Pulsed Plasma Rocket (PPR)
Phase I Final Report

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Executive Summary
The Pulsed Plasma Rocket (PPR) is a spacecraft propulsion concept that aims to address the dual needs for high specific impulse, $I_{sp}$, and high thrust in long-distance space travel. The PPR is derived from the 1960s NASA Project Orion and the more-recent Pulsed Fission Fusion (PuFF) concept under development by NASA Marshall Spaceflight Center (MSFC) [1,2]. The PPR is designed to be less complex, lower in mass, and more affordable than the PuFF concept, while still delivering the needed mission capabilities for effective space travel.

Most propulsion systems involve either electric thrusters or thermal rockets, which provide either high specific impulse ($I_{sp}$) or high thrust, respectively. While many electric propulsion concepts allow for a high specific impulse, thrust is often low, and this lengthens mission times. Electric thrusters with increased mass flow result in erosion and space charge concerns, or else require immense power sources. In the past, propulsion methods that allow for high $I_{sp}$ have been used for long-duration missions where slow acceleration, due to low thrust, is acceptable. In order to have high thrust, a system must have a high mass flow rate, which in turn requires extremely high power since the thermal power required is proportional to the square of the specific impulse and only linear with the mass flow. This also involves higher amounts of propellant relative to the desired payload, due to lower specific impulse.

The Pulsed Plasma Rocket focuses on avoiding these problems and achieving both high specific impulse and thrust by implementing a series of pulsed micro-explosions of very high power. To achieve this, the PPR uses fission processes to produce the energy required to eject plasma as a propellant. Using an unmoderated uranium barrel to assist in high neutron population growth, projectiles composed of moderated uranium are sent through the chamber via a coil gun at high speed. Neutrons within the barrel result in fission in the propellant projectile, while minimizing the fissions in the barrel itself. By inducing rapid fission within these targets, a plasma can be achieved with appropriate delivery of the neutrons. A current-carrying coil within the chamber assists in directing the plasma out of the barrel, and a magnetic compression nozzle transfers the expansion force of the plasma burst to the rocket as kinetic energy.

In Phase I of the PPR Project, Howe Industries focused on evaluating the process of completing a phase change of the projectile from a solid to a plasma in an extremely small amount of time. This research utilized the software MCNP6 and COMSOL Multiphysics for neutron population modeling and thermal calculations [3,4]. Results showed that high fission can be achieved in the time frame required using a control drum system and a fast reactor barrel.

Though the PPR design initially used a neutron pulse to provide the needed neutron population to the projectile for fission, it was found that supplemental systems were capable of rapidly achieving a phase change from solid to plasma. This was largely due to the development of a rotating control drum system, designed to be placed around the PPR barrel, that would assist in managing the desired neutron population. After completing simulations with the projectile, barrel, and drums, it was found that the neutron population could be spiked to create the plasma without an external neutron pulse. This resulted in the neutron pulse method being removed from the design.

In addition to the propulsion system design and analysis, Howe Industries completed an analysis with the help of the NASA Marshall Spaceflight Center for a theoretical mission to Mars using the
anticipated performance of the PPR. This work includes the evaluation of water shielding to protect a human crew, as well as mass comparison for various mission types and orbital trajectories. It was found in the analysis that, even with a water shield, the faster transit time due to lower mass without the water shielding resulted in the lowest exposure to radiation for a human crew.

Lastly, subsystem analysis for major components of the PPR was performed by subcontractors. Modeling of the projectile speed and material properties was performed by Hbar Technologies. Modeling of the plasma and nozzle expansion against magnetic fields was completed via the Smooth Particle Fluid with the MAXwell equation solver (SPFMax) software, used and developed by University of Alabama Huntsville. North Carolina State University provided input in the neutronics time-dependence evaluation.

The PPR system requires further specified study in the area of time-dependent neutronics analysis, as well as further thermodynamics analysis, to increase fidelity and determine the precise capabilities of the pulsed system. This, as well as demonstrations of high power thermal mitigation, projectile acceleration and pulsed magnetic field deflection of a plasma will be the primary foci of a Phase II study.

The PPR Phase I study found that a small amount of fuel can be excited into a plasma state using a fissioning system, and accelerated and ejected from a spacecraft, resulting in significant propulsion. The end result was a novel propulsion system which provides high Isp and high-thrust that would be optimal and revolutionary for interplanetary travel. This technology can significantly decrease the transit time to Mars as well as drastically increase payload masses and capabilities of spacecraft throughout the solar system.
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1. Introduction

The Pulsed Plasma Rocket (PPR) is an advanced nuclear propulsion concept that will serve as a third stage rocket for major space exploration missions. The primary technological advancement of the PPR is using a fission based nuclear power system to rapidly cause a phase change in a fuel projectile from solid to plasma during a pulsed cycle.

Currently, spacecraft propulsion systems benefit from a high specific impulse ($I_{sp}$), that is, a high ratio of momentum imparted to propellant consumed. Plasma can be accelerated significantly using electric or magnetic fields due to its own inherent electromagnetic properties. However, plasma itself is not a fuel that can be loaded into a tank and then used as propellant; it is extremely hot and therefore nearly impossible to contain in a stable state for long periods of time. By creating plasma in bursts, the PPR can overcome these difficulties and successfully use plasma as a high thrust, low mass fuel, allowing for a high $I_{sp}$.

The PPR aims to successfully achieve plasma bursts via a fission system, avoiding the complexities and steep power requirements of a fusion-dependent propulsion system such as that used by PuFF. To create these plasma bursts, a highly moderated Low Enriched Uranium (LEU) projectile can be used in combination with a subcritical nuclear system. A fast reactor LEU barrel with a short section of High Enriched Uranium (HEU) at its base will assist in neutron population growth. When the projectile is placed inside the subcritical barrel, the entire system becomes supercritical, and a $k_{eff}$ greater than 1 can be maintained.
To achieve a rapid phase change in the projectile from solid to plasma, rotating drums made of neutron absorbing material on one side and neutron reflecting material on the other are placed around the barrel. When only reflecting material from the drums faces inwards towards the critical assembly, neutrons in the system are reflected instead of absorbed, creating a sharp jump in the neutron population.

Once the projectile is near the end of the barrel, all drums are rotated inwards so that neutrons are reflected back into the system. However, merely rotating all the drums on the same cycle results in either long periods of high/low $k_{eff}$ values or multiple spikes per firing. To combat this, the drums are designed to rotate at different speeds, which forms a delta function in criticality right as the projectile is in the optimal position. This action results in the increased fission rate that is needed to heat the projectile into a plasma rapidly.

After ejecting pulses of plasma propellant from the system, a compression coil at the back of the ship will take kinetic energy from the plasma expansion and allow the ship to be moved forward. Design of this compression coil shows that from a $3.2e9$ J energy output from the plasma expansion per pulse, $29$ MJ can be regained.

**Transition of Projectile Fuel from Solid to Plasma**

![Diagram of projectile fuel transition](image)

1. 2.2 kg Projectile launched into barrel at 1600 m/s
2. System, consisting of the barrel and projectile, is now critical, and the projectile has become a gas
3. Gas is transitioned to a plasma due to additional fissions from the HEU-end and the reflection of neutrons by the control drums (drums not shown)

*Figure 2: The process of the projectile passing through the barrel (not to scale). The barrel is mostly made of HALEU, with a 10 cm section of HEU at the end to contribute to a higher criticality when the projectile transitions from gas to plasma.*
This 29 MJ pickup from the plasma burst assists the power system of the rocket, easily allowing continued firing. The kinetic energy the ship gains from the plasma bursts, meanwhile, translates to the high thrust output desired due to the rapid firing rate.

### 2. Neutronics Design

A critical component of the PPR design process is the neutronics modeling and analysis. The neutronic behavior determines the ability of the system to quickly produce a plasma from a solid projectile, since this phase change depends on a high number of fissions occurring in the solid to produce the needed thermal energy for the transition to a plasma.

The primary method of neutronics modeling, as completed by Howe Industries, was completed using MCNP6, a Monte Carlo-based particle transport software developed by Los Alamos National Laboratory [3]. MCNP6 takes initial inputs for a system and then predicts the neutron population growth given the system characteristics.

The premise for the operation of the PPR was that the barrel would be a sub-critical assembly which would become critical as the projectile fuel entered the system due to the injection of the additional nuclear material. This assembly has the benefit of intrinsic safety in that the barrel is not generating power without a projectile fuel additionally in place. However, the system works equally well using the control drums to control criticality. Both options were considered in the rocket design.

Both the barrel and the fuel projectile must be considered in the neutronics analysis. Because the fuel projectile is intended to be turned from a solid into a plasma via thermal energy produced by fission, the projectile was planned from the start to be made of a moderated uranium material. The goal being to maximize fissions and heat output in the projectile as it travels through the barrel so that by the end it has become a plasma that will propel the spacecraft forward. Simultaneously, the heat in the barrel was minimized to keep the barrel temperature low. This results in a “well” designed projectile, with optimal moderator to fuel ratios, and a “poorly” designed barrel which has no moderator and operates on a fast spectrum.

The main components of the neutronics analysis include the overall system analysis to establish feasibility and design requirements, and the analysis to evaluate the identified necessary subsystems. These subsystems include the bullet, barrel, and neutron population control system.

#### 2.1 Neutronics System Modeling

#### 2.1.1 Neutronics Modeling with MCNP6

The core functionality of the Pulsed Plasma Rocket depends on the ability of the design to produce a plasma from a fuel projectile at a pulsed rate. In order to produce this plasma from the projectiles, Howe Industries determined that a combination of a neutron control system and a reactor barrel that the fuel would travel through would be needed.
The barrel is a component of the system that must last for the ship's intended travel time. Its purpose is to assist in control of the neutron population of the entire system, specifically by raising the overall system criticality above 1. The barrel also serves as a component of the projectile chamber; the current-carrying coil that pushes the projectile forward via electromagnetism is embedded within the barrel to protect it from the heat of the plasma.

![Figure 3: A design of the PPR propulsion system made using Autodesk Inventor. Shown is the barrel, in green, along with the current-carrying coil that will allow control of the projectile and plasma. The coil is embedded in the barrel for most of the distance that the projectiles will travel so as to protect it from the high temperature plasma and neutrons.](image)

The energy multiplication in the system, which includes both the barrel and the fuel projectile, is assumed to follow:

\[
\frac{dN_{\text{fiss}}}{dt} = \frac{k_{\text{eff}}^{-1}}{l_p} * N_{\text{fiss}}
\]

where \(N_{\text{fiss}}\) is the number of fissions occurring, \(K_{\text{eff}}\) is the measure of criticality, and \(l_p\) is the reactor period. [5] From this relationship, it can be reasonably assumed that \(N_{\text{fiss}}\) will exponentially grow with time at a rate depending on \(K_{\text{eff}}\) and \(l_p\).

Hence, a smaller reactor period results in a faster rate of fissions. The reactor period for a thermal reactor is around 0.1 milliseconds and for a fast reactor it is around 0.1 microseconds. The PPR is designed to have a \(K_{\text{eff}}\) only slightly greater than 1, and for a thermal reactor this results in the necessary neutron growth taking several milliseconds to occur. Because of the projectile's injection speed and the time to grow the neutron population, a thermal reactor design results in an extremely
long barrel to meet the needs of the system. By using a fast reactor instead, the desired neutron population growth occurs in tens of microseconds, allowing for a shorter barrel. The injection speed must also be increased in this case to prevent the system going supercritical. However, the period of time in which the projectile is a hot, but uncontained, plasma is significantly shorter with a fast reactor period, which allows for the very rapid spiking of power necessary for interaction with the magnetic nozzle.

In the first design iteration, a neutron pulse was examined as a method of delivering a boost of neutrons to the system to force high population growth in the projectile so as to cause a phase change to a plasma. [6,7] Several configurations were modeled using MCNP6 to determine the K_{eff} value and thus the neutron population growth versus axial position of the bullet. It was found, however, that a neutron pulse could only provide 1 e12 neutrons, and this addition to the system did not result in a noticeable change to the total population.

Additionally, initial efforts determined that the attempt to drive the system supercritical with the projectile insertion would limit the maximum K_{eff} levels which could be achieved at the critical plasma formation point. After several iterations examining barrel length, bullet diameter, and bullet designs, it was determined that an additional method would be needed to reach the criticality desired.

This reinforced the idea of using rotating control drums to assist in neutron population management. The criticality of the system can be altered by drums along the outside of the barrel, as the drums will have neutron reflector material on one side and neutron absorbing material on the other side. When the reflectors are turned in, the criticality will increase. When turned out, criticality drops. Normally, this is done for control of a reactor and is not particularly dynamic. However, this project benefits from an extreme increase in criticality just as the projectile passes through the end of the barrel. The neutron absorption also assists in managing the neutron population between pulses, which keeps the barrel component from experiencing more fissions than necessary.

Ideally, a very brief peak in criticality can be produced for the moment that the projectile must complete its phase transition to a plasma. To achieve this, the control drum design included the modeling of a Fourier series to approximate a close equivalent to an impulse or delta function. Using this principle, continuously rotating drums at different speeds around the barrel will cause a single, sharp peak in criticality.
at each firing time. This will exponentially increase the power generated in the projectile by increasing the number of fissions occurring and allow it to become an ionized plasma in a matter of microseconds. The design and analysis of the rotating drums is discussed in Section 2.3.

Figure 6: Criticality levels of the system as the projectile passes through the barrel (top). The criticality is shown to change with time and position but remains significantly higher than a Keff of 1. The energy deposition in the bullet, HALEU barrel, and HEU sleeve versus axial position of the bullet are shown in the bottom figure. The Keff plot shows that the neutron population continues to grow while the energy plot shows that the growth favors the bullet over the barrel.
To determine that the criticality of the system would meet the requirements, modeling of the fuel projectile and barrel with MCNP6 was then performed with the drums rotated in for the moment of peak criticality. The projectile was first placed external to the bullet, then moved through the barrel. The results of these calculations are shown in Figure 6 above.

Because MCNP6 does not account for time dependencies and assumes steady state, the criticality at different positions in the barrel was found by modeling the projectile at eight different axial positions over the length of the barrel. This model does not include any neutron pulse or active criticality manipulation but demonstrates that the system can reach a criticality above 1 and it can be modeled in a transient analysis as it travels.

The power generation ratio between the projectile and barrel were also found, with the best geometry so far producing a ratio of 25:1, where 25 times more energy per unit mass deposition is seen in the projectile than the barrel. (See Section 2.4.1, Fuel Projectile Design) Thus, the projectile will heat much faster than the barrel.

As the bullet passes through the barrel the system will increase in supercriticality. The neutron population in the projectile will continue to increase due to this, and it will generate thermal power at an increasing rate. The barrel surrounding the projectile will have a fraction of the power deposited, and the projectile will pass by the affected area quickly. This will allow the neutron population in each section of the barrel to die down between firings, as well as allow a cooling system to remove waste heat.

The projectile will generate heat until the point that it melts but will continue to travel. Once it gets hot enough to gasify, it will begin to expand and attempt to contact the sides of the barrel. At that moment, an increase in power generation will be necessary to turn the gaseous projectile into a fully ionized plasma so it can interact with the magnetic field of the nozzle. The generation period of the reaction and the speed of the expanding gas are key components of this analysis.

Given the relation

\[ I_{sp} = \frac{C}{g_0} \]  

(2)

Where \( C \) is the effective exhaust velocity and \( g_0 \) is Earth's gravitational constant, it can be determined that for a desired \( I_{sp} \) of 5,000 s, the effective exhaust velocity is roughly 50,000 m/s. Thus, the approximate rate of expansion of the projectile matter should be on the same scale. As the gas only has to travel a few centimeters before contacting the wall, there are microseconds in which to fully ionize the plasma.

The reactor period for moderated LEU systems is on the order of 100 us, and for fast systems it is close to 10-100 ns. Therefore, there will be a number of periods in which to exponentially grow the power levels. The successful ionization will depend on the excess criticality of the system at that point, the reactor period, and the geometry of the system. In order to ensure success, the barrel may be flared at that point to form a “combustion chamber” and measures will be taken to increase criticality as much as possible. The flaring of the barrel has also shown to have value in protecting the structural integrity of the barrel from the extreme plasma temperature (see Section 2.5).
The primary method of increasing the criticality will be through the geometry of the barrel. It may become thicker at this point as necessary, so the criticality of the system spikes at that point. It may also include higher HEU loading, as a band of high enrichment will not constitute a large increase in cost or effort.

2.1.2 Validation of Neutronics Modeling via MAMMOTH

North Carolina State University provided an independent validation of Howe Industries’ neutronics modeling by examining the results with a different software approach. This modeling utilizes high-fidelity neutronics codes, Serpent, MAMMOTH, and RATTLESNAKE, to evaluate neutronics based on geometry cross-sections of the PPR design.

Serpent is a three-dimensional continuous-energy Monte Carlo reactor physics burnup calculation code which can be used to simulate particle transport for multiple applications [8]. Geometry descriptions in Serpent rely on universe-based constructive solid geometry models, which enables the description of any two- or three-dimensional fuel or reactor configuration. Serpent tracks particles using ray-tracing based surface tracking and rejection sampling-based delta-tracking and uses cross sections from continuous-energy ACE format cross section libraries and additional thermal scattering data libraries for common moderators. It is capable of adjusting cross sections based on nuclide temperatures on the fly using built-in Doppler-broadening preprocessing capabilities. A comparison was made between Serpent and MCNP6 for a previous design of the PPR, which shows excellent agreement.

The Multiphysics Object Oriented Simulation Environment (MOOSE) is a framework providing a flexible plug-in infrastructure that simplifies definitions of physics, material properties, multi-physics coupling, and postprocessing [9]. The MAMMOTH application was used to develop the PPR steady state model used by NCSU. The MAMMOTH application is a general reactor physics wrapper that leverages existing applications to solve complex multi-physics problems. MAMMOTH currently links the RATTLESNAKE radiation transport code, the RELAP-7 thermal-fluids code, and the BISON fuel performance code into a single simulation framework [10]. RATTLESNAKE is a radiation transport solver for the Boltzmann radiation transport

![General workflow of PPR modeling using Serpent and MAMMOTH](image-url)
equation capable of modeling neutron, photon, and thermal radiation interactions with materials [11]. RATTLESNAKE relies on user-provided material properties describing particle interaction with background media and fixed variables to compute quantities of interest.

In this work, A Monte Carlo model of PPR was built using Serpent 2 to prepare the steady state reference and neutronics data, as can be seen in Figure 7. The multigroup cross-sections are generated with Serpent-2.0 using the ENDF/B-VII.1 nuclear data library in 2-group energy structure. Since performing the energy structure optimization is possible due to the time constraint, the 2-group structure is selected to demonstrate the computational workflow. The Serpent cross-section generation is universe based, therefore, both heterogeneous and homogeneous universes are tallied in unique universes.

In MAMMOTH, cross-sections are generated externally and converted to a MAMMOTH compatible format, such as xml format, using an external utility. After the Serpent calculation is complete, the tabulated group constants and cross-sections (in your_input.sss_res) are then read by an external ISOXML utility, illustrated in the figures below. The ISOXML module processes
the data and prepares the XML file with cross-sections and reference fluxes by searching file name patterns based on grid index such as, `your_input_indexnumber.sss.res` with index 1. The index number is linked to how many state points (temperatures) are being evaluated. In this case, one state point is being evaluated with fuel temperature (`TBullet` in Figure 9) set to 1250K; therefore, the `indexnumber` is set to 1. The Serpent data is then read in two neutron energy groups (NGroup)

![Figure 9: Sample input of the ISOXML utility](image1)

and six delayed neutron groups (NDL Groups) in transport mode, implying that all the necessary cross-sections for the transport equations are being read. The xml format cross-sections (shown in Figure 10) are tabulated according to unique universes (ID=”2001”) and assigned accordingly in Rattlesnake.

![Figure 10: Sample xml format cross-sections generated using ISOXML utility](image2)

After the cross-sections are converted to a MAMMOTH-compatible format, a steady state model of the PPR was built using MAMMOTH as shown in Figure 11. The two-group neutron transport using the self-adjacent angular flux (SAAF) continuous finite element method (CFEM) weak form using the SN method of angular discretization was used to model the neutron transport for the steady state model. The materials used in the mesh were defined using the cross-sections generated using the ISOXML utility and assigned to their respective blocks.
All Serpent calculations are performed using 100,000 neutrons per cycle with 1,000 active cycles. Figure 12 shows the core eigenvalue as a function of the bullet computed by Serpent. It can be seen that as the relative position of the bullet to the barrel changes, the $k_{\text{eff}}$ fluctuates in the range of approximately 250 pcm (between 1.1177 and 1.1202). The peak value occurs when the bullet is approximately 10 cm and 40 cm in the barrel, while a dip is observed when the bullet is located in the center of the barrel. Further comparison of the neutron balance indicates that the lower criticality is mainly the result of a slightly higher fast neutron leakage rate probably caused by the geometric core configuration when the bullet is positioned at the center of the barrel. This figure differs from the MCNP6 models in figure 6 slightly due to the fact that this effort did not include the extra HEU band for increased criticality at the exit.

Figure 12: Core $k_{\text{eff}}$ against the bullet position. Values from this effort correspond strongly to the MCNP criticality modeling effort.
The computed kinetic parameters are shown in Table 2. They will be utilized in the time-dependent core model to be developed in the next phase.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron generation time (s)</td>
<td>1.0519E-6</td>
</tr>
<tr>
<td>Prompt neutron lifetime (s)</td>
<td>1.1779E-6</td>
</tr>
<tr>
<td>Effective delayed neutron fraction</td>
<td>7.3211E-3</td>
</tr>
</tbody>
</table>

Table 2: Time constants computed using perturbation theory by Serpent

Efforts have been made in this study to construct the high-fidelity simulation models using Serpent 2 and MAMMOTH to evaluate the preliminary design of the PPR. The focus has been placed on investigating the overall workflow and identifying methodologic and data gaps to assess in the next phase of the project. The current work is limited to the neutronics perspective including the generation of reference neutronics solution and multigroup cross sections using MC code Serpent 2, the development of computational mesh in MAMMOTH/Rattlesnake, and the testing predictive capability of steady-state transport solvers.

Further system design should take on evaluation and improvement of the performance of the fast reactor design, preliminarily assessed in Phase I studies, using the high-fidelity modeling and simulation tools and advanced optimization methods.

2.2 Laser Generated Neutron Pulse

As mentioned in the overview, the original concept for the PPR included using a fast pulse laser to inject an intense pulse of neutrons into the fuel projectile. Recent research by several teams had demonstrated that a sub-nanosecond laser pulse was capable of generating neutrons with energies greater than 10 MeV with an intensity of over 1e20 n/cm²/s [6,7]. Through this process, it was expected that using such a pulse could initiate fissions in the PPR fuel projectile. This could potentially be performed when k_{eff} was high to maximize fission production.

MCNP6 was used to model configurations where 1e12 neutrons were injected into the system. The results showed, however, that the added neutrons were significantly smaller than the already existing neutron population within the projectile. Modeling determined that 1e18 neutrons would be needed to convert the ~2kg projectile into a plasma, given a starting temperature of several eV. Thus, adding 1e12 neutrons would be an almost unnoticeable amount to the existing population.

After reviewing the modeled criticality results of the drum system with a fast barrel reactor, it was determined that there would be no need to include a neutron pulse laser in the PPR system due to
the high performance of the control drums and fast reactor alone. Therefore, the laser-generated neutron pulse was abandoned as a subsystem of the Pulsed Plasma Rocket design.

2.3 Control Drum Design and Modeling

To control criticality in the Pulsed Plasma Rocket (PPR) engine design, six rotating control drums are placed outside the LEU barrel. This drum control system must keep the criticality low to prevent overheating; criticality must only be increased for each executed firing time. Maximization of criticality will be optimized by the drums via a single periodic impulse. This will be achieved by rotating the drums at different, specified rates.

Howe Industries investigated the needed rotational speeds and periods of each of the six drums, which when combined as a system will produce the intended periodic impulse at a firing rate of 1 Hertz. The resulting equation of the approximated, normalized delta function Fourier expansion was then determined. Lastly, errors and commentary on the initial system controls were reviewed, in consideration of future areas of focus.

Figure 13: Image of an early 3D design including the control drums, shown as thin gray cylinders around the green barrel. Neutronics modeling has since determined that the control drums will be larger, but with a similar design implementation.
The basis of the rotating control drums for the PPR system is in Fourier series system modeling [12, 13]. The PPR system requires a periodic impulse, representing the maximization of criticality, with suppression of the output signal between each impulse to prevent overheating. The Dirac delta function can be used to model the ideal expected input. The definition of the Dirac delta function is:

$$\int_{-\infty}^{\infty} \delta(t - a) \, dt = 0$$  \hspace{1cm} (3)$$

$$\delta(t - a) \, dt = 1$$  \hspace{1cm} (4)

And this can be used to model the impulse response of the drum control system [12]. Each drum in the system can be modeled with a periodic function, where each function becomes a component of the system’s harmonics. This represents a Fourier Series, which start with the base form of

$$f(t) = \frac{1}{2} a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t)$$  \hspace{1cm} (5)

Where \(\omega_0\) is the fundamental frequency that depends on the period, \(T\), \(\omega_0 = \frac{2\pi}{T}\). The coefficients for a Fourier Series, \(a_p\) and \(b_p\), are known for the case of \(\delta(t - a)\):

$$a_n = \frac{1}{\pi} \int_{-\pi}^{\pi} \delta(t - a) \cos nt \, dt = \frac{1}{\pi} \cos na$$  \hspace{1cm} (6)

and

$$b_n = \frac{1}{\pi} \int_{-\pi}^{\pi} \delta(t - a) \sin nt \, dt = \frac{1}{\pi} \sin na$$  \hspace{1cm} (7)

These coefficients are then applied to the delta function’s Fourier series, resulting in

$$\delta(t - a) = \frac{1}{2\pi} + \sum_{n=1}^{\infty} \frac{1}{\pi} \{\cos na \cos nt + \sin na \sin nt\}$$  \hspace{1cm} (8)

$$\delta(t - a) = \frac{1}{2\pi} + \sum_{n=1}^{\infty} \{\cos(n(t - a))\}$$  \hspace{1cm} (9)

For the case of the PPR, the sine term can be removed. Using the above equation, the series can be expanded to six terms, \(n=6\), to model the individual equations that will apply to each of the six rotating drums.
Figure 14: Graph of six expanded terms of the Dirac delta Fourier equation, modified to model a pulsed wave. For the PPR control drum system, the result from these rotation periods would provide peak criticality approximately each second-long cycle, when each drum would be rotated so that the neutronics reflection material faces inwards.

Table 3: Equations, periods, and rotational speeds found for each of the six control drums to produce the desired signal suppression and single criticality spike.

<table>
<thead>
<tr>
<th>Drum</th>
<th>Equation</th>
<th>Rotational Speed (rad/s)</th>
<th>Period (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drum 1</td>
<td>$\frac{12}{25\pi}\cos 6.3(t-1)$</td>
<td>2.0121$\pi$</td>
<td>0.9940</td>
</tr>
<tr>
<td>Drum 2</td>
<td>$\frac{12}{25\pi}\cos 12.6(t-1)$</td>
<td>4.0057$\pi$</td>
<td>0.4993</td>
</tr>
<tr>
<td>Drum 3</td>
<td>$\frac{12}{25\pi}\cos 18.9(t-1)$</td>
<td>6.0085$\pi$</td>
<td>0.3329</td>
</tr>
<tr>
<td>Drum 4</td>
<td>$\frac{12}{25\pi}\cos 25.2(t-1)$</td>
<td>8.0113$\pi$</td>
<td>0.2496</td>
</tr>
<tr>
<td>Drum 5</td>
<td>$\frac{12}{25\pi}\cos 31.5(t-1)$</td>
<td>9.9451$\pi$</td>
<td>0.2011</td>
</tr>
<tr>
<td>Drum 6</td>
<td>$\frac{12}{25\pi}\cos 37.8(t-1)$</td>
<td>10.6818$\pi$</td>
<td>0.1872</td>
</tr>
</tbody>
</table>
Each drum equation follows the format of

$$\delta(t - a) = \frac{1}{2\pi} + \frac{1}{\pi} \sum_{n=1}^{\infty} \cos(t - a)$$

going to \(n = 6\). The final equation is as follows:

$$f(t) = \frac{12}{25\pi} [\cos 6.3(t - 1) + \cos 12.6(t - 1) + \cos 18.9(t - 1) + \cos 25.2(t - 1) + \cos 31.5(t - 1) + \cos 37.8(t - 1)]$$

Figure 15: Individual signals of each control drum. Combined, these signals undergo destructive interference, except for the result of a single extreme peak. This allows a pulse wave to be created with the different rotating drums.

The multipliers within the system were used to adjust the system so that there was no vertical displacement from zero greater than 1, to represent maximum criticality, and so that the frequency of the final result was 1, for a firing rate of 1 Hertz.

Though a basic model for six rotating control drums was created and supplies the desired impulse every cycle while suppressing the signal at other times, the period is not exactly 1 second. For the generated periodic signal, the period must be calculated to be closer to 1 second to prevent signal
drift over time. Otherwise, the exact period can be extracted from this model, and the firing rate of the LEU pellets could be designed to match this period.

To further study this design, the rotational speeds of the drums must be evaluated. In this analysis, the control drums are all being considered as point masses for simplicity. For the actual control drums, which have a currently proposed radii of 9 centimeters, the angular speed at the drum’s edge would be greater than the speed at the center. As an example, drum six has a rotational speed of approximately 10.68 radian per second, which results in about five 360-degree rotations every second. This speed would need to be checked against the engineering of the drum mechanism, to ensure that the drum can sustain this speed.

Further work on this system’s design should also include a more rigorous derivation of the six-term harmonic model, with a focus on the application of state system controls. However, this analysis shows that criticality can be effectively influenced and the desired delta function achieved with this process.

2.4 Fuel Projectile Design
2.4.1 Fuel Projectile Neutronics
The neutron generation rate, given in Section 2.1, demonstrates the benefits of using a fast reactor design due to the smaller reactor period.

However, the energy deposition in the bullet benefits from moderating the neutrons entering the fuel projectile from the barrel because the fission cross section of $^{235}$U is 512 barns at thermal energies and 1 barn at fast energies. Moderating the neutrons is done using materials with low atomic number, such as hydrogen, lithium, boron or carbon. Thus, the bullet is composed of combinations of these materials.

Howe Industries performed a series of MCNP6 calculations to determine the composition and form for the bullet. These calculations were used to evaluate if any Uranium was required in the projectile composition, or if exoergic, neutron absorbing reactions with Lithium-6 or Boron-10 would provide sufficient energy release. However, the fact that the resulting alpha particles were on the scale of 2 MeV and the reaction did not generate any subsequent neutrons, determined that the power generated in the projectile was insufficient for the purposes of this task.

In addition, several calculations were made to compare the moderating ability of Lithium-7, Boron-11, Carbon-12, and H$_2$O. The results of these calculations, made using MCNP6, are shown in Table 4. These showed that H$_2$O is the best moderator but is very close in performance to Lithium-7. Both are significantly better than carbon or boron.

The bullet design initially started out as a three-layered configuration with the HALEU layer in layer two, the middle layer, and moderator in the outer and inner most layers. This allowed any neutrons coming from the barrel to become moderated, and any neutrons formed in the projectile to be moderated. However, given that one of the goals is to minimize fissions in the barrel, removing the outer moderator layer was also explored later in the project as a way to maximize the energy deposition ratio.
**Table 4:** Three layers, or cells, of material including HALEU and various moderators were examined using MCNP6 to evaluate energy deposition in the fuel projectile.

<table>
<thead>
<tr>
<th>Cell 1</th>
<th>Cell 2</th>
<th>rho (g/cm³)</th>
<th>cell 3</th>
<th>Edep 1</th>
<th>Edep 2</th>
<th>Edep 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>U_{HALEU}</td>
<td>U_{HALEU}</td>
<td>19.3</td>
<td>H₂O</td>
<td>.031</td>
<td>.016</td>
<td>.009</td>
</tr>
<tr>
<td>U-C_{matrix}</td>
<td>U-C_{matrix}</td>
<td>.414</td>
<td>H₂O</td>
<td>.036</td>
<td>.022</td>
<td>.009</td>
</tr>
<tr>
<td>U-C_{matrix}</td>
<td>U-C_{matrix}</td>
<td>.414</td>
<td>7LiH</td>
<td>.035</td>
<td>.018</td>
<td>.099</td>
</tr>
<tr>
<td>U-Carb</td>
<td>U-Carb</td>
<td>13.63</td>
<td>7LiH</td>
<td>.024</td>
<td>.014</td>
<td>.013</td>
</tr>
<tr>
<td>7LiH</td>
<td>U-Carb</td>
<td>13.63</td>
<td>7LiH</td>
<td>.013</td>
<td>.011</td>
<td>.008</td>
</tr>
<tr>
<td>6LiH</td>
<td>U-Carb</td>
<td>13.63</td>
<td>6LiH</td>
<td>.019</td>
<td>.004</td>
<td>.016</td>
</tr>
<tr>
<td>B₂H₆</td>
<td>U-Carb</td>
<td>13.63</td>
<td>7LiH</td>
<td>.021</td>
<td>.011</td>
<td>.007</td>
</tr>
<tr>
<td>10B</td>
<td>10B</td>
<td>2.34</td>
<td>H₂O</td>
<td>.017</td>
<td>.0052</td>
<td>.008</td>
</tr>
<tr>
<td>10B₂H₆</td>
<td>10B₂H₆</td>
<td>1.22</td>
<td>H₂O</td>
<td>.061</td>
<td>.02</td>
<td>.0071</td>
</tr>
<tr>
<td>10B₂H₆</td>
<td>10B₂H₆</td>
<td>1.22</td>
<td>7LiH</td>
<td>.068</td>
<td>.024</td>
<td>.0081</td>
</tr>
<tr>
<td>6LiH</td>
<td>6LiH</td>
<td>.82</td>
<td>H₂O</td>
<td>.037</td>
<td>.0094</td>
<td>.0072</td>
</tr>
<tr>
<td>6LiH</td>
<td>6LiH</td>
<td>.82</td>
<td>7LiH</td>
<td>.037</td>
<td>.0098</td>
<td>.0091</td>
</tr>
</tbody>
</table>

*Figure 16: Chart displaying the various energy deposition results for the various moderators examined in Table 2-4.*

However, several calculations of various parameters reveal that a homogeneous mix of HALEU particles in a water ice matrix provide the best ratio of energy deposition, as shown in the figures below. In these analyses, energy deposition is still found across three radial regions of the projectile. This was done to determine the neutron distribution and verify that neutrons were still reaching the center region of the fuel projectile.
Table 5: Homogenous projectile design, consisting of HALEU and water ice, analyzed for energy deposition in the projectile and the ratio of the energy deposition in the projectile versus barrel.

<table>
<thead>
<tr>
<th>U at%</th>
<th>X</th>
<th>X at%</th>
<th>density (g/cm³)</th>
<th>Keff</th>
<th>Edep 1</th>
<th>Edep 2</th>
<th>Edep 3</th>
<th>Edep brill (MeV/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.7</td>
<td>LiH-nat 96.3</td>
<td>2.45</td>
<td>1.11</td>
<td>1.7e-4</td>
<td>1.7e-4</td>
<td>1.4e-4</td>
<td>3.8e-5</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>LiH-50%6Li 96.3</td>
<td>2.45</td>
<td>.94</td>
<td>.94e-4</td>
<td>.91e-4</td>
<td>1.4e-4</td>
<td>3.8e-5</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>LiH-nat 98.</td>
<td>1.74</td>
<td>1.108</td>
<td>1.67e-4</td>
<td>1.67e-4</td>
<td>1.33e-4</td>
<td>3.8e-5</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>LiH-nat 99.</td>
<td>1.282</td>
<td>1.106</td>
<td>1.44e-4</td>
<td>1.48e-4</td>
<td>1.21e-4</td>
<td>3.8-5</td>
<td></td>
</tr>
<tr>
<td>1.</td>
<td>LiH-100%6Li 99.</td>
<td>1.282</td>
<td>1.095</td>
<td>.97e-4</td>
<td>1.04e-4</td>
<td>1.12e-4</td>
<td>3.8e-5</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>LiH-nat 95.</td>
<td>2.982</td>
<td>1.11</td>
<td>1.8e-4</td>
<td>1.7e-4</td>
<td>1.4e-4</td>
<td>3.8e-5</td>
<td></td>
</tr>
<tr>
<td>0.</td>
<td>LiH-100%6Li 100.</td>
<td>71</td>
<td>1.095</td>
<td>1.34e-4</td>
<td>.14e-4</td>
<td>.15e-4</td>
<td>3.4e-5</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>H2O 97.5</td>
<td>1.915</td>
<td>1.133</td>
<td>10.7e-4</td>
<td>10.2e-4</td>
<td>6.4e-4</td>
<td>4.3e-5</td>
<td></td>
</tr>
</tbody>
</table>

Figure 17: Results from the homogenous projectile design. At top, the energy deposition ratio for the projectile versus barrel is displayed, and at bottom the criticality value Keff for each tested moderator and densities is shown.

The final bullet configuration is 0.02 atom % HALEU frozen in water ice with a 5.7 cm radius and 11 cm length. Thus, 1200 g HALEU and 1181 g H₂O. The bullet also contains an outer shell of iron to contain the ice as it melts during transit and to couple strongly to the coil gun injector magnetic fields.
2.4.2 Fuel Projectile Thermodynamics

A review of the thermodynamics of the projectile was completed by Hbar Technologies. This was in part to better design the coilgun system, discussed in Section 3.1, since the vaporization of the bullet and resultant thrust may require that the coilgun power systems also energize a set of coils downstream of the coilgun.

A simplistic geometry of the barrel is illustrated in the figure below. The projectile enters the left side of the barrel at an assumed temperature of 100 K and quickly heats up due to the moderation and absorption of neutrons and the fission events they induce. When the center of the bullet is 11 cm into the barrel, the average temperature of the bullet material (assumed to be in thermodynamic equilibrium) is at a temperature of 1 eV, or 11,605 K. This is above the boiling point of all the constituent materials and above the decomposition temperature of water. At this temperature all of the hydrogen is fully ionized.

![Figure 18: Illustration of a fuel projectile traversing the barrel. The barrel is placed downstream of the coilgun.](image)

The amount of heat necessary to elevate the temperature of the bullet to 1 eV is dominated by the latent heat of formation of the water and the heat of ionization of the hydrogen atoms. The contributions from the uranium (1.5% of total) and iron (3% of total) are negligible. Adding up everything, including the various heats of fusion and heat capacities, yields a total input energy of 201 MJ per projectile. Note that this is 57 times the kinetic energy of the object itself. The instantaneous thermal power is 5.4 TW, since the projectile traverses the 11 cm in a period just under 70 ms.

![Figure 19: Temperature milestones of the projectile as it traverses the barrel from left to right.](image)
As shown above, the temperature of the projectile rises sharply as it enters deeper into the barrel. For the purposes of Phase I it is assumed that the projectile material remains in thermodynamic equilibrium with the temperature increasing linearly over the remaining 22 cm in length.

The energy required to raise the bullet temperature from 1 eV to 500 eV (5.8 million degrees Kelvin) is 3180 MJ, or 900 times the kinetic energy of the bullet. Because it takes the projectile approximately 140 ms to traverse this 22 cm, the peak thermal power imparted to the projectile material is 46 TW. At the 11 cm position within the barrel the protons have a longitudinal root-mean-square (RMS) velocity of 91 m/s. At the 33 cm position the same protons have a longitudinal RMS velocity of 2039 m/s, faster than the terminal velocity of the projectile.

In the frame of the moving projectile, its length therefore increases, starting at 11 cm and ending up with a crudely estimated length of 49 cm at the exit of the barrel. Whereas the longitudinal density profile of the hydrogen within the projectile starts off as a square pulse, by the end of the barrel the density profile resembles a Gaussian bell-shaped curve.

Similarly, in the radial direction the projectile radius starts off at 5.7 cm. If the barrel is allowed to flare in radius so as not to constrain the RMS velocity of the protons near the radial edge, the barrel needs to increase to a radius of 24 cm by the time the protons exit. This represents a conical half-angle of the wall of approximately 45 degrees. This estimate is based on the assumption of the iron shell being in thermal equilibrium with all of the other materials within the projectile. Because the projectile heats up so fast, there is no time for conductive heating of the iron. Since all of the naturally occurring isotopes of iron have a thermal neutron absorption cross section less than 2.5 barns, direct neutron heating will not dominate. Therefore, it is highly probable that the iron sheath around the bullet will remain a solid far deeper into the barrel. This transient heating of the iron will be the subject of intense calculations during Phase II.

The core of the projectile heats up so rapidly that protons originally close to the center of the projectile do not have sufficient time to migrate to the barrel wall. Therefore, they build up a very high pressure at the center of mass. The precise thermodynamics of such a neutral two-component plasma, wherein the electrons and protons are not in thermodynamic equilibrium with one another (similar to a gas discharge tube), need to be studied more carefully during Phase II. The effect of a uranium barrel in intimate proximity to such a plasma also needs to be extensively studied at the same time.

2.4.3 Fuel Projectile Thrust Generation
The goal of the propulsion system is to generate a thrust of 100 kN. The acceleration of the projectiles toward the barrel alone generates an average thrust of 4.4 kN. Therefore, the other 95.6% of the thrust originates from the energy released by fission.

Consider a bullet traveling down a uniform barrel. When it turns into a plasma, the core of the plasma is at high pressure, meaning that the dominant population of hydrogen atoms in the plasma are bumping into each other with high frequency (short mean-free-paths). But the hydrogen atoms near the front and back of the original bullet are unconstrained and move away from the core at a RMS velocity dictated by their temperature. If the barrel could actually contain the radial pressure
and its surface did not invoke viscosity and friction, the plasma would come out of the barrel with the same average momentum of the bullet.

Without some mechanism for taking the radial velocity of the hydrogen atoms and converting them into longitudinal motion toward the back of the ship, no more thrust than the original 4.4 kN is generated. This is analogous to setting off a bomb in a pipe. Unless you cap one end of the pipe, there is no net momentum transfer.

In order to maintain constant internal barrel pressure, the previous section discussed the scenario wherein the barrel is flared. Unfortunately, that radial bore profile does not efficiently convert radial momentum into net backward longitudinal momentum. Because the velocity of the dominant protons previously composing the bullet are moving at velocities comparable to the terminal velocity of the bullet, and the bullet is now a two-component plasma rather than a collection of molecules, the problem is no longer calculable invoking the ideal gas law, Van der Walls forces, and Carnot cycles. Instead, the penetration and deceleration of protons and electrons in the barrel material via change in energy over position, elastic Coulomb scattering, and other particle physics concepts take over, requiring a completely different set of calculational tools.

Those tools include the calculation of focusing of elementary particles by various magnetic field configurations. For example, an azimuthal magnetic field generated by a wire running down the center of the plasma would focus the moving radially moving protons into the longitudinal direction, converting that radial momentum into needed longitudinal momentum. Unfortunately, such a magnetic field defocuses the electrons, driving them into the walls of the barrel.

Such a simplistic picture is not valid for very large populations of charged particles due to the effect of their respective electric charges. Basically, the motion of large, dense populations of charge create self-generated electric and magnetic fields that are orders of magnitude larger than the externally applied fields. An analogous example is the distortion of the Van Allen belts under the influence of the solar wind protons.

The projectiles contain 50 moles of water molecules. Once ionized, this translates into 100 moles of protons. The total charge of protons in the plasma pulse is 9.6 million Coulombs. Multiplying by the bullet velocity of 1600 m/s, the peak current within the pulse traveling down the barrel is 15 GigaAmperes. The electron current is equal and opposite. Any attempt at magnetic deflection will have a bigger effect on the electrons due to their smaller mass. But any change in their density distribution will generate a large radial charge imbalance, causing electrostatic forces that are far more powerful.

During Phase II it will be critical to innovate a system for harnessing the radial motion of the plasma particles into directed longitudinal momentum. In one potential solution, the mass of the bullet times the final temperature of the plasma means that 3180 MJ was imparted to the bullet by fission. The kinetic energy of the bullet imparted by the coilgun is 3.5 MJ. Assume that 30% of that heat is transferred into the barrel as the associated hydrogen gas escapes the barrel. That leaves 1000 MJ. Assuming 30% conversion efficiency into mechanical motion or electrical power, 300 MJ can be added to the kinetic energy of the bullets. That raises the average thrust contribution
of bullet acceleration up to 76 kN. Converting radial momentum of the plasma into backward longitudinal momentum then has to contribute the remaining 24 kN.

A far more elegant solution is suggested by the manufacturers of modern high-performance turbines in jet engines. These jet engines acquire superior characteristics when the combustion gases have a temperature higher than the operating temperature of the material comprising the turbine blades. The solution is to perforate the blades with small holes that allow for a thin layer of cool air to insulate the blades from the combustion gases.

![Graph](image)

**Figure 20: Thickness of liquid water needed to stop protons of a given kinetic energy.**

Similarly, a thin layer to steam can be used to scatter and stop the 150 eV protons that are expanding toward a traditional rocket nozzle. Figure 3.1 contains a plot of the penetration depth, or range, of a proton of a kinetic energy into liquid water. At 500 eV the protons a stopped within 18 nm. At these kinetic energies nuclear scattering is comparable to the effect of electrons, and large angle Coulomb scattering off of the hydrogen nuclei within the water molecules will cause a large percentage of incident protons to be reflected back into the plasma.

Just to be on the safe side, assume a steam layer near the inside surface of a traditional rocket nozzle that is equivalent to 100 nm of liquid water at a density of 1 g/cm³. If the nozzle is approximately one meter in diameter and one meter long, only one gram of insulating water is needed per bullet. Since each bullet contains 900 g of ice, the temperature dilution effect of this insulating water on exhaust velocity is negligible.

Similar to the jet turbine blades, the rocket nozzle can be composed of sintered and porous tungsten-rhenium that can wick the steam through the nozzle wall in pulses appropriately timed with respect to the plasma pulse arrival. The thermodynamics, particle physics, and thrust efficiency of this architecture will be extensively examined during Phase II.
2.5 Time Dependent Heat Generation

Howe Industries built a time dependent transport code for the PuFF project to determine fission induced heating rates and material temperatures. The code was altered to model the movement of the bullet in the barrel in the PPR project. The bullet was moved computationally along the axis with a time step of 5e-8 s. The bullet was injected at 1600 m/s. At each step, the axial location was found and the $K_{eff}$ and energy deposition were interpolated, as shown in Section 2.1.1. The change in the number of fissions was calculated using the equation describing energy multiplication in the system, given in Section 2.1. The energy from the fissions was uniformly distributed among all atoms in a region to determine the average temperature. The results of these calculations showed that a 11 cm long fuel projectile composed of a homogeneous mix of HALEU and water-ice gave the highest ratio of heating in the projectile to the barrel. The projectile has a mass of approximately 2.2 kg. The barrel was 33 cm long and consisted of HALEU metal except for a 10 cm long by 2 cm thick ring of HEU at the end of the bore. The mass of the barrel is 522 kg.

The results are plotted above. The temperature of the projectile hits 1 eV at the 21 cm position in the center, at which point the iron shell of the projectile will melt. All material of the fuel projectile will reach at least 1 eV at 25 cm into the barrel. This is slightly later than the assumed depth in the projectile thermal analysis, but still well within the acceptable range.

The high temperatures of the plasma-state projectile are a significant hurdle in the design of the PPR. Even a 1 eV plasma will erode the walls of the barrel tremendously. The initial intention in the design was to utilize a solenoidal magnetic field to contain the plasma. The coil that delivers this field would be inside the barrel, to keep it from being exposed directly to the hot temperatures within.

Calculations using the basic relation of magnetic field pressure,

$$P = \frac{B^2}{2\mu_0}$$  \hspace{1cm} (12)
Where \( B \) is the magnetic field, \( P \) is the pressure, and \( \mu_0 \) is vacuum permeability. The pressure here also correlates directly to energy density, Joules per cm\(^3\). As the plasma forms and expands outwards within the barrel chamber, the magnetic field was compressed and its strength increased. Because the pressure on the plasma follows \( B^2 \), the confinement pressure increases as the wall of the plasma approaches the wall of the barrel and keeps the plasma confined.

These calculations found that the magnetic field required to effectively confine the plasma was too large to produce. To remedy this issue, the barrel design changed so that a flare could be introduced earlier in than expected in the geometry, likely at 21 cm along the barrel length. This flare would allow more expansion of the plasma without endangering the barrel integrity.

The increased flare of the barrel will impact criticality and temperature growth, however. In future work on the PPR, this would be an area that would need to be further studied to ensure that the design is the best solution.

Additionally, the projectile confinement viability was examined by the University of Alabama-Huntsville team. Specifically, the confinement model was considered for the initial burn duration by ramping up a current so that the magnetic field pressure exceeded the gas pressure. Assuming a temperature of 1 eV inside the barrel, it was found that a liquid-density water slug would require a magnetic field strength of 250 T, which can be achieved by driving a pulsed current in a solenoid around the target such as shown in Figure 22.

![Figure 22: Illustration of a PPR water target enclosed in a solenoid field while in the sub-critical state.](image)

While this additional analysis showed that the solenoidal field could provide notable confinement pressure for the projectile target, this modeling did not account for the supercritical plasma-state confinement. It is this final state that likely requires further support, proposed currently to be the flaring of the barrel.
3. Supporting Systems

The operation of the PPR system relies on a pulsed mode where extremely high power and thrust takes place, and a rest period is used to return the system to normal. Systems that will support the actual plasma rocket mechanism will include: the projectile injector system, thermal management, a magnetic nozzle, and electrical power generation, i.e. closing the power balance loop.

3.1 Coilgun Design and System Integration

The system integration of a coilgun and associated power supplies and switching gear requires trade-offs between efficiency, mass, and volume. In addition, the vaporization of the bullet and resultant thrust may require that the coilgun power systems also energize a set of coils downstream of the coilgun, around the barrel that induces nuclear criticality. Because of this, the coilgun design involved a review of the projectile thermodynamics, as discusses in Section 2.4.2.

The basic parameters dictated by the nuclear physics of heating the bullet with a fast fission chain reaction are summarized below, as is a sketch of the bullet.

Table 6: Bullet characteristics treated as input variables.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass of the Uranium and Ice within Bullet (g)</td>
<td>2150</td>
</tr>
<tr>
<td>Terminal Velocity of the Bullet (m/s)</td>
<td>1600</td>
</tr>
<tr>
<td>Bullet Frequency (Hz)</td>
<td>1</td>
</tr>
<tr>
<td>Bullet Outside Diameter (cm)</td>
<td>11.4</td>
</tr>
<tr>
<td>Bullet Length (cm)</td>
<td>11</td>
</tr>
<tr>
<td>Thickness of Iron Shell Encompassing Bullet (cm)</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Figure 23: Sketch of the bullet, wherein an iron shell surrounds a mixture of ice and uranium.
Using the known densities of uranium, ice, and iron, the total mass of the bullet was calculated. The results of this calculation are summarized in Table 7. Using the other parameters listed in Table 7, the kinematics of the bullet were calculated as a function of the bullet acceleration rate. Assuming uniform acceleration, these kinematics dictate the peak power and length of the coilgun acceleration system. The peak power results are displayed in Figure 24. In these plots the bullet acceleration is quantified in units of Earth surface gravities (g’s), or 9.8 m/s². Smart munitions used by the United States military can survive accelerations throughout this range. Note that for a coilgun length of 10 m, the corresponding uniform acceleration rate of 13,060 g’s dictates a peak power delivered to the bullet of 282 MW. The average thrust applied to the ship due to the acceleration of the bullets is 4.4 kN, compared to the total propulsion system goal of 100 kN.

Table 7: Calculation results of the total mass of the bullet.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of Iron (g/cc)</td>
<td>7.86</td>
</tr>
<tr>
<td>Density of Uranium (g/cc)</td>
<td>19.1</td>
</tr>
<tr>
<td>Density of Ice (g/cc)</td>
<td>0.917</td>
</tr>
<tr>
<td>Volume of Iron (cc)</td>
<td>77.4</td>
</tr>
<tr>
<td>Mass of Iron Shell (g)</td>
<td>608</td>
</tr>
<tr>
<td>Total Mass of the Bullet (g)</td>
<td>2758</td>
</tr>
<tr>
<td>Bullet Terminal Kinetic Energy (MJ)</td>
<td>3.53</td>
</tr>
<tr>
<td>Average Power Invested into the Bullets (MW)</td>
<td>3.53</td>
</tr>
</tbody>
</table>

Given the specified terminal velocity of the bullet after the coilgun, the terminal kinetic energy of the bullet is calculated. Given the acceleration frequency of the bullets, the average power delivered to a stream of bullets is also listed. The efficiency of converting electrical power supplied to the coilgun to average bullet power is assumed to be 70%. The resulting power supply system must therefore be capable of sourcing 5 MW of average power.

The cost of a power supply system is not generally determined by the average power, but by the peak power it must deliver. This cost is driven by such components as high-current switches and capacitor banks. The traditional rate of $1 per Watt is used when estimating terrestrial systems. Assuming a peak power of 282 MW and a 70% conversion efficiency, this cost is found to be $400 million.

The other issue with high peak power systems is the radiation tolerance of the capacitor banks and the mass of the interconnecting conductors. These are issues that are proposed to be studied extensively in Phase II. Given these concerns, an alternative system of a dual coilgun was proposed.
The actual coilgun length is typically dictated by the length of uniform acceleration times a packing fraction. Systems such as particle accelerators use the concept of a packing fraction to estimate their actual length (in the case of linear accelerators) or circumference (in the case of synchrotrons). In these accelerators, the actual length of components such as RF cavities and bending magnets include power leads, insulators, vacuum valves, pump ports, and instrumentation. For example, a 100 MeV linear accelerator composed of RF cavities each delivering an acceleration rate of 1 MeV/m might actually be 200 m long, corresponding to a packing fraction of 50%.

The individual acceleration coils within a coilgun share many characteristics with RF cavities comprising linear particle accelerators. Therefore, for the purposes of this Phase I study a packing fraction of 50% is also assumed. Therefore, the actual length of the coilgun in Figure 24, corresponding to an acceleration rate of 13,060 g’s, is closer to 20 m.

For the purposes of this Phase I study it was assumed that the coolant maintaining the temperature of the barrel was water/steam. A loop was considered in which the steam temperature out of the barrel was 1200 K. At this temperature, the water molecules have a velocity of 1052 m/s, too low to fully accelerate a bullet up to 1600 m/s. But this steam velocity is sufficient to accelerate a magnetic projectile up to a lower velocity, for example 400 m/s. For a magnetic projectile of mass 90 kg, the exit kinetic energy from a steam cannon would be 7.2 MJ, twice the terminal kinetic energy of the bullet.

There is a modern-day allegory that justifies consideration of steam-driven projectiles rather than the use of railguns or coilguns. The most expensive aircraft carrier ever built cannot launch fighter jets since the electromagnetic catapult and catch system on US Navy’s $13.2BN USS Ford keeps breaking, three years after it entered service [28]. Older carriers use a steam-driven catapult for propulsion and hydraulic-engine arresting gear. An assessment of the Ford’s electromagnetic catapult was based on 3,975 launch and landing operations on the aircraft carrier during 11 post-delivery trials at sea, conducted from November 2019 through September 2020. The system was expected to be able to carry out 4,166 launches before experiencing operational mission failures. Instead, it managed just 181 cycles between failures, which well below the system design requirement. The dominant problem with the system is the high pulsed power electronics including the energy storage capacitors and high-current high-voltage switches.
In two-beam accelerators, a low-energy high-current beam excites a set of radiofrequency cavities that then transmit their power into a parallel set of cavities that accelerate a high-energy low-current beam. Modern klystron tubes power particle physics accelerators in a similar fashion. The same is true for conventional microwave ovens.

In a similar concept illustrated below, the slow and heavy magnetic projectile induces power in an array of primary windings that transmit their power to a set of secondary windings driving the bullet. This architecture completely eliminates the mass and complexity of high-voltage capacitors and high-power switches.

*Figure 25: Illustration of a two-beam coilgun architecture. This system could increase overall efficiency and cost-effectiveness of the PPR system by removing further electrical power system requirements.*

Because the magnetic projectile travels at a velocity lower than the bullet, and the magnetic projectile is slowing down while the bullet is speeding up, the relative spacing of the corresponding windings vary along each coil array. If a magnetic field is desired for confining the plasma within the barrel, additional primary windings can be added, converting magnetic projectile kinetic energy into magnetic potential energy. Once the magnetic projectile reaches the end of the primary coil array, a spring or some other mechanism is used to return it back into the cannon.

### 3.2 Nozzle Design

University of Alabama Huntsville (UAH) assisted in providing support in modeling Pulsed Plasma Rocket performance with magnetic nozzle designs to produce higher specific impulse. Notional performance goals are 5,000 s Isp and 100,000 N thrust. UAH utilized a 3D smooth-particle-hydrodynamics simulation tool SPFMax to model the plasma expansion against various magnetic field topologies. Additional analytical modeling included 1D gas expansion estimates for I_{sp} and
impulse bit and calculation of magnetic field pressure required for confinement of the PPR fuel targets prior to ignition and burn, at which conditions are estimated to be liquid density water at 1 to 2 eV.

3.2.1 Numerical Model

Smooth Particle Fluid with MAXwell equation solver (SPFMax) is a three-dimensional fluid code designed to model problems in inertial fusion, pulsed power, and propulsion [14]. SPFMax has been written in MATLAB, and supports both multicore and GPU computing. All post processing is done with a custom GUI-based tool called SPHplot also developed in MATLAB. SPFMax numerically integrates three components of position and momentum and either single temperature or two temperature energy equations on a distributed set of point masses in which the derivatives are evaluated using smooth particle hydrodynamic methods. The physics include real viscosities, tabular or ideal gas equation of state, heat transfer, shock capturing via artificial viscosity, thermal equilibration between ions and electrons, and single and multigroup radiation emission and absorption. Linear momentum and all particle-to-particle energy interactions conserve momentum and energy exactly by enforcing reciprocity between particle pairs. This is accomplished by averaging interactions between particles.

A new method for evolving electromagnetic fields was developed prior to, and during the period of this contract in order to better address the complicated physics of conductive plasmas expanding into and being redirected by an external magnetic field. Current density is now propagated by a network of transmission line equations based on Kirchoff’s voltage and current laws, with vacuum field propagation handled by efficient superposition of current carrying coil segments in which arbitrary and completely three-dimensional coil geometries can be defined. The governing equations for the electromagnetic field solver are the x, y, and z components of the current density time derivatives, which evolve in time based on local electric fields and finite resistivity,

\[
\begin{align*}
\frac{\partial j_{x,a}}{\partial t} &= (E_x + E_{\varepsilon,x})(\frac{h}{LA})_a + (\frac{\partial j_{x,a}}{\partial t})_\Omega \\
\frac{\partial j_{y,a}}{\partial t} &= (E_y + E_{\varepsilon,y})(\frac{h}{LA})_a + (\frac{\partial j_{y,a}}{\partial t})_\Omega \\
\frac{\partial j_{z,a}}{\partial t} &= (E_z + E_{\varepsilon,z})(\frac{h}{LA})_a + (\frac{\partial j_{z,a}}{\partial t})_\Omega
\end{align*}
\]  

(13) (14) (15)

In these expressions, h is the particle spacing, L is the particle inductance (typically 1-10 nH), and A is the cross-sectional area of the particle. In this form, the contributions to the electric field can come from a variety of sources, but are dominated by potential gradients and the motional electromotive force. The electric field due potential is evaluated with

\[ E = -\nabla \phi \]  

(16)
The electromotive force term is computed with

\[ E_{ea} = \sum_b v_{ab} \times B_b \]  

(17)

where \( v_{ab} \) is the relative velocity of particle \( a \) with respect to all other current sources. It is this latter term which dominates for pulsed magnetic nozzles. The relative velocity between the expanding particles and the stationary current carrying coils are primarily responsible for the electric field induced in the plasma, generating a conduction current parallel to the direction of the external coil current paths. As the current grows from this term in the plasma, the \( j \times B \) force is supposed to redirect the flow away from the nozzle wall and out of the exit. The shape of the coils is important for encouraging this trajectory for the plasma, and it is not obvious what coil geometries promote favorable redirection of the flow. During the course of the simulations, we encountered a numerical instability, in which the current inducted in the plasma enhances the field, accelerating the gas, augmenting the \( \nu \times B \) term, and feeding back into itself or neighboring particles creating a runaway effect. We are currently in the processing of incorporating energy conservation laws for the field and Lorentz acceleration terms to avoid this nonphysical result.

The correction for this numerical instability is underway but could not be completed by the end of the Phase I contract. The approach is documented here. The components of acceleration of a particle due to the current interacting with the local field are given as

\[
\begin{align*}
\left( \frac{\partial u}{\partial t} \right)_a &= \frac{1}{\rho_a} (j_y B_z - j_z B_y)_a \\
\left( \frac{\partial v}{\partial t} \right)_a &= \frac{1}{\rho_a} (j_z B_x - j_x B_z)_a \\
\left( \frac{\partial w}{\partial t} \right)_a &= \frac{1}{\rho_a} (j_x B_y - j_y B_x)_a
\end{align*}
\]

(18)

Time integration of the current driven by external circuits, as discussed above, is regulated by the electric field to conserve charge transport from the circuit into the simulation and vice versa. Internal currents are also generated when an sph particle experiences a relative velocity with any other current carrying element (i.e. other sph particles or external field coil segments). The acceleration in Eq. 18 does not prevent numerical instabilities between particle acceleration by the Lorentz force and the induced electric field generated by \( \nu \times B \). To enable sufficiently large time steps while avoiding these instabilities, conservation of field energy is utilized to determine the allowable acceleration of the particles. Energy conservation of the electromagnetic field per unit volume is discussed in numerous electrodynamic textbooks, such as Chapter 8 of Griffiths 2017 [15], and can be expressed as

\[ \frac{\partial \dot{\epsilon}_{mech}}{\partial t} + \frac{\partial \dot{\epsilon}_{em}}{\partial t} = - \nabla \cdot S \]  

(19)

where \( \dot{\epsilon} \) is energy density in SI units of J/m³, \( \dot{\epsilon}_{mech} \) is the mechanical energy density, \( \dot{\epsilon}_{em} \) is the field energy density, and \( S \) is the Poynting vector. \( S \) is defined as
\[ S \equiv \frac{1}{\mu_0} E \times B \]  
\[ (20) \]

The field energy density is

\[ e_{em} = \frac{1}{2} \left( \varepsilon_0 E^2 + \frac{1}{\mu_0} B^2 \right) \]  
\[ (21) \]

In SPFMax, it is then assumed that the mechanical energy is the kinetic energy

\[ e_{mech} = \frac{\rho}{2} (u^2 + v^2 + w^2) \]  
\[ (22) \]

Neglecting the time derivative of density, Eq. 18 can be expressed on a mass specific basis by dividing by \( \rho \) to determine the rate of change of specific energy allowable to an sph particle ‘a’,

\[ \left( \frac{\partial e_{mech}}{\partial t} \right)_a = -\frac{1}{2} \frac{\partial}{\partial t} \left( \varepsilon_0 E^2 + \frac{1}{\mu_0} B^2 \right)_a - \frac{1}{\mu_0 \rho} \nabla \cdot (E \times B)_a \]  
\[ (23) \]

The term \( \left( \partial e_{mech} / \partial t \right)_a \) is a scalar that does not provide the direction for the time rate of change of kinetic energy, but does provide the magnitude which scales the acceleration, to obtain the scaling factor, denoted \( f_{jXB} \), first an approximate rate of change of specific kinetic energy is evaluated using the acceleration terms from Eq. 17,

\[ \left( \frac{\partial e_{mech,jXB}}{\partial t} \right)_{guess} = \frac{\partial u}{\partial t} + v \frac{\partial v}{\partial t} + w \frac{\partial w}{\partial t} \]  
\[ (24) \]

\[ = \frac{u}{\rho} (j_y B_z - j_z B_y) + \frac{v}{\rho} (j_z B_x - j_x B_z) + \frac{w}{\rho} (j_x B_y - j_y B_x) \]

The scaling factor is

\[ f_{jXB} \equiv \frac{\left( \frac{\partial e_{mech}}{\partial t} \right)_a}{\left( \frac{\partial e_{mech,jXB}}{\partial t} \right)_{guess}} \]  
\[ (25) \]

The corrected time rate of change of specific kinetic energy is

\[ \left( \frac{\partial e_{mech,jXB}}{\partial t} \right)_{corrected} = u \frac{f_{jXB}}{\rho} (j_y B_z - j_z B_y) + v \frac{f_{jXB}}{\rho} (j_z B_x - j_x B_z) \]

\[ + w \frac{f_{jXB}}{\rho} (j_x B_y - j_y B_x) \]  
\[ (26) \]
Assuming that the velocity components do not change significantly in a time step, the final result of this is that the accelerations can be corrected with

\[
\left( \frac{\partial u}{\partial t} \right)_{a,\text{corrected}} = \frac{f_{jxB}}{\rho} (j_y B_z - j_z B_y) \\
\left( \frac{\partial v}{\partial t} \right)_{a,\text{corrected}} = \frac{f_{jxB}}{\rho} (j_z B_x - j_x B_z) \\
\left( \frac{\partial w}{\partial t} \right)_{a,\text{corrected}} = \frac{f_{jxB}}{\rho} (j_x B_y - j_y B_x)
\]

(27)

Prior to the start of Phase II, this fix will be implemented and pulsed nozzle modeling will be routine. We anticipate this based on a myriad of previous problems encountered with various physics in the code, in which energy and momentum conservation enforcing of these physics resulted ultimately in the correct and stable behavior. The results we present here give the promising early insight into how the current evolves for different topologies.

3.2.2 Modeling the Targets from Liquid to Plasma State

To model the PPR target transformation from liquid to a fully ionized plasma state, the equation of state for water is used, with the modeling spanning eleven orders of magnitude in density including compression beyond liquid density.

In application to water vapor, we assume that the composition consists of a mixture of H$_2$O, O$_2$, H$_2$, OH, O, H, H$^+$, O$^{8+}$ and e$^-$. The species consist of e distinct nuclei (O and H atoms and electrons), require six mass action laws, and three conservation laws. The equation of state is tabular and we assume local thermodynamic equilibrium among these species to be a function of specific internal energy and density. The equation of state was calculated from 100 K up to 100 keV. For densities above liquid density, the pressure increases with a power law modeled using the Anton-Schmidt equation for compression of condensed matter. The departure from ideal gas can readily be seen in the curve for $\rho = 2150$ kg/m$^3$, shown in Figure 26, where the pressure rise is exponential instead of linear for temperatures below 1 eV. At lower densities, the increased rise in pressure vs temperature indicates the onset of dissociation and ionization of various species. For fission-relevant burning plasma temperatures of 1 keV, all levels of density behave as ideal gas since the kinetic energy of the particles dominates over inter-particle forces.
3.2.3 3D Simulations of Plasma Expansion in a Magnetic Nozzle

The magnetic nozzle was simulated using solenoid and longitudinal windings, with the figure below showing representative examples of these topologies. In each case, the copper wires represent the segments through which current flows, and the field was computed as a superposition of magnetic fields with Biot’s Savart’s law. The black stream lines represent the direction of the fields, with the solenoid producing primarily axial (z) and radial (r) components. The longitudinal field produces purely azimuthal field. The colormetric slices of magnetic field pressure. Since the longitudinal windings give a null field on axis and increasing magnetic field pressure, it is believed that completed simulations will indicate this topology as the preferable one for producing directed thrust, as has been found in similar simulations previously [16].

![Figure 26: Tabular equation of state developed for water utilized in SPFMax simulations](image)

![Figure 27: Initial magnetic field topology with colormetric slices of magnetic field pressure for (a) solenoid and (b) longitudinal windings.](image)
Thermal expansion of an initially 1000 kg/m³, 1 keV water plasma are shown below. This figure gives the case for the solenoid winding. The plasma expansion radially into the field, developing azimuthal image currents as shown, mostly in the same direction as the external coil winding, due to motional back emf induced by the $v \times B$ motion. At 400 ns, the current pinches into a ring, and the increased $j \times B$ force results in erroneously high acceleration, which is currently being addressed in the model as discussed above.

Figure 28: Thermal expansion of a water plasma against a solenoidal magnetic nozzle at 0 ns, 200 ns, 300 ns, and 400 ns. The colormetric plot represents the expansion speed of the surface of the plasma. Current density vectors are included, showing the development of image currents which are induced by $v \times B$ motion and interact with the mostly axial field in the nozzle.

Figure 29 gives the case for the longitudinal winding. The plasma expansion radially into the field, developing mostly longitudinal image currents as shown due to motional back emf induced by the $v \times B$ motion. This simulation ran considerably longer, nearly 3.5 μs before suffering a similar crash due to anomalously high particle acceleration.
3.2.4 Estimates of Performance using 1D gas expansion

Since the simulations did not run to completion as discussed in Section 3.2.3, estimates of performance are provided by an analytical model now described.

Figure 30 below is an attempt to illustrate an approximate equivalence between steady state and pulsed nozzle. This allows us to estimate thrust and specific impulse for a pulsed system. In (a), stagnation conditions denoted as ‘0’ set the pressure and temperature in the combustion chamber (left), which in the pulsed nozzle is equivalent to the initial compressed, post-burn conditions of the fuel projectile target ‘i’(right) where the area A_i is determined by the outer radius of the target, and it is assumed that the gas initially expands at Mach 1 from this initial state, hence it is equivalence to the throat area. In (b) after choking sonic at the throat, the gas expands through the nozzle, lowering the pressure and temperature and increasing the velocity and Mach number. A comparable, intermediate expansion is seen for the pulsed target (right). Finally, in (c), at the exit, expansion against the nozzle ceases, and thrust, I_{sp}, and other exit conditions can be calculated for both the steady state and pulsed nozzles.
Figure 30: Sequence of plots to show the equivalence of the steady state and pulsed nozzle gas expansion processes. (Top) Stagnation conditions denoted as ‘0’ set the pressure and temperature in the combustion chamber (left), which in the pulsed nozzle is equivalent to the initial compressed, post-burn conditions of the fuel projectile target ‘i’ (right). (Mid) After choking sonic at the throat, the gas expands through the nozzle, lowering the pressure and temperature and increasing the velocity and Mach number. A comparable, intermediate expansion is seen for the pulsed target (right). (Bottom) At the exit, expansion against the nozzle ceases, and thrust, $I_{sp}$, and other exit conditions can be calculated for both the steady state and pulsed nozzles.
The Mach number can be related to the expansion ratio in the pulsed nozzle according to

\[
\left(\frac{A_{exit}}{A_i}\right)^2 = \frac{1}{M_{exit}^2} \left[ \frac{2}{\gamma + 1} \left( 1 + \frac{\gamma - 1}{2} M_{exit}^2 \right) \right]^{(\gamma + 1)/(\gamma - 1)}
\]

which is the familiar area-Mach relation. The exit pressure and temperature are then determined with

\[
\frac{p_i}{p_{exit}} = \left( 1 + \frac{\gamma - 1}{2} M_{exit}^2 \right)^{\gamma/(\gamma - 1)}
\]

and

\[
\frac{T_i}{T_{exit}} = \left( 1 + \frac{\gamma - 1}{2} M_{exit}^2 \right)^{\gamma/(\gamma - 1)}
\]

With the Mach number and temperature known, the velocity and specific impulse can be determined. Preliminary results are given below for Mach number at the exit and specific impulse plotted as a function of Area ratio, Figure 3-9. This shows that the specific impulse increases dramatically up to \( A_{exit}/A_i \) of approximately 10 and diminishing returns are achieved beyond that. It is anticipated that multidimensional modeling, radiation losses, and interactions with the magnetic field will create departures from this ideal behavior, but the basic qualitative scaling is expected to be retained.

![Figure 31: Preliminary ideal modeling of a pulsed nozzle. Exit Mach number and specific impulse are plotted vs expansion (Area) ratio.](image)

### 3.3 Barrel Cooling

Based on the results of the neutronics analysis by Howe Industries, it is known that a cooling system will need to be implemented around the barrel. Hbar Technologies contributed to the work done in investigating the design of this cooling system.

The design intent of the PPR is to isolate as much energy as possible into the fuel projectile, both to trigger rapid fissions within the projectile and to keep heat from entering the barrel surrounding the projectile. Based on results from MCNP6, the heat deposited into the bullet is 25 times higher
than the heat deposited into the barrel. This ratio means there is success in keeping heat from the barrel, however, the barrel will still require some amount of cooling. The energy within the projectiles each cycle will be 3180 MJ, and for the bullet the energy will be 127 MJ, or one-twenty-fifth of the projectile’s energy. This 127 MJ will need to be removed from the barrel approximately each cycle so that the barrel does not overheat.

At a radiator temperature of 1000 K, the minimum area required to dissipate this amount of average thermal power is 2243 m², or a square area 47 m on a side. By the time the heat conduction system is added, this is a very heavy subsystem.

Therefore, the cooling system was investigated wherein this heat was used to directly power the coilgun acceleration system. The next section describes a system that eliminates the need for capacitors and electrical switch gear, instead storing energy in the form of barrel coolant pressure. Assuming an ideal cycle wherein the water is boiled into steam each iteration of the cycle, up to a steam temperature of 1200 K, the cooling water absorbs 0.01 MJ/mole. To cool a barrel thermal power of 127 MW, a total of 12,700 moles of water per second must be circulated. This corresponds to 230 kg of water each bullet pulse.

The thermal systems will include a dynamic waste heat rejection cycle which flows through the barrel to keep it cool. As the system fires, the barrel will heat, and this in turn will heat a working fluid. Additionally, the radiative heat transfer of the plasma to the nozzle may be intense enough to melt bare material, so it will also require a coolant loop. Both of these active heat rejection cycles currently pass directly to radiators to reject waste heat. However, as the current design includes the capability of reaching criticality without the insertion of the projectile, it may be possible to use the barrel as a fission heat source when not actively firing to provide bi-modal operation and generate electric power for the ship at location.

3.4 Shielding

The PPR’s propulsion system depends on bursts of plasma, which in each cyclic firing will reach temperatures of up to 100 eV. While the barrel itself will be cooled using a liquid coolant, the end of the spacecraft, where the plasma is released, will need some components, particularly the nozzle, to be protected from the high intensity photonic heating that results from the close proximity to the thermonuclear events.

Previous efforts, performed by Howe Industries, for the PuFF NIAC project for containing high energy plasma as a propellant have resulted in the use of translucent sapphire to distribute photonic heating profiles volumetrically so the energy can be safely collected for processing.

Stefan Boltzmann’s law shows that the power radiated by an object or particle is proportional to temperature to the fourth power:

\[ P = A\varepsilon\sigma(T^4 - T_{amb}^4) \]  

(31)

The radiated power, \( P \), is equal to the object’s surface area, \( A \), times emissivity, \( \varepsilon \), Stefan Boltzmann’s constant of proportionality, \( \sigma = 5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4} \), and difference between the object’s temperature, \( T \), and the ambient temperature, \( T_{amb} \). The primary concern in this relation
is the temperature terms, as temperature to the fourth power results in a significant heat load to the nozzle. Incorporating the propellant’s view factor of the nozzle leads to the following equation for the radiative heat deposition in the nozzle:

\[
\dot{Q} = \frac{\sigma(T_1^4 - T_2^4)}{\frac{1}{A_1\epsilon_1} + \frac{1}{A_2\epsilon_2}}
\]

(32)

Analysis has shown that the intensity of radiative heat for the fraction of a second during the explosion is sufficient to ablate the surface of any material used to shield the ship from the plasma. This is largely due to the short time frame and the inability of the material to distribute the heat amongst a large enough mass of material to avoid gasifying.

To prevent this ablation, the use of a translucent material such as sapphire could be used in the design [17]. Such a translucent material can be used to distribute the radiative energy over a larger volume, and larger mass, and then spend the time between pulses actively cooling the material.

Demonstrating that this method is more capable than simply allowing a tungsten shield to attempt to absorb the energy will be performed in Phase II.

4. Mission Design

The Pulsed Plasma Rocket's pulsed nuclear propulsion allows it to travel quickly at high thrust and reduce travel times significantly. This is particularly useful when considering the travel times for interplanetary travel which are plagued by the large distances, and therefore travel times, between celestial bodies. These distances restrict transits to Hohmann-like transfers, for which there exist launch windows open for only weeks at a time and staggered up to years apart from one another.

In the case of a transit from Earth to Mars, the launch window for a mission to Mars is only open approximately once every 26 months [18]. This will become a significant challenge if humans seek to establish a colony on the Martian surface, due to extended periods between resupply times and limited or no capability for emergency response support. The limited availability of launch windows also increases radiation doses if a crewed mission is waiting to return from Mars.

Increasing launch window duration would greatly improve a colony’s chance of survival and enable more frequent supply runs. Because of the PPR's high thrust and I_sp capability, these benefits can be met. Howe Industries performed a low-level mission analysis of a potential PPR mission to Mars with the assistance of NASA MSFC to provide a demonstration of these advantages.

In addition, a study was done on the application of a water shield around the PPR's habitation module, as a method of absorbing incoming galactic cosmic ray (GCR) radiation. A trade study comparing the mass of the water shield and the fuel mass for the trip was done alongside the transit time minimization. There would need to be enough water mass to minimize the radiation dose astronauts will experience during the trip, and enough fuel to complete the round trip in as short a time as possible.
The results, evaluated by NASA MSFC and Howe Industries, found that water shielding did not produce high enough efficiency in blocking GCR radiation compared to short transit times. The finalized mission parameters were found to be an 85-day round-trip to Mars, allowing for 20 days allotted to a surface mission.

4.1 Mass Analysis

The Pulsed Plasma Rocket is designed to be launched into orbit as a third stage, beginning ignition in Low Earth Orbit (LEO).

The current design goal of the Pulsed Plasma Rocket is to start in a LEO orbit and quickly transport a 18,500 kg mass of habitat supplies to the Martian surface to support the development of a colony. The relevant and constant PPR design parameters for this conceptual analysis are listed in Table 4-1.

<table>
<thead>
<tr>
<th>PPR Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload Mass</td>
<td>18,500 kg</td>
</tr>
<tr>
<td>Housing Mass</td>
<td>3,200 kg</td>
</tr>
<tr>
<td>Propulsion System Mass</td>
<td>5,000 kg</td>
</tr>
<tr>
<td>Specific Impulse</td>
<td>5,000 s</td>
</tr>
<tr>
<td>Thrust</td>
<td>100,000 N</td>
</tr>
<tr>
<td>Starting LEO altitude</td>
<td>2,000 km</td>
</tr>
</tbody>
</table>

It is estimated that the water shield mass where a minimal amount of radiation reaches the astronauts is 30,900 kg, nominally known as the 30T shield mass. With this much water mass and a cap of 79,100 kg on the current design, the fuel mass for the 30T is 21,500 kg. The available delta-V the PPR can generate is found to be around 15.56 km/s using the rocket equation in Eq. 33 and the parameters from Table 8. This process is used to find the delta-V budgets for all design cases of interest that changes in decrements of 5 metric tons down to the 0T case; this can be found in Table 9.

\[
\Delta V = I_{sp} g_0 \ln \frac{m_o}{m_f}
\]

\[
\Delta V = -I_{sp} g_0 \ln \left( \frac{m_f}{m_o} \right)
\]  

(33)

Where \( I_{sp} \) is the specific impulse, \( g_0 \) is the acceleration of gravity on Earth, \( m_f \) is the final dry mass, \( m_o \) is the initial wet mass, and \( \Delta V \) is the delta-V budget.
Table 9: Varying shield mass and fuel mass cases for the PPR in increments of 5 metric tons; they are denoted by nominal designation based on the shield mass. The total mass considers the constant masses from Table SM1.

<table>
<thead>
<tr>
<th>Nominal Shield Mass</th>
<th>Actual Shield Mass (kg)</th>
<th>Fuel Mass (kg)</th>
<th>Total Mass (kg)</th>
<th>Delta-V Budget (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30T</td>
<td>30,900</td>
<td>21,500</td>
<td>79,100</td>
<td>15.56</td>
</tr>
<tr>
<td>25T</td>
<td>25,900</td>
<td>26,500</td>
<td>79,100</td>
<td>20.01</td>
</tr>
<tr>
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<td>20,900</td>
<td>31,500</td>
<td>79,100</td>
<td>24.91</td>
</tr>
<tr>
<td>15T</td>
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<td>79,100</td>
<td>30.36</td>
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<td>79,100</td>
<td>36.48</td>
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<tr>
<td>5T</td>
<td>5,900</td>
<td>46,500</td>
<td>79,100</td>
<td>43.48</td>
</tr>
<tr>
<td>0T</td>
<td>900</td>
<td>51,500</td>
<td>79,100</td>
<td>51.64</td>
</tr>
</tbody>
</table>

4.2 Mission Trajectory and Range Modeling

Calculating the optimal transit for varying delta-V budgets introduces a number of complications which if solved analytically would go beyond the scope of this project. Generally, a Hohmann transfer can be used to minimize delta-V requirements, and available launch windows quickly found from predicting the positions of the planets at various times in the future. However, to minimize transit times with a surplus of delta-V available, both the initial and return trajectories must be modified. This in turn changes the circularization burns for target insertion, which may also be at varying angles from the flight path.

In order to complete this conceptual analysis, the online tool called Trajectory Browser, created by a team from the NASA Ames Research Center, is utilized [19]. This tool acts as a search engine for previously computed trajectories to hundreds of small bodies around the solar system as well as planets. Once it obtains a trajectory, the site numerically solves for the trajectory path with Lambert’s problem using the Newton Raphson method or the Bisecton method if the former does not converge quickly enough. It needs to be noted that by relying on Lambert’s problem, the trajectories obtained only considers the Sun’s gravitational effects, considers all planets to be coplanar, and ignores external forces on the spacecraft such as solar radiation pressure, all of which is explained in the user guide [19]. The database includes solutions for minimizing delta-V, minimizing mission duration, and a number of other options as seen below.

Figure 32: Input parameters for the NASA Trajectory Browser, which allows for rapid analysis of previously optimized flight paths between planets.
Since only the Sun’s gravity is considered, the delta-V required to escape Earth’s gravity from LEO and the lunar gateway altitude and then subsequently Mars’ gravity from LMO (Low Mars Orbit) at 250 km must be calculated analytically. The difference between the orbital speed at those altitudes and their respective escape velocities is added onto the delta-V budgets from the trajectory browser. The escape velocity is calculated using Eq. 34 based on energy conservation [20].

\[ v_{\text{esc}} = \sqrt{\frac{2 \times \text{(Gravitational parameter of planet)}}{(\text{Radius of planet})}} \]  

(34)

The orbital speed formula pertaining to the altitude of the spacecraft is similar to the escape velocity and can be seen in Eq. 35.

\[ v_{\text{orbit}} = \sqrt{\frac{\text{(Gravitational parameter of planet)}}{(\text{Radius of planet})}} \]  

(35)

In the chronological order of the mission sequence, 2.86 km/s is needed to escape from LEO of 2000 km, 1.42 km/s is needed to arrive at and escape from LMO of 250 km, and 0.41 km/s is needed to arrive at a lunar orbit radius of 3.844e5 km for a total of 6.11 km/s that is added onto every delta-V budget.

One other limiting factor to the Trajectory Browser tool is that it draws from a database of pre-computed trajectories, and so this analysis is restricted to mission trajectories that are achievable by traditional chemical rockets. Because of this, the maximum delta-V that can be used by round-trip missions in the database is around 10 km/s which is well below the capabilities of most of the proposed designs in Table 9. Since the PPR uses pulsed nuclear propulsion, some extrapolation of the data obtained will need to occur and then verified using the General Mission Analysis Tool, or GMAT for short; this program is also developed by NASA and is used for high fidelity trajectory design after low fidelity design studies [21].

The trajectory browser tool works by taking in as inputs the mission type, launch year range, max duration of the mission, the max delta-V that can be used, and whether to minimize delta-V or mission duration. The mission type is set to be a round-trip to Mars and back to Earth, the launch year range is set to be between 2032-2036, the max duration is set to 1.5 years, and the max delta-V is set to 15 km/s. This retrieves two sets of similar trajectories that are somewhat continuous but still discrete in the mission duration and delta-V color scale, as seen in Figure 33.

Since it is desirable to provide an extrapolated range based on as large of a mission duration range as possible, the left collection of trajectories is chosen with its seemingly discontinuous group at the bottom. It can be found that these trajectories simply have a shorter stay time on Mars by 10 days from the original 30 day stay in the upper group. This is due to the necessary alignment of the planets to make the desired launch window, and although the duration of the transit is decreased, so too is the duration of the stay on Mars.
The delta-V and mission duration from all 21 trajectories are taken and plotted against one another with the mission duration on the y-axis in the figures below. Fitting a power curve to the entire data set reveals a R-squared value of 0.9792, a measure of how well the curve fits to the data points with a value of 1 meaning a perfect fit. This slight deviation is attributed to the discontinuity in the stay times at Mars and will increase the error in any extrapolation attempts. Because of this, power fits are applied to the two groups separately revealing an R-squared fit of 0.9505 for the 30 day stay and a R-squared fit of 0.9999 for the 20 day stay data. Then, in order to expand extrapolation ranges even more, the data is modified by adding 10 days to the 20 day stay trajectories and by taking out the lowest three delta-V budgets to achieve a R-squared value of 0.9901 for the entire data set. These four power fits can be seen in Figure 34.

Figure 33: Displayed are the trajectories retrieved for specified inputs to the trajectory browser tool created by NASA. The two data sets are similar in shape trajectories that vary in delta-V used and mission duration. The left distribution is used for this analysis because of the slight discontinuity at the bottom of the distribution which was caused by a 10-day shorter stay at Mars from the rest.
Figure 34: The four power fits generated from the data obtained using the Trajectory Browser tool. The top is the original or non-continuous data fit, the middle is the split fits, and the bottom is the modified or continuous fit.
The power fit equations allow for an estimated mission duration to be calculated using only the mission delta-V. This coupled with the analytical delta-V from gravity effects allows for a mission duration range to be calculated for each PPR design case. The range of mission durations can be seen in Table 10.

**Table 10: Mission duration range for each of the four power curves created and extrapolated outwards.**
The available delta-V shown is after the analytical delta-V due to gravity is considered. As expected, the further out the equations are extrapolated, the wider the range becomes.

<table>
<thead>
<tr>
<th>Nominal Shield Mass</th>
<th>Delta-V Available (km/s)</th>
<th>Non-Continuous (days)</th>
<th>30 Day Stay (days)</th>
<th>20 Day Stay (days)</th>
<th>Continuous (days)</th>
<th>Average (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>30T</td>
<td>9.45</td>
<td>396.26</td>
<td>397.32</td>
<td>381.36</td>
<td>398.98</td>
<td>393.48</td>
</tr>
<tr>
<td>25T</td>
<td>13.90</td>
<td>270.66</td>
<td>272.65</td>
<td>299.45</td>
<td>290.79</td>
<td>283.39</td>
</tr>
<tr>
<td>20T</td>
<td>18.80</td>
<td>200.92</td>
<td>203.13</td>
<td>247.89</td>
<td>227.09</td>
<td>219.76</td>
</tr>
<tr>
<td>15T</td>
<td>24.25</td>
<td>156.32</td>
<td>158.53</td>
<td>211.41</td>
<td>184.40</td>
<td>177.66</td>
</tr>
<tr>
<td>10T</td>
<td>30.37</td>
<td>125.17</td>
<td>127.27</td>
<td>183.61</td>
<td>153.34</td>
<td>147.35</td>
</tr>
<tr>
<td>5T</td>
<td>37.37</td>
<td>102.00</td>
<td>103.97</td>
<td>161.26</td>
<td>129.38</td>
<td>124.15</td>
</tr>
<tr>
<td>0T</td>
<td>45.53</td>
<td>83.92</td>
<td>85.75</td>
<td>142.49</td>
<td>110.05</td>
<td>105.55</td>
</tr>
</tbody>
</table>

Now by having the range defined by four power curves, it is imperative to prove that at least one of these design cases simulated in a high-fidelity program such as GMAT yields a mission duration within the estimated range. The chosen design case for this task is the 0T design since it is the furthest extrapolated range. Since there are two variations in the stay time, two solutions will be found using these stay times. To create the simulation, the starting date is chosen a bit ahead of the Trajectory Browser data Earth departure dates which start on April 7th, 2033 and end on May 7th, 2033. Estimating the extrapolation of the starting date gave the simulation a date of June 1st, 2033. From there, the PPR with specifications taken from Table 8 and 9 is placed at 2,000 km LEO and aligned for firing with Mars. After adjusting the initial delta-V impulsive burn forward and the transit time between the planets so that the spacecraft is relatively
close to Mars at the end of the rough trajectory, a targeting sequence is used to converge the trajectory in approximately 38 days, at which point, the PPR fires to circularize around Mars. After that, the spacecraft is propagated around Mars for 20 and later 30 days, and then the process of alignment and firing to Mars is repeated but for Earth as the target. The completed trajectory for the 20 day stay mission can be seen in Figure 34.

Both missions end with about 100 kg of fuel left which is a small enough amount considering the 51,500 kg the PPR started with. The 20 day stay takes about 97.87 days for its mission duration while the 30 day stay takes about 114.88 days. These both fall within the estimated power curves range which can be seen in Figure 35.

Both missions end with about 100 kg of fuel left which is a small enough amount considering the 51,500 kg the PPR started with. The 20 day stay takes about 97.87 days for its mission duration while the 30 day stay takes about 114.88 days. These both fall within the estimated power curves range which can be seen in Figure 35.

![Mission Duration vs Delta-V - All Four Extrapolated Power Curves](image)

*Figure 36: The extrapolated power curves from the original Trajectory Browser data at around 8-10 km/s. Both 20 and 30 day stay versions of the 0T PPR mission can be seen lying within the range of the extrapolated curves.*

Since the results from GMAT fall within the range, it can be said with relative confidence that the extrapolation holds at least for the 0T design case. In order to further prove the validity of the power curves, more of the design cases need to be simulated using GMAT and their corresponding results plotted.

**4.3 Radiation Exposure Analysis/Measuring the GCR Dosage during Transit**

Besides obtaining more validation points, the next step is to calculate the GCR dosages that astronauts will sustain while onboard the PPR and protected by the water shield. The tool that will
be utilized for calculating this dosage will be the OLTARIS online tool also created by NASA [22]. This tool can take in mission duration and design parameters pertaining to the PPR and its transit to Mars and back as inputs and calculate the dosage an astronaut onboard will receive during the trip. These dosages will then reveal which of the PPR design cases will be the safest and quickest methods of travel to Mars and back.

The OLTARIS tool works by taking in user defined spheres, slabs, or thickness distributions, and calculating the Galactic Cosmic Ray, GCRs, dosage or Solar Particle Event, SPEs, environments the distribution will experience for the transit time input into the tool. For this analysis, only the GCR dosage is considered. To start using the tool, the materials utilized in the spacecraft are generated which are air and water. Since the crew module the water shield protects is based on the cylindrical ISS crew module, specifications from that design are used for the PPR module. The ISS crew module’s dimensions are 4.57 m in diameter and 5.5 m in length [23] for which the volume is translated to that of a sphere since the PPR module will be represented as a sphere in OLTARIS. The reason for choosing a sphere is because GCR radiation will be coming in from all angles through the sphere and its layers of user defined materials, the water and air in this case. The final GCR dosage results are based on how much radiation goes through the central point in the sphere where a tissue model of an adult male will be placed in order to get the total effective dose in milli-Sieverts. The air and water are defined per the properties listed in the Figure 37 screenshots which are the properties at standard temperature and pressure and the current conditions on the ISS [24].

![Table](image)

**Figure 37:** properties for air and water used in the OLTARIS online tool. These were custom materials defined based on the STP conditions currently used for the ISS crew modules.

The representative sphere made from these materials has a layer of water on the outside with the inner layer/sphere being made of air. Of course, there would also be other material such as the various metal linings of the hull and not just the water by itself surrounding the air, but for the purposes of this analysis, only the effectiveness of the water shield is considered. And so, a sphere for every design case of interest is created with the air volume of 90.22 m$^3$ remaining constant between each case. The water shield volume and thickness are calculated based on the formula for a volume of a spherical shell in Eq. 36 and the mass of the water.

\[ V = \frac{4}{3} \pi (r^3 - (r - t)^3) \]  

(36)

Where $r$ is the shell outer radius, and $t$ is the thickness of the shell. The parameters for the 0T and 30T designs are shown in Figure 38.
With the spheres created, individual project jobs were generated for each with the settings found in Figure 38 for the 30T design case as an example. Starting from the top, the environment is selected to be interplanetary free space at 1 AU from the Sun which is assumed to be the case for the entire journey since Mars has a minimal magnetosphere that does little to mitigate GCR doses [25]. The GCR model is selected as “SINP 2016” since the user guide for OLTARIS mentions it is the latest numerical model for GCRs the tool contains [22]. For the mission definition, the historical solar maximum of 2001 and historical solar minimum of 2010 are used to find the GCR dosage range. The solar maximum is where GCR activity is at its lowest point, and the solar minimum is where GCR activity is at highest point [26]. In the geometry parameter, the corresponding sphere created previously is selected. While most of the response functions are selected, the one of interest for this analysis is the effective dose equivalent since it is necessary to know which of the design cases offers the most protection for astronauts.

Table 11: Mission GCR dosages calculated by the OLTARIS online tool for each of the design cases and the solar maximum and solar minimum states of the Sun.

<table>
<thead>
<tr>
<th>Nominal Water Shield Mass</th>
<th>2001 Solar Maximum</th>
<th>2010 Solar Minimum</th>
<th>Mission Duration (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Effective Total Dose (mSv)</td>
<td>mSv/day</td>
<td>mSv/year</td>
</tr>
<tr>
<td>30T</td>
<td>156.0</td>
<td>0.40</td>
<td>144.7</td>
</tr>
<tr>
<td>25T</td>
<td>114.7</td>
<td>0.40</td>
<td>147.8</td>
</tr>
<tr>
<td>20T</td>
<td>91.7</td>
<td>0.42</td>
<td>152.3</td>
</tr>
<tr>
<td>15T</td>
<td>77.5</td>
<td>0.44</td>
<td>159.2</td>
</tr>
<tr>
<td>10T</td>
<td>68.5</td>
<td>0.46</td>
<td>169.6</td>
</tr>
<tr>
<td>5T</td>
<td>63.1</td>
<td>0.51</td>
<td>185.6</td>
</tr>
<tr>
<td>0T</td>
<td>60.9</td>
<td>0.58</td>
<td>210.6</td>
</tr>
</tbody>
</table>
Figure 39: Project parameter selection screenshot that displays the settings used to calculate the effective GCR dose for the 30T PPR mission with an expected transit time of 393.48 days. All other cases have the same settings except for the geometry and mission.

It is clear from the table that while the more massive water shields hold back around 0.2 mSv per day more than the less massive water shields during the solar maximum, the significantly reduced transit times of the less massive shields are the dominating factor in regards to the total dosage of radiation. The 0T sphere receives less than half of the dosage the 30T receives at a fourth of the total mission time. These results imply that having a less massive water shield with fuel to take up the extra mass available would be the path to follow in terms of the astronaut crew’s health and safety during the journey. Though it needs to be noted that all the cases are far below the career exposure limits for astronauts at the age of 25 at around 1,250 mSv as per a space radiation handbook created by NASA [27]. Shown in the figure below are the total and per year dosages from Table 11 plotted against one another to visually show the trends split by solar maximum and minimum. The mSv/year curves appear to follow a power curve implying that adding more water shield mass would not introduce much more radiation protection and would just serve to increase the total dosage linearly due to the increased travel times.
Figure 40: The total effective GCR dose and mSv/year curves for the solar maximum of 2001 and solar minimum of 2010 are shown from top to bottom, respectively, in order of increasing water shield mass. The mSv/year curve follows a power distribution while the total dosage correspondingly transitions into linear distribution.

The analysis presented in this section reveals that the PPR design cases with less water mass are desirable for two major outcomes. The first major outcome is the fact that having less water shield mass allows for more fuel to be brought onboard and therefore for higher delta-V maneuvers to be performed by the PPR. These higher delta-V maneuvers significantly reduce transit times between the Earth and Mars. This enables the second major outcome which is the fact that the astronauts take in almost half the radiation dosage they would experience with the highest water shield mass design case strictly due to only needing a quarter of the transit time. Based on these results, it is highly suggested to choose the lowest water shield mass design case for the Pulsed Plasma Rocket spacecraft.
5. Conclusion

5.1 Phase I Summary of Results

From the initial concept of a fission-driven rapid-fire propulsion system, the Pulsed Plasma Rocket Phase I study cemented the theory behind the design requirements and found validity for the solid-to-plasma transition of the propulsion fuel projectiles.

With neutronics modeling, after determining the limits in the use of neutron laser pulses for the design, it was found that the needed control for the system could be achieved using control drums. Further neutronics modeling determined the moderator material for the fuel projectile that would be able to produce the required heat, through fissions, that would transform the fuel into a plasma state. The barrel was then studied to evaluate the ratio of energy deposition in the projectile versus the barrel to ensure that the system was resulting in significantly greater fissions in the projectile, as desired. Additional transient analysis showed that the criticality could be spiked near the end of the barrel using rotating drums and altered uranium loading to quickly flash the projectile from a gas to an ionized plasma.

Investigation of the confinement of the plasma within the barrel found that it is likely the barrel will need to be flared to protect it from overexposure to the plasma's thermal radiation, rather than relying solely on magnetic confinement of the plasma via a solenoid.

The kinetic requirements of the projectile system were also evaluated, and a study examining the best ejection system was completed. Though a traditional coilgun was found to be sufficient when taking into account the speed provided by the coilgun itself as well as any electromagnetic acceleration from the phase transition to plasma, there was a secondary method of using a dual-beam coilgun that may provide further benefits to the system.

The PPR study also resulted in the further development and utilization of a 3D smooth-particle-hydrodynamics simulation tool, Smooth Particle Fluid with MAXwell equation solver (SPFMax), to model the plasma expansion against various magnetic field topologies. These investigations were able to demonstrate the key features which include generation of complex field topologies from 3D nozzle windings, generation of high temperature equations of state for water, thermal expansion inside the nozzle, and development of image currents on the surface of the plasma during the expansion against the field. Additional analytical modeling included 1D gas expansion estimates for Iₛ País impulse bit and calculation of magnetic field pressure required for confinement of the PPR fuel targets prior to ignition and burn.

A mission analysis of the PPR was also completed to show the benefits of a completed Pulsed Plasma Rocket design. This analysis solidifies the immense benefit in space travel times, and hence reduced radiation dosage to any crew as well, that comes from the high specific impulse and high thrust of this propulsion concept.

From these findings, the initial conceptual validity of the Pulsed Plasma Rocket has been extensively studied. Results showed that the propulsion system's basic constraints can be met, with the desired performance outcomes achieved. Further study is needed to fully solidify concept design and produce a firm, applicable conclusion for the Phase I results.
Further outcomes from the PPR project include the benefits of investigation into novel nuclear systems. Significant current and future focus of the PPR centers around transient nuclear behavior and plasma control. The ability to model transient nuclear systems can potentially lead to more advanced reactors for terrestrial power generation. Current systems use traditional power conversion systems, such as Rankine or Brayton cycles. The pulsed nature of the PPR and the energetic plasma it produces could potentially lead to the use of magnetohydrodynamic converters or complex dynamic nuclear systems.

In other applications, the PPR concept could be operated with no nuclear material in the bullet, with the drums and barrel instead providing the criticality, and the propulsion system could instead produce a jet of superheated steam or plasma. This type of system could be used in space for debris deorbiting to impart large momentum changes to wayward objects without needing to physically couple to the object, similar to the COBRa [17].

The high irradiance shield of the PPR could be used in other projects, potentially allowing for other thermonuclear spacecraft designs, the ability to pass extremely close to the sun, or even survive directed energy attacks from lasers.

These multiple applications of the Pulsed Plasma Rocket’s technological properties add to the beneficial outcomes of the project.

5.2 Areas for Further Investigation and Experimental Validation

Phase II will support three experimental efforts to support the design plan. Testing will take place in year 2, with year 1 being used to design the experiments:

1) Demonstration of the timing and efficiency of coil gun acceleration with a sub-scale bullet- The coil gun demonstration will include a physical prototype of the EM launching system to insert the projectile. The scaled model will include a functioning launcher as well as barrel and nozzle mockups. The projectile will be monitored during transit and computational models used to overlay neutronic and thermal models to the real-world example. Heaters, flywheels, pistons, or other aspects determined in the Subsystem Analysis section of the design plan will be included. Once constructed, this model will demonstrate the simplicity of the system and pave the way forward by showing timing, thermal, and support issues. This experimental demonstration will be performed by Hbar technologies through a subcontract and will take place in Year 2.

2) Demonstration of a pulsed magnetic field deflection of a plasma jet – This experiment will be performed by UAH through a subcontract in Year 2 and will involve validating SPFMax codes by altering a plasma with a pulsed magnetic field. The plasma jet facility at UAH will be used to generate the plasma, and an electromagnetic coil will quickly engage to alter the pathway of the plasma. Changes in the position and geometry will be measured and compared to the SPFMax modeling results to validate the code. The validated code will then produce the predicted Isp values for the PPR engine to be used in the design plan.
Additionally, the SPFMax software used in some of the electromagnetic system modeling for the plasma expansion remains in development. During the PPR study, an energy conservation technique was developed for preventing the observed problem of anomalously high particle acceleration resulting in large induced currents, which in turn amplify the field and the acceleration, leading to runaway particles and nonphysical results. Continuous improvements to the SPFMax system will allow higher-quality results for further design modeling. Ultimately, end-to-end simulations of PPR fuel ignition and expansion in 3D are the goal for the Phase II program.

3) Demonstration of the survivability of sapphire liner under extremely high-power density illumination- This experiment will compare the ability of an actively cooled transparent shield to better resist the photonic heating effects of a pulsed source than that of an actively cooled tungsten shield. The experiment will be performed at Howe Industries in Year 2, and will involve firing a high power, pulsed laser at both a tungsten plate and a transparent shield made of quartz. Howe Industries has a 30 Joule, 1ms laser and a 2.5 J, 2e-9 s pulse width laser to provide pulses capable of simulating a high intensity pulse of light commensurate with the PPR nozzle. This laser will be focused onto the target and fired repeatedly, as the target is actively cooled. Damage to both targets will be compared to assess the ablation rates and the optimal system selected for the final design.

6. Acknowledgements
We would like to acknowledge the NASA NIAC program for allowing us the opportunity to pursue this research effort.

7. References


