving momentum, we have $mV = Mv$, so a 100-fold reduction in FF velocity, V, corresponds to a 100-fold increase in mass loading, M, and a 99% inelastic heating of this additional gas. Using our previous formula for the thrust, we now have the same input energy but at 1/100 the Isp, resulting in 40 kN of thrust at Isp=5000 seconds, which for a DPFFR of 300 metric tonnes dry, has an acceleration of 0.13 m/s^2 or about $g/75$. While the thrust is greatly increased by mass-loading the FF, the wet mass of the rocket is increased by this addition of this inert material, and therefore we search for an optimal value for the Isp, choosing the minimum travel time as our optimization criterion. In order to calculate the travel time for such a rocket, we simplify the trajectory calculation by assuming that half the trip is acceleration and half is deceleration. Then given a distance to Mars of ~140Gm and depending on the dry mass of the engine, we find an Isp~10,000 seconds for a duration T~50 days is optimal.

This additional thrust is achievable without the complication of high voltage grids whose finite lifetime limits the thrust of NEP. Additionally, the DPFFR has a smoothly adjustable Isp, making a single engine capable of optimization for multiple destinations. While the design of this "afterburner" is beyond the scope of this paper, its promise of a flexible interplanetary transport system justifies the the further development of the DPFFR and motivates our system engineering design below.

VII. OPTIMIZATION OF DPFFR

The optimization code involved drawing up a moderator design in MCNPX that achieved $k_{eff} > 1$. The magnetic field coils were then modelled with BiotSavart and adjustable currents. The dust was modelled as a low density fluid confined to a cylindrical shell. The thickness of the shell or height of

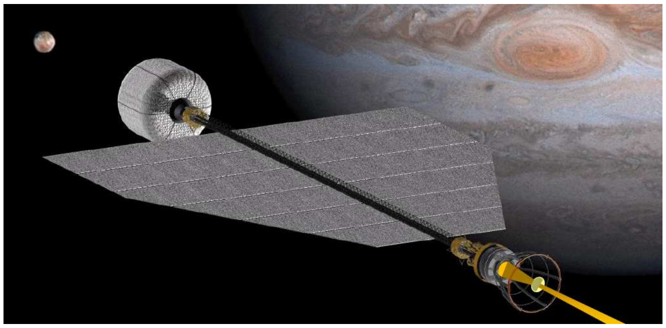


Fig. 4. Artist's conception of a deep space mission powered by fission fragment rocket.

the cylinder was one of the fit parameters. The volume was divided into equal volume bins, and FF were traced from each bin at different energies and pitch angles. At each step of the relativistic ODE particle tracer, the energy loss to the dusty fluid was calculated using semi-empirical energy loss formula, the particle energy adjusted accordingly, and a new equilibrium charge state calculated. When the particle lost all its energy, or had exited the engine, the next particle was traced. If any of the FF struck the walls of the engine, we reran the run at higher magnetic field to avoid this failure mode. Statistics on the fate of ten thousand FF particles was calculated for each run, giving a statistical error of $\sqrt(n)/n < 1\%$.

The fit parameters were then adjusted, modifying the magnetic field strength or thickness of the dust cloud. If the geometry of the dust cloud changed, the moderator was assumed to adjust as well. In early runs, the efficiency of extracting FF power was optimized, though this led to very large magnetic field strengths. In later runs, a mass model of the magnets, moderator and necessary radiators was used to put limits on the magnetic field strength, and the acceleration of the DPFFR was optimized. Solutions of the optimizer were run through MCNPX to make sure that the neutronics remained essentially unchanged. While this approach was able to optimize slight changes to the geometry such as changing aspect ratio, the different geometry models required separate runs of the optimizer.

VIII. CONCLUSIONS

As we discussed in our earlier paper, the DPFFR must be operated in a vacuum, and to prevent radioactive contamination of the Earth's atmosphere, (which as discussed earlier is very minimal), it must be operated outside the Earth's magnetosphere. In addition, the low thrust of the engine suggests that the launch point should be out of the Earth's gravity well. We therefore assume that the spacecraft is assembled or serviced in orbit so that conventional rockets deliver the components to a dock at the L2 Lagrange point. We then model a deep space probe launching from a dock at L2, a 6 month rendezvous with Callisto, and returning to its dock at L2. This mission was also studied for a conceptual NEP rocket called "HOPE",[6, 7] and to demonstrate the significance of the DPFFR, we construct a table comparing the two missions.

While the engine performance of the HOPE mission is optimistic, the principal difference between the two missions lies in the acceleration, which is a direct consequence of the low thrust of the DPFFR. As we discussed earlier, this is easily remedied with an afterburner that converts excess Isp into thrust. While this is the topic of current research, the preliminary calculations above show that tuning the Isp to the mission will allow the DPFFR to outperform the HOPE mission without making any great changes to the system engineering.

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