THE DUSTY PLASMA FISSION FRAGMENT ROCKET ENGINE: DESIGN CONSTRAINTS AND PERFORMANCE. Robert B. Sheldon[1] and Rodney L. Clark[2], [1]Grassmere Dynamics, LLC (513 Bain Dr., Huntsville AL 35803-1174, rbs@rbsp.info), [2]Grassmere Dynamics, LLC (774 Bob Stiles Rd, Gurley, AL, 35748, USA, rod.clark@grassmeredynamics.com).

Introduction: The Dusty Plasma Fission Fragment Rocket Engine DPFFRE,[1],[2] is a promising solution to the difficulty of using the highest energy density fuel in the vacuum of space, where ordinary planetary reactors would overheat and melt. Surprisingly, the limits on space nuclear propulsion are not feasibility or safety related, but thermal. The importance of thermal limits can be seen in the two main contenders for space nuclear propulsion.

Nuclear Thermal Propulsion. NTP keeps the nuclear reactor cool by carrying a coolant, which doubles as a propellant. Because the nuclear fuel must be kept from melting, the propellant can only heat to about 2800K, the melting point of most ceramic fuels, providing about 800 seconds of thrust. While this doubles the efficiency of chemical LH/LOX engines, it still does not tap the full potential of a nuclear fuel with a million times greater energy density. Practically, NTP can easily reach the Moon, but Mars remains an expensive destination.

Nuclear Electric Propulsion. NEP uses the nuclear fuel as an electric power source, which drives an electric propulsion system involving ions or plasmas. The efficiency of the system is determined by the conversion efficiency of the heat-to-electricity segment, (typically a Brayton cycle) where the ideal thermodynamic Carnot efficiency is determined by the difference between the input and output temperatures. The lower the output temperature, the better the efficiency, but also the larger the radiator, so typically performance is optimized by raising the input temperature to the melting point of the reactor again. Practically, NEP is capable of high ISP but at low thrust, which raises the travel time and unfortunately, also the heat-induced damage to the power plant, a consequence which stymied the unmanned Prometheus mission to Jupiter.

It is safe to say that any technology that raises the Carnot efficiency or the operating temperature of a space nuclear reactor will directly improve both NTP and NEP, with the practical benefit of making manned Mars missions or unmanned Jupiter missions feasible. Therefore the DPFFRE is not a competitor to NEP or NTP, but an enabling technology to solve the materials problem of high temperature nuclear reactions.

Solving the heat problem. When a fissile nuclear fuel fissions, the nuclear fragments are stopped by as little as ten microns of fuel. But if the fuel is divided into micron-sized dust, the fission fragments can escape without heating the fuel. So the first step in solving the temperature problem is to avoid heating the fuel, which we achieve with a dusty plasma of submicron sized fuel grains. The charge on each dust grain—a dusty plasma—prevents dust grains from coalescing into larger units. An electric field manipulates this neutral dust cloud with modest voltages of a few tens of volts, while a magnetic field directs the much more energetic fission fragments to a “power converter”, where they can either heat hydrogen, as in NTP, or deposit electricity, as in NEP. Some heat is still generated in the dusty fuel, which is also bathed in the neutron and gamma ray environment of a reactor, but fortunately the large surface to volume ratio of the dust permits it to radiate this heat away as infrared radiation (IR), where the dust acts as its own space radiator. Balancing the input and output energy budget shows that a DPFFRE can operate at 10's to 100's GWth without exceeding the melting point of the same ceramic fuel, as discussed earlier [1][2]. In this paper we discuss the limitations imposed by the energy conversion from fission fragments to thrust or electricity.

Fission Fragment Jet Energy: In previous work we used a “pancake” design for the dusty fuel, where the magnetic field was perpendicular to the surface of the pancake-shaped dust cloud. This permitted the fission fragments (FF) to escape the dust without additional encounters with other dust grains, and therefore keep over 90% of their formation energy. We used MCNPX to design a critical reactor by retaining and thermalizing the neutrons in a 1-meter thick deuterated, C-13 hydrocarbon moderator shell. Because the fuel has such low density, the reactor is neutronically reentrant, requiring many transits of a thermal neutron before a fission is initiated. This means the moderator must have a very low neutron capture cross section, which we achieved with Beryllium, Carbon-13 and Deuterium compounds. These compounds lose their hydrogen at about 550K, which turns out to be a more stringent temperature limitation than the melting point of the fuel!

Unfortunately, a geometry that kept the neutrons in did not allow the FF out. Our initial pancake design used a magnetic bottle to funnel the FF through a small opening, but at the cost of reflecting most of the FF back into the reactor. After attempting an iterative optimization with higher multipole magnetic fields, we confirmed what particle beam physicists have known for decades—there's no static solution to the problem of increasing the phase space density of charged particles. Getting most of the FF out of the reactor could not be achieved by sending them through a small hole. Since neutrons move in straight lines, however, we could send the FF around a corner, and found that a torus-shaped reactor permitted critical densities of neutrons while extracting all the FF.

This design, however, replaces the pancake cloud with a long cylinder of dust, and now the dust had to be kept below some critical density to permit FF to escape. Since the neutronics is proportional to mass (volume * density), one needed only to increase the volume to achieve the lower density. As it turned out, the small but finite neutron capture cross section of the moderator foiled this scaling, so that more and more critical mass was needed at larger scale sizes, raising the dust density while the FF path length increased. This meant that the DPPFRE had an optimal size for extracting maximum FF energy, or conversely, most of the FF energy went into heating the dusty fuel no matter what scalesize was used. For U235, this resulted in about 3% FF energy extraction, whereas for Pu239 it went up to about 5% FF energy extraction.

This modest success in changing fuel caused us to look for the most fissile fuel available—Am242m. With about ten times larger fission cross section as compared to Pu239, we could use about ten times less dust, achieve ten times lower densities, and extract about 50% of the FF energy. Availability of this fuel is unknown, since much of the data is classified, although stockpiles of its mother nucleide are in the tens of tons. Fortunately, a manned mission to Mars is calculated to use up only about a ton of the fuel [3], which we estimate at current production rates to permit about one mission per year.

Fission Fragment Thrust Conversion: If 1GWe of FF is generated by our DPFFRE at a staggeringly high ISP of 500,000 seconds, the maximum thrust is only 110N, of which we achieve about 55N for our design. While this makes the DPFFRE ideal for missions to the nearest star, it fails utterly as a planetary mission, not even able to escape the Moon as it slowly spirals its way out of Earth orbit! And while there is no fuel limitation to increasing the reactor power to 10GWe or possibly even 100GWe, the moderator would overheat, as well as magnets and other components exposed to the gamma/neutron environment.

We need a way to convert the FF energy into thrust, and the most direct method is to heat hydrogen as NTP does. The difference with NTP, is that the "temperature" of the FF is not a 2800K surface, but a million degree plasma. Therefore much higher hydrogen temperatures are possible, and in fact, controlled simply by changing the hydrogen mass flow into a fixed jet power FF exhaust, where we used tokamak neutral beam heating codes to model the heating of hydrogen by a FF beam.

With this control over the final ISP of the rocket, we could optimize the mission by changing any two of three variables: reactor power, hydrogen mass flow, or ISP. As Werka and Percy describe[3], the optimum for a manned mission to Mars was found at an ISP=32,000 seconds.

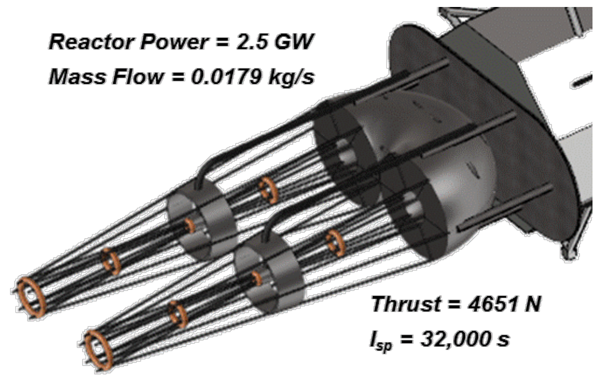

Fig 1. Torus-shaped reactor vessel with dual FF exhaust into hydrogen filled magnetic nozzles controlled by beryllium solenoids in a carbon-fiber support.

While we did not do a systems engineering study on the NEP approach to unmanned missions, the design smoothly extrapolates from NTP to NEP as the ISP rises. This is because at the highest ISP, the hydrogen cannot be heated simply by collisions with the FF, but must be electrically controlled in a magnetic nozzle using plasma properties of ionized hydrogen, which becomes nearly indistinguishable from a VASIMIR style NEP.

Conclusions: The DPFFRE is a high-performance space nuclear reactor that can be coupled to either a NTP or a NEP style thrust converter to transform the low-thrust, high-ISP Fission Fragment plasma into an effective space propulsion system. Systems studies have been conducted on an NTP-like converter for a manned mission to Mars, which conclude that a 70 day trip time and a 120 ton payload is achievable, but many other space missions and configurations are possible that will benefit from this game-changing technology.

References:

[1] Clark, R. L. and Sheldon, R. B. (2005) *AIAA JPC*, 2005-4460. [2] Clark, R. L., Sheldon, R. B., and Werka, R. O., (2013) *NETS2013*, 2014-6790. [3] Werka, R. O. and Percy, T. (2014) *NETS2014*, 2014-####.