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HYBRID FUEL COUPLING IN A PULSED Z-PINCH ROCKET ENGINE

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The work presented here sought to explore a portion of the parameter space of a hybrid nuclear fuel in regards to ignition and burn by analyzing the effect of initial geometry and thermodynamic conditions. The authors performed 0D power balance and 1D burn wave calculations to determine temperature progression and energy production for defined initial conditions. Geometries examined are representative of concept fuels for a Pulsed Fission-Fusion (PuFF) engine. This work focuses on lithium deuteride and uranium 235 for the fuel since these are seen as leading candidates for PuFF. Presented below is a power balance illustrating a reduction in the energy and density required to breakeven of hybrid fuels in comparison with fusion fuels. Also the impact of fusion and fissile fuel quantities upon initial energies is presented. One can see that the initial energy required to breakeven in a hybrid cylindrical nuclear fuel decreases with decreasing fissile liner thickness, decreasing fusion fuel core radius, and increasing compression ratio of the fusion fuel.

I. Introduction

As we embrace the challenge of traveling through deep space and exploring our solar system we find that we require ever larger quantities of energy. Higher energy densities and propulsive efficiencies are needed to enable more ambitious deep space missions. Propulsion systems that are chemical reaction based are limited in efficiency, ~450 s of specific impulse. Electric propulsion systems and perhaps other methods such as solar sails can achieve significantly higher specific impulse but are limited to very low levels of thrust, approximately tens of newtons. Nuclear reactions, on the other hand, have the potential to reach levels of thrust more useful for transporting astronauts and payloads quickly while achieving orders of magnitude increase in specific impulse and specific energy. Nuclear reactions have specific energy on the order of $8x10^7$ kJ/kg compared to chemical systems which have specific energy on the order of 14 kJ/kg.[1]

While there are different schemes for accessing fission energy for propulsion; e.g. nuclear thermal, nuclear electric, fusion systems offer the most gains in power and specific impulse. Fusion reactions are notoriously difficult to achieve; however, due to the extreme energy requirements and the instabilities that arise in confining or imploding the system. Hybrid reactions that employ both fission and fusion reactions may be a more effective approach to successful implementation of fusion system. When combined in a hybrid reaction the fission and fusion fuels boost each other's reaction rates. Heat from fission fuel increases the reactivity of the fusion fuel and the neutron flux may breed additional fuel to fuse. Additionally, the neutron flux from the fusion fuel will induce fission. This coupling can drastically reduce the driving energy required to initiate the burn and drastically improve output. This concept has been examined in the past by Winterberg[2] and is being investigated in support of a Pulsed Fission-Fusion (PuFF) engine concept at Marshall Space Flight Center and the University of Alabama in Huntsville.[3]

In addition to the reaction, the mechanism for achieving the conditions required to initiate the reaction is also quite important. Research has focused largely on Magnetic Confinement Fusion (MCF) and Inertial Confinement Fusion (ICF). MCF contains plasma at a steady state at low densities as opposed to ICF which implodes small quantities of fuel in ultra-short high density reactions. These methods struggle to reach the temperatures required due to limitations of materials and instabilities that arise in both processes. Magnetic Confinement Fusion (MCF) also known as Magnetized Target Fusion (MTF) operates at an intermediate density regime and employs a magnetic field to trap charge particles in order to reduce energy lost. This drastically reduces the driving energy required. Research into this method suggests this approach may offer a means of achieving the conditions necessary for nuclear fusion. The PuFF engine research seeks to operate and take advantage of the MIF regime.[4,5]

II. Pulsed Fission-Fusion Engine

The Pulsed Fission-Fusion (PuFF) concept engine uses a z-pinch configuration with a fusion core and a fission liner to boost energy production and reduce power required to drive the reaction, hence a hybrid target. The fission process heats the fusion fuel, increasing the fusion reaction rate. The fusion products then enhance fission reaction. The processes boost each other's reaction rates. This system reduces driver requirements and more efficiently converts the nuclear to jet power leading to a smaller overall system and higher specific power (alpha).

The alpha and I_{sp} of this system is estimated to be approximately 15 kW/kg and 30,000 s respectively. That is orders of magnitude improvement over competing systems such as nuclear electric, solar electric, and nuclear thermal propulsion that suffer from lower available power and less efficient thermodynamic cycles. PuFF will meet an unfilled capability needed for manned missions to the outer planets and vastly faster travel throughout the solar system.[3,6]

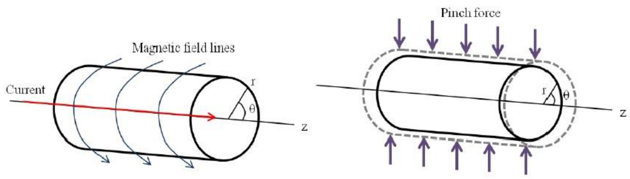

Fig. 1 Z-Pinch Diagram

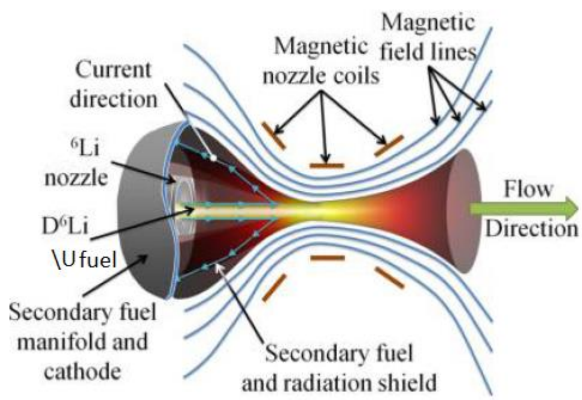

Fig. 2 PuFF Engine Diagram

The z-pinch that drives the reaction is an electromagnetic process in which a large current is discharged through a geometry of cylindrical and annular layers of fuel and propellant. This generates an azimuthal magnetic field and a compressive force toward the axis as seen in Figure 1. The z-pinch is accomplished in the PuFF engine by ejecting a fuel pellet and connecting the circuit with liquid lithium jets. This is illustrated in Figure 2. The z-pinch compresses the fuel and lithium to the initial conditions required for ignition and burn of the nuclear fuel. Following ignition and burn, the hot plasma expands through a magnetic nozzle to produce thrust and recapture energy for the next pulse. [3,6]

The vehicle provides the electromagnetic pulse through a system of linear transformer drivers (LTDs). LTDs are a technology that can generate high power fast electrical pulses in far lower mass systems than technology previously allowed. The hot dense plasma expands through a nozzle formed from magnetic field lines. The magnetic field directs the plasma expansion while protecting hardware. The expansion of the plasma also compresses the magnetic field which allows for some of the energy produced to be recaptured to recharge the system. These systems function together to create the z-pinch, burn, and expansion for engine operation. While, breakeven fusion is difficult to achieve, the hybrid design of this system is expected to significantly reduce the energy barrier to achieving this milestone. The system is leveraging fission to realize fusion in order to enable a revolutionary architecture for human exploration. The vehicle originally evolved from the HOPE study and has continued to be matured through a NIAC phase 1 in 2013 and a NIAC phase II in 2018 with work continuing between the two. [3,6]

III. Approach

The authors have developed a power balance and one dimensional burn wave model to guide fuel design by exploring the parameter space and inform more robust modeling efforts. The power balance model calculates the energy production and loss of the system across a defined temperature – density parameter space. The result of the power balance model is a Lindl-Widner diagram with contours defining the line at which energy produced exceeds energy lost, thus crossing the line into higher temperature and densities the system breaks even. The one dimensional model calculates the energy produced and lost in the system for each time step as a burn wave propagates from the axis and determines the gain in energy of the system. The geometries and materials of the model are chosen to align with existing concepts of the PuFF engine fuel.

The total energy produced in the system is a sum of the positive production and negative losses. Energy is produced by fusion reactions, including primary reactions and secondary reactions (e.g. Tritium breeding and burning in D^6Li), and from fission reactions. Heat from the fission fuel heats both the hot spot and cold fusion fuel, thus greatly boosting energy production. A portion of the energy produced escapes the system. Additional losses occur due to thermal conduction, synchrotron radiation, bremsstrahlung radiation, and mechanical work.[7] The contributions of these mechanisms are added together for each time step as the burn wave expands in the 1D model. The expansion velocity is derived from the perfect gas equation of state, continuity, and momentum equations for a moving shock wave.[8]

In making these calculations, the model varies the radii of the materials and sets the length equal to the radius of the fusion fuel. An exponential density profile is defined for the fusion material in such a way that the peak compression ratio is at the axis and the outer edge is at solid density. The fissile fuel is kept at solid density. This profile is expected to be more representative of the point at which the compression shock wave rebounds at which point a higher density near the axis will likely benefit fusion reactions. The initial size of the hot spot in the 1D model is set at 10% of the fusion fuel radius.

Changing the initial hot spot size would also change the initial reacting mass and temperature for a given starting energy. Lower starting energies may be found to breakeven in a small initial hot spot if the energy density is sufficient. Magnetic field in this instance is kept at 0 to limit the analysis. Material outside the hot spot is initially defined at room temperature whereas the hot spot is given an initial energy for the 1D model.

This analysis focused on the coupled relationship between the quantity of fusion and fissile fuels by varying radii and determining initial conditions leading to modest energy yields (1.5 to 2 MJ). This analysis provides a look at the trends to shed light on the optimal relative fuel quantities to achieve breakeven in a z-pinch with PuFF engine like fuel.

IV. Results

Both power balance and 1D burn wave calculations were used to explore the parameter space for a PuFF engine like cylindrical hybrid nuclear fuel. The power balance illustrates the significant impact of the coupled nature of the hybrid process when compared with pure fusion reactions. The 1D calculations provide additional insight into the coupling of the fusion and fission processes.

I.A. Power Balance

The power balance of a hybrid cylindrical nuclear fuel calculates the power balance across a grid of temperature and density values, in the case studied here for a geometry with a fusion radius of 0.4 cm and a fission radius of 0.5 cm. Contour lines are drawn along the line of energy balance. Thus the contours are the breakeven lines above which energy production is positive in the system.

The power balance presented is conducted for a PuFF like hybrid target along with pure fusion reaction of deuterium-tritium (DT), deuterium-deuterium (DD), and lithium-deuteride (D^6Li). One can see the power balance in Figure 3. The figure shows contours across several orders of magnitude of temperature and areal density. Areal density is defined as the density multiplied by a scale length, in this case fusion fuel radius. One can see that the hybrid reaction can reach breakeven significantly below that of pure fusion reactions. The breakeven line for the hybrid fuel drops below 1 keV at approximately solid density and above. One can see the significant advantage to the hybrid reaction.

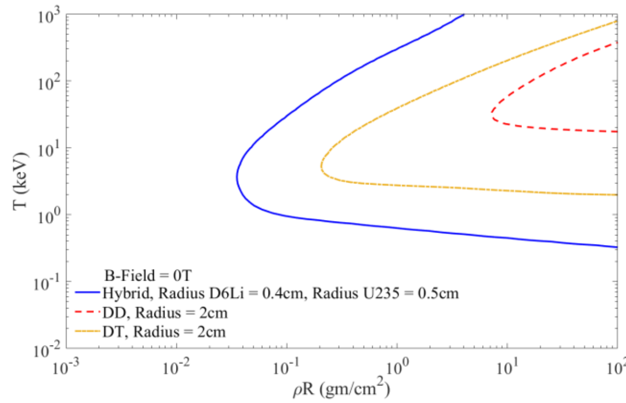

Fig. 3 Power balance of hybrid and pure fusion reactions.

I.B. Hybrid Fuel Coupling

The burn wave calculations were carried out for several geometric variations in which fusion and fission fuel radii were changed. The impact upon the initial energy required to breakeven and achieve a modest yield of 1.5 to 2 MJ was studied. Two density profiles were used. The two profiles had maximum compression ratios of 10 and 20 times solid density at the axis while each exponentially decreased to solid density at the edge of the fusion fuel. Two fusion fuel radii were explored, 0.25 cm and 0.15 cm. Fission fuel thickness was varied for each fusion fuel radius to ascertain the impact upon initial energy required to breakeven. Figure 4 plots the starting energy for a yield of 1.5 to 2 MJ for each geometry and density profile.

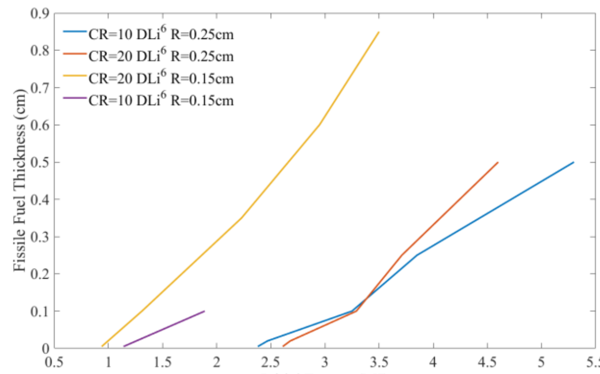

Fig. 4 Initial energy plotted against uranium thickness

One can see in Figure 4 that the initial energy required drops with decreasing uranium thickness. This may be counter intuitive initially but this likely results from less heat absorbing mass thus faster heating of the cold fuel. One can also see that initial energy drops significantly for the smaller radii of fusion fuel. Similarly, this is likely due to less cold fuel mass resulting in faster heating of the cold fuel into which the burn wave is expanding. One should note that the lower density profile with a CR of 10 cannot breakeven above 0.1 cm fissile thickness at fusion radius of 0.15 cm because of the reduced reaction mass. Generally speaking, higher compression ratios in the fusion fuel and limited fusion and fissile fuel thickness result in a hybrid fuel with the minimal initial energy requirements to breakeven.

V. Conclusions

Hybrid nuclear reactions offer a promising method of achieving fusion reactions at significantly reduced requirements as compared to stand alone fusion. The driving energy, which puts the fuel in a state which induces a burn wave, could perhaps be reduced one or more orders of magnitude by introducing fission reactions. As seen in this analysis, it may be possible to achieve breakeven in a hybrid nuclear z-pinch with initial target energies of only 1 to 4 MJ. Introduction of an external neutron source may further decrease the required driving energy and increase the yield. In addition to the dramatic effect of hybrid reaction coupling, one should make note of the trend in which smaller fuel targets trend toward lower initial state energies. While there is a lower limit in the required quantity of reaction mass an excess mass quenches the reaction and drives up initial energy requirements.

This work serves as a precursor to more robust modeling of the compression, burn and expansion of the hybrid nuclear fuel in a PuFF engine. This and future modeling efforts will drive the design of experiments. Future experiments will strive to develop the fuel and PuFF cycle while seeking to demonstrate a breakeven pulsed power driven hybrid nuclear z-pinch.

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