Development of a Head-End Ignition System for the Sustainer Motor of a Two-Stage Sounding Rocket

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The mission objective of Georgia Tech Experimental Rocketry (GTXR), a project team of the Ramblin' Rocket Club, is to reach the Kármán Line using a two-stage sounding rocket. The second stage "sustainer" motor implements head-end ignition (HEI) with an igniter that must operate in high-altitude, low-pressure environments. The solid propellant in the motor requires a high pressure buildup and heat in order to begin burning. GTXR found that commercial off-the-shelf (COTS) igniters are more susceptible to firing from electrostatic discharge, making them unreliable and unsafe. As an alternative, the team developed an ignition system using nichrome wire to combust iron (III) thermite and Boron-Potassium Nitrate (BPN), consequently igniting ammonium perchlorate composite propellant (APCP) cast into the igniter, which generates the required pressure and temperature to ignite the primary propellant grains. To develop the igniter, the team reviewed the thermodynamic properties of the potential reactants, iteratively tested the current and pressure thresholds needed for ignition, and sized the igniter from overall vehicle design constraints. This test campaign indicated a minimum of 5A of current is necessary for ignition, and provided a preliminary understanding of the pressure required and generated by the igniter. The findings of this investigation are instrumental in the development of future HEI systems, outlining effective chemical compositions and metrics for reliable ignition. Design specifications and further characterization of ignition pressures through vacuum testing are later discussed and analyzed.

I. Nomenclature

P	=	pressure in combustion chamber at time t, lb_f/in^2
δ	=	density of charge material, lb_m/in^3
Δ	=	loading density = C/V, lb_m/in^3
V	=	design volume of combustion chamber, in^3
C	=	original mass of charge, lb_m
λ	=	impetus = RT/M, in-lb_f/lb_m
R	=	universal gas constant, in.-lb_f/R-mol
T	=	flame temperature, °R
M	=	weighted mean molecular mass of gaseous products, lb_m/mol
G	=	fraction of original charge mass consumed by time
P_A	=	atmospheric pressure, psi

II. Introduction

The development of a reliable head-end ignition (HEI) system is vital to ensure the ignition of the second-stage "sustainer" motor of a two-stage sounding rocket. GTXR is a collegiate project team aiming to send the first two-stage solid-propellant sounding rocket to the Kármán Line, the 100 km altitude marker that formally defines the boundary between Earth's atmosphere and outer space [1]. GTXR is a project team under the Ramblin' Rocket Club, a registered student organization at the Georgia Institute of Technology, and GTXR's propulsion team focuses on the development and testing of solid rocket motors (SRMs).

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The success a SRM is contingent on a reliable and safe ignition, which is often done through the use of an electronic match (e-match). The sustainer igniter must also be able to reliably ignite at lower ambient pressures.

This paper outlines the design, manufacturing, testing, and integration of a pyrogen igniter made with iron (III) thermite and BPN as led by the GTXR igniter team in the 2024-2025 academic year.

III. Background

GTXR's solid propellant motors of GTXR are composed of a custom APCP formulation, GT-GOLD, which requires high pressure generation at the surface and sufficient heat to ignite. From previous igniter development investigations, the pressure at which the motor ignites was estimated to be 80psi, which led the team to aim for a build-up of over 80psi by the igniter puck in order to be considered reliable and successful. The historical ignition of these SRMs has been through the use of COTS ignition systems which utilize e-matches. However, these COTS systems can be dangerous due to the susceptibility of fire due to friction, impact, and electrostatic discharge [2].

To counteract this, GTXR has created a variety of experimental igniters, utilizing thermite, BPN, lacquer, black powder, and APCP. In place of the e-match, a 34-gauge Nichrome 80 bridgewire is looped onto copper wires, which is then inserted into a pyrogen igniter [3]. The bridgewire is buried into a combustible mixture that replaces the explosive charge on the e-match, and the mixture is placed in the hollow center of a miniature GT-GOLD grain that is cast into the igniter. To allow pressure to build up, the igniter is capped by a sheet of paper.

This year, the team evaluated a variety of combustibles, including iron (III) thermite ($Fe_2O_{3/}Al$), BPN ($BKNO_3$), GT-Gold (cast and powdered), and black powder (usually composed of potassium nitrate, charcoal, and sulfur). These compounds were further analyzed to choose the combination that would yield the best results with the most reliability. To assess effectiveness, the team utilized NASA'S Chemical Equilibrium with Applications (CEA) software to understand the thermodynamic properties of the reactants [4]. This was a valid method under the assumption that the gaseous products of the reaction behave as an ideal gas as suggested by the NASA report, "*Solid Rocket Motor Igniters*" [4, 5].

IV. Methodology

A. CEA

The team designed a preliminary pyrogen igniter design with 0.75 inches of 34-Gauge Nichrome 80 bridgewire that melts into a mixture of combustibles. While heat transferred from the nichrome can initiate combustion prior to the wire melting, melting was chosen as a requirement to begin ignition to reproduce results. CEA was used to determine which compounds make up the mixture of combustibles. The simulation operates under the assumption that the energy gained through combustion has already been added to the control volume, and thus the process is adiabatic [4]. The simulation was set up as a combustion at assigned volume problem, which kept the internal energy inside the volume constant under the assumption that the products of the combustion reaction behave as ideal gases [5]. Densities of the reactants (found in the Handbook of Chemistry and Physics) were calculated by measuring the mass of the three chemicals (BPN, thermite, and black powder) in a 3D-printed tube used for testing, which mimics the hollow center of the GT-GOLD grain cast in the pyrogen igniter [6]. The initial temperature of the reaction was set as the melting temperature of the nichrome bridgewire, 2552 °F, with the assumption that the powder in contact with the melted bridgewire would ignite first [7]. The temperature input was increased if the reaction did not occur from the melting of the nichrome to explore whether the exothermic burning of the other compounds could ignite the total mixture instead. The results of these simulations are found in Table 1.

Table 1 CEA Results For Each Compound

Compound	Simulated Ignition Temperature (°F)	Δ Specific Enthalpy (kJ/kg)	Pressure (psi)	Final Temperature (°F)
Iron (III) Thermite	5030.33	5897.93	29066.43	11177.24
BPN	2552	4909.48	135325.58	13017.34
Black Powder	2552	12905.2	258048.24	17562.128

The output of the CEA problem highlights the dramatic change in temperature and pressure for black powder. However, due to the risk of bursting the paper seal of the pyrogen igniter prior to ignition of the GT-GOLD within the igniter, the team was hesitant to use a combustible that generated pressures as high as black powder, and BPN combustion was the preferred method to build pressure within the igniter. Iron (III) thermite was chosen to be used in conjunction with the BPN due to the highly exothermic nature of the reaction, highlighted by the change in specific enthalpy of the reaction. Although iron (III) thermite requires a higher temperature to react than provided by the nichrome bridgewire, the BPN reaction provides a sufficient increase in temperature for the thermite reaction to occur. This indicates that ignition would be composed of a multi-stage reaction, with the melting nichrome causing the ignition of the BPN, then causing the ignition of the iron (III) thermite, which then ignites the GT-GOLD pyrogen grain, before igniting the sustainer motor grains.

B. BPN to Iron (III) Thermite Ratio

To evaluate the optimal ratio of BPN to thermite, both reactants were combined in a combustion at assigned volume problem. The problem was run with the BPN mass fractions of 40, 43, 45, 47, 50, 53, 57, and 60 percent. The initial temperature of the reaction was set as the melting temperature of nichrome, 2552 °F. The resulting pressures, temperatures, and change in specific enthalpy relative to the percent weight of BPN are graphed in Fig. 1 through Fig. 3 respectively.

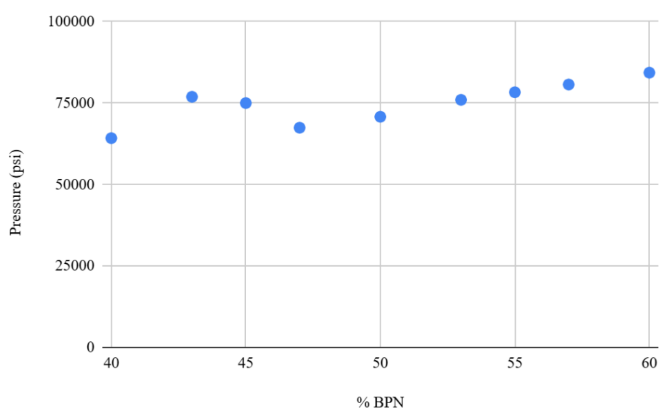

Fig. 1 Percent Weight of BPN vs Pressure

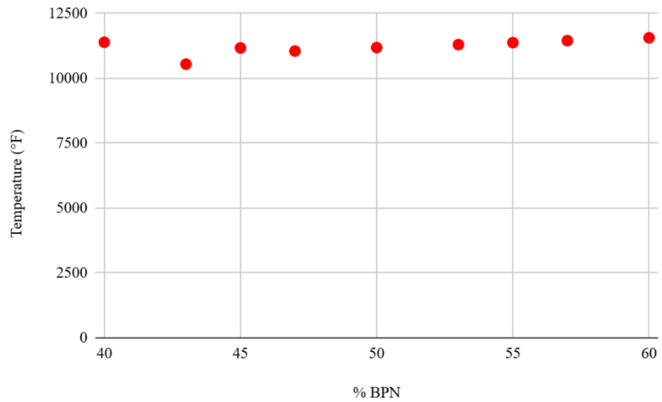

Fig. 2 Percent Weight of BPN vs Temperature

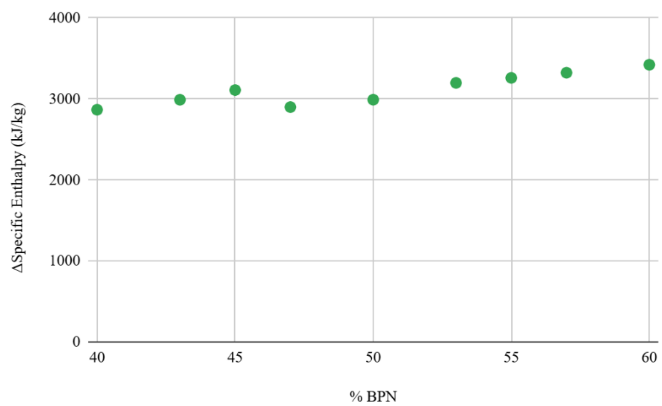

Fig. 3 Percent Weight of BPN vs Change in Specific Enthalpy

As demonstrated by the CEA results, an optimal percentage of BPN would be 60% due to the greatest change in specific enthalpy, pressure, and temperature. However, large batches of a BPN and thermite mixture containing 43% BPN had already been manufactured in previous years. To pursue a solution that was both economical and effective, the team this year moved forward with a 43% BPN, 57% iron (III) thermite solution due to its ability to develop higher pressure, compensating for a lower increase in temperature and change in specific enthalpy.

C. Ignition Pressure

The volumes of the BPN-thermite mixture and the GT-GOLD pyrogen grain take up within the igniter were determined based on vehicle design constraints. The BPN-thermite mixture is placed in a volume of $0.197in^3$, as this is the volume required for the insertion of two nichrome bridgewires. The volume of the GT-GOLD is $0.98in^3$, as this is the remaining volume available within the sustainer motor to house the igniter. To evaluate whether or not this geometry provides ample pressure for ignition, the equation of state describing chamber pressure due to ignition was used. The equation of state (1) of the gases released by the igniter calculates pressure under the assumption that the ignition process is adiabatic and that the products behave as an ideal gas [5].

$$P = \frac{\delta}{\delta - \Delta}\Delta\lambda G + P_A \tag{1}$$

The equations for ignition of the BPN-thermite mixture and the ignition of the GT-GOLD were set up under different conditions. The loading density of the BPN-thermite was calculated by setting the design volume of the combustion chamber (V) as $0.197in^3$, since the combustion reaction initially occurs within the sealed igniter. The atmospheric pressure was set to 0 to account for that initial state. For the GT-GOLD reaction, V was set as the volume of the sustainer motor's combustion chamber prior to propellant ignition. Atmospheric pressure was set to 6.75psi since the seal on the igniter would have burst and the inside of the sustainer could be exposed to atmospheric pressure at the altitude of ignition, which is approximately 20,000ft. Estimates of λ, the impetus, for GT-GOLD and BPN were found [5]. The impetus of the thermite was derived using the results of the 43% BPN CEA problem. G was set as 1 to calculate the total pressure built by the reaction.

The resulting pressure of the GT-GOLD reaction is calculated to be 447.78psi, and the BPN-thermite reaction results in 1861.82psi. The BPN-thermite reaction will likely not develop that pressure since the equation was solved under the assumption that the seal doesn't break. However, even considering the loss of pressure from the seal bursting, it is likely that the pressure experienced by the GT-GOLD pyrogen grain will be enough to ignite it. While this equation operates under ideal gas and adiabatic assumptions, the pressures generated with this igniter geometry are far greater than the estimated 80psi required for GT-GOLD ignition.

D. BPN-Iron (III) Thermite Ignition Testing

HEI for the sustainer motor requires ignition via an ignition board developed by GTXR's avionics team. To determine the amount of current the board needs to provide for instantaneous ignition, the igniter development team performed rigorous ignition testing using a benchtop power supply to supply power to the igniter. During the tests, a controlled current was supplied through the Nichrome bridgewire and copper wire configuration to combust 43% BPN and 57% iron (III) thermite powder. In each test, the nichrome wire was buried in the BPN-thermite mixture. Each test was timed with a stopwatch and enough current was supplied to entirely melt the nichrome. For this reason, 2A of current was set as the lower boundary of current supplied for ignition testing, as this was the lowest current supplied where the nichrome would melt within 1 second. 7A was set as the upper boundary as this is the maximum current the ignition board can supply. To determine the current required for instantaneous ignition, the team performed multiple tests at increasing currents ranging from 2A to 7A, at increments of 0.5 Amps. The stopwatches utilized measured to an accuracy of 0.01 seconds, and times less than this accuracy range were considered negligible and noted as 0 s. The average ignition time taken from three tests at each amperage is listed in Table 2.

Table 2 Ignition Time at Each Amperage

Amperage	Time (s)
2.0	0.82
2.5	0.56
3.0	0.33
3.5	0.12
4.0	0.12
4.5	0.00
5.0	0.00
5.5	0.00
6.0	0.00
6.5	0.00
7.0	0.00

Testing indicated that 4.5A of current was enough to melt the nichrome wire and ignite the thermite and BPN. The igniter and avionics teams decided to provide 5A of current from the ignition board for added reliability.

E. GT-GOLD Ignition Testing

To evaluate the dependency of GT-GOLD ignition on the loading density as suggested by the equation of state (eqn. 1), GT-GOLD in fine grain powder form and flake form of varying masses were ignited with e-matches in both closed and open air conditions. Mass was varied to evaluate whether the combustion of GT-GOLD would propagate through all of propellant because the loading density of the combusting GT-GOLD increases when buried within GT-GOLD that has yet to ignite. All e-matches were fired successfully, but not all batches of GT-GOLD ignited. The results are shown in Table 3.

Table 3 Ignition Effects of Powder and Flake Samples in Open Air and Closed Environments

Mass (g)	Powder or Flakes	Open Air or Closed	Effect
2.1	Powder	Closed	Ignited
2.1	Powder	Open Air	No effect
3.1	Powder	Closed	Ignited
4.2	Powder	Open Air	Charred surface, no ignition
5.7	Powder	Open Air	Ignited
6.5	Flakes	Open Air	Charred surface, no ignition
8.6	Powder	Closed	Ignited
9.75	Flakes	Open Air	Charred surface, no ignition
13	Powder	Open Air	Ignited
19.5	Flakes	Open Air	Ignited

Testing indicates that the chances of ignition increase in enclosed containers as opposed to open containers due to higher pressure buildup in enclosed volumes, which have higher loading densities. This is exemplified in how 4.2g of GT-GOLD powder exposed to open air only experienced charring at the surface in contact with the e-match, while 2.1g and 3.1g of powdered GT-GOLD ignited successfully due to the closed container. The increased volume around the e-match in open air condition prevents the build up of ample pressure, preventing the GT-GOLD from igniting. Flakes of GT-GOLD seemed to have greater difficulty in igniting than the powder, potentially because the gaps in the flakes did not form a compact layer around the e-match, decreasing loading density. The reactant surface area of the flakes was also less than the powder. These results are applicable to the BPN and thermite mixture due to the similarities in the combustion reactions. This test highlights the need for the BPN and iron (III) thermite mixture to be finely powdered and densely packed into the GT-GOLD pyrogen grain. Additionally, the nichrome bridgewire needs to be entirely encapsulated in the powder mixture and the igniter needs to be sealed shut to ensure ignition.

F. Vacuum Testing

To ensure the ignition of the formula at the ambient pressure conditions at which the sustainer motor will need to ignite, the team tested the igniter in a vacuum chamber. The use of a vacuum chamber also allows for the measurement of the pressure produced by the igniter in a controlled environment.

The vacuum setup consisted of the Sanatron Acrylic Vacuum Chamber and the Across International Supervac Vacuum Pump 5C, which has a 5.6 cubic feet per minute flow rate and can pull to -101kPa [8]. The chamber also contains external wiring to the inside of the chamber, which were used to connect to the igniter and an altimeter, which was used to measure chamber pressure. The pump and chamber were connected through a hose that was clamped to the the chamber and the pump on either end, and the tight seal of the connections was tested through leak checks and tests with the altimeter to ensure vacuum was being pulled. The chamber was set up to be fully connected to the pump with an altimeter set inside in the furthest corner of the chamber, and a test element containing either BPN-thermite mixture or GT-GOLD propellant dust (and embedded with a nichrome wire) was put into the chamber on top of a metal block. The chamber was then closed and locked, and the altimeter was turned on to begin reading pressure. From there, the pump began to pull vacuum for around 4 minutes , after which it was turned off and the inlet valve was closed, to seal the chamber. The wiring was then connected to a 9V battery to begin the ignition, which was timed and video-recorded. At the end of the burn, the chamber was vented from the exhaust valve and the altimeter recording was stopped.

Preliminary results from the altimeter indicated that the vacuum chamber was depressurized to 1.9psi. The ignition of the sustainer motor nominally occurs around 20,000ft above the Earth's surface, where ambient pressure is around 6.75 psi, indicating that the igniter would easily ignite the motor under the ambient conditions at the projected altitude

[9].

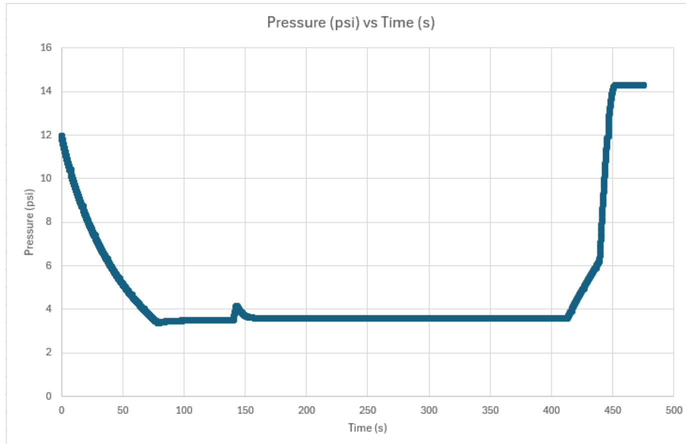

Fig. 4 Pressure vs. Time for Total Vacuum Test

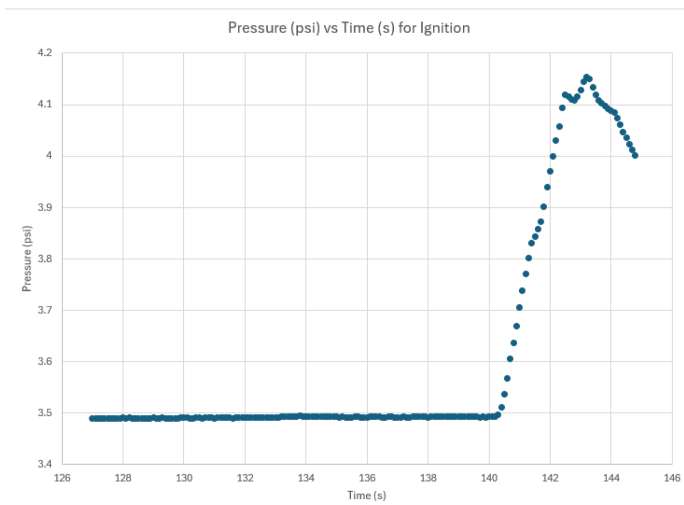

Fig. 5 Pressure vs. Time at Ignition

Under the assumption that the pressure inside the motor (which will be lightly plugged before the motor burn) is higher than the ambient pressure outside the motor, these results boost confidence in the reliability of the motor ignition at high altitude conditions.

G. Data Reduction

The analysis of the altimeter data was processed using Microsoft Excel. Most of the data was already digested within the Altus Metrum altimeter software, and the Excel files were used to derive the graphs in section IV.F.

Two methods were used in order to calculate the ideal pressure generated within the igniter test article: the state equation (1) with the experimental results of the vacuum chamber testing referenced in section IV.C and CEA-based analysis [5]. The relationship below (1) yielded a result of 1863.72psi. In the CEA method, the simulation was used to find the specific heat at constant pressure (C_p) and specific enthalpy (dh) of the test article during ignition. Using these values, applied equation 2 to find the temperature of the test article, assuming that the chamber temperature was the initial temperature of the test article.

$$dh = c_p dT \tag{2}$$

Then, equation 3 was used to find (p_1). The inputs to the equation are $v_1 = 1 \times 10^{-6} m^3$, $T_1 = 17.86K$ (as found through the CEA, $p_2 = 4554.00Pa$, $v_2 = 0.1310965Pa$, and $T_2 = 291.05K$.

$$\frac{p_1 v_1}{T_1} = \frac{p_2 v_2}{T_2} \tag{3}$$

The result of these calculations was a pressure of 5259.928psi within the test article. The variance between the ideal and experimental values for pressure could be attributed to the various assumptions applied to the equations. The ideal pressure was calculated with the ideal gas model within the CEA simulations, the assumption of a closed control volume (whereas the test article has no seal), and the assumption of adiabatic and isothermal reactions make our calculations a highly idealized version of the realistic reaction. Although both pressure values are quite large, this is attributed to the small volume of the test article itself, which would generate a large amount of pressure under the previously listed assumptions. The data, however, remains relevant as it provides a general experimental understanding of the pressure created by the BPN-thermite mixture. Even considering that pressure is lost to the surroundings due to the opening at the top of the test article, the testing provides additional assurance that the build up in pressure within the igniter (due to the combustion of BPN and thermite) could be sufficient to trigger ignition of the GT-GOLD pyrogen grain. Further investigation with the equivalency of the two control volumes (between the igniter test article and the vacuum chamber environment) will be necessary for future analysis.

V. Results and Discussion

A. The Igniter

The team developed a pyrogen igniter with a GT-GOLD grain, BPN, and iron (III) thermite. The weight ratios of the BPN and thermite are 43% and 57% to maximize the pressure generated by the mixture. 5A of current will be supplied to melt a 2 0.75in long 34-gauge Nichrome 80 bridgewire to begin the instantaneous ignition of the igniter. The heat transfered from the melted nichrome causes the combustion of the BPN, which then causes the combustion of the iron (III) thermite. Collectively, the BPN and thermite will build enough pressure and heat to ignite the GT-GOLD pyrogen grain, which then causes the ignition of sustainer motor. To increase the pressure within the igniter, it is sealed with paper. The GT-GOLD pyrogen grain has a volume of $0.98in^3$ and the BPN and thermite make up a combined volume of $0.197in^3$. Since testing highlighted the need to maximize the loading density and contain the combustion reactions in a small volume to increase the generated pressure, the Nichrome bridgewire is encased in finely powdered BPN and Iron (III) Thermite, and the powder is packed densely into the GT-GOLD grain. This is shown in Fig. 6, where the red cylinder is the BPN and thermite that is packed into the gray GT-GOLD grain.

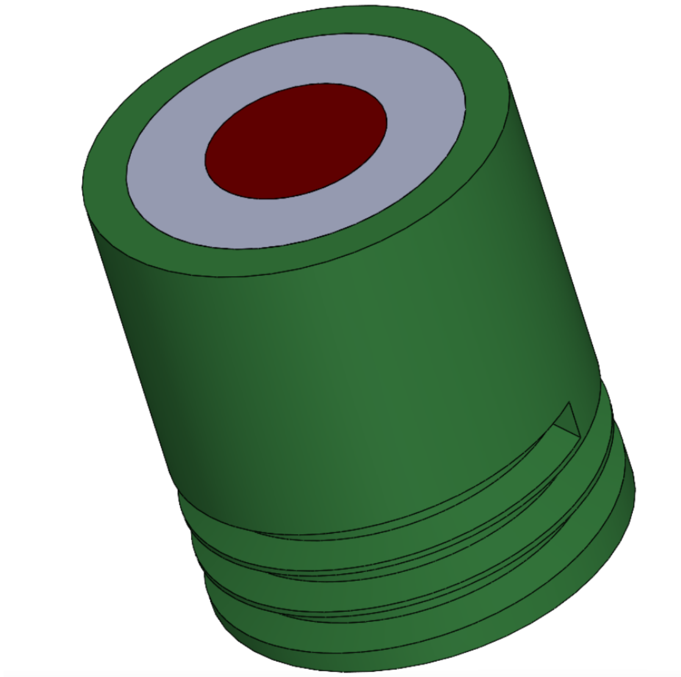

Fig. 6   Final Igniter Design

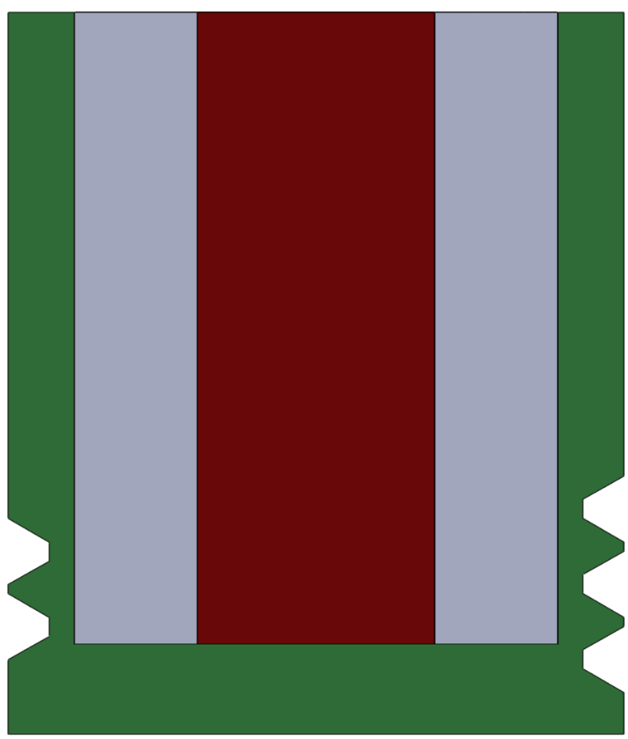

Fig. 7   Cross Section of Igniter

B. Head-End Ignition System

The pyrogen igniter will be integrated with a threaded insert in the forward closure of the SRM, and will extend into the sustainer motor grains to initiate the burn. The igniter is connected to an ignition board which supplies 5A of current to the two nichrome bridgewires when a flight computer sends the sustainer ignition command. The wire connections pass through a 1/4inch NPT Passthrough that is screwed into the forward closure, as seen in Fig.8 .

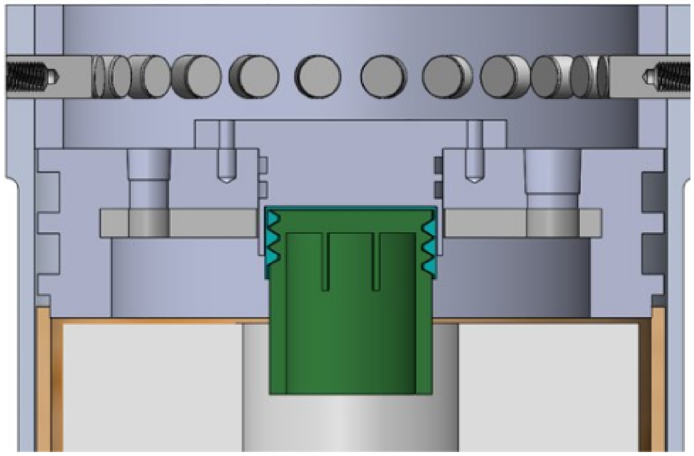

Fig. 8 Forward Closure Integration with Igniter Puck

C. Significance and Next Steps

This ignition system is the basis for future HEI systems within GTXR. If successful during launch of GTXR's *Live and Let Fly Vehicle* in July 2025, the reliability of this system for sustainer motor ignition will be proven. This igniter reliably ignites at lower ambient pressures within the vacuum chamber than the ambient pressure at the current ignition altitude, suggesting it could be used in future motors with higher ignition altitudes. To continue the development of reliable and efficient HEI systems, next steps are to include further vacuum testing of the ingiter formula, particularly to refine pressure and temperature analysis, as well as testing a fully assembled igniter to see how it may perform under ignition conditions. Further investigations include both theoretically and experimentally assessing the heat required and produced at every step of ignition and whether less pressure is required when heat requirements are met. Additionally, alternative ratios of BPN and iron(III) thermite should be explored.

Acknowledgments

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