The Pulsed Fission-Fusion (PuFF) Engine: Development Status

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I. Abstract

The PuFF (Pulsed Fission Fusion) project aims to revolutionize space travel through nuclear propulsion. PuFF will produce both high specific impulse (I_{sp} 5,000-30,000 sec) and high thrust (10-100 kN), enabling quick (~1 month) transit times to Mars, the outer planets and exiting the solar system (~5 years).

PuFF creates thrust by imploding a fission-fusion target using a Z-pinch. The process involves using the Lorentz ($j \times B$) force to create gigapascal to terapascal pressures. Liquid lithium is injected in both a cylinder and cone. When the two connect, a circuit with a network of capacitors (referred to here as the pulser) is completed, and a 10-25 MA pulse flows down the lithium. The Z-pinch slams the lithium onto a fission-fusion target. The resulting compression (5-10 by volume) reaches super-criticality and explodes. The expanding plasma is then directed out of the back of the engine by a magnetic nozzle.

II. Introduction

Figure 1 below illustrates the PuFF concept. Here the bottom figure shows a magnetic nozzle connected to a Lithium filled tank and a series of capacitors. A nuclear target is injected into the nozzle and a cone and cylinder of liquid lithium is formed around the target. A high current pulse flowing down the conical shell and back up the cylinder compresses the lithium onto the target. The top image shows the Lorentz force acting on the lithium.

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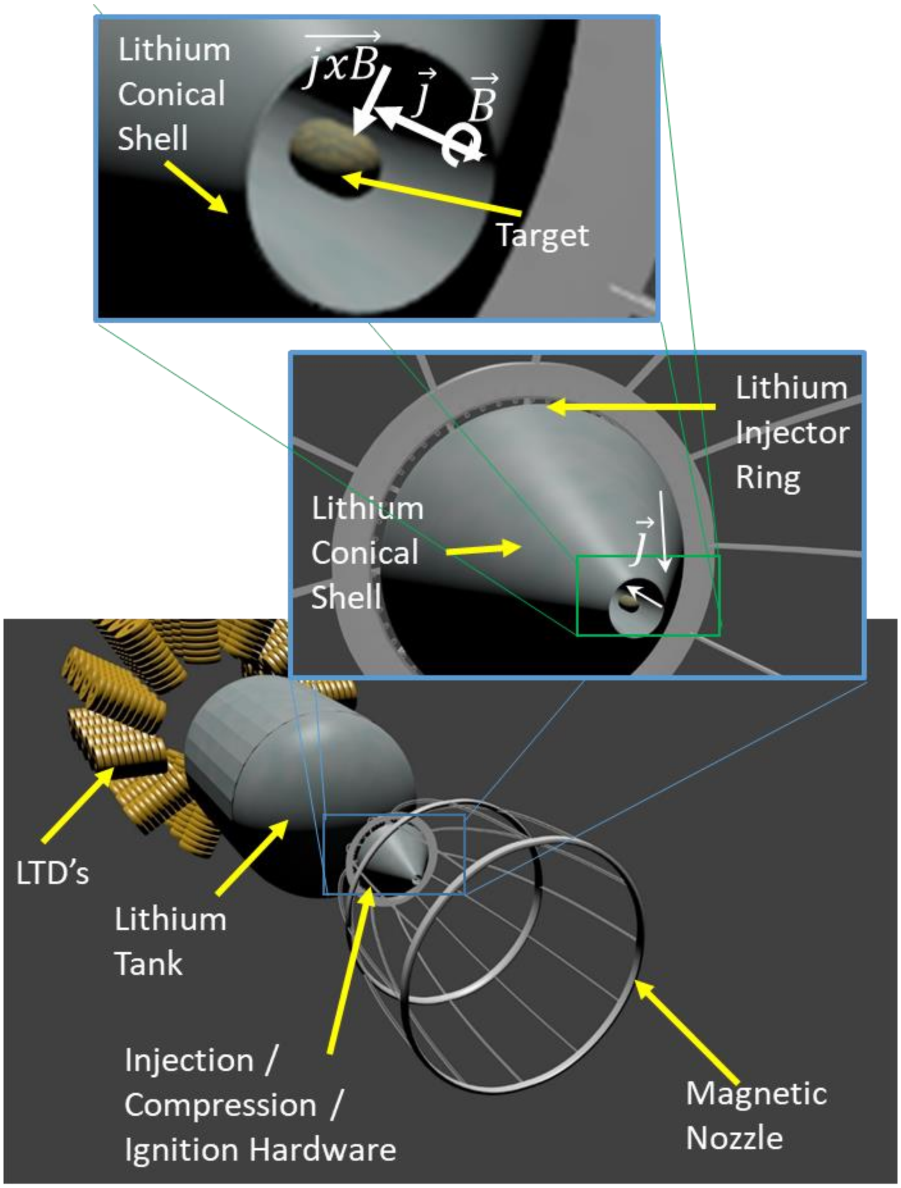


Figure 1 - Visualization of the PuFF process

This compressive process would happen about once per second to produce forces on the order of 10's of kilonewtons with specific impulses on the order of 5 to 25 thousand seconds. There are several vehicle systems that are necessary to make this process a reality.

Figure 2 shows the overall vehicle in profile. Here we see some vehicle systems that are not shown in figure 1. A strong radiation shield is necessary given the nature of the propulsion system. A target storage system organizes the fission/fusion material before injection. High and low temperature radiators are needed to cool the nozzle and radiation shield respectively. And this vehicle concept shows a solid, pusher plate nozzle instead of a magnetic nozzle.

The engine system is divided into seven subsystems; pulser, lithium injection, target injection, magnetic nozzle, radiation shielding and thermal. Each of these subsystems are discussed in the sections below. Afterwards the paper discusses some development plans for the PuFF engine.

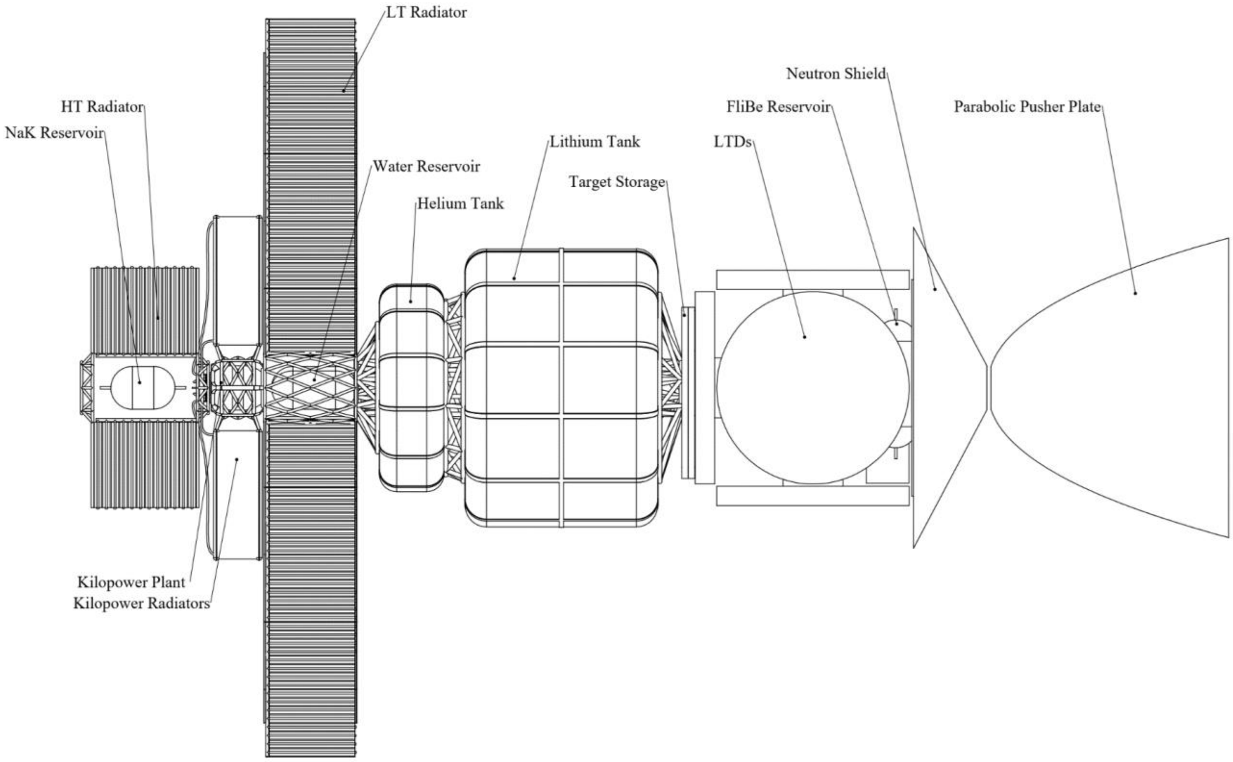


Figure 3 - Side view of the Block 1 PuFF concept.

III.Pulser subsystem.

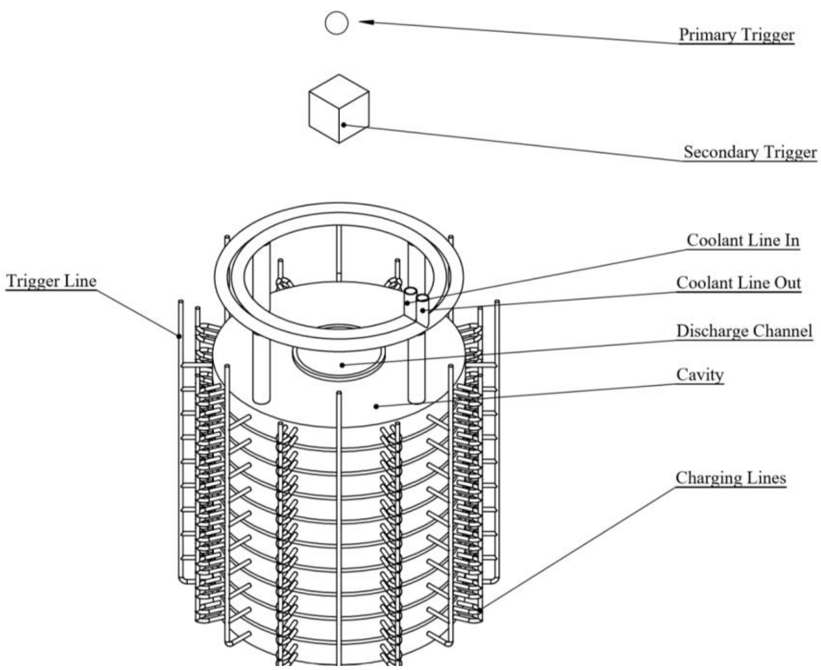


Figure 2 - Pulser subsystem.

The pulser subsystem is responsible for delivering the pulse to power the Z-pinch for target implosion. The pulse must deliver 10-25 MA within a width of 2-15 μs. Linear Transformer Drivers (LTDs) are an advantageous option for supplying the pulse due to their compact design (and therefore reduced size and mass) compared to traditional pulsed power systems. LTDs can also be constructed using off-the-shelf capacitors. The pulse is delivered from the LTDs to a central line (bus) that carries it to the injected lithium liner for target implosion.

The LTD assembly includes an array of capacitors that are charged by the power generation subsystem and fired in parallel using spark gap switches. These spark gap switches must be injected with high voltage from a secondary trigger assembly for field distortion. This trigger, in turn, is prompted by a lower-voltage, primary trigger assembly. Electrical components in these assemblies, especially the spark-gap switches, will heat during repeated firing and will be cooled by the moderate-temperature, gas-phase of the ship's cryogenics.

The primary trigger assembly serves to activate the secondary trigger, which is capable of injecting high voltage into the spark-gap switches in the LTDs. The primary trigger will take an analog or digital signal from the ship's computer and fire an 801-C power supply into a PT-55 voltage inversion generator for pulse shaping, which in turn feeds into a PA-80. The PA-80 is a common trigger for Marx bank systems and outputs 80 kV. This pulse fires the secondary trigger assembly.

The secondary trigger stores enough energy to inject 200 kV to trigger the spark-gap switches in the LTDs. This is double the voltage that the capacitors in the LTDs will be charged to and ensures extremely low jitter in closing the switches (1-100 ns). However, the energy in the secondary trigger is held off by a similar switch until time to fire the engine, and this switch is triggered by the 80-kV pulse coming out of the primary trigger. There are two design options for the secondary trigger energy storage: a mini-Marx bank of capacitors or a large water line (a large co-axial cable with water being used as the dielectric medium).

IV. Lithium Injection

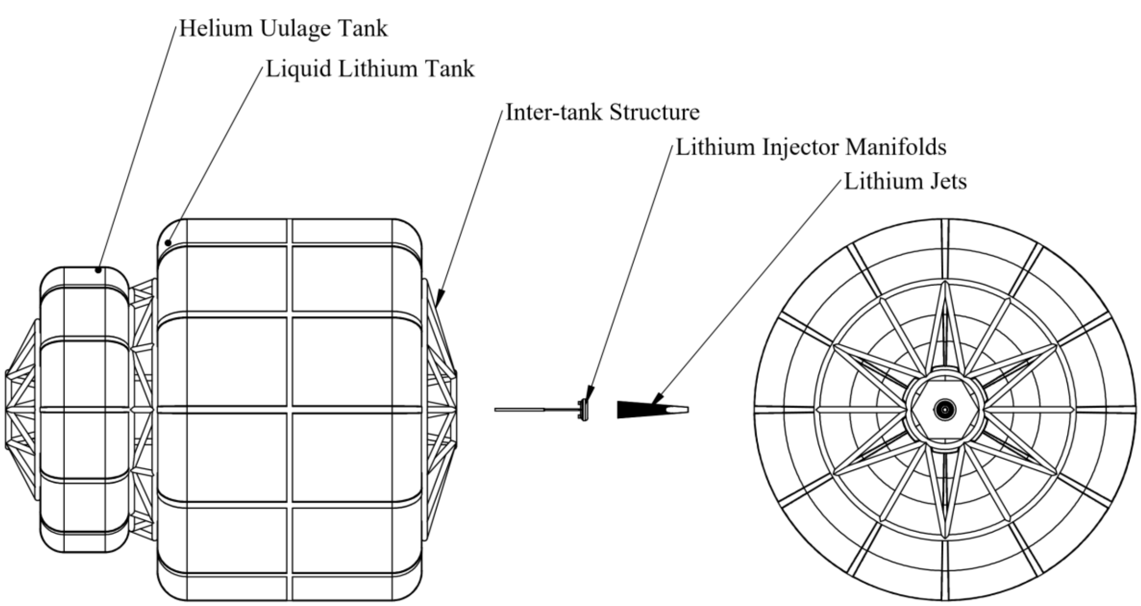


Figure 4 - Lithium propellant subsystem

Lithium is an excellent propulsive medium for the PuFF concept. Its low atomic number results in a high exit velocity and thus specific impulse. It is a conductive metal so it can carry the current needed for the z-pinch. Injecting lithium creates a sacrificial anode/cathode that makes the possibility of operating over multiple implosions possible.

Lithium is difficult to handle being very corrosive and reactive with a wide range of materials. When in contact with water it forms Lithium Hydroxide (LiOH) and gaseous hydrogen (H_2). The hydrogen component of this reaction is especially a concern for its potential to combust or even detonate in the presence of oxygen. Another risk is when Lithium encounters nitrogen which results in a reaction that forms Lithium Nitride (Li_3N). Li3-N is potentially even more corrosive than elemental lithium. These properties of lithium underline the need for special efforts to be made to ensure a maximum purity of the lithium used in experiments and applications. The lithium must not come into contact with air or humidity and must be contained in vessels whose alloys have a minimum amount of nitrogen impurities to limit the contamination and increase in the lithium's corrosiveness. Finally, Lithium is the lightest or least dense metal having half the density of water at room temperature when it is at 200C. This means that for a given mass, liquid lithium will occupy a greater volume than any other metal making its storage a rather bulky affair.

The lithium jets must be injected in streams that eventually create a cone and cylinder as seen in the figure below. Seperating into individual streams prevents the current from flowing azimuthally which would deform the z-pinch. However the individual streams cause some mutual inductance that adds resistance to the entire circuit.

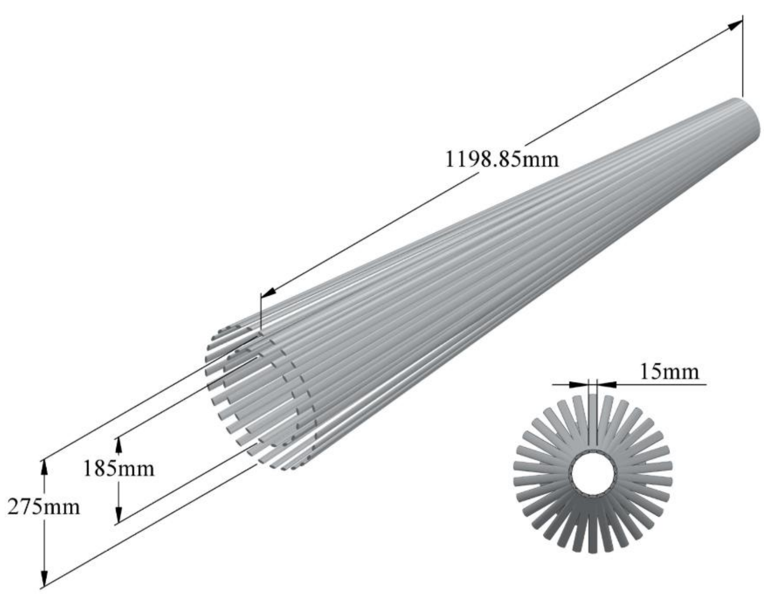


Figure 5 - visualization of the lithium streams comprising the cone and cylinder surrounding the target

The liquid lithium streams or jets must be as smooth as possible because their inductance is proportional to their surface area and must be minimized to reduce the size of the pulsed power systems. Therefore, the stability of the jets is of primal importance to multiple systems. This means the jets must remain in laminar flow until they converge.

In the following jet stability calculation, an arbitrary value of 4 has been assigned to the disturbance factor a/δ_0[i] The symbol "δ_0" represents an infinitesimal disturbance in the flow at the exit of a nozzle and "a" is the radius of the jet. When the infinitesimal disturbance grows to equal the radius of the jet, the flow becomes broken up and is no longer stable because the kinetic energy of the flow will seek to distribute itself over a wider area thus expanding the disturbance and separating the jet into different streams and eventually droplets .

$$\frac{Z}{d} = ln\frac{a}{\delta_0}\left\{We^{0.5} + \frac{3\,We}{Re}\right\} \qquad \textbf{Eq 1}^{i}$$

where

$$R_e = \frac{\rho v D}{\mu} \qquad \textbf{Eq 2}$$

and

$$We = \frac{\rho v^2 l}{\sigma} \qquad \textbf{Eq 3}$$

V.Target Storage and Injection

Target storage of fission capable elements is a challenge. These targets must be easily picked and injected at a rate of 1 Hz; but also be held, spaced apart, so they do not reach criticality. Furthermore, in event of a launch accident the worst case scenario is the target storage system falls into water. With water moderation the system is more likely to reach criticality and would make a runaway reactor meltdown. Thus the storage design must address these issues.

The pellet storage system modeled, as seen in Figure 6, has 104,000, 93% enriched uranium pellets resting on two boron plates. The pellets have a diameter of 3cm and a height of 2.77cm, and the boron plates are one centimeter in thickness. The center to center distance of the pellets is 3.3 cm. The entire storage system is 35 cm in height and 8 meters in diameter with a 1 meter diameter hole in the middle to make way for the lithium. The sabot is 1mm in thickness for the samarium cobalt (SmCo), neodymium (Nd), and copper (Cu) cases. For the copper-boron case (CuB) and the two boric acid cases (CuHBo and CuHBo2), the boron encasing is 0.5mm thick and the copper encasing is 0.5mm thick as well.

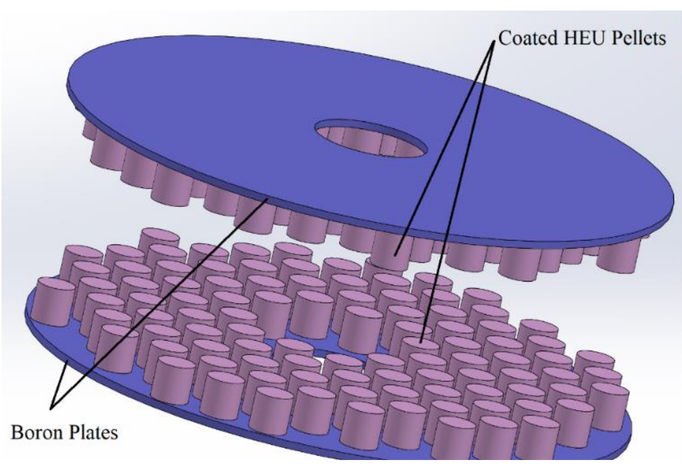


Figure 6 - Concept drawings of original Pellet Storage System. Image not drawn to scale.

To effectively calculate the k_{eff} while the storage system was sinking, MCNP models were created for every centimeter of depth at which the storage system was submerged in water from the moment the storage system lands on water until it is completely submerged. Additionally, further analysis was conducted to ensure that that the system remained subcritical in a vacuum, air, and submerged 100cm under water.

Figure 7 shows the how the k_{eff} changes as the structure sinks in water. All sabot options demonstrate a peak k_{eff} at 3-10 cm immersion; further immersion causes the system to become over moderated.

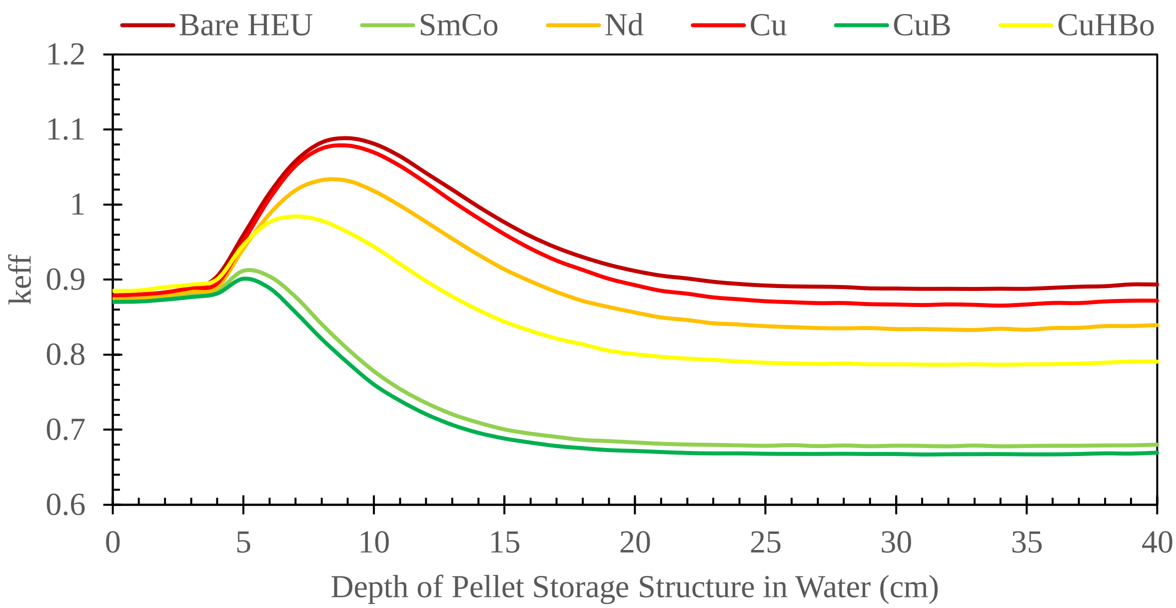


Figure 7 - keff is measured as the pellet storage structure sinks in water using the original pellet storage configuration

The arrangements that meet the requirement of having a k_{eff} below 0.95 are the samarium cobalt sabot (SmCo), the boron-copper sabot (CuB), and the boric acid-copper sabot with the plate in between the layers of pellets (CuHBo2). From these options, the only two that could possibly be manufactured are the samarium cobalt and boric acid-copper options.

Target injection must be sent at a constant rate and precise velocity to ensure proper delivery of the fuel in the implosion sequence. After a review of different methods of giving a velocity to the targets, the coil gun system was chosen as a preferred alternative. The advantages of such a system are that apart for the projectile itself, there are no moving parts that could cause the system to jam. In addition, there is no contact between the target and its injection system as compared to a rail gun, where a sabot/sled would have to be in contact with the rails to close the circuit, creating a large amount of friction and heat. Finally, coil guns are reputedly much more accurate than railguns or mechanical systems, a crucial factor when considering that the location of the target in the nozzle at the moment of implosion needs to be accurate within a few millimeters. The fuel target needs to arrive in the nozzle with a position error no more than ¼ of its diameter or cannot be off by more than 2.5mm when it reaches its final position.

A coil gun is an electromechanical device designed to give momentum to a projectile by pulling it through an energized coil through electromotive forces. The efficiency of the device is determined by the strength of the magnetic field and the effect on the projectile. The currents and fields induced in the projectile are dependent on its material properties especially the permittivity and permissivity, or the way a material reacts to a nearby magnetic field. The target is a solid cylinder of Uranium 235 which is less susceptible to being affected by magnetic fields than iron by several orders of magnitude. For this reason, the target will probably have to be surrounded by an iron sabot to increase the overall efficiency at which the magnetic field of the coil gun pulls on the target.

A computer based analytical model was made to offer insight in the field strengths needed to achieve the required velocities. The first step was to create a coil geometry in CAD that has an internal diameter of 100mm, is 100mm in length and has 10 turns of copper wire 4mm in radius. This geometry of this single coil is shown in the image below.

The following step was to import the above described geometry into COMSOL, a Multiphysics simulator, and setup the simulation. The coil was defined as being made of copper, with 10 turns and exited by 10 Amperes of current.

The results of that first simulation underlined the need for more turns in the coil since the predicted field strength at the center of the coil was ≈12mT and the simulated one was no more than 5mT.

Figure 8 - Geometry used for coil simulations

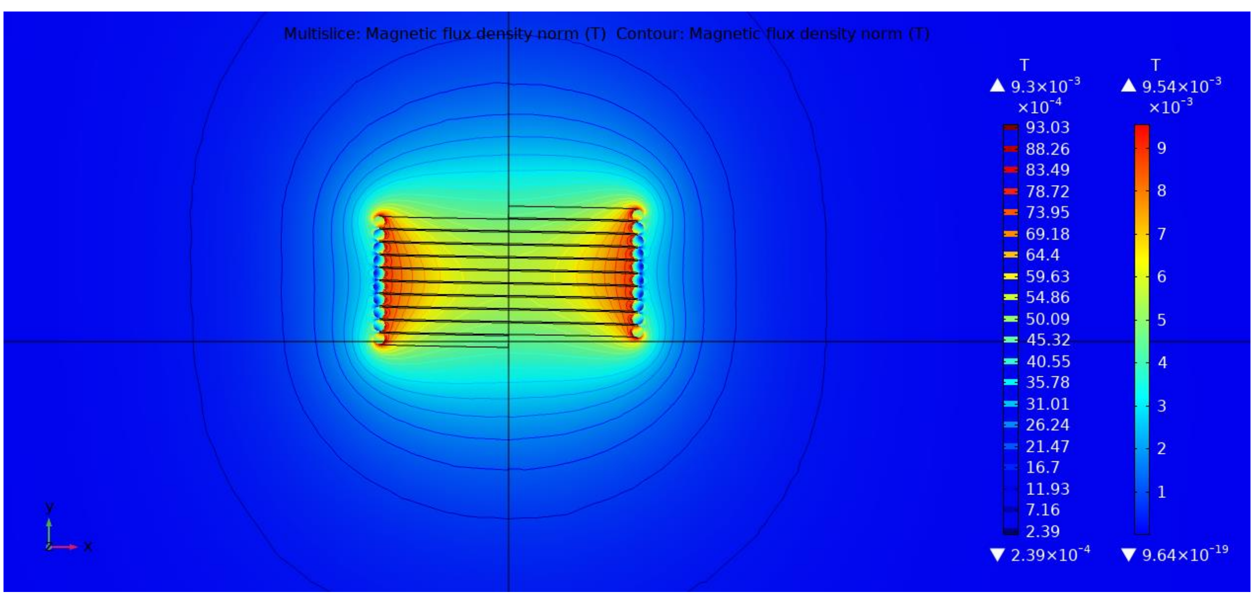


Figure 9 - 10 turn coil magnetic fields strength simulation at 10A

The procedure was then repeated with four of the same coil used previously producing a total coil that was 400mm in length and had 40 turn, still powered by 10A. The results of this second simulation are shown below.

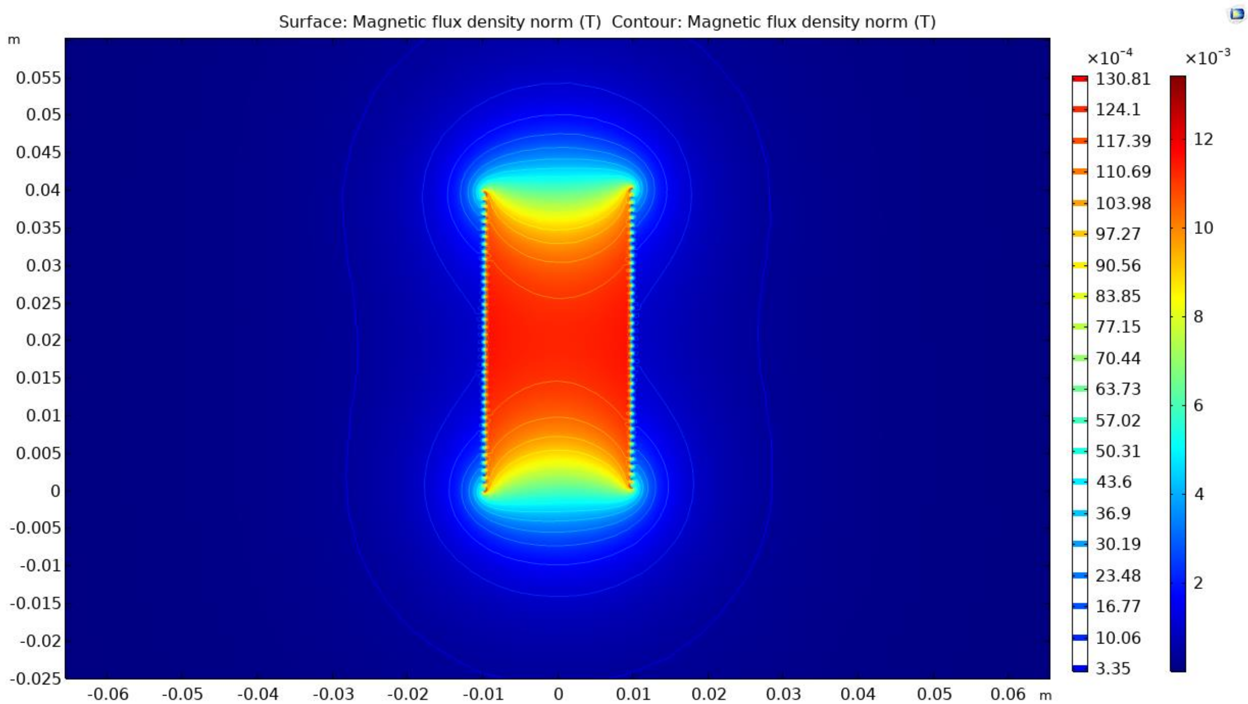


Figure 10 - 40 turn coil magnetic fields strength simulation at 10A

Increasing the number of turns by a factor of four saw the magnetic field strength increase to a value closer to the predicted ne, around 12mT. The final step in this preliminary study by simulation was to insert a sabot emulator, in this case a rod of iron with very high permittivity to observe the interaction between the field created by the energized coil and the ferritic material. The results of this final step in this preliminary approach are shown in the image below.

The last simulation seemed to show that the iron rod was interacting well with the coils and was being magnetized.

VI.Nozzle Operation

The expansion of the fusion-grade plasma against the nozzle is simulated using a Smoothed Particle Fluid with Maxwell equation (SPFMax) solver code. SPFMax is a three-dimensional fluid code specifically designed to model problems in inertial fusion, pulsed power, and propulsion. It numerically integrates the three components of position, momentum, and either single or two-temperature energy equations over a distributed set of point masses, “particles,” in which the derivatives are evaluated using smooth particle hydrodynamic methods. Definitions of particle geometry, material properties, and initial conditions are taken as inputs to generate a model. After a fuel target is placed in the nozzle with initial conditions equal to post-implosion conditions, SPFMax simulates the expansion of the gas as seen above. Physical and thermodynamic properties are integrated between points and catalogued. Properties of the propellant particles as they are ejected from the nozzle are used to calculate performance values such as thrust, specific impulse, and efficiency. An example of an expansion of propellant particles inside a nozzle is shown below.

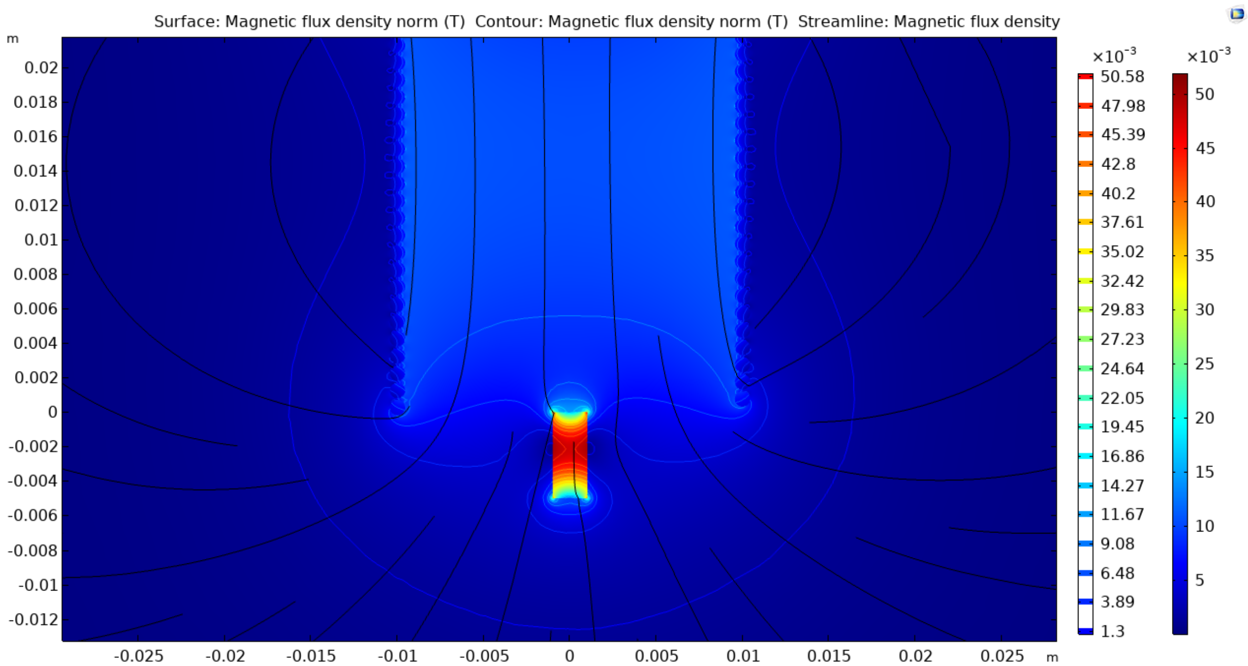


Figure 11 - 40 turn coil magnetic field interactions with iron rod

SPFMax simulates with particles instead of meshes thus, resolution of the simulation is defined by particle counts. The more particles used to approximate a geometry, the more accurate the results. Unfortunately, the time it takes to run a simulation is directly proportional the particle counts in the created geometries. In order to minimize the number of particles required as well as minimize the error in the results from low particle counts. A convergence study was conducted in order to minimize the number of particles and minimize the error in the results from low particle counts. A pair of baseline test cases (BTCs) were used to create a batch of files with varied particle resolutions from roughly 1,000 to 50,000 particles.

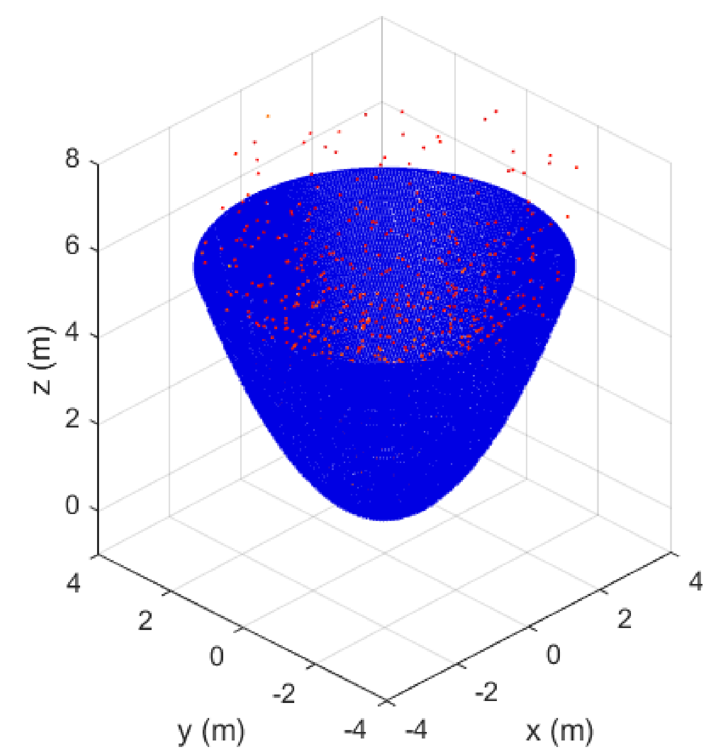


Figure 12 - SPFMax simulation of Lithium and fission/fusion fuel plasma in a solid parabolic nozzle.

VII.Radiation Shielding

The PuFF concept implodes a thermonuclear target which then emits a neutron and gamma/x-ray flux isotopically. Crew and vehicle must be protected from the damage caused by these fluences. Therefore, an effective neutron and photon shield is of the upmost importance to ensure the reliability of the vehicle and the safety of the crew.

Lithium hydride, polyethylene, paraffin wax, lead, depleted uranium, and tungsten were evaluated as potential shielding materials in MCNP to determine which materials would attenuate neutrons and photons the best while causing the least amount of energy deposition to the nozzle.

The probability distribution for both neutrons and photons are needed for the MCNP input file. For U-235, the probability of neutrons produced from fission to be a certain energy is known as the Watt's Function[ii] and is defined as:

$$P(E) = 0.4865\sinh\left(\sqrt{2E}\right)e^{-E}MeV^{-1} \qquad \textbf{Eq 4}$$

Where P(E) is the probability of a neutron produced from fission having an energy of E. The gamma distribution is defined as[iii]

$$N(E) = \begin{Bmatrix} 6.6 & 0.1 < E < 0.6MeV \\ 20.2e^{-1.78E} & 0.6 < E < 1.5MeV \\ 7.2e^{-1.09E} & 1.5 < E < 10.5MeV \end{Bmatrix} \qquad \textbf{Eq 5}$$

The integral of the function was taken and then normalized to find the probability of the photons being within a certain energy range.

The first parabolic nozzle geometry analyzed is composed Inconel 625 with a thickness of 3.6cm, an outer diameter of 750cm, and a length of 625cm. Surrounding the nozzle is FLiBe coolant at a thickness of 3.6cm. The fission source is an isotropic point source located 62.5cm away from the vertex of the parabolic nozzle. A 500g lithium cylinder, compressed by a factor of 10, lies between the source and the nozzle vertex. This target and lithium configuration is the baseline for the rest of the analysis.

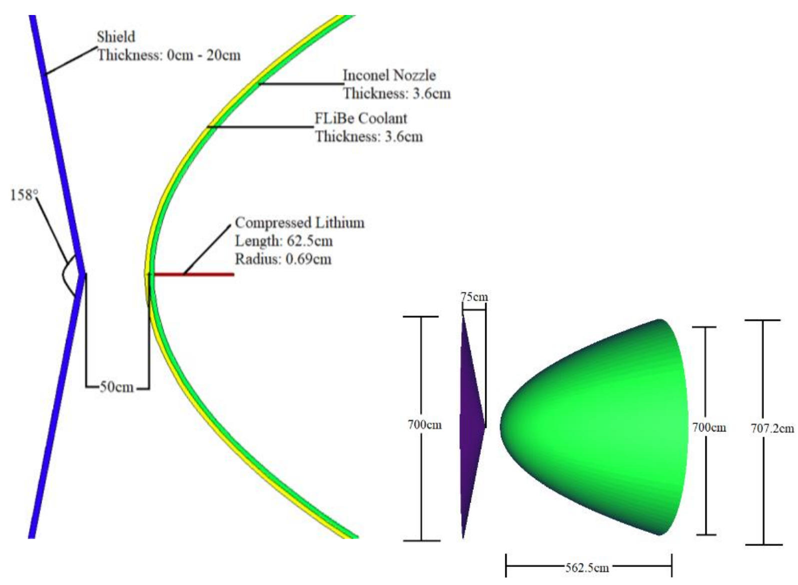
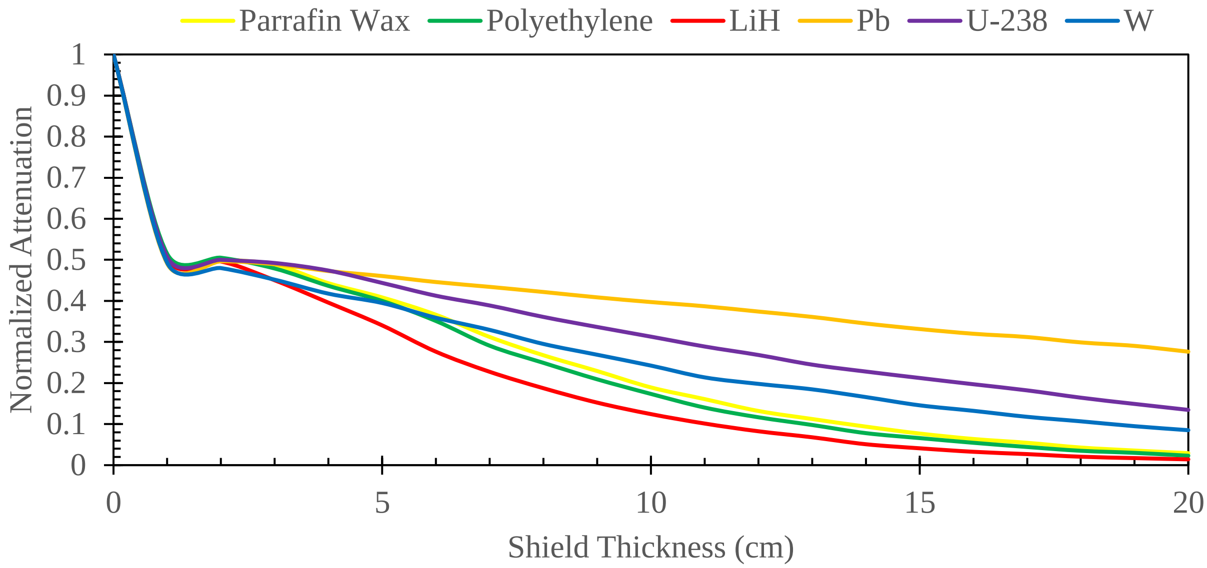


Figure 13 - Close-up cross-sectional view and 3D view of nozzle and shield

The shield is conical and is 750cm in diameter with an interior angle of 158°. MCNP models were created for shields varying in thickness from 0cm to 20cm. The shield attenuation as well as the energy deposition of the source particles to the nozzle and coolant were measured across varying shield thicknesses. Figure 14 below shows neutron and gamma attenuation by material and shield thickness.



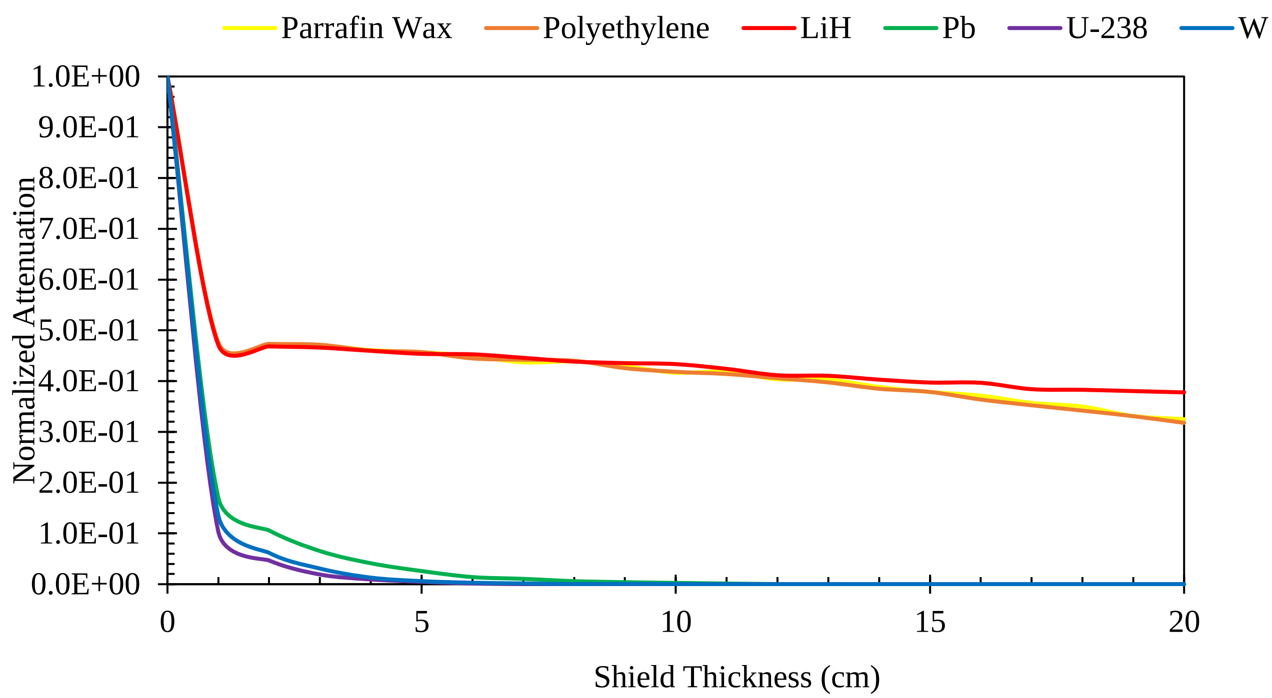


Figure 14 - Neutron (top) and photon (bottom) attenuation by different materials at different thicknesses.

VIII. Conclusions

The PuFF concept is a work in progress, but significant development on critical vehicle subsystems have been done. The work documented herein remains under development as of this publication date and our team continues to move towards a completed vehicle conceptual design.

Acknowledgments

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