A Six Component Model for Dusty Plasma Nuclear Fission Fragment Propulsion

Rodney L. Clark[1], Robert B. Sheldon[1,2]

[1]Grassmere Dynamics, LLC, Gurley, AL 35748-8909 256-776-9471 rod.clark@grassmeredynamics.com
[1,2]RB Sheldon Consulting, Huntsville, AL 35803 256-6538592; rbs@rbsp.info

Abstract. A dusty plasma nuclear fission fragment rocket employs a cloud of nanometer-sized dust of fissionable material inside a magnetized moderator from which the fission fragments emerge to form the high velocity exhaust. The negatively charged dust, free electrons, and positively charged ions form a 3-component "dusty plasma" that can be confined and manipulated as charged fluid. The fission fragments exit the ~100nm dust with velocities approaching 5% the speed of light, giving this rocket an ISP~500,000 seconds, as discussed in previous papers. Despite 1-10 GW power densities, this ultra-high ISP results in very little thrust, which is only ideal for a starship drive. The thrust can be increased by expanding the size of the dusty plasma core, however, collisions with the dust lower the ISP to ~70,000s and the dust begins to vaporize. In this paper we explicitly backfill the dusty plasma with neutral hydrogen gas to provide a mass-loading of the fission fragment exhaust that increases the thrust, making a variable-ISP rocket. The neutral gas also heats and transfers thermal energy to the dust, which must be accounted for in this design. We model this novel rocket with a six-component dusty plasma, finding the temperature equilibrium between fissile dust, hydrogen gas, free electrons, free protons, fission fragments, and photons. For certain operating regimes, the dusty plasma rocket is competitive with nuclear thermal rockets, but by throttling the hydrogen, can transition to a fuel saving high-ISP engine for interplanetary missions. We considered the possibility of using the fission fragments to heat a deuterium-tritium gas mixture to fusion temperatures, but several hurdles must be overcome for this fission-fusion concept to work.

Keywords: Fission fragment nuclear rocket, dusty plasma, thermal equilibrium, variable ISP

THE FISSION FRAGMENT DUST REACTOR

This study examined in some detail the properties of a fission reactor consisting of a dusty plasma consisting of fissionable dust grains embedded in a hydrogen plasma. Such a reactor has been proposed as a source of heated hydrogen propellant in a high Specific Impulse (ISP) rocket engine and as a possible high temperature thermal reactor. The advantage of such concepts arises from the singular properties of dusty plasmas which have been studied extensively in astrophysics. In particular the large surface area of a cloud of fine grain dust particles allows for efficient radiative cooling to the reactor walls which in turn allows the reactor to operate at very high temperatures approaching the melting point of the dust grains.

As shown conceptually in FIGURE 1, this study examines a fission reactor consisting of a plasma mixture containing fissionable uranium dust, fission fragments, electrons and hydrogen.

The entire mixture is contained by a magnetic field and surrounded by a neutron moderating material. When the reactor becomes critical, fissionable dust particles begin to emit the fission fragments. The high speed fission fragments interact with and heat the dust and hydrogen gas in the mixture. The fuel of fine dust grains becomes charged as a result of emission of positive charged fission fragments and collisions with electrons and hydrogen ions, which forms a dusty plasma that can be confined and manipulated with external electrostatic fields. Some of the fission heated hydrogen plasma may be extracted forming a rocket exhaust, or the plasma may be entirely confined to produce power. The primary power output from the Dusty Plasma Fission Fragment Reactor (DPFFR) is copious qualities of Infrared Radiation (IR) incident on the reactor wall. This power is extracted from the reactor through wall cooling loop. The Brayton Cycle could be used to produce electrical power. The criticality of a DPFFR dust reactor has been previous shown using industry standard tools (MCNP) [1].

FIGURE 1 Schematic of Dusty Plasma Fission Fragment Reactor Concept

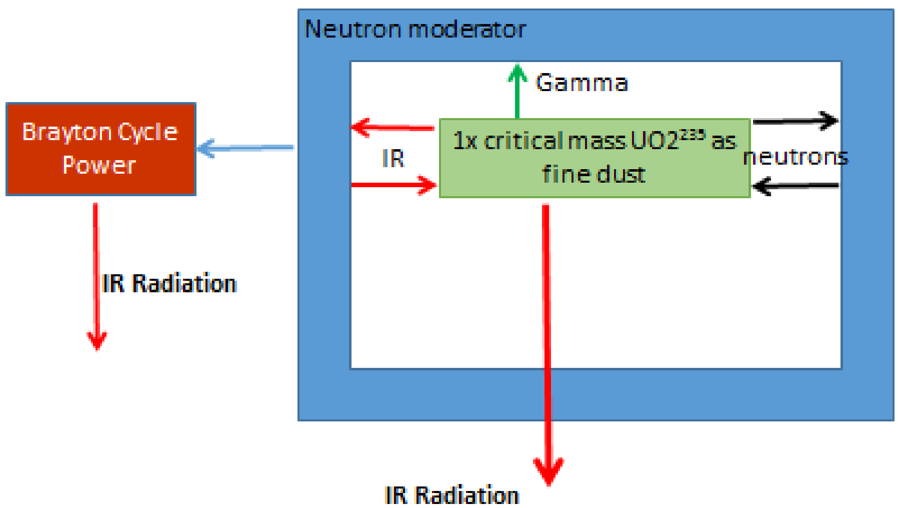


FIGURE 2 presents the results of a criticality study using MCNP computer code on two different reactor geometries, a right circular cylinder and a compact spherical torus shape. The results show the required density of dust grains of three fissionable fuels versus the major radius of the resulting reactor. These results can be used to size the reactor. As the DPFFR operates at very low hydrogen pressure there is effectively minimal structural loads on the reactor vessel other than to support its own weight and that of the moderator and wall cooling system.

A simulation of the conditions inside a DPFFR must also consider the effectiveness with which the fission fragments that escape the small dust grains transfer their kinetic energy to other dust grains and to the hydrogen electron plasma. This is the subject of this study.

The reservoir plasma generation

To investigate the heating of hydrogen dust mixture by fission fragments several computer models were used. The SRIM (plot label Tr) and GEANT4 (label G4) [2], were used to compute the energy deposited by the fission fragments into the fissionable dust, where SRIM is more accurate at low energies, and GEANT4 at high energies. FIGURE 3 shows the rate of energy deposition into a Uranium-235 dust cloud vs. the fission fragment range. Different colors correspond to different dust densities. Higher dust densities result in shorter ranges.

FIGURE 2 Critical Density versus Radius for a Cylindrical Reactor for Cylinder & Torus Geometries

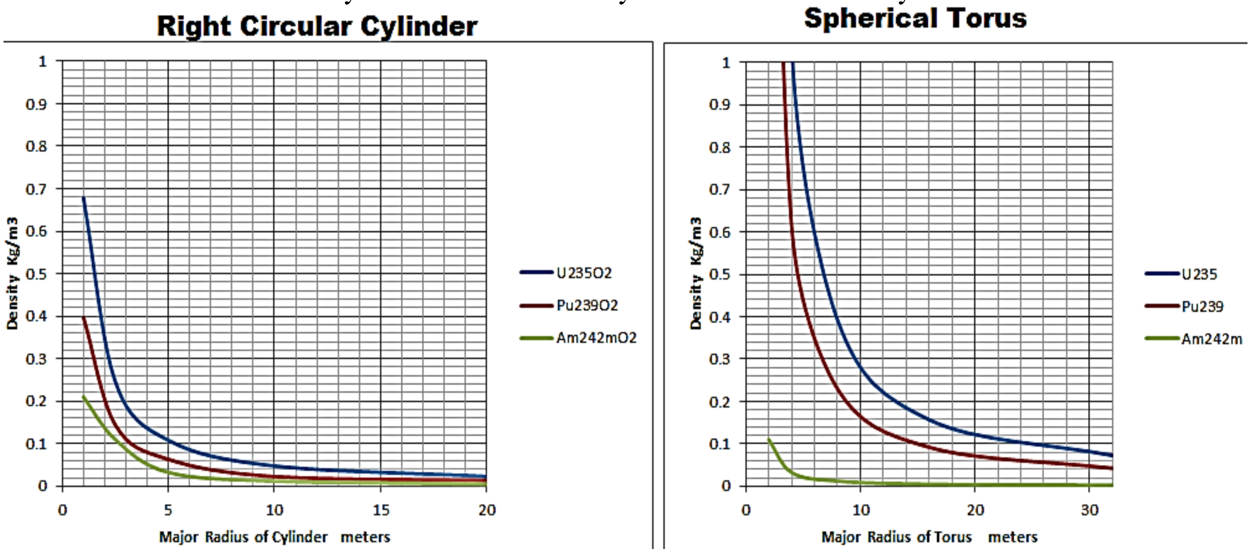
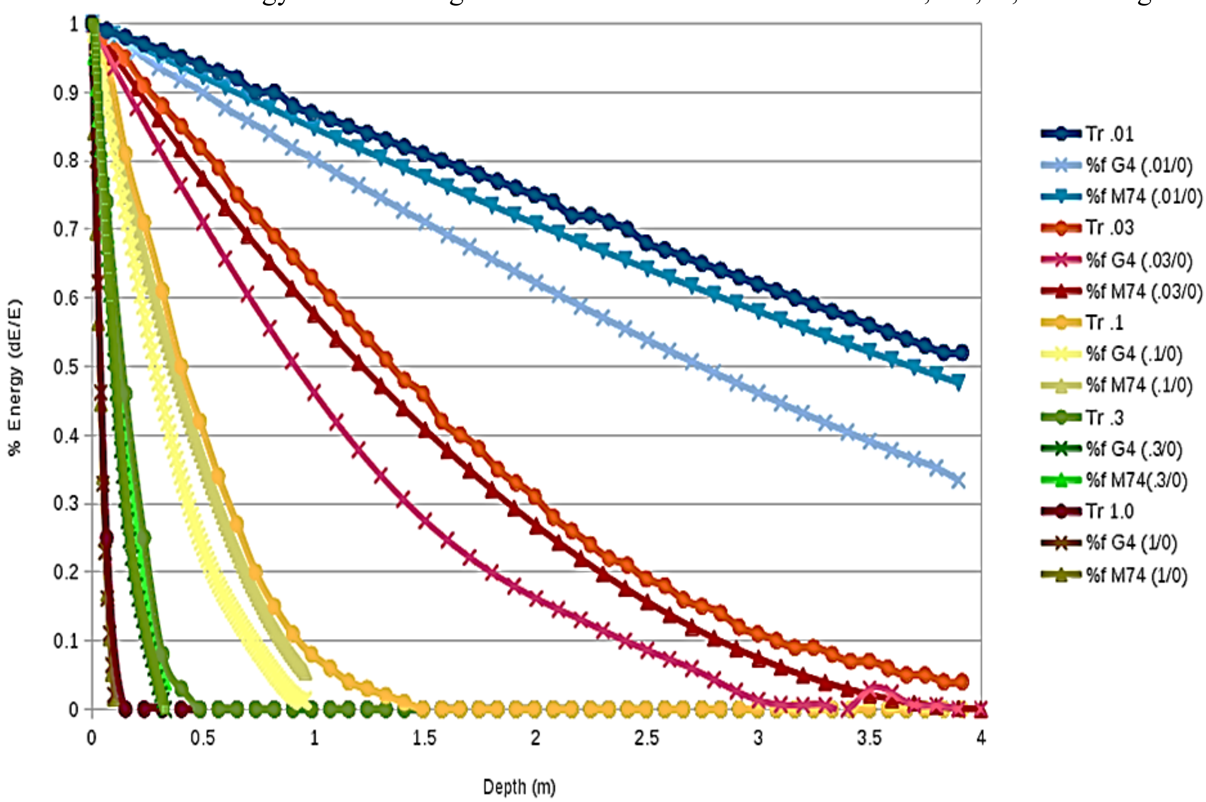
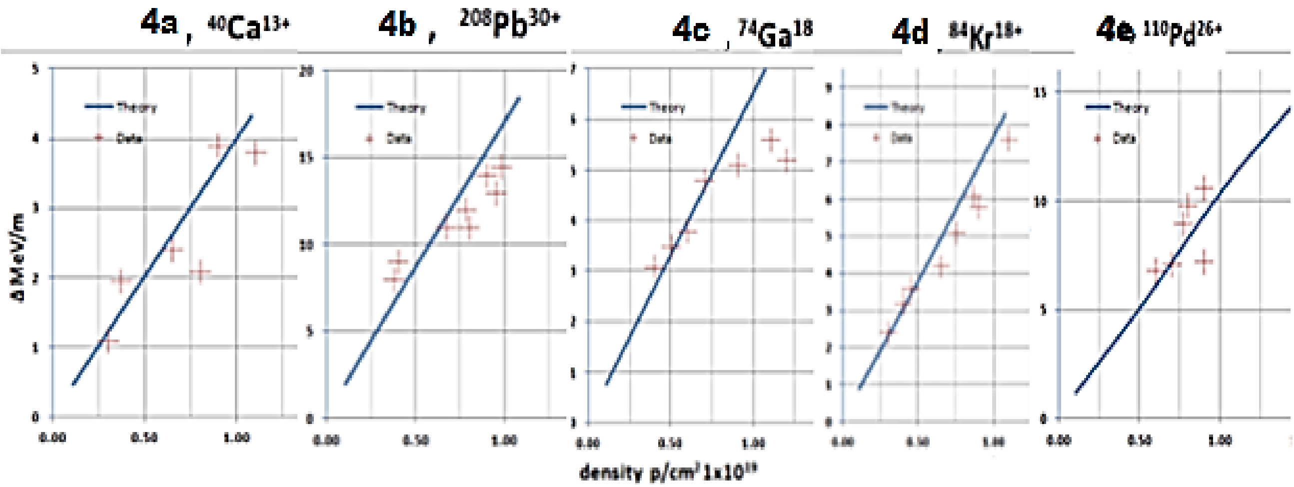


FIGURE 3 FF Energy Loss vs. Range in solid U-235 dust at densities of .01, .03, .1, .3. & 1 mg/cc.



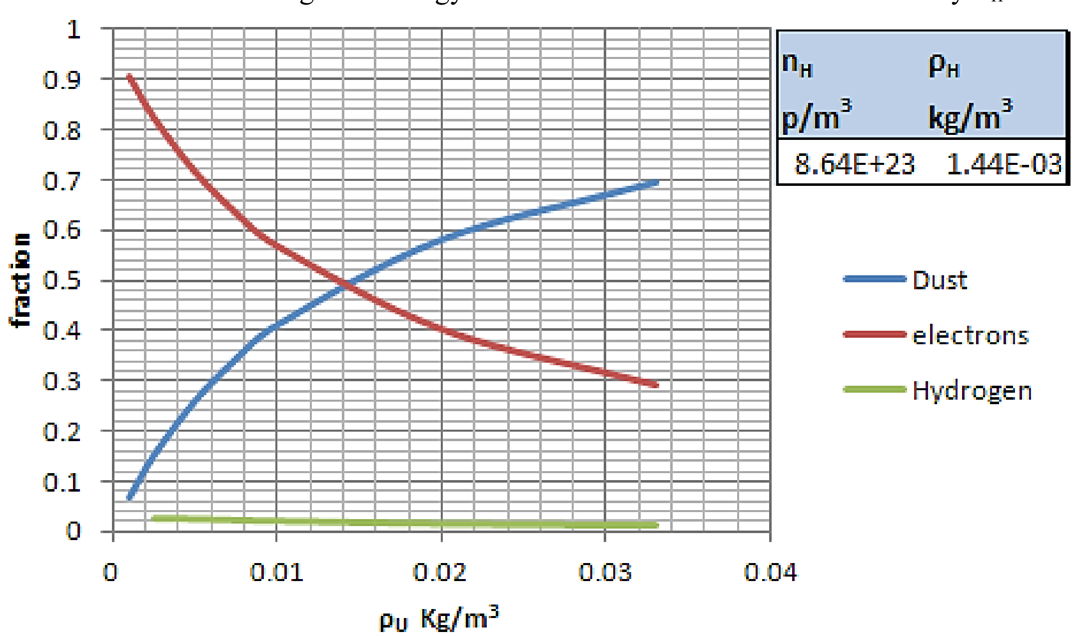
To determine the rate at which the fission fragments heat the hydrogen plasma a third computer model, FF-HEAT, was developed. This computer program is based on the theory of the Coulomb collision integral [3]. The model was validated by comparison with experimental data [4], [5]. Figure 4 compares the predictions of this model to data for various fission fragments penetrating hydrogen plasma, a) Ca-40 below the low-mass FF peak, b) Pb-208 above the high-mass FF peak, and c) Ga-74, d) Kr-84, and Pd-110 lying on the FF mass peak. There is good agreement between the model and data.

FIGURE 4 - Theory & Experiment of the fission fragment energy loss vs. H^+ plasma density.



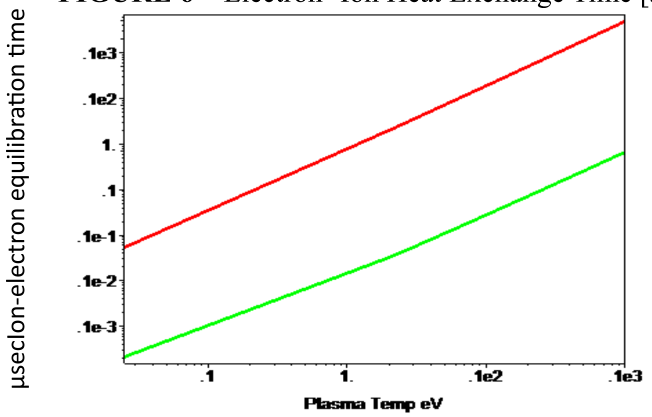
FF-HEAT and SRIM were used to investigate the FF heating of various dust hydrogen mixtures. Using these models various trade studies were performed. FIGURE 5 shows the fraction of FF energy deposited into a dusty hydrogen electron plasma mixture at a temperature of 252 eV and a density of 1.44 x 10^{-3} kg per cubic meter for varying dust densities. This figure informs us that mixtures with low dust densities preferentially heat the electrons rather than the hydrogen ions.

FIGURE 5 - Fraction of Fragment Energy Transferred to Plasma versus Dust density T_H =252 eV



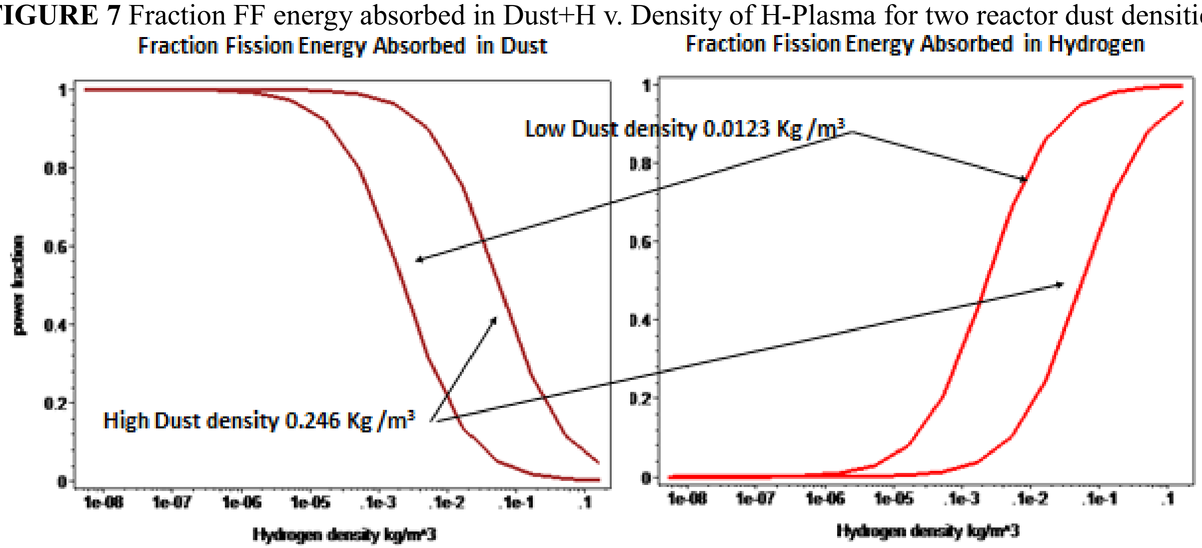
As shown in FIGURE 6, this energy is quickly transferred to the hydrogen ions under the plasma conditions of interest. Even so the electrons may be hotter than the ions. The final result is that energy transferred to plasma electrons is effectively transferred to the hydrogen.

FIGURE 6 – Electron- Ion Heat Exchange Time [3]



The trade studies in FIGURE 7, show low temperature mixtures with low uranium dust density and high hydrogen density are more effective at stopping fission fragments. The lower limit on uranium dust density is set by the requirements of reactor nucleonics given in FIGURE 2, where the critical dust density as a function of reactor major radius for three nuclear fuels is plotted.

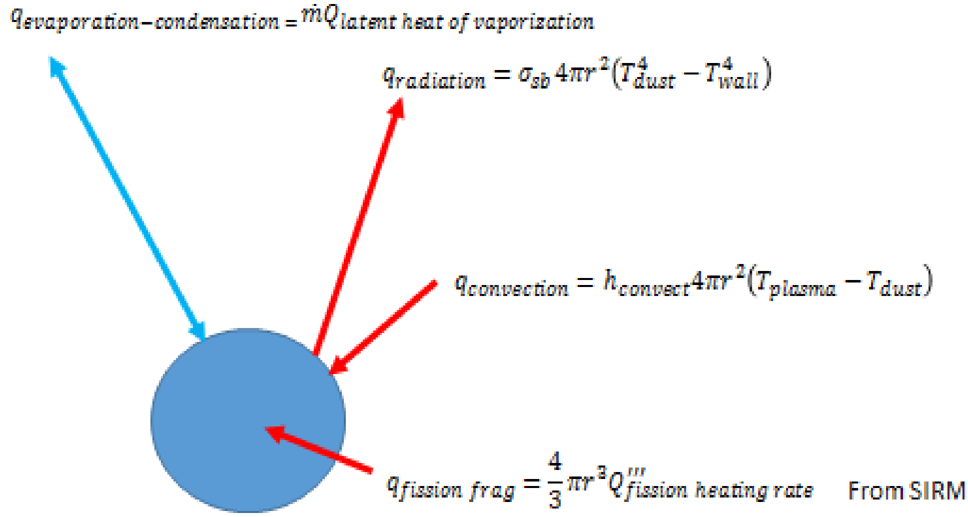
FIGURE 7 Fraction FF energy absorbed in Dust+H v. Density of H-Plasma for two reactor dust densities



The upper limit on reactor power is determined by two factors: effectiveness of fission fragment heating and dust cooling. Dust cooling requirements also put constraints on the hydrogen density.

For the dust to remain below its melting point, the frictional heat gained from the fission fragments burrowing out to the surface, and the conducted heat gained from the flowing hot hydrogen plasma must be offset by the radiative heat loss by infrared radiation from the dust surface to the reactor walls. For this to happen the plasma must remain transparent to infrared radiation so the particles can see the walls, and the thermal energy transferred to the dust by conduction from the flowing plasma must remain below that which would melt the dust particles. The dust grains might experience mass loss by vaporization, or gain by condensation depending on plasma conditions. FIGURE 8 shows the factors in determining thermal balance.

FIGURE 8 Dust Grain Thermal and Mass Transfer Balance Considerations [6]



The Knudsen number is the ratio of the molecular mean free path to the dust particle size. Typical particle size may be 100 nanometers. The molecular mean-free-path is a function of hydrogen plasma density. Free molecular flow applies when the Knudsen number is greater than 10. The hydrogen density at which the Knudsen number equals 10 is 3.73 kg/m^3. At densities below this, the hydrogen plasma acts as a rarified gas with respect to the dust grains. Thus, the rarefied nature of the hydrogen plasma must be considered when calculating heat transfer to the dust from the plasma. Reference [6] is used to calculate the rarefied gas convective heat transfer from the dust to the surrounding hydrogen plasma.

FIGURE 9 Convective Heat Transfer Coefficient for Dust grain in Flowing Hydrogen Plasma [6]

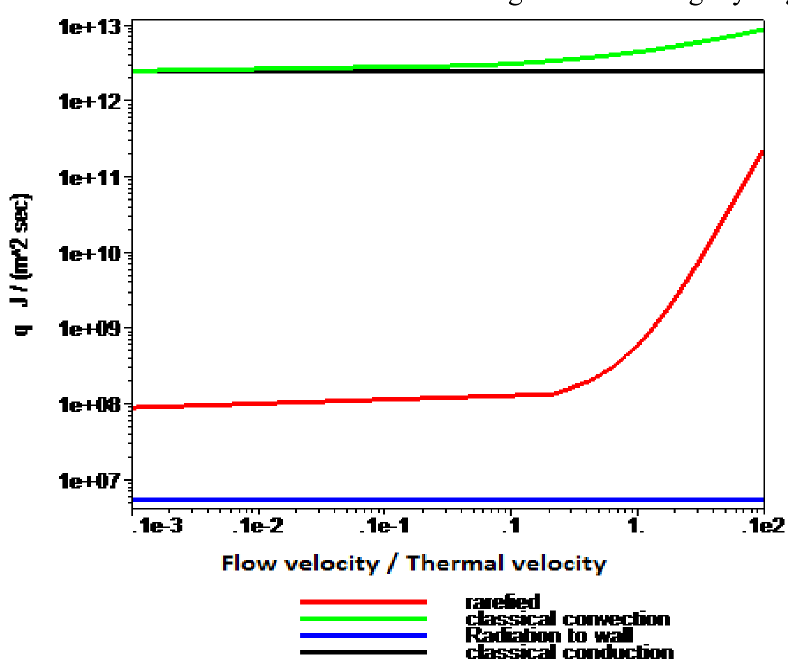


FIGURE 9 shows the results of this calculation in the case of 100 nm dust grains. The rarefied heat transfer coefficient is much smaller than the atmospheric pressure convective heat transfer coefficient. This result explains how dust can coexist with a hot hydrogen plasma as is commonly observed in reactive ion etching machines and in fusion experiments and other plasma machines. At low hydrogen pressure hot hydrogen can coexist with solid dust particles.

FIGURE 10 H-Plasma Density vs. Plasma Temperature for UO_2 fuel dust at 3120K melting point

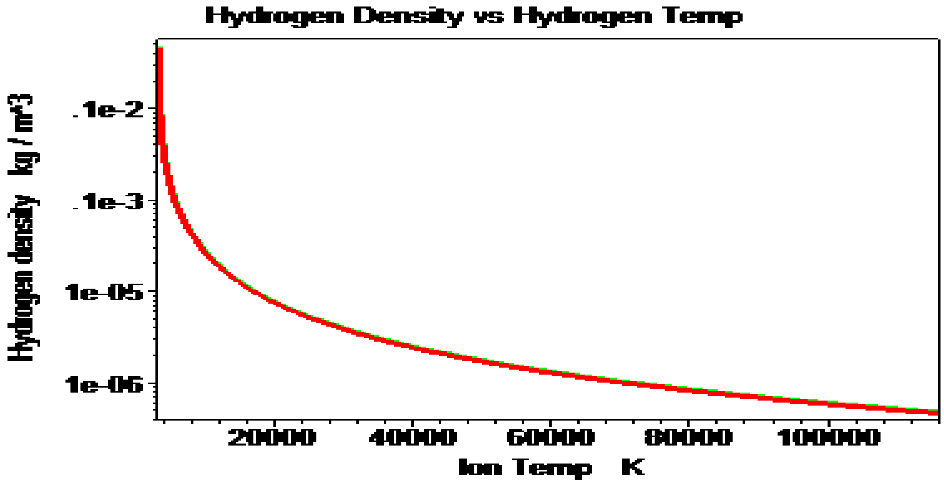


FIGURE 10 show the conditions of temperature and density under which hydrogen can coexist with 100 nm dust grains without the occurrence of melting or vaporizing. It is interesting to see that hydrogen at 100,000 degrees Kelvin can coexist with solid dust albite at very low densities.

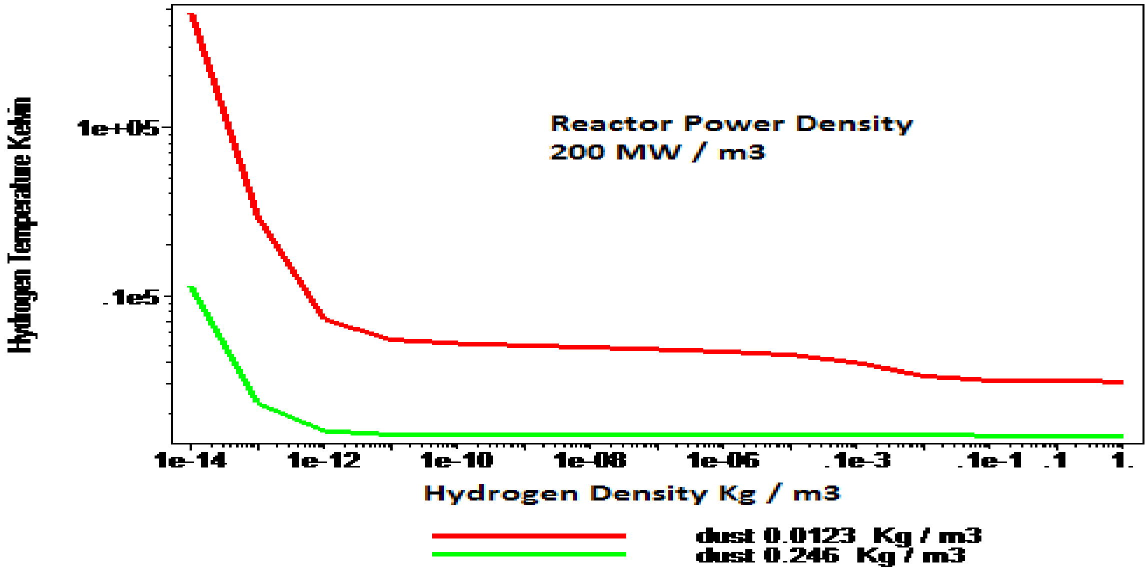
Although hot low density hydrogen can coexist with solid dust it must be demonstrated that fission fragments can raise hydrogen to theses temperatures. To this end a multicomponent equilibrium heat transfer model was developed that considered the fission fragment heating of dust, hydrogen and electrons together with the convective heat exchange between these plasma components and with the reactor vessel containment wall. FIGURE 11 shows the particle to particle interactions considered in this model.

FIGURE 11 Matrix elements considered in the exchange of heat between dusty plasma components.

	fission frag ↓	ions ↓	electrons ↓	dust ↓	wall ↓
fission frag →	0	x	x	x	0
electrons →	0	x	0	x	0
ions →	0	0	x	x	0
dust →	0	x	x	0	x
IR from wall to→	0	0	0	x	0

FIGURE 12 shows a typical result from this simulation. Shown is the hydrogen temperature that can be obtained by fission fragment heating as a function of hydrogen density for two reactor dust densities. Results show that it is possible to heat low density hydrogen well above the dust melting point while retaining solid dust grains, or produce hot dense hydrogen gas at temperatures very close the dust melting point, either of which might be useful for power generation or high impulse rocket thrust.

FIGURE 12 Equilibrium H-Gas Temp v. H-Density at two dust densities w/same Reactor Power Density.



Charge State of Fissioning Dust

To compute the maximum dust/hydrogen density, it is necessary to know the charge state of the fissioning dust. Determining this is the subject of another NASA/MSFC-funded project which is attempting an experiment to measure the charge state of a grain of Cf^{252} which is spontaneously fissioning [7]. When the charge state is known it will be possible to determine the maximum hydrogen density at which the dust can remain confined.

FIGURE 13 Dust Grain Charge Balance [8].

$\Phi_{dust} = \frac{q_{dust}}{C_{dust}}$ Dust Potential

C_{dust} = r exp($-r/\lambda_D$) Dust Capacitance

λ_D Debye length of plasma

r dust radius

q_{ff} avg. fission fragment charge

q_{ele} electron charge

q_{ion} electron charge

q_{dust} dust charge

n_{ele} electron density

n_{ion} ion density

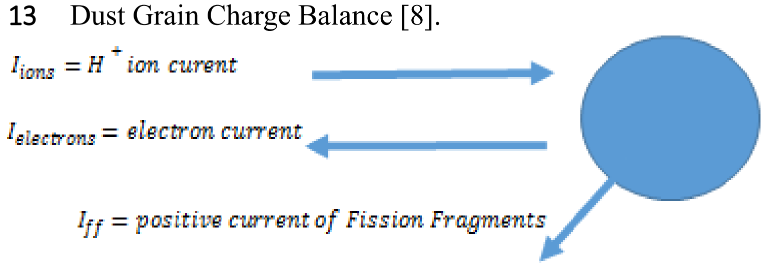
n_{dust} dust density

T_{ele} electron temperature

T_{ion} ion temperature

$N_{fission}$ total number of fissions / sec

k_B Boltzmann constant



$$I_{electron} = 4\pi r^2 q_{ele}\, n_{ele} \left(\frac{k_B T_{ele}}{2\pi m_{ele}}\right)^{1/2} \left(1 - \frac{\Phi_{dust} q_{ele}}{T_{ele} k_B}\right) \quad for \ \ q_{ele}\Phi_{dust} < 0$$

$$= 4\pi r^2 q_{ele}\, n_{ele} \left(\frac{k_B T_{ele}}{2\pi m_{ele}}\right)^{1/2} e^{\frac{-\Phi_{dust} q_{ele}}{T_{ele} k_B}} \quad for \ \ q_{ele}\Phi_{dust} > 0$$

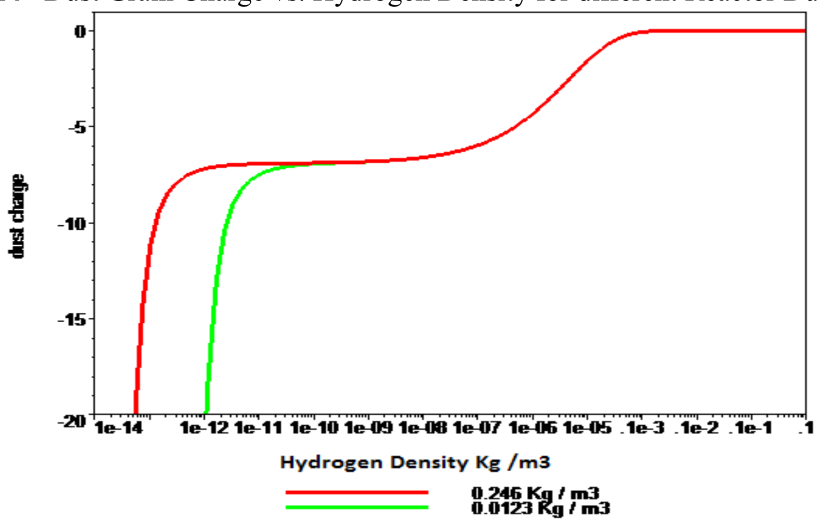
$$I_{ion} = 4\pi r^2 q_{ione}\, n_{ion} \left(\frac{k_B T_{ion}}{2\pi m_{ion}}\right)^{1/2} \left(1 - \frac{\Phi_{dust} q_{ion}}{T_{ion} k_B}\right) \quad for \ \ q_{ion}\Phi_{dust} < 0$$

$$= 4\pi r^2 q_{ion}\, n_{ion} \left(\frac{k_B T_{ion}}{2\pi m_{ion}}\right)^{1/2} e^{\frac{-\Phi_{dust} q_{ion}}{T_{ele} k_B}} \quad for \ \ q_{ion}\Phi_{dust} > 0$$

$$I_{ff} = q_{ff} \frac{N_{fission}}{n_{dust}}$$

For present purposes the charge state can be estimated by considering the various interactions of the dust grain. FIGURE 13 shows the balance between positive current from the charged fission fragments leaving the dust grains, negative current of electrons and the positive current of hydrogen ions. Following the discussion in reference [8] an equilibrium charge state model was constructed. The results of this model are shown in FIGURE 14. It appears that the 100 nm fissioning dust grain has a charge plateau. At high hydrogen ion densities the positive ion current neutralizes the effect of fission negative charging and at low hydrogen densities the charge runs away with no mechanism to neutralize the charge from fission. In between exist a charge plateau of 7 electron charges.

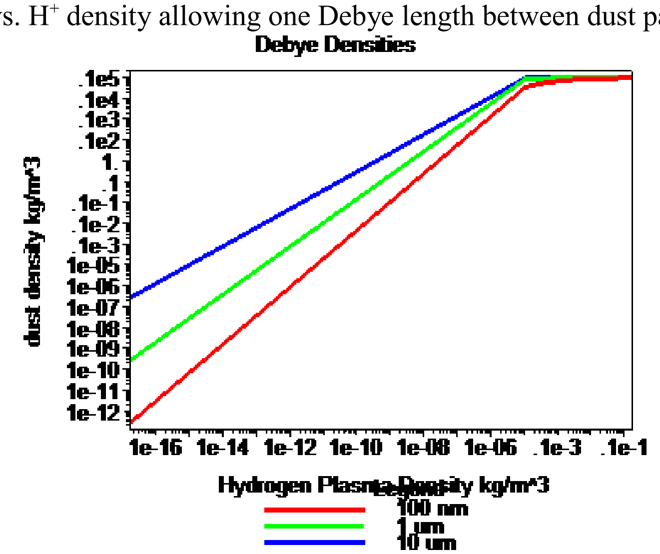
FIGURE 14 Dust Grain Charge vs. Hydrogen Density for different Reactor Dust Densities



Packing Density of Fissioning Dust

In order to pack negatively charged dust into a small volume, the hydrogen plasma in the region between dust grains must have enough positive charge to neutralize the repulsion of the dust grains. The radius of a sphere with sufficient plasma inside is called the Debye radius.

FIGURE 15 Dust vs. H^+ density allowing one Debye length between dust particles of three radii.

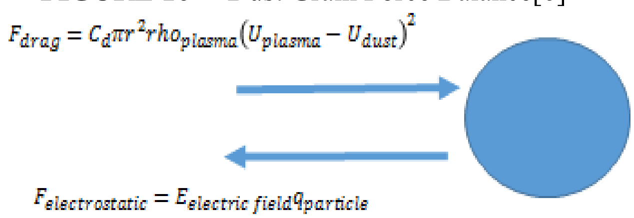


To prevent agglomeration of the dust grains the average distance between dust grains must be greater than the plasma Debye distance. The maximum dust density for which this condition is true is calculated for various hydrogen plasma densities and shown in FIGURE 15. Dust grain densities must remain below that shown in the curves for the appropriate grain size to meet or exceed this Debye spacing criteria.

Confinement of Fissioning Plasma

For confinement of the dust in the reactor reservoir, the hydrogen density must be sufficiently low that the drag caused by the flowing propellant does not sweep the dust particle out the nozzle. However as the dust will be charged an electrostatic field can be used to offset the drag force caused by the flow. FIGURE 16 shows this force balance.

FIGURE 16 Dust Grain Force Balance[6]

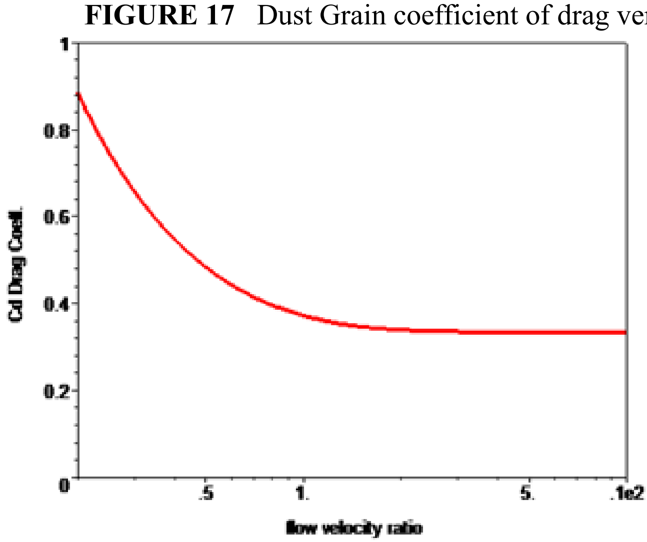


$E_{electric\ field}$ = Electric Field surrounding dust grain
$q_{particle}$ = Charge on Dust Grain

C_d = Drag Coefficient of Dust Grain
r = dust particle radius
rho_{plasma} = density bulk plasma
U_{plasma} = Flow velocity of bulk plasma
U_{dust} = Flow velocity of dust

Following the methods of reference [6] the dust drag coefficient can be computed for various plasma flow velocities. FIGURE 17 shows the results. From the drag coefficient and the given flow velocity of the hydrogen plasma the strength of the electrostatic field necessary to retain the dust in the reactor vessel can be obtained.

FIGURE 17 Dust Grain coefficient of drag versus velocity ratio.[6]



$S = \frac{v_m}{U}$ flow velocity ratio
v_m = most probable ion velocity
U = flow velocity

A Fission Fragment Dust Reactor Point Design

All the various aspects of a FFR considered individually above can be combined to develop a first order design of a complete reactor. For simplicity a non-flowing reactor is considered. Hydrogen and dust are confined by the reactor vessel surrounded by 0.5 m thick moderator. A 2.5

meter radius cylinder $U^{235}O_2$ fuel high dust density compact design and a 10 meter radius cylinder radius $Am^{242}O_2$ low dust density design are considered. FIGURE 2 is used to determine dust densities required for a critical reactor. Hydrogen density and temperature are determined from FIGURE 12. The grain charge state is taken from FIGURE 14 and the required dust densities are checked with FIGURE 15 to verify that the hydrogen and dust densities are compatible with a dusty plasma. Table 1 summarizes these two point designs, where the maximum hydrogen temperature (which gives the maximum thrust ISP rocket) is determined.

TABLE 1. Two point designs keeping dust temp<3120K melting, and space between dust grains is > plasma Debye length. (100 nm dust grains, -7 charge state), reactor power 200 MW /m^3

Reactor Fuel	Fuel (Kg/m^3)	Fuel Temp (Kelvin)	H2 Temp. (Kelvin)	Propellant H2 (Kg/m^3)	Reactor Cylinder (radius, height, m)	Critical Mass (Kg)	Moderator Mass (Kg)
$Am^{242m}O_2$	0.0123	3088	4906	1x10^{-8}	10 , 20	77.28	515,1000
$U^{235}O_2$	0.246	1465	1477	1x10^{-7}	2.5 , 5	24.15	34,500

CONCLUSION

A first order model of a dusty plasma fission reactor is constructed. The model considers the interactions between the various species present in the plasma, fission fragments, 100 nm fuel dust grains, electrons and hydrogen ions, to determine the plasma conditions in the reactor. Two point designs are considered. Results indicate feasibility of such reactors as a large IR power source, and potentially as a source of hydrogen plasma.

ACKNOWLEDGMENTS

This work was supported by NASA/Marshall contract 4200458897. The authors the especially acknowledge the encouragement and constant involvement of Robert Werka.

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