A Half-Gigawatt Space Power System using Dusty Plasma Fission Fragment Reactor

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Abstract. A dusty plasma nuclear fission fragment reactor employs a cloud of nanometer-sized dust of fissionable material inside a magnetized moderator. 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 nanometer dust has such a large surface to volume ratio, that it is capable of remaining solid at 3000K while radiating 10-100 GW of radiant power, as discussed in previous work. This ``nuclear light bulb" power source solves the intractable problems of previous designs: confining charged dust rather than hot gas; eliminating the need for quartz windows; and not requiring gas cooling. Unlike previous designs the radiation is in the near-infrared, so that conversion to electricity is inefficient. While Brayton-cycle power converters are often advertised as a space power solution, they require additional radiators and additional mass. Several recent technologies, however, can convert NIR into electric power at improved efficiency and with no moving parts. We model the conversion efficiency of a space system consisting of radiators, moderator, direct fission-fragment converter, and IR converter panels as a viable solution to the growing need for MW space power systems.

Keywords: Fission fragment nuclear reactor, dusty plasma, mass to power ratio, infrared power conversion

INTRODUCTION

This paper complements the paper "A Six Component Model for Dusty Plasma Nuclear Fission Fragment Propulsion" by Clark and Sheldon (CS16) [1], where we look at the advantages of nuclear energy for space electric-power generation. The nucleonics and thermal design of a dusty plasma fission fragment reactor are discussed there, while this paper addresses the application of a DPFFR to a space power system. The two competing technologies for in-space power are currently solar and radioisotope thermal, which we discuss in turn.

While various schemes have been proposed to extract the ~1.3kW/m^2 of solar radiant energy at Earth orbit, the relatively low power density combined with the ~30% efficiency of advanced solar panels, limit spacecraft to <100 kW power plants. Solar power drops another 75% if the spacecraft is to go to Mars, or 96% if it is headed for Jupiter, making solar panels infeasible for outer planet missions, for manned flight, for Discovery class spacecraft using electric propulsion, and in particular, for the VASIMR electric plasma propulsion engine [2].

Currently, missions to the outer planets use radioisotope generators based on Pu238, Sr90, or ESA's proposed Am241 [3]. The power/mass ratios range between 2-5 W/kg, and the efficiency of the current generation of radioisotope thermal generators (RTG) hover around 7%, with improvements using either thermovoltaics or Stirling engines expected to achieve ~20%.[4] In either case, some 80-93% of the heat must be rejected by the in-space radiators, at the relatively low temperatures of the "cold" side, generally around 350K. A 100kWe (electricity generation), would then weigh some 20-50 tons, and must radiate somewhere between 500-

2500kWt (heat energy) into space, requiring about 1 ton of radiators, using the numbers from the proposed Prometheus mission to Jupiter.[5] Coupling this power plant to an advanced ion/plasma engine using the published numbers for the VASIMR-200 electric propulsion engine with 2.5 N of thrust per 100 kWe, produces an acceleration of <0.00001g, which if launched in low earth orbit (LEO), generates such tight spirals that it has trouble escaping collision with the Moon. As the VASIMR website acknowledges, electric propulsion beyond the Moon will require a nuclear reactor power source with a much higher power/mass ratio.

So the critical numbers for space power will be the ability to get > 1kWe/kg, and provide power for typical outer-planet mission lifetimes of 1-10 years.

THE FISSION FRAGMENT DUST REACTOR

From CS16 Figure 2 we show the critical dust density for Am/Pu/U fuels using a 50 cm thick moderator for various reactor radii. Since the hot neutrons are nearly indifferent to size, the larger radii have higher volume (neutron generation) to surface area (neutron loss), and hence lower dust densities. However the larger radii also have greater moderator volume, which at ~1000 kg/m^3 densities, can quickly dominate the mass budget. Using a compact 1 meter radius right-circular cylinder with volume $2\pi r^3$ and area $6\pi r^2$, and using a moderator thickness of 0.5 m with density 1000 kg/m^3, we can comfortably operate at 200 MW/m^3 for a total of 628 MW and moderator mass of 9424 kg. The amount of fuel in the system is negligible, with only 1.25 kg needed for Am242m, and 4.27 kg for U235. Then the thermal power/mass ratio is a hefty, 66 kWt/kg without radiator mass included.

In order to calculate the electric power/mass ratio, the radiator mass must be estimated. For a closed system, the fission fragment (FF) energy goes entirely into the dust, which itself is cooled by radiation, so the output of this reactor is infrared light (IR) from the hot dust, plus some visible light from non-thermal excitations by the fission fragments. From CS16 table 1, the temperature in the reactor at 200 MW/m^3 is about 1400K, far below the ~3000K melting point of the fuel, so that most of the power comes out as long-wavelength IR. The IR can be used in photovoltaic conversion at about 20% efficiency, or, as suggested in a recent patent, [6,7] absorbed by nano-patterned copper panels, where it excites plasmons and is directly converted into electricity at 84% theoretical efficiency. Despite being very large, these efficiencies are very close to direct electrical conversion of the charged FF, as discussed in Clark & Sheldon [8,9], which suggests that there are several ways to achieve these high values. The key point is that the DPFFR is not generating heat but FF and light, with substantial improvement over the thermal Carnot efficiency. Unfortunately, the uncharged fission products are not so easily controlled, so about 15% of the energy is lost in the fission neutrons and gamma-rays, which are principally absorbed by the moderator and will require active cooling.

Using these optimistic numbers, we then have a heat load of 628 MWt*0.15 = 94 MWt heat load into the moderator, plus 628 MW * 0.85 * 0.16 = 85 MWt heat load into electrical converters. The moderator heat load has to be removed at ~500K temperature, or the moderator oil begins to decompose and lose hydrogen. The direct current FF, or the plasmon converters are metal-insulator-metal nanostructures, which decompose near the melting point of the Ag-Au used in their construction, or about 1200K. Since the efficiency of the radiators goes as the fourth power of the temperature, this high a temperature permits the power-converter radiators to be very efficient, so the dominant size and mass will be for the moderator radiators.

Using results from a 2014 PhD on carbon fiber radiator design,[10] we have 0.3 kg/kWt or 300 kg/MWt, which when multiplied by our 94 MWt of waste heat, produces 28,000 kg for the moderator radiator. Scaling by $(85/94)(500/1200)^4$ for the improved efficiency of the higher temperature radiators, we get about 1000 kg for the power conversion radiators. Then the electrical power to mass ratio is 448 MWe/(9424+29000)kg = 11 kWe/kg, certainly enough for VASIMR to escape LEO orbit.

DISCUSSION

Using the unique feature of the DPFFR that the majority of its power is extracted in the IR, we optimistically estimate an 84% electrical power conversion efficiency. But even if this optimism were misplaced, and the efficiency were substantially lower, the high temperature of the FF/IR power converter mitigates the mass of the radiator needed to dissipate the heat load, and therefore softens its impact on the design. For example, using a pessimistic 50% power conversion efficiency, the radiator mass is increased by only a few tons, and the energy drops to 266 MWe, for a still respectable 6.5 kWe/kg ratio.

A nuclear reactor has a nearly infinite power range that is controlled by managing the neutron density of the core, from a few watts up to Gigawatts. As discussed in the earlier papers, the radiative cooling of a dusty plasma fuel is so efficient that tens of Gigawatts are possible before the fuel melts, which is the limitation of solid core reactors.

The walls of the DPFFR chamber must reflect most of the IR radiation that is emitted by the core, which is another limitation of the design. Typical CO2 continuous wave (cw) laser mirrors have a damage threshold around 25 kW/cm^2 at 1000 nm IR wavelength, which for our small chamber with 188,500 cm^2, permits a 4.7GW total fluence. So with proper cooling of the moderator and mirrors, this fluence is not the limiting factor. There will also be a large neutron fluence, which is deadly to metallic surfaces, but less dangerous for ceramics and low-Z mirrors such as carbon-fiber based designs. There has been a great deal of work on the 1st wall in tokomak and fusion energy reactors, so we do not think this will be a limitation on the design.

However, the limitation of DPFFR is not a melted core, or an ablated liner, but a vaporized moderator that must surround the core. It is in the moderator that the neutrons lose most of their heat and then reenter the core to generate further fissions. For a ground-based power plant, this is an advantage, because the moderator can be designed to be a much larger volume than the core, and much more easily cooled. But for in-space power, the larger mass of the moderator reduces the power/mass ratio, and so the core must be kept highly compact. This need for a compact moderator, means that the limitation for in-space reactors are the limitations in power flux per area, or power per volume that must be removed. And even if the materials in the moderator can handle the high heat flux, ultimately the radiators have to be designed to remove that heat, which adds mass to the system and reduces the power/mass ratio.

So it is not the energy conversion efficiency, but the moderator that plays the most important role in both the mass of the reactor and the mass of the radiators. It was for this reason that the Prometheus nuclear-electric mission intended for Jupiter used a fast neutron reactor design without moderators that was originally developed for submarines. That design, while mature, was limited by the working temperature of the materials and required a less efficient, Carnot-limited Brayton-cycle converter. Because of this Carnot-cycle limitation, the designers felt compelled to operate the Braytons at a much higher temperature to get the power/mass ratio they needed, and became the justification for cancelling the Prometheus mission. Not until this DPFFR design, could nuclear reactors provide sufficiently high power/mass ratios, where the extra mass of the moderator was traded for a higher efficiency reactor. And if further improvements in the DPFFR moderator can be realized, say, by using higher temperature aromatic ring oils, or hydrogen-doped beryllium moderators, then radiator mass can be reduced further with a direct improvement in the power/mass performance of this space DPFFR.

CONCLUSION

A half-gigawatt design of a dusty plasma fission fragment reactor is used to calculate the power per kilogram of the in-space power plant at a theoretical 11 kWe/kg, or approximately 2000 times better than RTGs. More conservative estimates for the IR to electrical power conversion reduce this number to about 6 kWe/kg, but the real improvements that can achieve 20-100 kWe/kg will come from advanced moderator materials.

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